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Water Recovery Final Report

D 2.5.2 Recovery & optimization of water

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DECEMBER 2021

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NEREUS FINAL REPORT

D 2.5.2 Recovery & optimization of water

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DECEMBER 2021
MIDDELBURG, THE NETHERLANDS

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1 Introduction

The NEREUS (New Energy and Resources from Urban Sanitation) Project is an Interreg 2 Seas project with a consortium of 8 project partners across the United Kingdom, the Netherlands, Belgium, and France, working on the goal of recovering valuable resources from domestic wastewater. The partners working on this project were VITO NV, DuCoop CVBA, water-link, Agglomeration of Saint-Omer (CAPSO), HZ University of Applied Sciences, University of Portsmouth Higher Education Corporation, Southern Water Services Ltd and Evides Industrial Water B.V.

The project was born from a combination of global pressures, such as the scarcity of freshwater and finite resources, as well as the desire to increase the reuse of wastewater. To achieve this, the project aimed for the adoption of technologies that recover important resources and enable the principal of a circular economy in the 2 Seas region[1].

The focus was to treat municipal/domestic wastewater, in order to transform it into valuable resources, and/or to efficiently remove micro-pollutants, resulting in reusable water as a final product. Hence, in order to achieve the desired objectives, NEREUS ran from October 2017 to December 2021, and during that time, focused on the recovery and reuse of water, resources (e.g. nutrients), and energy.

As domestic wastewater contains finite nutrients in its composition, such as phosphorus, nitrogen, potassium, and calcium, it offers significant potential for reuse. Additionally, it also contains energy and heat, that can be used as a sustainable source of energy in order to reduce CO_2 emissions. Therefore, wastewater treatment can lead to the recovery of these important environmental assets, along with water reuse as irrigation, process, or even drinking water. Thus, NEREUS partners have set up several demo cases to investigate and demonstrate these possibilities.

This report specifically presents and discusses results achieved among project pilot partners, Evides, water-link and DuCoop, who aimed to recover water from their wastewater streams. It also compares results regarding technologies used, recovered products, product quality and process optimization.

[1] 2Seas region: Covers coastal areas of England, France, Belgium (Flanders) and the Netherlands which are connected by the Channel and the North Sea (Interreg 2 Seas, n.d.)

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2 Pilot plants

As mentioned, this report will investigate water as a resource which was recovered by the project partners Evides (NL), water-link (BE) and DuCoop (BE). In order to be able to recover water from urban wastewater, each partner designed, built and operated a pilot scale wastewater treatment plant upon which they could perform their research. These three particular pilot plants varied greatly in size and focus; Evides has had two pilot plants over the course of the project which tested numerous technologies to recover many resources, including water. Water-link also had several pilot locations over the duration of the project; covering small scale domestic and commercial scale. DuCoop had a unique approach which was a treatment plant in the basement of an apartment building, treating and recovering resources from the wastewater produced by the apartments.

2.1 Evides Industry water

Evides is a Dutch water company involved in many aspects of water treatment, such as producing drinking and process water and treating domestic and industrial wastewater. Along with this, they develop, with their partners, sustainable solutions to recover valuable resources. In the NEREUS project, it was the branch Evides Industry Water who were a project partner and who ran the pilot plant.

Evides focused on the recovery of all three central products with their treatment train. The pilot was initially located in a commercial area in Rotterdam with the aim of delivering recovered resources and irrigation water back to an urban farming restaurant (*Uit Je Eigen Stad*). However, due to changes in circumstances involving the restaurant that were outside the control of Evides, the pilot location was moved to *Harnaschpolder*, *Den Hoorn*, where resources are recovered from a municipal wastewater treatment plant (WWTP).

2.1.1 Stream profile

The term stream profile refers to the characteristics of the influent stream that is entering the pilot location and from which the resources and water will be recovered. As previously introduced, domestic wastewater was the chosen wastewater type to be treated. It can be divided into different streams according to their origin and composition: black water, which is water from toilets, and grey water (GW) from showers, laundry, and kitchen (de Graaff et al., 2010; Luostarinen et al., 2007).

According to de Graaff et al. (2010), these sources should be treated according to their quantity and composition, in order to achieve a successful resource recovery. Table 1 presents general compositions of both black (BW) and grey water. In this report, for each plant, the type of wastewater is identified, and its composition is presented.

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Table 1 - Average characteristics of domestic wastewater, black water, and grey water

Parameter (mg/L)	Domestic wastewater	Black water	Grey water
BOD	350	300 – 600	100 – 400
COD	750	900 – 1500	200 – 700
Total nitrogen (TN)	60	100 – 300	8 – 30
Total phosphorus (TP)	15	40 – 90	2 – 7

Note. Adapted from Henze & Yves, 2008

COD: Chemical Oxygen Demand

BOD: Biological Oxygen Demand

The stream profile of the Evides pilot plant can be classified as grey water and domestic wastewater, respectively *Uit Je Eigen Stad* and *Harnaschpolder.* These streams can be found in Table 2 and 3. A view inside Evides' pilot plant, in Den Hoorn, is presented in Figure 1.

Table 2 - Uit Je Eigen Stad stream profile

Parameter	Unit	Value
Average Daily Flow	m^3/h	2.9
TSS	mg/L	25
COD	mg/L	58
BOD	mg/L	18
Total Kjeldahl nitrogen (TKN)	mg/L	15
Total nitrogen (TN)	mg/L	16
Total phosphorus (TP)	mg/L	1.4

Table 3 - Harnaschpolder stream profile

Parameter	Unit	Value
Average Daily Flow	m^3/h	2.9
TSS	mg/L	270
COD	mg/L	550
BOD	mg/L	240
Total Kjeldahl nitrogen (TKN)	mg/L	55
Total nitrogen (TN)	mg/L	67
Total phosphorus (TP)	mg/L	8

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Figure 1 - Evides' pilot plant in Den Hoorn

2.1.2 Recovered resources

As mentioned in section 2.1.1, Evides' train initially was meant recover irrigation water to be reused at an urban farming restaurant (*Uit Je Eigen Stad*). Due to the change of the plant to *Harnaschpolder* WWTP, Evides no longer had an end user for their recovered water. However, the main goal remained as recovering irrigation water at the permeate stream of a reverse osmosis unit.

2.2 Water-link

Water-link is a Belgian water company and is the biggest water-producer in Flanders, delivering drinking water (DW) to the households and businesses in Antwerp, and in several different qualities for industries. The main customers are chemical and petrochemical companies in the harbour of Antwerp (NEREUS Project, 2018). The company aims to contribute to the circular economy and to focus on eco-design (Water-link, n.d.), by investing in resource recovery from wastewater.

Over the duration of the NEREUS project, for varying reasons, water-link have had several pilot locations. Water-link's first pilot plant was located in the new city district *Antwerp Nieuw Zuid*, and aimed to recover drinking water from kitchen wastewater of a restaurant and event location named *Plein Publiek*. Figure 2 shows a photograph of pilot location one at *Plein Publiek*; the treatment train itself was housed in a shipping container adjacent to the property.

Due to changes involving the event location water-link were no longer able to continue their water treatment at this location, therefore, the pilot was then moved to *Aquafin* WWTP (the third location). The goal is to treat the WWTP's effluent with an UF/RO setup, and examine the permeate as a new source for drinking water production. This phase started in October 2021.

The second pilot location ran parallel to the first and was a residential unit located in the basement of an employee of the water-link company. This residential unit had the aim of treating the grey water from the house and transforming it into drinking water to be used by the residents themselves. Figure 3 shows a photograph of this residential pilot. After the NEREUS trial, this unit was further used, in 2021, as a trial set up for testing several different kinds of wastewater. The processes and results of these trials and at *Aquafin* are therefore not covered within this report.

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Figure 2 - Water-link's pilot plant

Note. The pilot plant is situated in this photograph at *Plein Publiek*, later moved to *Aquafin*

(W. (Waterlink) Bossaerts, 2021)

Figure 3 - Water-link's residential unit

(W. (Waterlink) Bossaerts, 2021)

2.2.1 Stream profile

The stream profile of the effluents that water-link treated can be classified as grey water. Specifically, Plein Publiek stream was a heavy grey water, because it was a mixture of kitchen and sinks, whilst the stream from the residential unit was classified as light grey, containing only shower/bath/sink water. These stream characteristics are presented in Tables 4 and 5, which show the differences between heavy and light grey water, respectively. As explained in section 2.2, the pilot used in *Plein Publiek* moved, in October 2021, to be used at the WWTP *Aquafin*. Therefore, its effluent is the feed of the new pilot, and its composition is presented in Appendix A, Table A1.

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Table 4 - Plein Publiek stream profile

Parameter	Unit	Value
Average Daily Flow	m^3/h	1.40
Min – Max pH	-	6.60 – 6.90
Average pH	-	6.75
Conductivity (EC)	mS/cm^2	0.65
COD	mg/L	680.00
Total Nitrogen (TN)	mg/L	15.60
Ammonium (NH_4 – N)	mg/L	4.40
Total Phosphorous (TP)	mg/L	2.10
Zinc (Zn)	mg/L	0.15
Copper (Cu)	mg/L	0.04
Iron (Fe)	mg/L	0.36
Titanium (Ti)	mg/L	0.19
Aluminium (Al)	mg/L	0.58

Table 5 - Residential unit stream profile

Parameter	Unit	Value
Average Daily Flow	L/d	250
Average pH	-	7.25
Conductivity (EC)	mS/cm^2	1600.00
COD	mg/L	12.00
Kjeldahl nitrogen	mg/L	0.82
Ammonium (NH_4 – N)	mg/L	0.90
Phosphate (PO_4 – P)	mg/L	0.16
Zinc (Zn)	µg/L	<60.00
Copper (Cu)	µg/L	47.00.00
Iron (Fe)	µg/L	<100.00
Aluminium (Al)	µg/L	<100.00

2.2.2 Recovered resource

Water-link proposed to produce high-quality drinking water with an expected recovery of 75-80%. Initially, starting in 2017, the company tested the water production from kitchen wastewater of pop-up restaurant and event location *Plein Publiek*, in order to validate the proposed processes and technologies. Then, in 2018, a similar group of technologies served at a residential unit, located in the basement of the home of one of water-link's employees. Both units aimed to transform wastewater into drinking water

Within the NEREUS project, water-link invested in new concepts for decentralized drinking water production. The whole process was initially built to have a low energy consumption and was meant to enable water-link to close the process loop and ensure a circular economy.

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2.3 DuCoop

DuCoop is a Belgium cooperative that provides sustainability services to the residents of *De Nieuwe Dokken*, an urban district in the city of Ghent. With their services, they contribute to combatting climate change by closing loops: energy (heating, electricity and mobility), water and raw materials (waste treatment) (DuCoop, n.d.). The mentioned urban district, where the company's pilot plant is located, is presented in Figure 4.

Within the NEREUS project, DuCoop focused on recovering water and energy with innovative technologies. They aimed to demonstrate a scalable design for use in sustainable urban districts, and also, to contribute to the development of new sustainable business models with smart energy management (NEREUS Project, 2018). Figure 5 shows a photograph of part of the treatment plant situated in the basement of the apartment building at *De Nieuwe Dokken.*

Figure 4 - De Nieuwe Dokken district

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Figure 5 - DuCoop's wastewater treatment plant at De Nieuwe Dokken

2.3.1 Stream profile

DuCoop treated two different types of effluent: black water, from sanitary and kitchen waste, and grey water from residential washing machines, shower, etc. The black water was not treated within the scope of the NEREUS project, however, the treated black water was used as part of the influent of the treatment train covered in this report and the NEREUS project, as seen in *section 3.3.1*. Therefore, the characteristics of the black water stream can be found in Appendix A, Table A2, and the characteristics of the grey water stream is presented in Table 6.

Table 6 - Nieuwe Dokken's (grey water) stream profile

Parameter	Unit	Value
Average Daily Flow	m^3/d	11.4
pH		7.4
COD	mg/L	1439.0
Total Nitrogen (TN)	mg/L	149.0
Total Phosphorous (TP)	mg/L	43.0

Note. Data concerns the influent quality during August 2021.

2.3.2 Recovered resource

Figure 6 shows a visual representation of the resources DuCoop aimed to recover and from which stream at *De Nieuwe Dokken*. Their specific goal for water was to recover process/industrial water from grey and black water, being collected and treated at the urban district itself. After purification, it gets a second life as process water at the neighbouring company *Christeyns,* a soap factory.

With this process, they aimed to guarantee adequate removal of water pollutants in a decentralized wastewater treatment plant with a small footprint. Hence, contributing to mitigating challenges regarding climate change and depletion of natural resources. When *De Nieuwe Dokken* is at full capacity the treatment plant will be capable of recovering 30,000m^3 of water per year, which is >90% of total consumption (NEREUS Project, n.d.)

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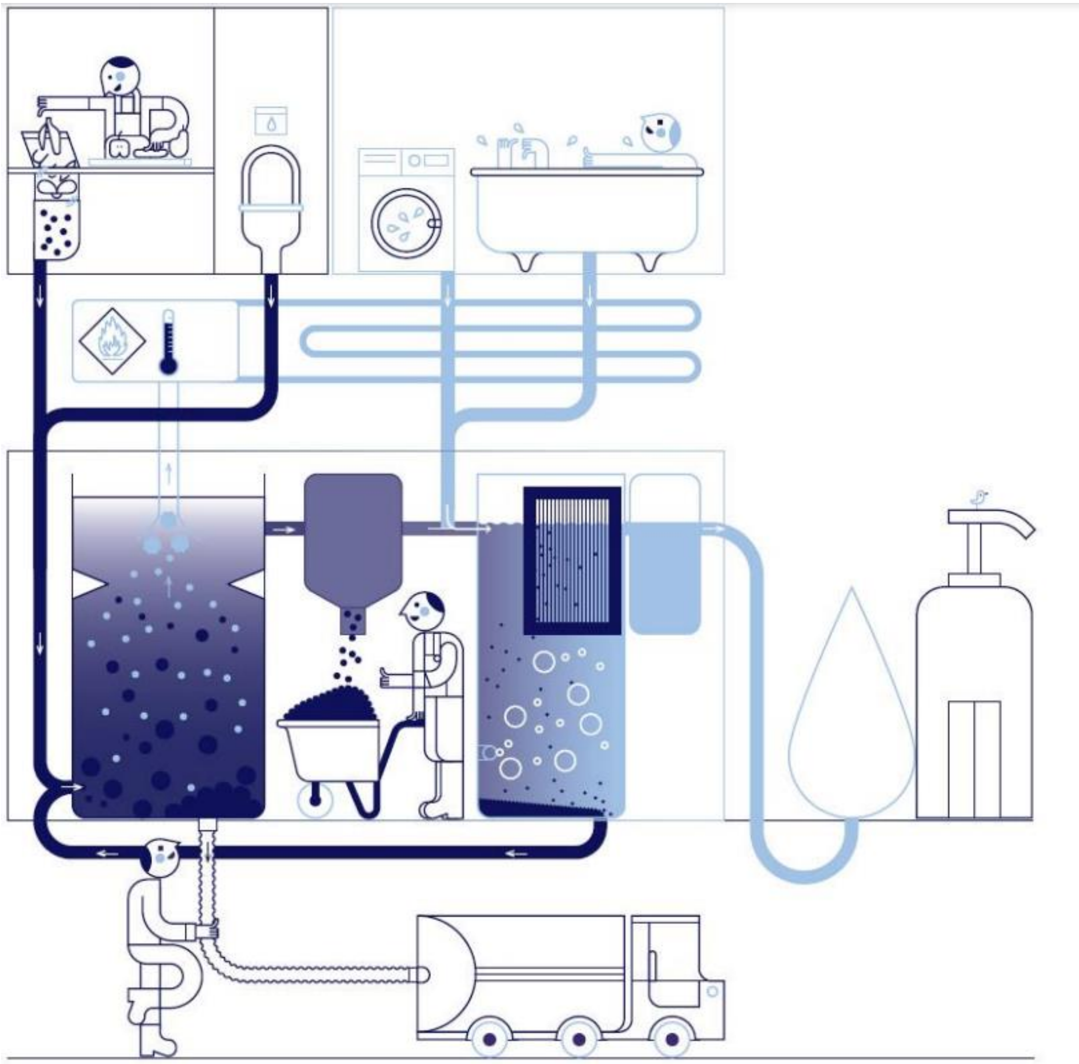

Figure 6 - Illustration of the resources being recovered at De Nieuwe Dokken

Note. The figure shows the different sources of wastewater and their use for resource recovery. Black water is treated together with kitchen waste for nutrient and energy recovery (biogas). Grey water is converted into process water, where the waste heat of the process is also recovered.
(DuCoop, 2018)

3 Methods

In order for the intended resources to be recovered from the source wastewater, a treatment train made up of various technologies was designed and installed at each pilot plant. The complexity of the treatment train was dependent on the resource or in some case number of resources to be recovered. In this chapter, a process flow diagram and technology description per pilot partner is reported.

3.1 Evides Industry Water

3.1.1 Process flow diagram

Figure 7 shown below contains Evides' process flow diagram involved in the water recovery route (highlighted in the diagram):

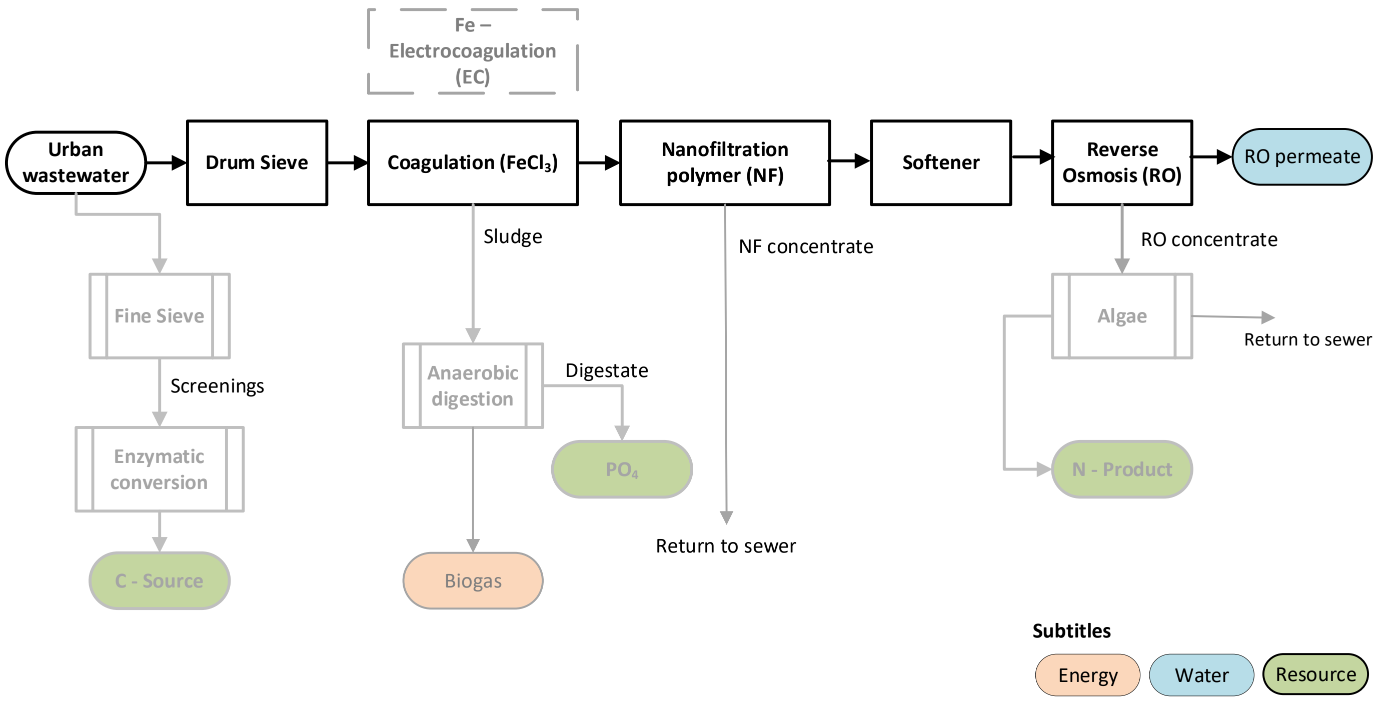

Figure 7 - Evides' water recovery process flow diagram

3.1.2 Technologies

A treatment train containing various technologies was used to recover water, as shown in Figure 7. These technologies are described below:

- Sieves: Sieves are perforated metal plates, commonly applied as a primary treatment, as they aim to remove large particles from the wastewater (VITO, 2010). Therefore, to fulfil the EU Council Directive criteria, 1991, it must remove at least 20% of organic matter, measured as biological oxygen demand (BOD), and 50% of the total suspended solids (TSS)(Council Directive, 1992).

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In Evides pilot plant, two different types of sieves were used: drum and fine sieve. The drum sieve consists in a rotating perforated drum, in which the fluid passes through, whilst retaining the solid particles (Trevi, n.d.; VITO, 2010). This technology was used as a primary treatment for water purification.

- Electro-coagulation (EC): Consists of pairs of metal sheets called electrodes, that are arranged in pairs of anodes and cathodes, made of iron (Fe) (Naje & Abbas, 2013; Rodrigues, 2019). To achieve the coagulation, a metal with positive charge is required, as it will neutralize the negative charge of dissolved and suspended particles in the water (Safe Water, n.d.). When using the EC, the electrochemical reactions needed to achieve the coagulation are induced by a direct current electric field applied to the electrodes (Naje & Abbas, 2013; Rodrigues, 2019). Therefore, the particles will attach to each other and form large agglomerates that settle to the bottom.

  In this research, the EC was initially used with the aim for phosphorus recovery and water treatment. At this part of the process, dissolved and suspended particles coagulate and are removed from the water as sludge.

  After a period of testing running the pilot with EC, Evides decided to change it to a traditional coagulation process with iron (III) chloride ($FeCl_3$) dosing.

- Chemical coagulation ($FeCl_3$): Coagulation is a conventional process, in which chemicals are added, and react with colloidal particles to form large aggregates. These can then be more easily and rapidly removed by flocculation or membrane filtration (Oriekhova & Stoll, 2014). According to Racar et al., (2017), some conventional coagulants are ferric or aluminum salts, that enable the formed aggregates to be removed as sludge.

  This process was applied in order to replace the EC unit, by dosing $FeCl_3$, as coagulant. Although following a different method, it was still used to remove the colloidal particles, as an initial treatment for water.

- Nanofiltration (NF): Is a pressure-driven membrane process, for liquid-phase separations, used to remove solutes with low molecular weight (Mulyanti & Susanto, 2018). Nanofiltration membranes have a characteristic pore size of 1 – 5 nm and its operating pressure varies between 7 – 30 bar. Therefore, its properties are classified between non-porous Reverse Osmosis (RO) membranes (where transport is governed by a solution-diffusion mechanism) and porous Ultrafiltration (UF) membranes (where separation is usually assumed to be due to size exclusion and, in some cases, charge effects) (Shon et al., 2013). Furthermore, these membranes have negative surface charge at neutral pH, which influences the rejection of cations. Consequently, both charge effects and sieving mechanisms influence the rejection behavior of solutes in NF membranes (Al-Amoudi & Lovitt, 2007; Rodrigues, 2019), making it highly selective.

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Water that leaves the coagulation unit was used to feed the nanofiltration operation, aiming to remove cations, polyvalent ions, and organic matter. Their unit consisted of two stages (first stage 2 membrane modules, second stage 1 membrane module). The compounds that were retained by the membrane are the concentrated phase and were returned to the sewer. Cleaner water, with ion species that permeated the membrane, flow to the next process unit. To achieve their goals, Evides used a 800Da polymeric membrane.

- Softener (Ion exchange): Water softening is a technique that serves the removal of the ions that cause the water to be hard, in most cases calcium and magnesium ions (Lenntech B.V., n.d.). Ion exchange (IX) is one of the most utilized techniques for softening, due to low energy requirements and its high performance on removing monovalent and divalent ions, although it has high chemicals costs (Claudia & Vassilis, 2014)

  Evides used SAC resins in their IX columns in order to demineralize water prior to going to the RO unit. These resins can neutralize strong bases and convert neutral salts into their corresponding acids, and are utilized in most softening and full demineralization applications (SUEZ, n.d.)

- Reverse Osmosis (RO): Reverse osmosis is a process for desalinating water using membranes that are permeable to water but essentially impermeable to salt. Different to other membrane processes, such as NF, RO membranes are dense and do not have distinct pores (Baker, 2004). This technology consists of the inverse of the natural osmosis. That means that in this process, water flows through a semi-permeable membrane from the more concentrated to the more diluted solution. For this to be possible, the applied pressure on RO, that ranges from 10 to 70 bar, must be enough so that water can be able to overcome the osmotic pressure (Shon et al., 2011; Rodrigues, 2019).

  A vertical RO (vRO) was the final unit used in this treatment train and was responsible for rejecting salts that were still present in the water. Thus, the permeated fluid is the end product.

Furthermore, the operational parameters of some technologies of the treatment train used are presented in Appendix B, Table B1.

3.2 Water-link

3.2.1 Process flow diagram

Figures 8 and 9 illustrate water-link's treatment trains for water recovery, at *Plein Publiek* and residential unit, respectively.

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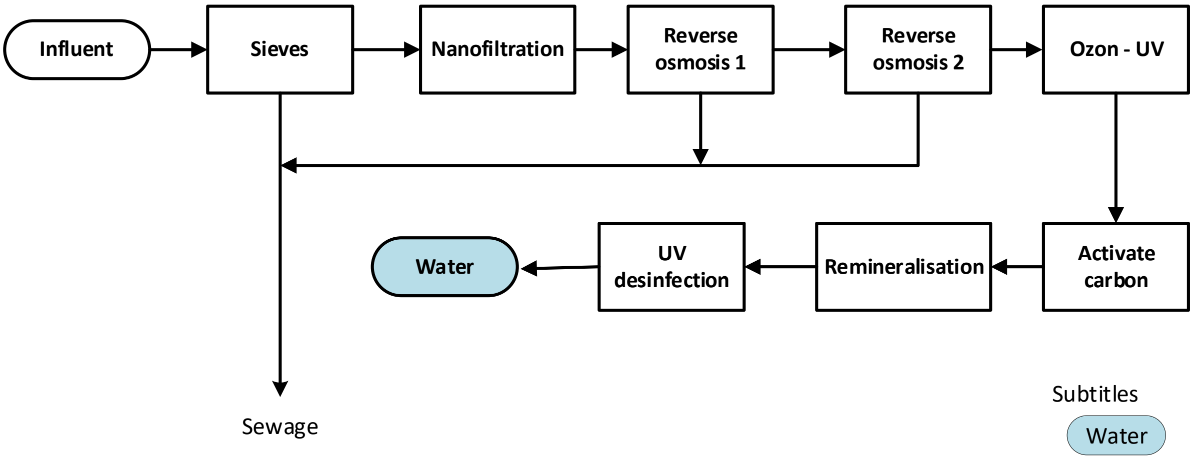

Figure 8 - Water-link's water recovery process flow diagram at Plein Publiek

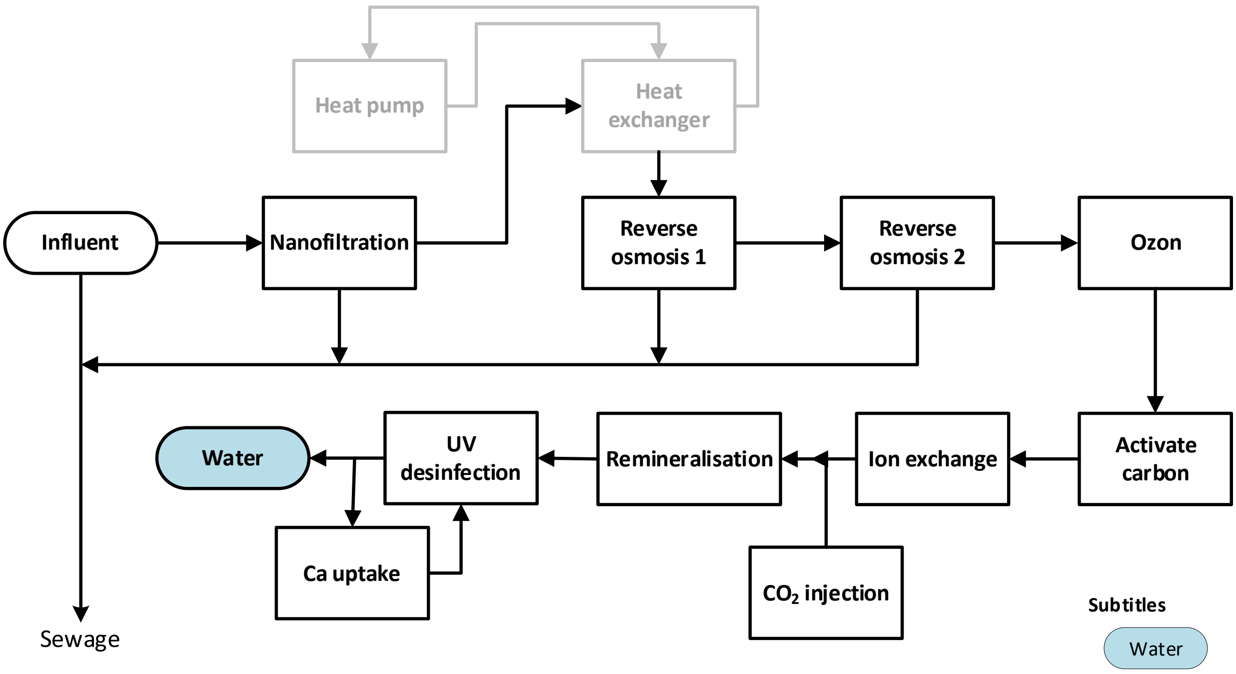

Figure 9 - Water-link's water recovery process flow diagram at the residential unit

3.2.2 Technologies

As seen in the process diagram, several different technologies were tested aiming to achieve a high-quality purified water:

- Sieves: This technology has been explained in *section 3.1.2*. It was used as the first step in the *Plein Publiek* treatment train, as it is commonly applied as a primary treatment, for water recovery.
- Nanofiltration: The NF technology has been explained in *section 3.1.2.* The NF implemented in this unit consisted of a ceramic membrane. Unlike the polymeric membranes, the ceramic can be used with raw wastewater, without the need of coagulation processes before-hand.

For this reason, the nanofiltration follows the sieve unit for the removal of cations and polyvalent ions.

- Reverse Osmosis: The RO technology has been explained in *3.1.2*. Water-link used RO in two steps in a row, with the aim of achieving high water purification efficiency. RO units were applied in order to remove extra ions (usually monovalent ions) that permeated through the NF membrane.

- Ozone + Ultraviolet Light (UV) irradiation: Ozone and UV treatments are particularly effective when applied together, and have been used for several years for inactivation of pathogenic organisms in water and wastewater (Couch, 2007). Ozone is a powerful oxidant that reacts with organic compounds. Short-wave UV radiation is effective at breaking molecular bonds in the DNA of microorganisms. When these technologies are combined, OH radicals are formed upon ozone decomposition, which are the key components in the Advanced Oxidation Processes (AOP), resulting in an enhancement of organic matter degradation (Couch, 2007; Ince & Tezcanli-Güyer, 2004).

  Ozone + UV technology was used as an advanced oxidation process (AOP) for removing viruses, bacteria and odor. It also aimed to remove organic compounds, as it was verified that they have permeated the RO membrane

- Activated Carbon (AC): Activated carbon is a versatile porous adsorbent with a high surface area and adsorption affinity, having thus the ability to adsorb a large number of chemical substances. These characteristics have made the process of adsorption on AC one of the most effective in removing pollutants from water and also economically feasible (Katsigiannis et al., 2015; B. Li et al., 2019). Additionally, this adsorbent does not generate toxins or pharmacologically active products (Delgado et al., 2019; Katsigiannis et al., 2015).

  The treatment train included activated carbon in order to increase organic and odor removal.

- Ion exchange: This technology has been explained in *section 3.1.2*. It was used in water-link's process in order to remove ions that still permeated the RO membrane.

- Remineralization: Water that is obtained from desalination technologies such as RO, is very low in minerals. When used to recover drinking water, it can affect its taste and also its health aspects (Lesimple et al., 2020). According to the World Health Organization (WHO), remineralization is an important step of water recovery, as essential minerals removed during desalination should be added before distribution (Lesimple et al., 2020; WHO, 2011).

  Remineralization was done with a remineralization filter with a prior CO_2 injection, to increase calcium uptake. Secondly, the remineralization product was changed to a classic marble.

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- UV disinfection: UV radiation is used as a water treatment technique due to its strong germicidal (inactivating) ability, being an effective disinfectant against bacteria, viruses, and protozoans. The radiation works affecting microorganisms by altering the DNA in the cells and impeding reproduction. Therefore, the organisms are inactivated, but not removed from water (Oram, n.d.). It is a chemical-free process that generates no by-products, therefore recommended as a substitute for chemical additives (X. Li et al., 2019; USEPA, 2006).

  According to water-link, during the Ozone + UV process, the total organic carbon (TOC) was expected to be broken down to smaller molecular pieces, which are more likely to be biodegradable. Therefore, the activated carbon would be used as a substrate for both oxygen and TOC, creating a high biological effluent. Thus, the UV technology was used for disinfection; also removing bacteria, viruses and protozoans.

3.3 DuCoop

3.3.1 Process flow diagram

Figure 10 presents DuCoop's process flow diagram for the water recovery route.

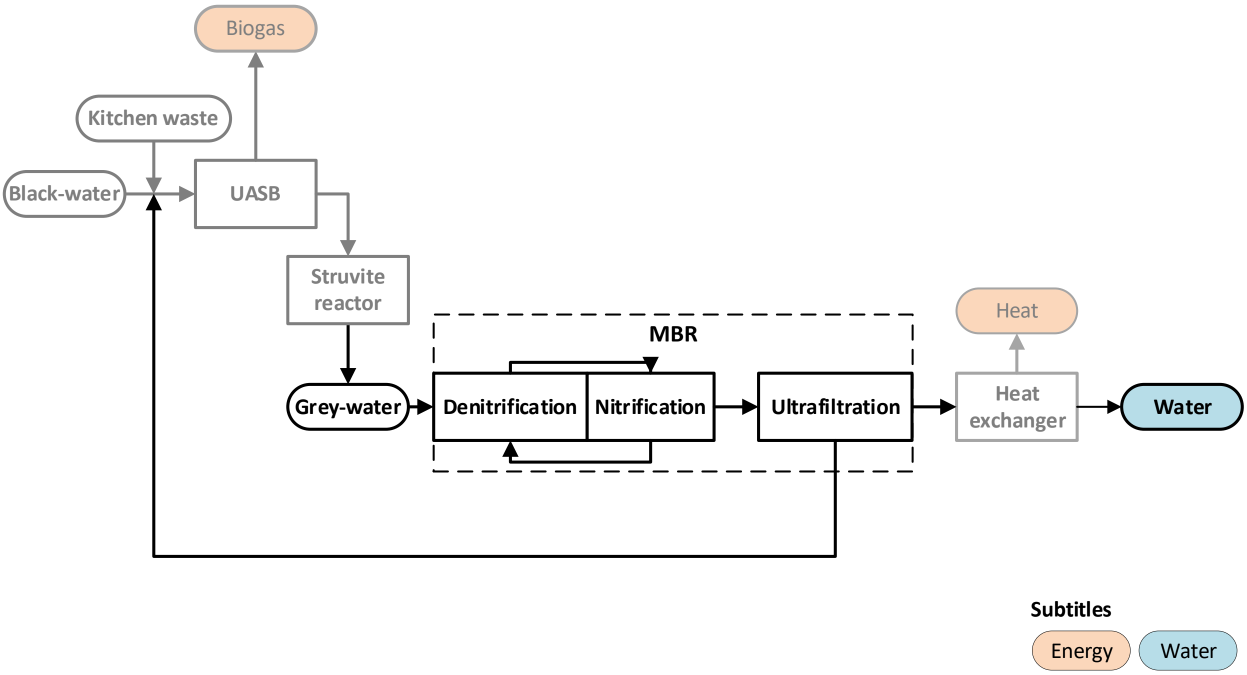

Figure 10 - DuCoop's water recovery process flow diagram

3.3.2 Technologies

The set of technologies used to treat black and grey water into process water, in DuCoop's treatment train, are explained below:

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- Upflow Anaerobic Sludge Blanket (UASB) Reactor: UASB is a high-rate anaerobic[2] digester used to treat sewage, designed to be operated with a short hydraulic retention time (HRT[3]) (Chong et al., 2012). This type of reactor has a very dense sludge bed, and above it, a sludge blanket zone, enabling the biological reactions to take place between them. As this process happens, soluble organic compounds in the influent are converted to biogas, consisting of mainly methane and carbon dioxide (Aiyuk et al., 2006). This technology has a high removal efficiency, except for pathogens and nutrients, therefore, requiring a post-treatment to reach discharge standards (Chong et al., 2012).

  The UASB reactor was used as a primary treatment, for water recovery, at DuCoop's plant. Its influent was black water and kitchen waste. As the effluent from a UASB reactor typically still contains nutrient and organic matter, it was subsequently fed to a struvite reactor to remove phosporus. After this treatment step it is combined with grey water, into the nitrification/denitrification unit to enhance removal. It should be noted that the UASB and struvite reactor was not covered by the scope of the NEREUS project, however the effluent from the UASB was fed into the rest of the treatment train which was covered by the NEREUS project and therefore had an impact on the rest of the process.

- Membrane bioreactor (MBR) + ultrafiltration (UF): A MBR connects membrane filtration to a biological active sludge system, replacing the sedimentation basin in classic biological purification. This process ensures that floating matter is retained and separates the sludge from the fluid (EMIS, 2010). This combination also avoids secondary clarification and tertiary steps and is a promising alternative to conventional treatment, as membranes can achieve a high degree of water purification (Zaviska et al., 2013).

  The MBR used by DuCoop includes both nitrification and denitrification, These processes are used for nitrogen removal and involve microbial elimination of ammonium (Thakur & Medhi, 2019). Nitrification is a microbial process by which reduced nitrogen compounds (primarily ammonia) are sequentially oxidized to nitrite (NO_2^-) and nitrate (NO_3^-) under aerobic conditions (USEPA, 2002). Denitrification is the sequential process, and involves the reduction of both ionic nitrogen oxides, under anaerobic conditions, into molecular nitrogen. The combination of these techniques aims to have a complete conversion into dinitrogen (N_2), however, some factors such as dissolved oxygen, carbon source, and pH have to be monitored in order to avoid the formation of NO_2 (nitrous oxide) (Formen, 2019; Thakur & Medhi, 2019; Vázquez-Torres & Bäumler, 2016).

  At DuCoop's plant, a MBR with ultrafiltration membranes was used to treat grey water and the effluent from the UASB unit. Due to this anaerobic reactor, the influent of the MBR unit had sometimes a high amount of organic matter in its composition due to periodic sludge washout. For this reason, nitrification and denitrification techniques were applied in order to convert ammonium into N_2, which is a non-pollutant gas. The UF's role was to retain particles and sludge that come from the biological reactor. Water that permeated the membrane is the final product: process water. Additionally, an external carbon source (glycerine) was dosed in the reactor when not all nitrogen was removed in the nitrification/denitrication steps.

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[2] A process that occurs without oxygen presence.

[3] Represents the average time that components stay inside the reactor.

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Furthermore, operational conditions of the MBR are presented in Appendix B, Table B2.

- Chemical coagulation ($FeCl_3$): This technology is explained on section 3.2.1.

  Iron chloride was dosed in the anoxic tank of the MBR, as a coagulant, in order to remove inorganic soluble phosphorus. These impurities coagulate and are removed from the water as sludge.

4 Results

This chapter focus on the results obtained by each pilot partner when recovering the aimed type of water, as well as the recovery percentage and quality of the end product. It also presents the process optimization applied in each plant and the conditions chosen as the best for achieving their targets.

4.1 Evides Industry Water

4.1.1 Recovery percentage

The permeate flow of the reverse osmosis unit was about 0.2 m^3/h, representing an overall recovery of 7.1%. According to Evides, the water recovery is low due to losses in buffering and on the side/concentrate streams of the process units.

4.1.2 Recovered product

The final product is the water recovered at the permeate of the reverse osmosis unit. According to Evides, the water could be used for irrigation purposes, but would have to be qualitatively analyzed to get an end-of-waste status and be safe for reuse. As they did not have a customer for their final product at *Harnaschpolder*, this analytical step was not performed.

4.1.3 Process optimization

The removal of large particles by coagulation played an important role for the water recovery route. Initially Evides tested an iron electro-coagulation unit, that was later replaced by coagulation with iron chloride dosing.

The first tests concerning the EC-pilot consisted of applying different amperages, varying between 200 – 800 A. The results indicated that applying 500 A resulted in a better coagulation and turbidity removal, however, not appropriate for running the treatment train (Steenbakker, 2019). An important remark is that the sample was not the same within the tests, meaning that they had a different initial turbidity, which can affect the comparison of its removal efficiency. It was also concluded that the flocculation vessel, which is part of the EC system, almost did not contribute to the settling and removal of particulates. The results of these tests, after 30 minutes of sedimentation, are presented in Figure 11.

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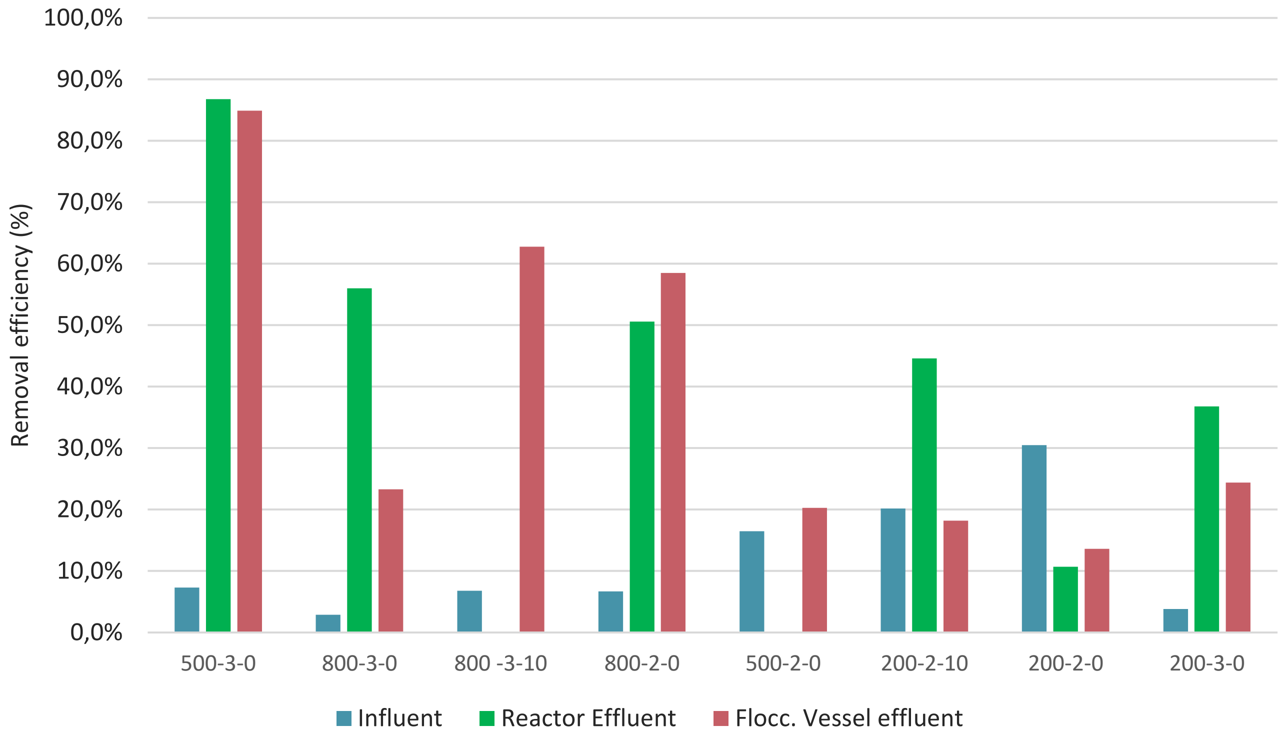

Figure 11 - Efficiency of turbidity removal for EC tests

Note. The x axes corresponds to the tests performed and given numbers stands for: current (A) – influent flow (m^3/h) – mixer (%).

Therefore, new lab tests were done (in a jar-tester) with a slow mixing of the flocculation tank, which improved the turbidity removal. The jar-test experiments presented results up to a turbidity removal of 80%, particulate COD of 90% and total phosphorus (TP) of 90% (van den Brink & van de Griek, 2019).

Although the initial improvements led to increased particulate removal on a lab-scale, these results could not be achieved in the pilot setup. Additionally, Evides faced challenges with iron precipitates accumulating inside the bottom of the EC reactor, on the NF membrane and also in its permeate. Figure 12 is a picture of the Fe deposition on the NF membrane surface.

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Figure 12 - Iron deposition on the NF membrane

Some hypotheses were that the oxidation of Fe(II) to Fe(III) was not sufficient, the flocculation and settling were not optimal and the design of the EC reactor. After some optimization trials, such as changing the aeration rate and the reactor design, the water quality was not satisfactory and Evides decided to replace the EC unit for a coagulation reactor with $FeCl_3$ dosing. They found the optimum iron dosing to be 20 mg/L, as higher dosages did not add extra benefit.

Following the train, the water then leaves the coagulation unit and is treated by a two stage nanofiltration. Evides tested different membranes, from NXFiltration, for salt removal: MWCO of 400 and 800 Da. Both of the membranes presented a good permeation flow rate, and the chosen one was the 800 Da with a permeability of 8 – 12 L/m^2.h.bar. As both of the membranes were satisfactory for permeation and overall turbidity rejection (95 – 98%), the 800 Da membrane was chosen due to its ability to let more nitrogen pass through, which enables its recovery. This process, related to nutrient recovery, is explained on the *D2.4.1 NEREUS Resource recovery final report,* section 4.1.3.2.

For the reverse osmosis unit, not many optimization tests were performed. As this is the last unit of the treatment train, it was not continuously operated and assessed due to challenges that occurred in earlier units. Nevertheless, according to Evides, the RO was stable when operated and the fouling that occurred could be successfully removed with chemical cleaning.

4.1.4 Full scale design

According to Steenbakker & van den Brink, 2021, the plant should be a full scale in order to be economically feasible. It was concluded that resource recovery can reach a full scale design depending on the stream, source and application. However, they do not intend to go full-scale with this same setup.

4.2 Water-link

4.2.1 Recovery percentage

As water-link did not have as an initial goal a recovery percentage target, it was not measured for both pilot plants.

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4.2.2 Recovered product

Water recovered at the *Plein Publiek* pilot was not suitable for drinking water, as it was biologically unstable, especially for BOD/COD and ammonium. The main reason for this is that the feed stream of this unit was “heavy” grey water, this means that it carried a high load of organic matter, due to kitchen sinks. According to water-link, a biological treatment is therefore necessary with this type of wastewater in order to achieve drinking water standards.

For the residential unit, the final treated water was not yet suitable for drinking water, having as impurities ammonium and nitrate. A main reason for this is that due to the COVID pandemic the unit could not be operated, and therefore, the project had to be stopped within the NEREUS project. However, according to water-link the drinking water standards are within reach, being technically possible to achieve the desired quality.

4.2.3 Process optimization

Due to the aim of recovering drinking water, water-link invested in highly efficient filtration technologies, such as NF and RO, and also on organic and pathogen removal. A way of analyzing the amount of organic compounds in the water, and therefore, its removal, is by measuring the total organic carbon (TOC). Thus, a major part of the optimization focused on obtaining an efficient way of removing it (W. Bossaerts, 2020).

During the running of the pilot, only a minor removal of TOC on the 2nd stage of the reverse osmosis (RO-2) was observed, when compared with the effluent of the RO-1. For this reason, water-link tested adjusting the pH of the RO-2 feed from 6.5 to 8.5. This change increased the organic retention by about 8%.

The effectiveness of TOC removal by ozonation + UV and hydrogen peroxide (H_2O_2) + UV was also investigated. Figure 13 shows the graph of the obtained results of the TOC concentration per time of the applied technologies. After three hours, the test that used the ozone achieved lower concentrations of TOC, and therefore, a higher removal, being chosen as a group of technologies to treat the RO effluent.

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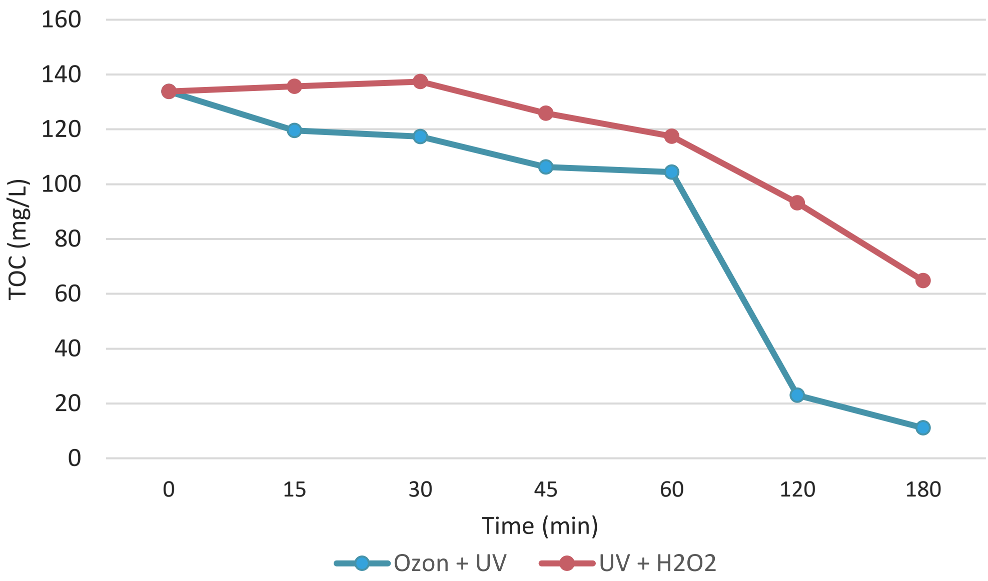

Figure 13 - Ozon x H_2O_2 for TOC removal

It was concluded that the Ozon UV could treat water by removing an overload of BOD and COD, however, this cannot be done in an economic way. This happens because a high amount of Ozon is necessary to treat the water.

Following the Ozon + UV tests, the use of activated carbon was investigated. The use of carbon presented an improvement of 30% TOC removal, when using a mass of 5g. This treatment was also tested with a higher amount of carbon, 10 and 20 g, which, however, did not achieved any major difference (max of 35% removal).

Within the tests and results achieved, water-link concluded that the treatment of heavy grey water, in the case of *Plein Publiek,* requires a biological treatment in order to remove the small organic components. This process is necessary when water is aimed to be reused as drinking water.

4.2.4 Full scale design

Both plants remain pilot scale and will be used as a test facility for both industrial and/or domestic treated wastewaters. In the new application of the container unit (old *Plein Publiek*), the biological treatment will no longer be necessary as their feed will be pre-treated wastewater. Therefore, an ultrafiltration system was added to the train as an alternative pre-treatment. According to water-link, a full-scale design can then be made with the results obtained from this pilot.

The residential unit is going to be used to perform bench scale tests on wastewater to examine the possibilities for its reuse. All previously installed process steps (activated carbon, Ozon, UV, remineralization) are selectable in the treatment train, in order to obtain the water quality foreseen by the supplier of the wastewater.

4.3 DuCoop

The design for DuCoop's plant is for 90m^3/day but it is only running at 15m^3/day, thus, about 17% of the full scale. Therefore, the results achieved and presented in this section corresponds to the plant working with 17% of the capacity.

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4.3.1 Recovery percentage

Currently, DuCoop's plant treats an average of 11.4 m^3/d of influent grey water into process water. A direct comparison between their influent and effluent flow rate would not be realistic for accounting their recovery due to the different residence time of the reactors.

Therefore, a comparison between the volume treated and produced during the year of 2020 was used for this calculation. DuCoop treated 4450 m^3 of water, producing 30 m^3 of sludge, this is, 0.7% of waste. Thus, the water recovery achieved by the plant was of about 99.3%.

4.3.2 Recovered product

The aim for the water recovered in this treatment train was for it to be used as process water, the composition of which is presented in Table 7. This table also contains the limit concentration established for effluent discharge, shared by DuCoop according to their permit.

Table 7 - DuCoop's recovered water quality

Parameter	Unit	Value	Limit
Average Daily Flow	m^3/d	14.6	-
pH	-	7.2 ± 0.2	6-9
COD	mg COD/L	23.4 ± 10.0	125.0
Total Nitrogen (TN)	mg N/L	20.0 ± 16.0 [a]	15.0
Ammonium (NH_4)	mg N/L	2.5 ± 2.2	-
Nitrate (NO_3)	mg N/L	17.2 ± 14.0 [a]	-
Total Phosphorous (TP)	mg P/L	0.66	2.0
Temperature	°C	28.5 ± 0.5	30.0

(Camps, 2021)

Note. The table presents an average of the water quality of July, August and September 2021.

[a] Due to instabilities in the aerobic treatment, the effluent nitrogen exceeded the limit on two separate occasions during this period (59 and 27 mg N/L), hence the high standard deviation. Prior to discharge the effluent was then further denitrified to comply with legislation.

For DuCoop, the water treatment plant is producing an effluent which is suitable for reuse and which complies to their permit. Some technical issues have caused problems with the denitrification of the water treatment plant, which sometimes led to an unstable nitrogen removal, as seen in Table 7. These problems were then remedied, and the treatment plant currently produces an effluent suitable for reuse.

Based on the water quality, the removal for COD, TN and TP was obtained and is shown in Figure 14.

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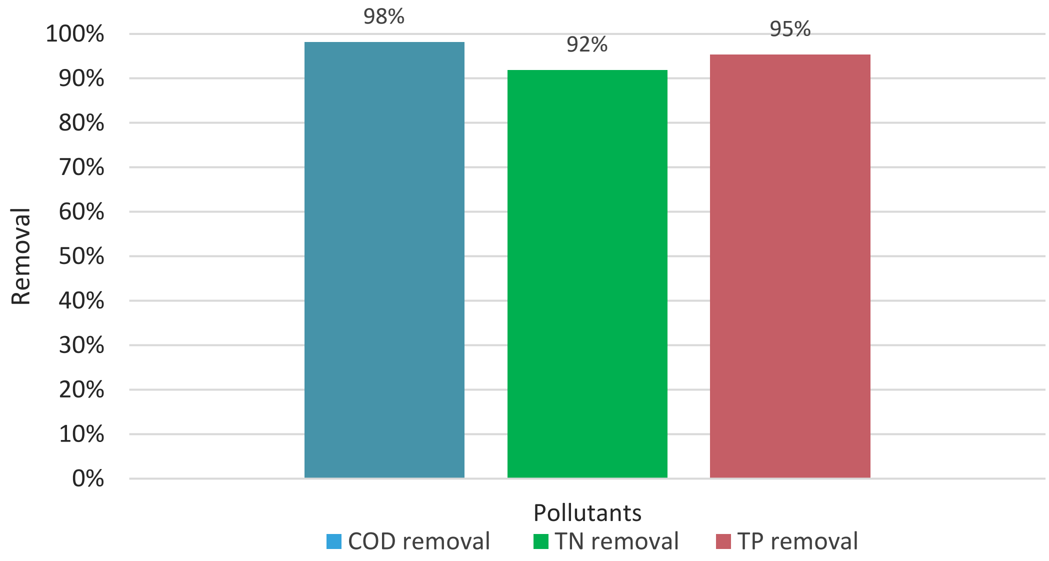

Figure 14 - Pollutant removal on DuCoop's water treatment

DuCoop's process presented a high average removal rate for all three pollutants; all in excess of 90%. As seen in Figure 14, the lowest overall removal was of total nitrogen, which was the constituent responsible for most of the challenges for the water recovery route, due to the high presence of nitrate on the MBR. The process for obtaining high TN removal is further explained in section 4.3.3.

The reclaimed water from *De Nieuwe Dokken* is reused mainly in the soap factory *Christeyns*. There, the reclaimed water of DuCoop is aimed to be used to produce soft and demineralized water, used in the production process. When using the reclaimed water of DuCoop in total, 30000 m^3 of tap water will be saved per year, since *Christeyns* is now using tap water for their production. Post treatment of the reclaimed water is necessary to ensure quality. Production tests have been done on products at *Christeyns,* which were made with reclaimed water (pretreated with activated carbon and a softener). These tests have been so far successful.

Another reuse on site is the use of water collected in the rainwater tanks, located at *De Nieuwe Dokken*, for toilet flushing. The rainwater quality parameters are well matched for the reuse in this context.

4.3.3 Process optimization

In order to achieve the desired water quality for reuse, some operational parameters of the (UF) MBR had to be tested and optimized. As mentioned before, nitrogen was the pollutant which was sporadically in excess of the effluent standard. To solve this, DuCoop worked by identifying the probable causes and setting action plans.

By measuring the concentration of nitrogen constituents, the excessive TN was attributed mainly to nitrate; therefore, a low denitrification rate in the anoxic tank. This is illustrated in Figure 15. The main cause was identified as an underload of the bioreactor (15 – 25% of design load), due to the district not yet being fully inhabited. Underloading the reactor led to over-aeration inside it, and therefore, the occurrence of poor denitrification at times. Another variable that influenced the denitrification rate was the external carbon dosing, which sometimes faced technical issues.

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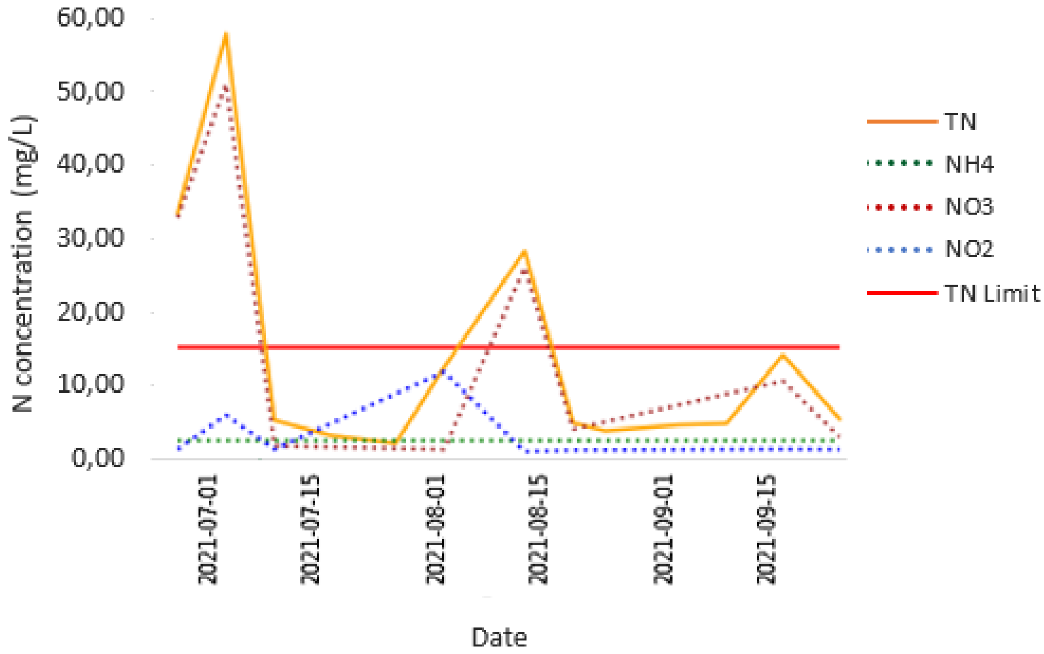

Figure 15 - Nitrogen concentration on MBR permeate

Therefore, the following procedures were aimed at improving denitrification:

- Feed the reactor in batches, instead of continuous, to increase instantaneous load;
- Optimize the aeration control to avoid oxygen peaks, as over-aeration leads to the release of nitrate;
- Adjust the addition of carbon source on the anoxic reactor, in order to provide sufficient COD to denitrify the excess of nitrates;
- Reduce the recirculation over the UF membrane so that it only occurs when the filtration happens. Since the UF membrane is continuously aerated, this also reduces over-aeration in the reactor.

By running the plant in different situations, as mentioned above, DuCoop concluded that, by reducing the aeration time (<50%) and providing sufficient carbon source (± 500 g COD/m^3) for denitrification, the goals were achieved.

Another lesson, learned by facing those challenges, is that in a future case, designing the reactors with a variable volume would enable working with different loads. Currently, the reactor has a minimum set volume to work with, thus having no flexibility in load on the treatment plant.

4.3.4 Full scale design

The plant is already full scale and designed for operating 90 m^3/d of grey water, collecting wastewater from 400 apartments and 1200 PE. As already explained, until the end of the NEREUS project, the plant operated with a maximum of 17% of the capacity, because the complex at *De Nieuwe Dokken* was not completed. It is expected that by the end of 2022 there will be an acceptable load which would give more representative numbers of the plant.

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5 Discussion

During this report, characteristics of the resources being recovered, along with the technologies used and the obtained results have been presented per pilot partner. In order to enable a discussion about all of these recovery processes, this chapter will focus on comparing the main aspects and results of their processes; their technologies, recovered product and achievement of initial goals and targets.

5.1 Technologies and process conditions

As all the technologies involved have already been presented per pilot partner in *chapter 3,* the aim here is to provide a better view and comparison of them. Therefore, Table 8 presents the overall process conditions that have been presented in this report.

Table 8 - Overall process overview per recovered resource

	Evides Irrigation water	**water-link** Drinking water	**DuCoop** Process water
Main technologies	• Coagulation • Membranes • IX resins	• Membranes • Disinfection • IX resin • Remineralization	• MBR (activated sludge + membrane)
External dosing	• $FeCl_3$	• pH adjustment	• $FeCl_3$ • Carbon source
Operational variables	• Pressure	• Pressure • pH	• Pressure • Flow (recirculation)
Barriers	5	8	2

All three pilots recovered water as an end product, however, from different stream types and for different purposes; as process and drinking water. For these reasons, it is interesting to point out and discuss the similarities and differences in their treatment trains.

From the main technologies listed in Table 8, it is possible to conclude that membranes have an important role when recovering water. Both Evides and water-link had nanofiltration and reverse osmosis membranes in their train, and DuCoop used an ultrafiltration membrane in their MBR unit. DuCoop's train was the only one that used biological treatment to remove larger particles and organic material; as Evides used coagulation and water-link disinfection units. However, it was noted by both Evides and water-link that a biological unit seems to be needed in order to achieve their desired final quality.

In terms of the size of the treatment train, represented by the barriers in Table 8, the quantity of units is directly related to the influent stream and the end product. For example, both DuCoop and water-link treated grey water but had a different number of process units in their treatment train. As water-link aimed to produce drinking water, they had to meet stricter quality requirements, and therefore, more units were needed to achieve this.

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5.2 Recovery percentages

Table 9 presents the recovery percentage achieved for each water type; the end product recovered by the pilot partners.

Table 9 - Water recovery percentage per pilot partner

Evides Irrigation water	**water-link** Drinking water	**DuCoop** Process water
7.1%	-	99.3%

5.3 Quality of recovered products

Table 10 contains the quality of the resources recovered at the pilot plants. It aims to provide the characteristics of the products in order to discuss whether it is suitable or not for the intended end use.

Table 10 - Quality of recovered water per pilot partner

	Evides	**water-link**		**DuCoop**
	Irrigation water	DW: Plein Publiek	DW: Residential	Process water
Overall aspect	• RO permeate;	• Heavy grey water as source; • Requires biological treatment	• Light grey water as source; • Technically feasible	• Approved overall quality; • Sporadic high NO_3 in effluent
Impurities	• Micropollutants (paracetamol and caffeine)	• COD/BOD; • NH_4	• NO_3 and NH_4; • No Ca uptake	• All below permit limit
Suitable for end use	• Conditional (No end user)	• No: DW end quality not achieved	• Not yet: DW quality within reach	• Yes: reused at soap factory and rainwater pit (when it is empty)

As seen in Table 10, each partner aimed to recover a different type of water (different end quality and use) from various influent types:

- Evides: (initially) irrigation water from grey water and then from municipal wastewater;
- water-link: drinking water from residential grey water and from "heavy" grey water (kitchen sink included);
- DuCoop: Water suitable to produce process water from mixed grey and, previously treated, black water and kitchen waste.

The influent type, the end use goal and the technologies applied have a direct impact in the final water quality and its suitability for reuse. Therefore, based on the final composition of the recovered water, the type of end product determines the suitability for their use, being drinking water the most strict of them.

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According to Evides, their produced water could be reused as irrigation water, but would need to be qualitatively checked to get an end-of-waste status. They did not apply for it with the recovered water at *Harnaschpolde*r due to not having a potential costumer for the product.

Water-link concluded that their recovered water was not yet suitable for being reused as drinking water. According to them, with the current setup at *Plein Publiek*, the water had still levels higher than the limits for ammonia and some organic pollutants, and also presented odor when leaving the RO unit. They remarked that a biological unit is necessary in this case.

For the residential unit, the final product is listed as not yet suitable, because during the time the pilot was running, the quality did not meet DW standards. However, according to water-link, this process is technically possible and was within reach of achievement, although could not be concluded due to the unit being stopped, as explained in section *4.2.2.*

The water recovered by DuCoop had an approved overall quality to replace drinking water for the production of process water. Although some sporadic high concentration of nitrates on the effluent, after process optimization they've managed to achieve an average water quality that complies with their permit. Therefore, the recovered water was suitable for its reuse as process water in a nearby soap factory.

5.4 Initial goals and targets

An assessment of the pilot plants' end products was done by comparing the initial goals and recovery targets with the achieved ones. This assessment is presented in the form of a table containing a color coded conclusion, per recovery percentage and other goals. Table 11 contains this color code definition, and the assessment is covered in Table 12.

Table 11 - Color code definition

Color	Definition
	• Recovery target achieved • Goals achieved
	• At least 50% of recovery target achieved • Goals partially achieved
	• Less than 50% of the recovery target achieved • None of goals achieved

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Table 12 - Comparison of the initial and achieved targets and goals

	Evides	water-link		DuCoop
	Irrigation water	DW: Plein Publiek	DW: Residential	Process water
Recovery target	-	-	-	95.0%
Achieved	**7.1%**	**-**	**-**	**99.3%**
Goals	• Recover irrigation water	• Recover drinking water	• Recover drinking water	• Recover process water to be reused
Achieved goals				

DuCoop recovered over 99% of their feed water, and therefore achieved their recovery target. Evides and water-link did not have a recovery target as an initial goal and focused on achieving a specific water quality range, in order to enable its reuse.

Concerning the achievement of initial goal, Evides was considered as partially achieving it. They managed to treat water that could later be used for irrigation purposes. However, in the case of having a costumer for their product, the final water quality should still be measured to assess its suitability and safety for reuse.

Water-link managed to run the two proposed pilots; treating effluent streams from a restaurant and a residence. However, the final recovered water at *Plein Publiek* unit was not suitable for the drinking water standards. Organic pollutants and also odour were still present in the final product; therefore, the goal at this unit was considered as not achieved. At the residential unit, the goal was partially achieved, as the final product was no yet suitable for drinking water, but the treatment train was considered feasible and also technically possible to achieve the desired end quality.

DuCoop managed to recover process water with their treatment train. The plant is full scale and provides water for being reused at a soap factory and also for toilet flushing. Therefore, they successfully achieved their goals.

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6 Conclusion

This report covered the experiences on recovering different water types from wastewater by partners Evides, water-link and DuCoop, during the NEREUS project. The fact that the pilots focused on recovering water for different end use and from different sources, enabled the comparison between the recovery process and on the various types of technologies used. The report also aimed to share and illustrate the optimization processes applied by the project partners in order to achieve the aimed final quality.

The end products aimed to be recovered were irrigation, drinking and process water, respectively by Evides, Water-Link and DuCoop. These final products, and therefore, their end quality, directly influence the methodology and technologies applied in each case; the stricter the final quality, the higher the amount of units (barriers) needed. This also occurs for more polluted influent streams. In order to achieve the composition standards, it was noticed by all partners the importance of having a biological treatment on the train, or even have a WWTP secondary effluent as a feed stream.

Among all pollutants, the ones most frequently out of the desired range were nitrates, ammonium and organics, which corroborates for the need of a biological treatment. However, it's important to remark that adding this type of unit would have an impact on the whole treatment train. For example, in Evides case, it would not enable the recovery of nitrogen on the reverse osmosis concentrate, due to it being previously removed, which was one of Evides goals for resource recovery. Therefore, setting a treatment train can be challenging and must consider all recovery goals involved.

Another important type of unit process for water recovery is membrane filtration. This could be noticed as it was present in all partners trains: nanofiltration and reverse osmosis were used by Evides and water-link, and DuCoop had an MBR with an ultrafiltration membrane. When recovering specifically drinking water, one more set of technologies is needed for removing pathogens and odour: the disinfection units, such as ozonation and ultraviolet light irradiation.

Therefore, with the results obtained by the pilot partners, that were presented and discussed in this report, it is possible to conclude that different types of water can be recovered from wastewater and be reused. DuCoop's demo case corroborates with this, as their recovered process water is being reused in a soap factory process, and collected rainwater is reused for toilet flushing. Nevertheless, there are also challenges present in the recovery process, especially for end products that have a stricter standard as drinking water, that also faces an approval factor from users. Therefore, research should continue in order to improve the processes, the feasibility and acceptability of water recovery.

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This project has received funding from the Interreg 2 Seas programme 2014-2020
co-funded by the European Regional Development Fund under subsidy contract No 2S03-011.

Appendix A

Extra influent quality data

Table A1 – Aquafin WWTP effluent composition

Parameter	Unit	Value
COD	mg/L	29.12
Total Nitrogen (TN)	mg/L	8.13
Ammonium (NH_4 – N)	mg/L	2.09
Nitrate (NO_3 - N)	Mg/L	5.42
Total Phosphorous (TP)	mg/L	0.46
Phosphate (PO_4 – P)	mg/L	0.18
Zinc (Zn)	mg/L	0.03
Copper (Cu)	mg/L	0.01

Table A2 – Nieuwe Dokken's (black water) stream profile

Parameter	Unit	Value
Average Daily Flow	m^3/d	3.10
pH		7.4
COD	mg/L	7283.0

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Appendix B

Pilot plants operational conditions

Table B1 – Evides' pilot plant operational conditions

Technology/Input	Parameter	Value
Drum sieves	Supplier and type	Toro Defender 416
	Pore size (mm)	0.25
Electro-coagulation	Amperage (A)	150-1400
Nanofiltration	MWCO (Da)	800
	Supplier	NXFiltration
	Pressure (bar)	3.0
Vertical reverse osmosis	Supplier and type	DOW LE4040
	Surface area	7.2 m^2

Steenbakker (2019)

Table B2 – DuCoop's MBR operational conditions

Parameter	Value
TMP (mbar)	159
Net flow (m^3/h)	2.5
Flux (L/m^2.h)	20.7
Permeability (L/m^2.h.bar)	130.0

(Camps, 2021)

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co-funded by the European Regional Development Fund
under subsidy contract No 2S03-011.