D1.3 New approaches and best practices for closing the water cycle

AUTHORS: Q. PLANA AND CS LEADERS

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[1] PU = Public
PP = Restricted to other programme participants (including the Commission Services)
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Executive summary

During the last decades, climate change impacts have been noticed around the world. In Europe, the quantity of high temperature periods during the summer or drought episodes are becoming more frequent. Those factors are increasing the water scarcity among the European countries, especially southern countries such as Spain or Greece. This is reflected in their national legislations on water reuse, which were implemented in 2007 and in 2011.

Due to increasing water scarcity, circular economy implementation is becoming necessary in the water sector, not only for water regeneration but also for material and energy recovery from water sources, like wastewater. Through ten case studies located all around Europe, the NextGen project demonstrates, particularly in tasks T1.2-T1.4 within WP1, 26 different potential technologies to close the water, energy, and materials cycles in the water sector. Specifically, this deliverable is focused on closing the water cycle through technologies and case studies. The technologies include membrane-based wastewater treatment for water reuse, a feasibility study on reclaimed water production at a local and regional level, rainwater harvesting systems, and groundwater storage systems. Each technology section is meant to be standalone including a presentation of each demonstration case and the main results and outcomes.

Feasibility study on reclaimed water production at a local and regional level

Prior to implementing circular economy solutions for water recovery at full-scale and at a local or regional revel, it is recommended to conduct a feasibility evaluation. The study carried out in Timişoara also integrated potential stakeholders which could benefit from the implementation of advanced treatments for the wastewater in order to obtain the reclaimed water for reuse, established collaboration with the local and regional administration, and conducted dissemination and communication activities to increase the knowledge and awareness on water scarcity, water reuse and circular economy. The study focused on recovering 100% of the current WWTP effluent (10 800 m^3/h (See Table 1)). Three clients for reclaimed water use, as well as the cost to build the reclaimed water distribution network and the water quality required for the selected uses, were identified.

Table 1. Feasibility study on reclaimed water production.

Case study	Technology	Water uses	Quantified impact
Timişoara	Feasibility study on reclaimed water production	Urban, industrial and agricultural use	Theoretical study; 10 800 m^3/h

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Advanced treatment technologies for water reuse

Five different technologies for producing reclaimed water from wastewater have been tested in Spernal, Athens, La Trappe, Costa Brava and Gotland. All the technologies were at technology readiness level (TRL) 7 and demonstrated their ability to produce reclaimed water of different quality levels to allow a diversity of uses such as urban, industrial, private, agricultural, and other non-potable uses according to regional and European regulations (See Table 2). The five technologies were also implemented at pilot scale, although their water flow ranged from 0.1 (at La Trappe) to 20 m^3/h (in Spernal). Additionally, these technologies demonstrated their modularity, flexibility, and scalability for future implementation at pilot- and full-scale. However, further investigation and testing is recommended, since the TRLs of 7-8 and operation of each technology may vary depending on inlet water quality characteristics.

Table 2. Membrane-based systems for reclaimed water production.

Case study	Technology	Water use	Quantified impact
Spernal	Anaerobic membrane bioreactor	Farming and industrial use	TRL 7; 500 m^3/d
Athens	Membrane bioreactor (sewer mining unit)	Urban irrigation and other non-potable use	TRL 8; 25 m^3/d
La Trappe	Metabolic network reactor + MELiSSA Microfiltration/reverse osmosis membranes	Bottle washing, aeroponics and aquaculture	TRL 7; 100 L/h
Costa Brava	Ultrafiltration + regenerated reverse osmosis membranes	Private use	TRL 7; 2 m^3/h
Gotland	Decentralized reverse osmosis membrane system	Indirect drinking water supply	TRL 7; 1.6 m^3/h

Rainwater harvesting systems

The studies carried out in Gotland and in Filton Airfield demonstrated that significant savings, in terms of drinking water demand, can be achieved when harvesting rainwater in the studied area (See Table 3). For example, with a surface of 110 km^2, it is possible to store 100 000 m^3/y, meaning 25 % of the annual demand. In case of the Filton Airfield, where several theoretical scenarios varying the catchment surface between 13 000 - 30 000 m^2 were evaluated, it was possible to reduce 10-75 % of drinking water demand when using the harvested rainwater for toilet flushing and public irrigation in the area.

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Table 3. Rainwater harvesting systems.

Case study	Technology	Water uses	Quantified impact
Gotland	Innovative floodgate	Urban and agricultural use	TRL 7; storage: 100 000 m^3/y, 25 % of water savings per year
Filton Airfield	Alternative water source	Toilet flushing and public irrigation	Theoretical study; 10 – 75 % of water savings per year

Aquifer storage systems

Like rainwater harvesting systems, aquifer storage systems allow storage of a significant water volume from rainwater harvesting (See Table 4). Thus, the stored volume can reduce groundwater demand when recovered water is used for non-potable purposes. In case of Westland, the water demand for horticulture irrigation is met by rainwater stored in shallow basins and by (unsustainable) desalinated brackish groundwater. The aquifer storage of 4.8 Mm^3/y of excess rainwater in a waterbanking system at half of the horticulture companies reduces the net groundwater extraction with more than 80%. The Gotland study evaluated the same catchment surface and water storage as in the aforementioned rainwater harvesting system, therefore the annual water savings were calculated to be the same (25% annually).

Table 4. Groundwater storage systems.

Case study	Technology	Water uses	Quantified impact
Westland	Aquifer storage and recovery	Horticulture irrigation	Theoretical study; aquifer rainwater storage: 4.8 Mm^3/y; 80 % reduction of net groundwater extraction
Gotland	Real time measurements	Urban and agricultural uses	Study; storage 100 000 m^3/y; 25 % of water savings per year

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List of abbreviations

AnMBR	Anaerobic membrane bioreactor
AOC	Assimilable organic carbon
ASR	Aquifer storage and recovery
ASP	Activated sludge process
ATP	Adenosinetriphosphate
BFR	Biofilm formation rate
BOD	Biochemical oxygen demand
CAPEX	Capital Expenditures
CEB	Chemical enhanced backwashing
CFU	Colony forming unit
CIP	Cleaning in place
COD	Chemical oxygen demand
CODMn	Chemical Oxygen Demand Of Permanganate
DO	Dissolved oxygen
EC	Emerging compounds
EYDAP	Athens Water Supply and Sewerage Company
FC	Faecal coliform
FC	Filter coefficient
HRT	Hydraulic retention time
ICT	Information and Communications Technology
IEX	Ion exchange
IRR	Internal Rate of Return
IVL	Swedish Environmental Research Institute
KPI	Key performance indicators
KTH	Royal Institute of Technology
LCC	Life cycle cost
LOD	Limit of detection
MBR	Membrane bioreactor
MFI	Melt flow index
MLSS	Mixed liquor suspended solids
MNR	Metabolic network reactor
NF	Nanofiltration
NTU	Nephelometric turbidity unit
OLR	Organic loading rate
OPEX	Operating Expenditures
PBP	Payback period
PVDF	Polyvinylidene fluoride
RC	Runoff coefficient
RO	Reverse osmosis
sCOD	Soluble chemical oxygen demand
SCE	Stormwater capture efficiency
SDI	Silt density index
SGU	Geological Survey of Sweden
SIMDEUM	SIMulation of water Demand, an End-Use Model

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SM	Sewer mining
SRT	Solids retention time
TC	Total coliforms
TCO	Total Cost of Ownership
TDS	Total dissolved solids
TMP	Transmembrane pressure
TN	Total nitrogen
TOC	Total organic carbon
TP	Total phosphorous
TRL	Technology readiness level
TrOCs	Trace organic compounds
TSS	Total suspended solids
UASB	Upflow anaerobic sludge blanket reactor
UF	Ultrafiltration
UV	Ultraviolet
UWOT	Urban water operating tool
VCF	Volume Concentration Factor
VFAs	Volatile fatty acids
VSS	Volatile suspended solids
WFD	Water Framework Directive
WL	WatchList
WSE	Water savings efficiency
WWTP	Wastewater treatment plant
YAS	Yield after spillage
YBS	Yield before spillage

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1. Introduction

The NextGen project aims to demonstrate the viability of technical, business and governance solutions towards a circular economy (CE) in the water sector. In Work Package 1 (WP1), aiming to close water, energy, and materials cycles, several technologies were implemented in 10 demonstration cases, providing evidence demonstrating the feasibility of innovative technological solutions: Braunschweig (DE), Costa Brava (ES), Westland (NL), Altenrhein (CH), Spernal (UK), La Trappe (NL), Gotland (SE), Athens (GR), Filton Airfield (UK) and Timişoara (RO). The specific objective of the WP, to promote the feasibility and test the technologies applied, were presented together with the pre-existing infrastructure in *D1.1 Baseline conditions* (Kleyböcker et al., 2019) and first results in *D1.2 Operational demo cases* (Serra et al., 2020). The current deliverable is focused on the demonstrated technologies and the studies specifically within the water cycle (See Figure 1). The case studies involved on the technologies' implementation and the feasibility studies within the water cycle are summarized in Table 5 together with the future uses of the reclaimed or collected water.

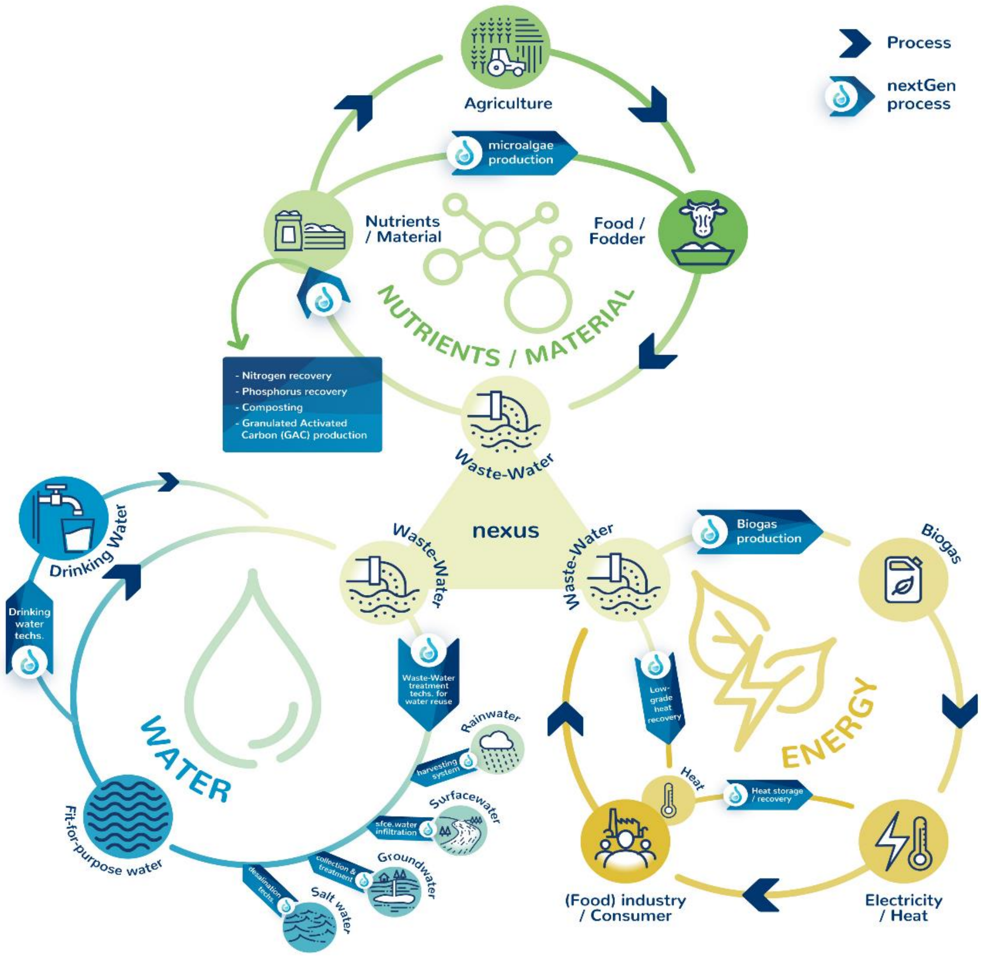

Figure 1. Circular economy nexus between water, energy, and materials cycles in the water sector.

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Table 5. Overview of the NextGen technologies for water treatment and storage.

	Case study	Technology	Purpose of the water reuse
Wastewater treatment technologies	**Spernal**	Anaerobic membrane bioreactor	Farming, industrial uses
	Athens	Membrane bioreactor & UV disinfection	Urban irrigation, other non-potable uses
	La Trappe	Membrane bioreactor coupled to a MELiSSA membrane system (MF/RO)	Bottle washing, aeroponics and aquaculture
	Tossa de Mar	Ultrafiltration + reverse osmosis regenerated membranes	Private uses
	Gotland	Ultrafiltration + reverse osmosis + UV disinfection	Indirect drinking water supply
Feasibility study for water reuse	**Timişoara**	Study on reclaimed water production	Urban, industrial, and agricultural uses
Rainwater harvesting studies	**Gotland**	Innovative floodgate for rainwater storage	Urban and agricultural uses
	Filton Airfield	Study of alternative water sources at district level	Toilet flushing and public irrigation
Groundwater storage studies	**Westland**	Study of aquifer storage and recovery systems	Horticulture irrigation
	Gotland	Real time measurements for water balance control	Private households

Complementary to the current deliverable, the technologies tested within the energy and materials cycles are presented in *D1.4 New approaches and best practices closing the energy cycle in the water sector* (Kim et al., 2022), and *D1.5 New approaches and best practices closing the materials cycle in the water sector* (Kleyböcker et al., 2022). Although the technologies presented in deliverables D1.4 and D1.5 are focused on energy and materials cycles, some technologies may also contribute to closing the water cycle but are not reflected in the current deliverable.

The results obtained from the different case studies and presented within the three aforementioned deliverables were used as the basis of the environmental and economical assessments in WP2, which were summarized in deliverables D2.1 and D2.2. The outcomes from evaluating the future implementations and scaling up of the demonstrated technologies were considered in WP5.

The different technologies demonstrated, and the feasibility studies presented in deliverables D1.3, D1.4 and D1.5 were grouped per case study. The case study deliverables, considered non-official, can be accessed in the case study section of the Water Europe Marketplace at the following link: https://mp.uwmh.eu/l/CaseStudy/.

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2. Feasibility study on reclaimed water production possibility and regional demand in Timişoara (RO)

Authors: Ciprian Nanu and Ioana Groza (BDGroup)

2.1. Description of the demo site

The Timişoara water and wastewater system is operated by Aquatim SA (publicly owned company). The water system has undergone significant transitions in the last decades (Figure 2) with new drinking water and wastewater treatment plants as well as leakage reductions in the distribution systems. The new Timişoara wastewater plant is designed for 440,000 PE and is currently undergoing re-construction and modernization.
The industrial clients of Aquatim SA are located in the outskirts of the city as well as in several industrial areas (developed in the past decade, often using the infrastructure facilities from the past centralized political regime). Aquatim SA's clients were considered to be valuable partners for the implementation of water reuse concept. The Timișoara municipal company managing the public parks (Horticultura SA), one Timișoara based company producing solid and liquid detergents (Dalli Production Romania) and the Research and Development Station in Agriculture (SCDA) in Lovrin were shortlisted to be part of the water reuse study in the NextGen project.

Figure 2. Aerial photo of the Timişoara area (left) and the WWTP (right).

The WWTPs in Aquatim SA are going through a refurbishment and expansion phase due to the European subsidies at their disposal. WWTPs under construction, as well as the one in Lovrin, should comply with the standard for wastewater discharge in surface waters (namely NTPA 001/002). It was considered that for both WWTPs , in Timișoara and in Lovrin, only additional disinfection steps will be needed to comply with the new EU Regulation 2020/741

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on minimum requirements for water reuse (European Union, 2020). Two of the three selected clients in the case study need water for irrigation (agricultural and horticultural cases), while the third (a detergent production unit) has its own further treatment of the water and is rather interested in the cost of reclaimed water.
The three cases investigated showed that wastewater reuse is not easy to implement in the current way of placing the WWTPs - downstream and outside settlements. The cost of return the reclaimed water back in the city/localities is going to be too high due to the pumping needed. Also, returning reclaimed water back where would be needed requires expensive solutions to cross the city old area. Besides, in both Lovrin and Timişoara, the potential users of the WWTP effluent cannot implement the water reuse systems alone. The proposed projects need to be thoroughly analysed from perspective of the potential pilot case owners. Apart from Dalli Production Romania, who was interested in using the wastewater in its production process if it would cost less than potable water used today, the other two cases served rather as examples of what could be done in terms of reuse. Following the assessments conducted in NextGen, some opportunities and barriers were extracted.

2.2. Motivation for implementing circular economy solutions in the water sector

The implementation of the Urban Wastewater Treatment Directive (91/271/EEC) along with available European subsidies, have contributed to the upgrade of the water supply networks and WWTPs in Romania. It started in large cities and continued with the medium and small cites as well as the rural areas. The construction of new water supply and wastewater management systems is in full swing in Timiș county (Western Romania).
The study of water reuse in the Timişoara Metropolitan area shows that a more profound cost-benefit analysis understanding of the economic viability and opportunity of water reuse systems is needed. The involvement of various stakeholders available locally is also important, along with understanding the capacity of water resources management and societal involvement.
Even though water reuse is currently implemented in some European countries, water reuse projects will only succeed in Romania if water-related and industrial authorities along with users will understand and apply the Integrated Water Resources Management (IRWM) concept.

2.3. Actions and CS objectives

Table 6. Actions and objectives of the case study in Timişoara.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target

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# 10 **Timişoara**	Sub-Task 1.2.5 Feasibility water reuse of the Timişoara	Reuse of effluent for urban, industrial and agricultural applications	Study of potential water reuse	4	250,000 m3/d Secondary effluent	T1.2.5. Water yield of the system (% of reclaimed water produced).

2.4. Unique selling points

Water reuse:

- Water scarcity and rain pattern changes resulting from climate change have an immediate effect on all agricultural products (including wheat, barley, orchards, vegetables) and agricultural production systems. Currently used irrigation systems do not consider climate change effects. Social acceptance is a particular point to consider when applying technologies for wastewater reuse.
- The sector considered in the Timişoara NextGen case study was the public activities sector: this includes reuse on stadiums, in public parks, in shopping malls or in supermarkets. The municipal investment in water reuse technologies could make the required water available anytime, while preserving freshwater sources.
- All other industries in Timiș County could consider installations/equipment within their premises (such as the boilers or cooling systems, or the meat washing in meat producing sector) and review their sustainability strategies, as the technologies for water reuse are already available (on limited scale) on the local markets.

2.5. Principal characteristics of the technology

No dedicated technology was developed and applied in the Timişoara case study. The objective of the study was to analyze and to assess the opportunities for wastewater reuse from the Timişoara and Lovrin WWTPs for selected urban, industrial, and agricultural applications. The study included an analysis of potential wastewater reuse options, and a study of the three identified users in the Timiș county region.

Opportunities for the proposed options for wastewater reuse are related to:

- willingness and openness of potential users towards wastewater reuse
- climate change impacts on precipitation pattern and rising temperatures
- running European R&D projects regarding the wastewater reuse in process industries

Barriers to the proposed options for wastewater reuse are related to:

- public-public and public-private cooperation is not sufficiently developed to implement projects as complex as the reuse of wastewater in the city
- institutional capacity at local level
- installation of water and wastewater pipes in a city, especially with more historical areas, is a challenge most of the time and even sometimes impossible
- lack of disinfection technologies at WWTPs

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- geographical location of the WWTPs downstream of the cities and localities and the energy input needed to pump the wastewater back in the cities and localities
- uncertainty about water demand for industrial & agricultural uses
- lack of knowledge and low societal acceptance
- lack of communication & dissemination activities regardingwater reuse

2.6. Technology implementation requirements

Table 7 shows that in the Timişoara case study, several aspects were discussed and correlations between the current market needs for several industry segments were identified.

Table 7. Needs for several industry segments in Timis county.

Customer segment	Customer problem/needs
Industry	Technical: WWTP Timişoara is located downstream city while the industrial platforms are upstream. To pump the wastewater back in the city might make it more expensive than using freshwater and, in historical cities as Timişoara, it might be impossible to install the needed underground or surface pipes. A potential relocation or building a new WWTP or better installation of a unit as in the Athens case study might be taken in consideration if there will enough reclaimed water demand to base decision to install such a unit. Funding: Although there are financial sources for project application, the Aquatim SA does not have currently the capacity to apply and run such projects. Cooperation: At the moment, local partnerships and cooperation on projects between Timişoara stakeholders is limited. The current service contract between the municipality and water utility offering water and clean wastewater must be changed, to add more competencies and areas of activities for the water utility. Legislative: current water legislation in Romania should comply with European (more flexible and business oriented) legislation.
Landscape gardening and agricultural companies (farms)	There is no experience in Romania in the agricultural/horticulturalį's related to wastewater reuse. Many customers have their privately owned and financed wells and consider this the right way to use their water. There is no wastewater reuse project known at the Timişoara level of cooperation.
Research institutes	The cooperation between R&D organizations and water utilities is weak. They need to start cooperating with local/national organizations in their field of expertise (including providers of new water technologies). Applications for innovative projects should be developed and submitted (as it is the Athens Case Study in the NextGen, that could be considered as a pioneer in their field).
Municipalities and local administration in the rural area	Investments for development or rehabilitation of water supply and wastewater management systems should reduce operational costs as well as support resilient and circular water systems. Now, the client base in rural areas is slowly increasing. Implementation of the Water Framework Directive is beneficial for both the water sector and the clients, especially in rural areas where families are currently using unsecured water wells which are not subject to water quality control or monitoring.

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Changing the current Aquatim SA business model

Figure 3 shows the connections made during the development of the water reuse applications, considering the main potential groups of customers.

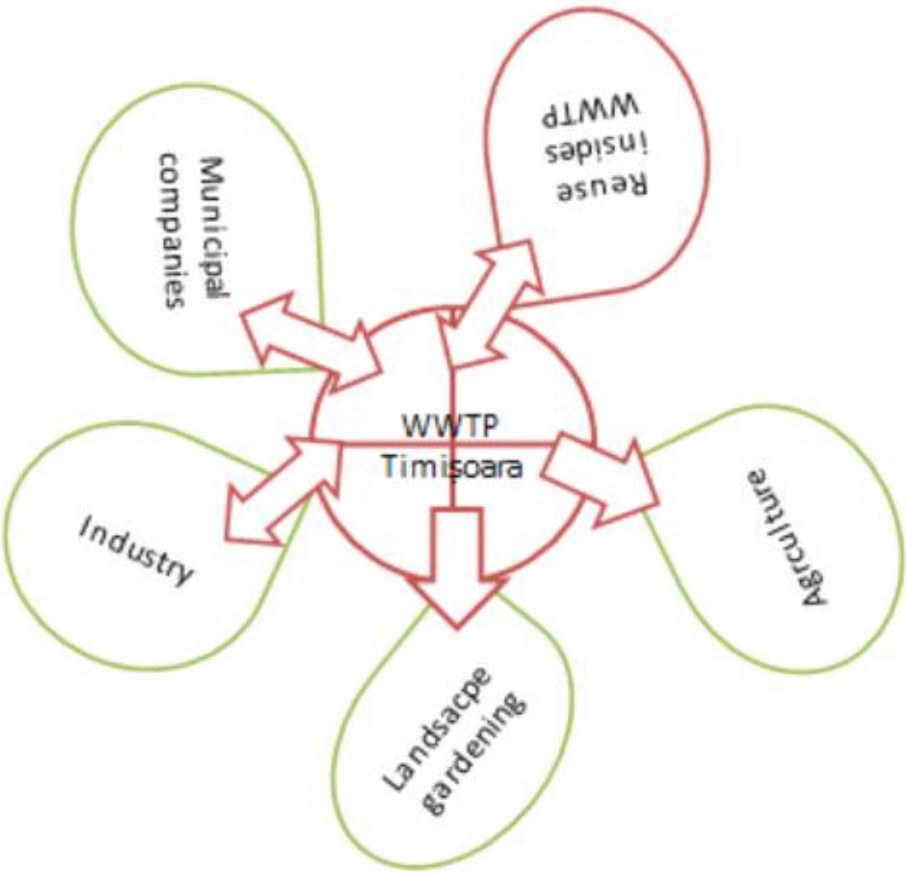

Figure 3. Potential sectors interested in water reuse applications.

The interested groups/ sectors surveyed for water reuse application in the Timişoara operational case were:

1. Agricultural group
2. Industrial group
3. Municipal services group (including urban irrigation (park watering services) and the fire brigade)

Special attention has been given to water reuse inside the cleaning technological (in-factory) processes within Aquatim SA. Currently, the WWTP Timișoara, as well as other WWTPs in Romania, use clean/potable water to wash their equipment. The treated wastewater could be reused for this activity.

During the first phases of the project implementation, the Romanian partners identified several organizations belonging to each of the interest groups listed above.

The current business model used in Aquatim SA is mostly linear. Aquatim SA is buying raw water from the Banat River Administration Basin (headquartered in Timişoara but covering several parts of territories in other counties as well).

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In recent years Aquatim SA started to collaborate in various projects with academia - not only local actors, but also a Technical University in Iasi, Northeastern Romania, as well as in EU funded projects such as NextGen, which have slowly brought innovation into the usual process.

2.7. Results obtained

The study carried out in 2021 initially aimed to map and develop coordinated actions with several potential sectors aiming to reuse wastewater, within the area of Timis County and several other smaller areas where Aquatim SA's services are offered.
The main activities were focused on agriculture, local industries, and some municipal services.

Agriculture

Timiș county has approximately 693 034 ha of agricultural area, of which 530 808 ha is arable land. Beside agriculture, there are also vineyards and orchards as well as pastures. According to the Timiș County Council, the agricultural potential is remarkable due to the extended flat areas and very good soil quality.
Spring irrigation of crops, usually done during the sowing of the crops, requires 200-300 $m^3$of water, while the reserve irrigation applied in the autumn required an additional 300 m^3/ha for wheat, 900 m^3/ha for maize, and 950 m^3/ha for soy. Also, during vegetation periods, irrigation is done based on a schedule that establishes how many times per year and when the crops should be irrigated. Irrigation should be applied when the soil humidity is under the minimum limit and should be stopped in case of precipitation. Therefore, if the normal precipitation during the vegetation period *cannot fulfil the amount of water needed*, this results in a water deficit of approximately 30 m^3/ha for wheat, 1 030 m^3/ha for maize and 2 730 m^3/ha for soy per year.
The local organization selected to be part of this current study was *SCDA Lovrin*. SCDA Lovrin is located approximately 50 km far from Timişoara and its main activity is to develop new varieties for cereal crops. For this purpose, they own 2200 ha for research and testing activities that are currently not irrigated. Only the offices of the SCDA Lovrin are connected to the water network of Lovrin village (currently under development). The water supply network is being extended and a wastewater management system is being installed.
For SCDA Lovrin alone, irrigating agricultural crops using groundwater is too expensive of an investment. For the current needs, SCDA Lovrin uses approximately 3 600 m^3/year, but this amount could be lowered if reclaimed water could be used for restrooms (a conclusion agreed to by management after visiting and promoting water reuse concept).
The water masterplan for Timiș county foresees a new WWTP in the village of Lovrin. The WWTP was already under construction in 2021, at approximately 500 m west of the village and approximate 5 km from SCDA Lovrin, located in the eastern part of the village (Figure 4).

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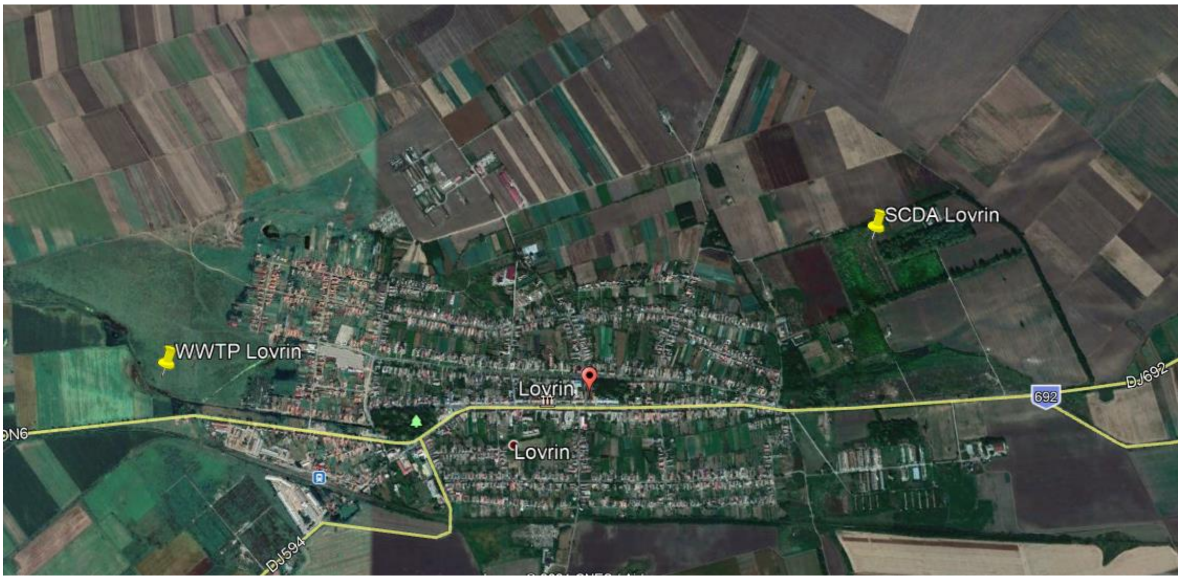

Figure 4. Aerial image of Lovrin and location of the WWTP Lovrin and SCDA Lovrin. Source: Google maps, BDG

The impact of climate change was also monitored at SCDA Lovrin. In accordance with available local data, during 2014-2018 the temperature was above the multiannual average by 1-2.2°C. Also, the quantity of precipitation was greater the multiannual average of 500 mm for 5 consecutive years. The experts also noticed that the precipitation distribution does not match the growing season of the crops, which has an impact on production quantity and quality, pests and diseases, weed growing and soil erosion.

The Lovrin WWTP is already in the development phase, but the final design does not include a disinfection step, therefore the cost for disinfection, pumping unit and pipes needed to divert the reclaimed water towards SCDA Lovrin were included in the estimation. Table 8 summarizes the estimated costs of implementing the project and using the effluent wastewater from Lovrin WWTP (serviced by Aquatim SA) at SCDA Lovrin.

Table 8. Estimated costs to implement the project and use of the effluent from Lovrin WWTP. Note: The figures in table are estimated for local construction costs using prices from 2021.

Wastewater from Lovrin WWTP	EUR
UV lamps (2x) – including installation	40 000
Automatic pumping station including the unit construction for pumps	103 093
Pipe (5 km) – including digging and covering the ditch	206 185
Pipes for transport of water in the field	5 000
Basin + pumps	12 000
Water pivot	74 427
Total	**440 705**

The analysis of the economic efficiency indicators specific to the investment performed for the agricultural sector, namely SCDA Lovrin, has been done according to the following hypotheses:

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- The investment is considered for 30 years of full operation. Given that there is no forecast for population decline or mass migration from the area, we consider that the time horizon in which the investment can operate (30 years) is reasonable.
- Accessing grants worth 410,705 EUR, which represents ~93% of the total investment value. These funds can be accessed through the Operational Program for Sustainable Development 2021-2027 or other forthcoming programs.
- As local council Lovrin is interested to setup a cold swimming basin and/or to re-establish the wetland area nearby the future WWTP besides income, there are also plenty of environmental benefits which add to the value. The following can be mentioned (not an exhaustive list):
    - the recreational activities of the population are enhanced and this can lead to the reduction of the number of people with anxiety, depression, obesity.
    - reducing the pressure on hospitals;
    - thermal waters used during balneary-physiotherapy, in case tourism services are a priority, and could be added to the water reuse process;
    - reducing the carbon footprint of companies that manage water resources (not calculated by local water utility or other organizations at the moment);
    - reducing the carbon footprint of the population seeking recreation activities.
- In the first 10 years, the expenditures are higher, but are expected to be reduced due to the expansion of agricultural areas which will be irrigated.
- Discount rate considered: 8%.

Taking into considerations the items below, with large percentage (93%) of investment coming from other subsidies, the individual investments required are shown in Table 9.

Table 9. Results of the investments.

Item	Indicators	Value (EUR)
1	General investment (own investment SCDA Lovrin)	30 000.00
2	Costs water, maintenance & operations /season – year 1-10	8 861.00
	Costs water, maintenance & operations /season – year 11-30	2 000.00
3	Income – Crop/season	9 000.00
4	Annualized Investment	27 777.78
5	Annualized Cost-total	88 126.58
6	Net Present Value (NPV)	4 860.13
7	Internal Rate of Return (IRR)	8.543%

The investigations done for the studied cases (in the 3 sectors) revealed that currently, agricultural projects have the highest chances for wastewater reuse, especially as precipitation pattern changes have both quantitative and qualitative direct impact on agricultural crops.

Industrial production

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement N°776541

The local partner selected to be part of the water reuse study was Dalli Production SRL., a detergent manufacturer part of Dalli Group Germany. Dalli Production in Timişoara manufacturing plant can be divided in two main product categories:

- one line is the ‘’solid detergents line’’, with approximately 10% of total water consumption, and
- the other one is the ‘’liquid detergents line’’, which uses approximately 90% of the total water consumption.

For the liquid detergents, the water quality parameters are very important, therefore, the potable water from the public network is further treated through reverse osmosis filtration and UV disinfection (within the premises of Dalli). The water also needs a very low conductivity of approximately 3 µS/cm.

The Dalli Production plant is located on an industrial platform in Timişoara. The most favourable route for bringing the treated wastewater in this case was to use the former industrial water treatment unit- built approximately 100 years ago. This unit consists of two sedimentation basins where water from Bega River was pumped and from there it was sent through a network of pipes to the industrial area. The former industrial unit has a central location that could be used to divert the wastewater to the industrial platform.

In the past, the processing industries located at the Timişoara industrial platform used the Bega River as their fresh water source, which underwent sedimentation processes in the industrial water unit. Afterwards, the processes industrial water was delivered to the factories. The industrial water delivery system was organized in the 20th century when the city started to develop.

Identifying the possible wastewater route to be used in the case of Dalli Production was part of the study. The Aquatim Timișoara WWTP, which can be used for this purpose, is located in the southwest of Timişoara city and the wastewater after tertiary treatment is discharged in a channel that transports the water further to Bega River. The wastewater collection and discharge are done gravitationally, therefore, if wastewater would be returned to the city, this would require pumping and construction of the needed infrastructure for transport. In order to potentially supply wastewater to users such as Dalli Production or other potential wastewater users on the industrial platforms, the most feasible solution considered was to pump the wastewater from the Timişoara WWTP to the industrial water unit, where the sedimentation basins could be used as a buffer. This would involve installing approximately 8 km of pipe in the Bega Channel, a pumping station at the Timişoara WWTP, installation of a transport pipe in the Bega channel if it would be possible to obtain the needed permit from Banat River Basin Administration, and restoration of the sedimentation basins at the Industrial Water Unit.

The cost estimation for the investment in wastewater reuse system (to be financed by Aquatim SA) is shown in Table 10.

Table 10. Cost estimation of the investment in water reuse system for industrial production.

Item	Cost/unit	Total cost (Euro)	Remarks
Pipe for water	40.81 Euro /m	324,000	PEHD, PE 80, Pn 10 D=200 mm, L=8 100 m
Pumping station with pumping house construction	145 000 Euro	145,000	
Sedimentation basin rehabilitation for water storage (cover with waterproof foil)	20.41 Euro/m^2	70,000	115 m x 30 m = 3 450 m^2
Total		**539,000 Euro**	

Besides the costs estimated above (at level of year 2021), further treatment of the wastewater would be needed, mainly disinfection, but also equipment to better remove phosphates, nitrates, plastic micro-particles, or pharmaceuticals. On the demand side, a wastewater effluent reuse project also should be realized, in order to connect the industrial water unit with the Dalli Production premises (as well as other potential industrial users of Aquatim SA effluent).

During the case study, the challenge was to identify a route to avoid the Timişoara historical area (as the wastewater pipe from industrial water unit to Dalli Production must be installed underground). The estimated costs for this part of the investment are shown in Table 11. Investments items taken in consideration for Dalli case are presented in Table 12.

Table 11. Estimated costs of the investment to connect the industrial water unit with Dalli Production.

Item	Cost/unit	Total (Euro)	Remarks
Water pipe	32.65 Euro/m	60 800 Euro	PEHD PE 100, Pn6, D=125 mm, L=1 900 m
Cost to repair roads	51.02 Euro/m^2	42 750 Euro	Approx. 45% of the total pipe length
Total		**103 550 Euro**	
Pumping station	120 000 Euro	+ 120 000 Euro	Pumping will be needed from Industrial Water Unit to Dalli Production site/ industrial platforms

Table 12. Total investments for Dalli case.

Item	Cost/unit	Total (Euro)
Water pipe	32.65 Euro/m	60 800.00
Cost to repair roads	51.02 Euro/m^2	42 750.00
Total I		**103 550.00**
Pumping station	120 000 Euro	60 000.00
Costs estimated for the proposal to use the Bega channel for pipe installation		199 666.67
Total II		**259 666.67**
TOTAL INVESTEMENT		**363 216.67**

Considering several important parameters of the investment in the case of Dalli Production in Timişoara, the cost efficiency of the investment it is shown in Table 12.

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Table 13. Cost efficiency of the investment in Dalli Production case.

Item	Indicators	Value
1	Investment	363 216.67 €
2	Costs water, maintenance & operations -year 1-10	500.00 €
	Costs water, maintenance & operations -year 11-30	1 000.00 €
3	Income	5 000.00 €
4	Annualized Investment	336 311.73 €
5	Annualized Cost-total	331 295.52 €
6	Net Present Value (NPV)	-279 636.23 €
7	Internal Rate of Return (IRR)	-5.95%
8	Investment recovery time	85.46 years

At the end of the study, Dalli Production concluded that use of reclaimed water considering the proposed/simulated investment is going to be expensive -more expensive that using potable water for their industrial lines.

Municipal Services (Horticultura SA)

The city of Timişoara is known for its parks and is called the "Flowers city". Although the current mayor has a new approach regarding the green infrastructure in the city, water for irrigation will be needed anyway due to climate change impacts, such as long periods with high temperatures combined with droughts periods that have negative impacts on vegetation. Another reason to consider water reuse in this case is because of the groundwater in the area, which is rich in iron and creates problems for (classical) irrigation systems which use it. Currently there are irrigation systems using groundwater installed in some public parks: Rozelor, Copiilor, Justiției and Central (only one is working at the time of the study, in 2021).
A more feasible solution would be to reuse the wastewater for Horticultura's production unit. The production unit of Horticultura, where the greenhouses (0.64 ha) are located, is another industrial area of Timişoara, smaller than others, but still with potential users for the Aquatim effluent (besides Horticultura greenhouses). Potential users include Continental Automotive (tires manufacturing and the second largest potable water consumer of Aquatim), TRW Automotive Safety Systems (manufactures wheels), and Retim (collects municipal waste and needs water to wash the garbage bins and trucks).
The Horticultura municipal greenhouses have low water consumption, but if combined with the other potential users mentioned above and if everyone would be willing to share the costs for the needed infrastructure, could use the effluent from the industrial water unit.
Similar conditions exist for the Dalli Production case: the first step towards investing in a water reuse project accepted would be to develop a project between the current Timişoara WWTP to their buffer (industrial water unit). According to the industrial partners in Timişoara, the initial investment should come from the water utility in Timişoara. The second part of the

investment would be to install a pipe from industrial water unit to the location of the industrial platform, where Dalli, Horticultura and other users are located.
Prior to installing a wastewater pipe from the Industrial Water Unit to the Horticultura production unit, similar challenges exist as for the Dalli production site - route identification, installation of underground pipes and obtaining the needed permits.
The costs estimated for the municipal Horticultura are in the same range as the Dalli Production, at level of 2021 (See Table 14). Similarly, the investments costs and indicators for the Hordicultura case are shown in Table 15 and Table 16.

Table 14. Estimated costs for the municipal Horticultura.

Item	Cost/unit	Total cost (Euro)	Remarks
Water pipe	32.65 Euro/m	73 600 Euro	PEHD PE 100, Pn6, D=125 mm, L=2 300 m
Cost to repair roads	51.02 Euro/m^2	63 250 Euro	55% of the total pipe length
Total		**136 850 Euro**	
Pumping station	120 000 Euro	+ 120 000 Euro	Pumping will be needed from Industrial Water unit to Horticultura location

Table 15. Investment costs for Horticultura SA case.

Item	Cost/unit	Total cost (Euro)
Water pipe	32.65 Euro/m	73 600.00
Cost to repair roads	51.02 Euro/m^2	63 250.00
Total I		**136 850.00**
Pumping station	120 000 Euro	60 000.00
Costs estimated for the proposal to use the Bega channel for pipe installation		199 666.67
Total II		**259 666.67**
TOTAL INVESTEMENT		**396 516.67**

Table 16. Investment indicators for Horticultura case.

Item	Indicators	Value
1	Investment	396 516.67 €
2	Costs water, maintenance & operations -year 1-10	500.00 €
	Costs water, maintenance & operations -year 11-30	1 000.00 €
3	Income	5 000.00 €
4	Annualized Investment	367 145.06 €
5	Annualized Cost-total	374 584.84 €
6	Net Present Value (NPV)	-322 925.55 €
7	Internal Rate of Return (IRR)	-6.37%
8	Investment recovery time	93.30 years

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The current Timişoara setup (positioning of the WWTP, the industrial water unit, the industrial platforms, etc.) makes it difficult to transport the wastewater back to the city. Investments cannot be recovered in a decent period of time, considering that the working hypothesis was that the system will be in operation for 30 years. The investment recovery time could be higher if further costs which were not identified during this research project would be added to these initial costs.

2.8. Comparison of baseline situation and NextGen KPIs

Timiș County does not currently have a water deficit, but the precipitation pattern change has already impacted the agricultural sector, an important one for Timiș county. The county has approximately 693 034 ha of agricultural area, out of which 530 808 ha is arable land. Besides agriculture, there are also vineyards, orchards, and pastures. According to the Timiș County Council, the agricultural potential is remarkable due to the extended flat areas and very good soil.

As the study of SCDA Lovrin and other R&D projects showed, the precipitation deficit in the agricultural sector occurs when water is needed the most, when the plants are in full growing season. That is why the wastewater reuse from SCDA Lovrin could be a best practices example, especially as the local authority Lovrin is willing to cooperate and identify other potential uses for the reclaimed water.

The proposed projects could have various impacts (positive or negative, intentional, or random). Some of these consequences derived from projects were identified in Table 17.

Table 17. Identified consequences derived from projects that could be estimated.

Items	Impacts	Unit
Wastewater infrastructure	In Timișoara, wastewater could be used for irrigation systems within the city –the currently used groundwater is not suitable due to high iron content	Euros
	Washing the streets	m^3 of fresh water saved
	For firefighters	m^3 of fresh water saved
	In Lovrin area, wastewater could be reused for more agricultural holdings than just SCDA Lovrin	Euros
Uses of the resource	Increase the quantity of water available for non-potable use	m^3
	Secure water supply during drought periods	m^3
	Water quality after treatment used for different actions	Wastewater quality threshold values
Public health	Biological risks associated with the wastewater reuse	People & animals exposed
	Chemical risks associated with the wastewater reuse	People & animals exposed

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Environment	Avoid pollution of the rivers (Bega and Galațca)	Wastewater quality threshold values
	Maintain the aquifer level and depth	Km^2 and meters depth
	Wetland could be setup to enhance biodiversity	Visitors
Education	Increase awareness about freshwater resources protection	No. of people
	Increase the acceptance for wastewater reuse	No. of people

The environmental and the public health impacts are very important to evaluate as they could have negative consequences if the potential pollutants are not removed by the established treatment train. Wastewater analyses should be performed regularly and in case further treatment is needed, the necessary equipment should be installed in order to continue the wastewater reuse.

Although the economic viability of the proposed projects for wastewater reuse must be proved by project implementation, the initial calculation is a key point from which to start developing a project proposal and accessing public funds for co-financing. Other aspects, such as over-estimation of the potential users of the treated wastewater, which is closely linked with public acceptance of this type of water, or environmental issues, could affect the final success of the proposed projects. Especially for SCDA Lovrin case, which is most likely to be implemented, it worth considering the benefits associated with the irrigated agricultural land use. The cooperation between Aquatim SA and SCDA Lovrin could lead to a more sustainable water management in the future for the whole region. The sludge produced at the Lovrin WWTP could be turned into biogas together with agricultural waste. The treated wastewater could be used for irrigating the green areas in Lovrin or by other farmers in the region. Storage basins or storage lakes could be setup in the area. Further adapting the wastewater treatment to match the quality required for bathing waters, such as for a cold-water swimming pool proposed by the local Lovrin municipality, could be implemented.

Although the current situations are not favorable for wastewater reuse, the change in precipitation pattern and long drought period could foster the implementation of irrigation systems, and wastewater has the largest potential to be reused. The current sanitation network expansion work in the rural areas could already be used to install the needed train treatment so the wastewater could be used for irrigation and for other agricultural activities. The most relevant data that could be taken in consideration for the needed investments are the Internal Rate of Return (IRR) and Net Present Value (NPV) (See Table 18).

Table 18. Internal Rate of Return (IRR) and Net Present Value (NPV) obtained after the economic analysis of the three cases.

Case study	IRR (%)	NPV (Euro)
SCDA Lovrin	8.54%	4 860.13
Dalli Production Romania	-5.95%	-279 925.23
Horticultura	-6.37%	-322 925,55

At the first glimpse the SCDA Lovrin case study seems to be the most robust. The future WWTP Lovrin is only 5 km away, the instalment of the disinfection step is not very complicated, the future National Strategic Plan 2023-2027 foresees funding opportunities for irrigation systems, and the local council is willing to support SCDA Lovrin by participating and using the treated wastewater for a swimming basin or a lake. Therefore, although the investment cost is quite high if considered individually by the potential partners (Aquatim, University of

Agricultural Sciences (USAMV), Timişoara/SCDA Lovrin/Local council Lovrin), the willingness of the local council to support, the existence of facilities at USAMV Timişoara to analyse the soil and plants as well as the available funding opportunities, makes the agricultural case study most feasible for a partnership setup and future project development and implementation.
For the municipal case studies of, Dalli Production and Horticultura, without economic or regulatory benefits, the economic analysis showed that the needed investment as well as the cost of the treated wastewater and IRRs are negative even if the system operation was considered for 30 years. The location of the Timişoara WWTP, approximate 8 km from the city center, the location of the two case studies in different industrial platforms, and the challenges to identify the most feasible routes for pipes, increased the sensitivity of potential projects. Additional unknown variables included the approval for pipe installation both in the Bega river and to the two industrial platforms, the uncertainty of the partnership for available financing programs or for the next programming period, the increasing prices for energy (pumping will be needed in at least two locations), the commitment needed from the beginning to the end of the project, implementation of which may take longer than 2 years for implementation, as well as other variables currently unknown.

2.9. Lessons learned

<table>
<tr><td>Required competence</td><td>LOW HIGH</td></tr>
<tr><td colspan="2">Which knowledge is required to operate a water reuse project?
1. Basic knowledge about circular water and the role in the local circular economy.
2. Modern technologies available on the local market.
3. Cost assessment regarding the water reuse. Since the local conditions in Timişoara are not probably favorable for the transport of reused water products, several scenario options must be developed for the future projects. Knowledge transfer for water when considered as a business is needed.
What kind of training is necessary?
1. Project management for the assessment, design, and management of a water reuse project.
2. A course on correlation between water reuse, health, and environmental topics.
3. Funding opportunities for considering water reuse as a local business.</td></tr>
<tr><td>Maintenance</td><td>LOW HIGH</td></tr>
<tr><td colspan="2">Not applicable, theoretical study</td></tr>
<tr><td>Technological risks</td><td>LOW HIGH</td></tr>
<tr><td colspan="2">Not applicable, theoretical study</td></tr>
</table>

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2.10. Best practice guidelines for operating the technology

Initial market approach

The current approach within the NextGen Water project investigated the possibility for reusing the treated wastewater of Aquatim SA's WWTPs in Timişoara and in Lovrin. The possibility of new investment in a WWTP in Timişoara was not taken in consideration. The wastewater flow used was based on current parameters within Aquatim SA WWTP in Timișoara and the foreseen parameters in Lovrin.

The first step was to evaluate the economic profile of Timiș county and Timişoara city to determine the list of stakeholders of relevant local industries which required analysis.

Based on the consumers (clients) data of Aquatim SA and the new European regulation for wastewater reuse in agriculture, a list of potential companies/institutions were selected. The initial list included 5 entities in the agriculture/horticulture sector and top 10 largest Aquatim SA consumers.

The next step was to inform (e-mail, telephone) the selected entities about the NextGen Water project and scope of the water reuse requirements.

The stakeholders' selection process was hampered by various unknown factors such as water legislation (in Romania there is no currently clear legislation for wastewater reuse therefore is unclear for companies if they can or cannot reuse water. The Water Law[1] mentions ''water reuse'' in just one article), the changes of potable water resources due to climate change impact on water availability. There were also known factors, such as the cost of fresh and potable water, the bureaucracy for obtaining various permits, or the current local wastewater balance.

Following the selection process three entities were selected: SDCA Lovrin in the agriculture sector, Dalli Production Romania in the process industry, and Horticultura SA in the municipal services sector.

Establishing the content of the water reuse study

In Romania, the framework for a feasibility study for projects implemented with public funds is established by the GD 907/2016[2]. For this feasibility study on the potential of wastewater reuse developed within the NextGen Water project, the model used was the one developed within the AQUAREC project that elaborate a *Handbook on feasibility studies for water reuse systems* (Urkiaga et al., 2006). Since currently there is no real project development for water reuse, the investigation was limited to estimation and assumptions.

[1] https://legislatie.just.ro/Public/DetaliiDocument/8565

[2] http://legislatie.just.ro/Public/DetaliiDocument/185166

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3. Advanced wastewater treatment technologies for water reuse

3.1 Anaerobic membrane bioreactor (AnMBR) in Spernal (UK)

Authors: Ana Soares (UCRAN) and Peter Vale (STW)

3.1.1. Description of the demo site

The Spernal wastewater treatment plant (WWTP) is a medium sized plant serving the towns of Redditch and Studley and is located approximately 24 km south of Birmingham (UK) (Figure 5). The site has a dry weather flow of 1,150 m^3/h (or 27 600 m^3/day) serving 92 000 population equivalents. Spernal WWTP includes a preliminary treatment, primary treatment, an activated sludge plant, secondary clarifiers, and sand filters. The treated effluent is discharged to the Arrow River, which is designated as a sensitive area under the Urban WasteWater Treatment Directive (UWWTD) and has an overall water body status of moderate under the Water Framework Directive (WFD). The sludge produced on site and in other local rural works is further treated in anaerobic digesters and dewatered before being recycled to local farmland and industries. The biogas produced by digesters is burnt in combined heat and power (CHP) engines to produce heat and electricity.

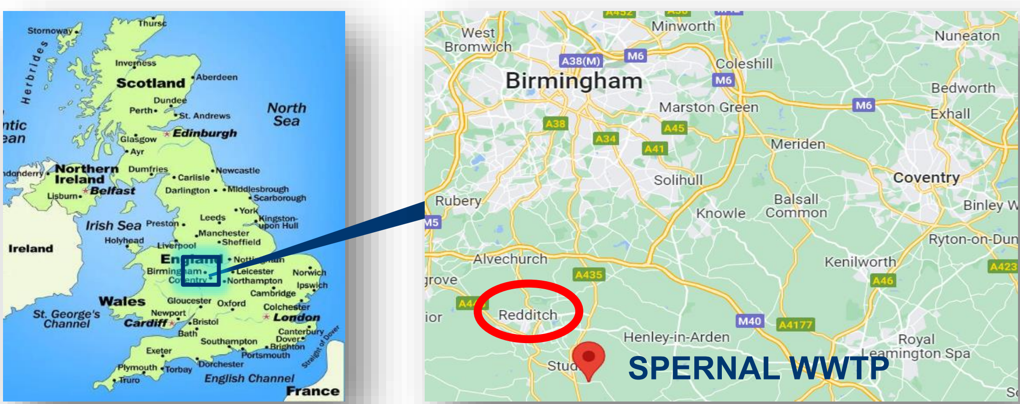

Figure 5. Location of the Spernal wastewater treatment plant (WWTP) within the United Kingdom (left) and local map (right).

Spernal serves as Severn Trent Water's "Urban Strategy Demonstration Site" where emerging technologies compatible with low energy demand, low greenhouse gas emissions and a circular economy approach are evaluated (Figure 6). The "Urban Strategy Demonstration Site" contains all the infrastructure needed: power, wastewater feed, drainage, telemetry, and biogas handling equipment necessary for the NextGen trials, together with office and laboratory facilities. Among the technologies tested is a multi-stream, demonstration scale

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anaerobic wastewater treatment plant for carbon management, and ion exchange processes for nutrient management (Figure 7). The demonstration plant incorporates an anaerobic membrane bioreactor (AnMBR) complete with a membrane degassing unit to recover dissolved methane. The AnMBR combines several benefits such as no energy for aeration needed to remove COD/BOD, low sludge production and associated treatment efforts, biogas production (production of electricity/heat), and a high-quality effluent which can be reused in several applications (e.g. farming and industrial use). The ion exchange (IEX) process enables targeted ammonia (N) and phosphorus (P) removal and recovery to produce a high-quality effluent whilst recovering calcium phosphate salts and ammonia sulphate solutions.

Figure 6. Aerial picture showing the Urban Strategy Demonstration Site at Spernal WWTP and the location where the NextGen demonstrator was built.

Figure 7. Aerial picture showing the NextGen demonstrator including the anaerobic membrane reactor and degassing unit.

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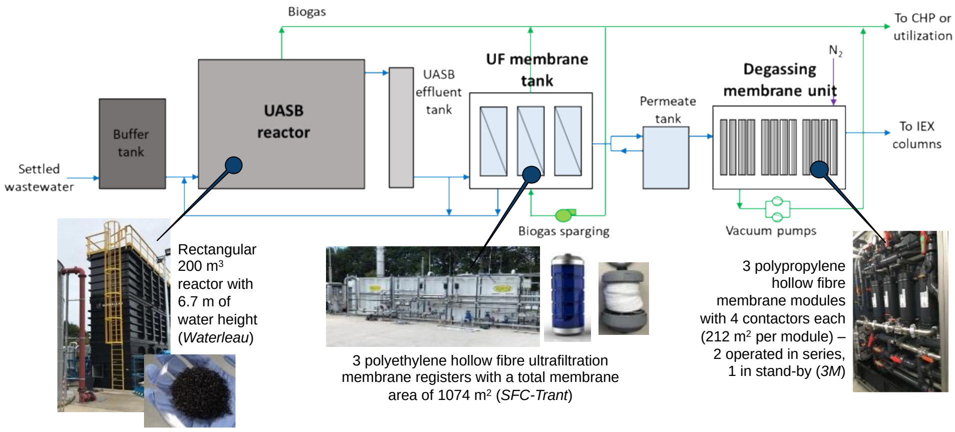

Figure 8. Schematic representation of the process.

The data gathered at the Spernal WWTP innovative technology flowsheet aims to demonstrate and showcase the viability of this transformative approach to wastewater treatment in cold-climate northern European countries, enabling future energy recovery combined with effective nutrients recovery. The project confirms the optimal design and operating parameters for delivering a comprehensive energy balance and cost benefit assessment.

3.1.2. Motivation for implementing circular economy solutions in the water sector

As the water sector is a relatively large user of energy and a significant emitter of fugitive greenhouse gases (nitrous oxide and methane), it is therefore incumbent on water utilities to address the challenge of climate change by striving to reduce their carbon footprints. Transitioning to a more circular way of operating, reducing the amount of energy and chemicals required for treating water, and recovering and reusing the energy, materials and water which are plentiful in wastewater will become a central strategy of water utilities.
The AnMBR/ion exchange flowsheet, once proven, can deliver an energy neutral wastewater treatment process, reduce process emissions by removing the main contributor to nitrous emissions – biological nitrification and denitrification - and facilitate resource recovery through producing a solids' free, disinfected effluent ideal for nutrient (N and P) recovery and/or the recovery of water and nutrients through fertigation.

3.1.3. Actions and CS objectives

Table 19. Actions and objectives of the Spernal case study.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
# 5 **Spernal**	**Sub-Task 1.2.3 Multi-stream anaerobic MBR for**	Spernal wastewater treatment plant serves as Severn	Decentralized water treatment by a multi-stream	TRL 6 → 7	500 m3/d (max)	Pathogen and solids free effluent which can be reused

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Location: Sperna l WWTP	**district-scale reuse applications (Spernal)**	Trent Water's "Urban Strategy Demonstration Site"	anaerobic membrane bioreactor (AnMBR)			in a number of applications (e.g. farming and industrial use).

3.1.4. Unique selling points

Anaerobic membrane reactor combined with an effluent methane degassing system:

- No aeration energy required for removal of chemical and biological oxygen demand
- Low sludge production and associated treatment efforts
- Chemical free process removes methane from liquids
- Up to 99% methane recovered from the dissolved fraction
- Pathogen and solids free effluent which can be reused in a number of applications (e.g. farming and industrial use)
- Compact equipment with low footprint – low operation costs.

3.1.5. Principal characteristics of the technology

Anaerobic membrane bioreactors (AnMBR) combine an upflow anaerobic sludge blanket reactor (UASB) with physical separation membranes, ultrafiltration (UF) for solid-liquid separation, and membrane contactor for gas-liquid separation. As shown in Figure 9, the UF membrane system is integrated with the UASB through the side-stream recirculation line configuration, and the technologies should be evaluated together. The combined technologies result in solids and organic contaminant removal from wastewater, and biogas production for energy recovery. The AnMBR typically treats 200 m^3/d (max 500 m^3/d) of settled wastewater. In the UASB reactor (Waterleau), inoculated with mesophilic industrial granular sludge, the recirculation (with the UASB effluent and/or from the UF membrane tank) is used to sustain an up-flow velocity of 0.8 m/h and a hydraulic retention time (HRT) of 8-10 h. The three-polyethylene hollow fibre ultrafiltration membrane reactor (C-MEM from SFC-Trant) has a total membrane area of 1 074 m^2 and is sparged with the biogas produced in the UASB reactor. The HRT in the UF is 1.3 h and the flux is 10 LMH (L/m^2.h).

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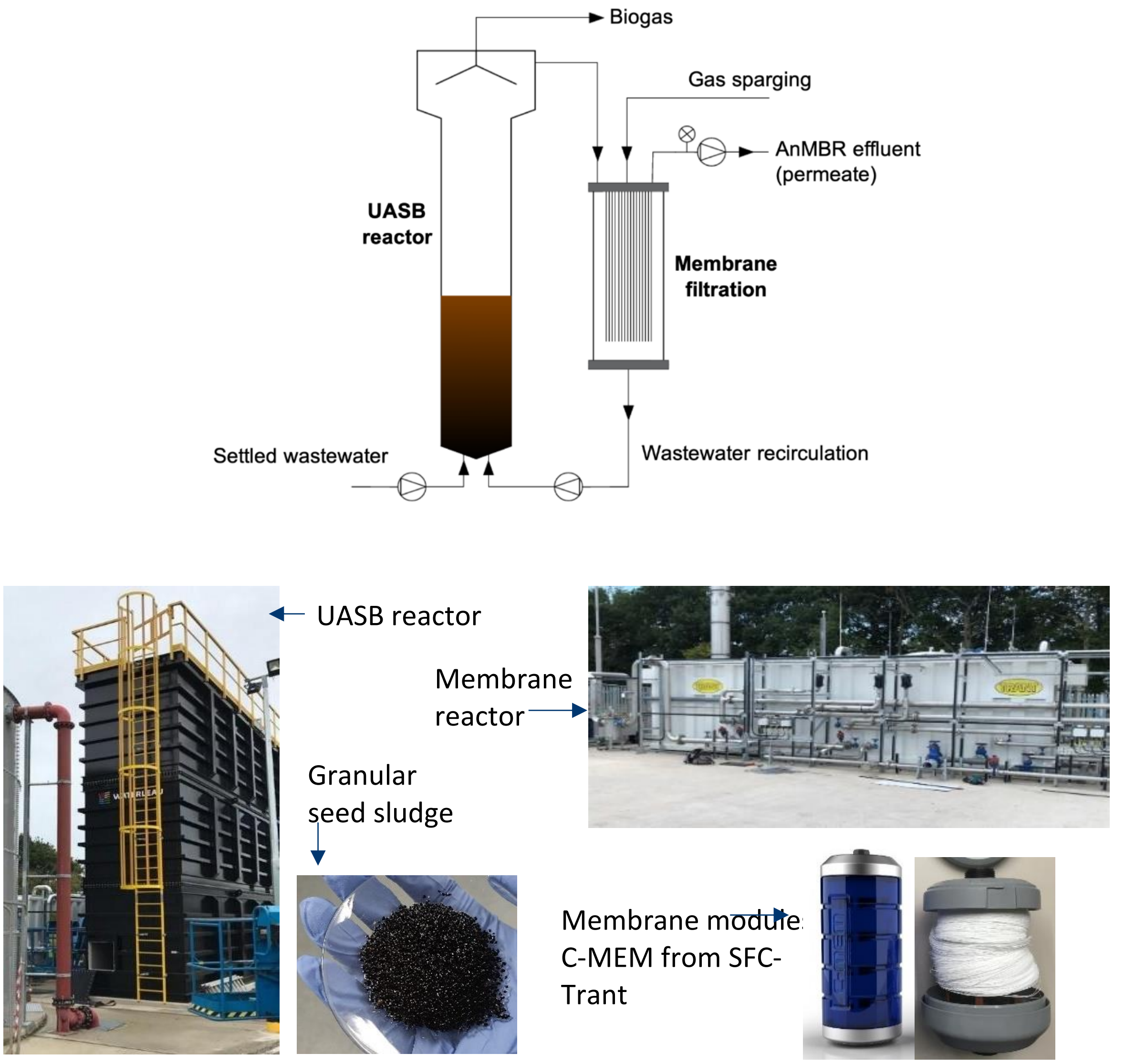

Figure 9. Schematic representation of the process of the AnMBR (top) and pictures of the technologies at Spernal WWTP (bottom).

3.1.6. Technology implementation requirements

There are several parameters that affect biogas production from anaerobic membrane bioreactors (AnMBRs), including hydraulic retention time (HRT), solids retention time (SRT), temperature, pH, and organic loading rate (OLR). The feasibility of anaerobic wastewater treatment in the UK has been demonstrated through pilot-scale trials which have taken place at Cranfield University since 2003. The work completed to date has showed that treating municipal low strength wastewater (COD <400 mg/L) at real temperatures (6-22°C, with an average of 14°C) in an AnMBR is feasible, and they have the potential to replace traditional energy consuming aerobic wastewater treatment processes. Hydrolysis is the limiting step, therefore long sludge retention times are required to ensure stable biogas production, and solids can be maintained in the reactor by using a membrane filtration after the UASB. This combined system has been thoroughly investigated at pilot-scale. The operational envelope includes fluxes of 8-13 LMH and HRT 4-12 h (Table 20). Membrane fouling is of physical nature and can be controlled by intermittent gas sparing practices using biogas, whilst still maintaining the process energy efficiency. The flow to the membrane tank can be turned

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up-down easily and its design was completed using the average flow rather than full-flow to treatment. COD removals of 60-70% can be regularly achieved, whereas 90-95% removal can be achieved when coupling the UASB with a membrane, which produces effluents with 0 mg TSS/L, <20 mg COD/L and <10 mg BOD/L. The methane composition in the biogas is high (80%), which facilitates its upgrading (e.g.: car fuel 96-98% CH4) or other uses. Despite the capacity and advantages on anMBR, nutrients removal in the anaerobic reactor is negligible (5-10% phosphate removal and ammonia increase by 5-15% due to solids hydrolysis). Post-treatment for nutrients removal/recovery is necessary.

Table 20. Required operating conditions of the AnMBR.

Parameter	Units	Min	Max	Reference
Anaerobic bioreactor				
pH	-	6	8.2	Paissoni et al. (2022)
Temperature	°C	4	25	
Flow rate	m^3/d			
Hydraulic retention time (HRT)	day	3	15	
Sludge retention time (SRT)	day	10	150	
Membrane contactor				
pH	-	6	8.2	Paissoni et al. (2022)
Temperature	°C	4	25	
Flow rate	m^3/d			
Water flux	$L/m^2.h$	5	50	
Specific gas demand per membrane area	$m^3/m^2 \cdot h$	1	10	

Other practical requirements necessary for implementing the technology:

- An old asset that is expired, such as an activated sludge process (ASP) or trickling filters, and a WWTP in need of reconstruction
- A green field site (very rare)
- A WWTP needing a significant upgrade
- Refurbishing and upgrading a rural WWTP (often with <2,000 PE) (just the UASB)
- A WWTP that requires the production of water for reuse (e.g., fertigation)
- Available fresh settled wastewater, ideally with low sulphate concentrations, favours the anMBR biological processes and performance

3.1.7. Results obtained

The AnMBR was initially fed from September-November 2021. After 4 weeks of operation (from start-up period), the system was achieving >95% TSS removal, mostly due to the UF membrane (Figure 10). The SO_4 removal was >80%, indicating an active community of sulphate-reducing bacteria in the UASB reactor and no biogas production was observed after 1 month of operation. Overall, the AnMBR performance was not as expected. After thorough investigative work, the main reason for the limited performance and no biogas production was the septic influent to the AnMBR. This happened because the influent was first stored in a buffer tank with large capacity and very long HRT, which caused the tank to act as an uncontrolled anaerobic reactor. Under these conditions, the sulphate (over 100 mg/L, Figure 10) and COD were converted to H_2S, decreasing the oxidation reduction potential (ORP) of the

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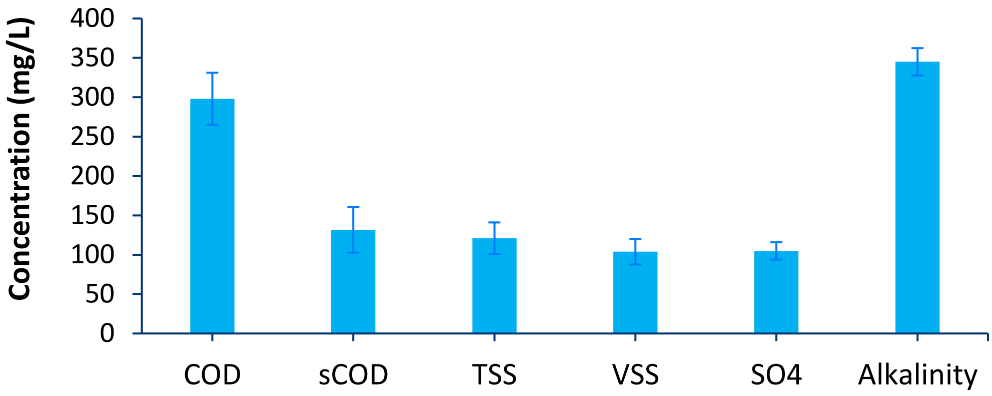
wastewater to -100 to -200 mV, causing the wastewater to become septic. Under such circumstances, specifically the very low ORP and high sulphates, the microbial community in the UASB gradually shifted from anaerobic digestion to sulphate reducing bacteria. To solve the problem, modifications were made to the buffer tank to reduce the HRT, and a new procedure for regularly cleaning the buffer tank was implemented.



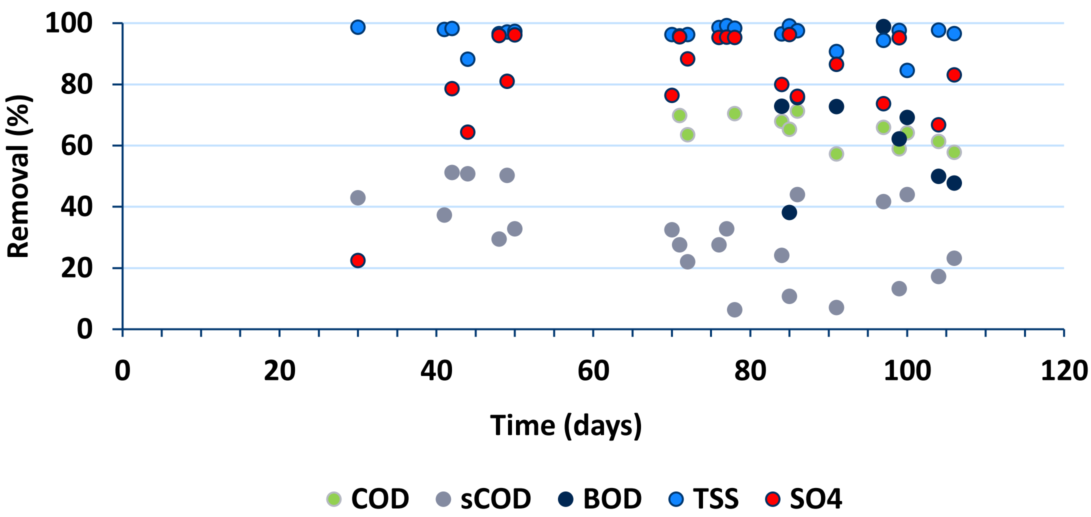


Figure 10. Influent characterisation of the AnMBR between Sep.-Nov 2021 (top) and percentage removals of various wastewater pollutants (bottom).

From 22/11/2021 to 31/05/2022 the demonstration plant faced several issues that took some time to diagnose and fix. The first one was a blockage in the UASB influent pump, which prevented the influent from reaching the system. The problem was related with rag accumulation and was fixed by cleaning some internal components in the reactor. The second major issue was a compressor fail, also required for the UASB operation, as the valves were open and closed using compressed air. Due to supply chain issues the spare compressor was not readily available, leading to a long shutdown of the system. The AnMBR was finally put back in operation on 31/05/2022. Issues with the UF cleaning and high transmembrane pressure were also recorded, and these have not been fully solved.

The AnMBR was re-seeded on 08/06/2022 to guarantee fresh active biomass in the reactor and also to ensure that methanogenic activity could be re-established, after the issues with septicity and long period without any feeding or recirculation.

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The AnMBR was started again on the 13/06/2022 after re-seeding with granular sludge supplied by Waterleau from an industrial wastewater treatment plant.

From the 13/06/2022 to the 12/07/2022, the temperature of the influent wastewater was on average 17.7±0.6°C. The characterisation of the influent settled wastewater (Table 21) shows low concentrations of COD (171 mg/L) and sCOD (91 mg/L), a BOD/COD ratio of 0.26 and a COD/SO_4 ratio of 1.39, which may hinder the conversion of organic matter into methane, due to low availability of biodegradable substrate. Sulphates reduction remained a concern as this biological induced reaction uses available carbon (i.e.: sCOD, that was already present in low concentrations), reducing its availability for biogas production.

Table 21. Characterization of the influent settled wastewater, fed to the UASB reactor.

	Temperature	pH	COD	soluble COD **(sCOD)**	BOD	Total suspended solids (TSS)	Volatile suspended solids (VSS)	Conductivity
	°C		mg/L	mg/L	mg/L	mg/L	mg/L	mS/cm
Average	17.7	8.08	171	91	45	46	40	957
Standard deviation	0.6	0.53	27	9	13	14	13	57
	NH_4-N	Total P	PO_4-P	SO_4-S	COD:SO4	Alkalinity	Volatile fatty acids (VFAs)	
	mg/L	mg/L	mg/L	mg/L		mg CaCO3/L	mg/L	
Average	23.7	3.0	1.9	124	1.39	308	100	
Standard deviation	2.1	0.5	0.2	9	0.25	14	16	

The data presented in Figure 11 shows the pollutant removals in the AnMBR from 13/06/2022 to 12/07/2022, which can be considered the start-up period, of special relevance for the biological reactor. During this period the removals were on average 60% COD, 76% BOD and 71% TSS (Figure 11). The methane content in the biogas increased steadily, reaching values of 60% and a production of 63 L/h (Figure 12 and Table 22). The AnMBR is still going through the start-up phase, in day 12/07/2022. Stable operation (i.e., after start-up) is defined when the COD removal is above 80% and methane concentration in the biogas is 70%. An odd value that is also being investigated is the TSS removal, which is expected to be 100% after the UF. A potential explanation is the solids accumulation in the autosamplers, and frequent cleaning has been advised together with grab samples to verify the data. Expected removals in the AnMBR once the issues have been solved and stable operation is reach are in the order of BOD >80%, COD>90% and TSS of 100%.

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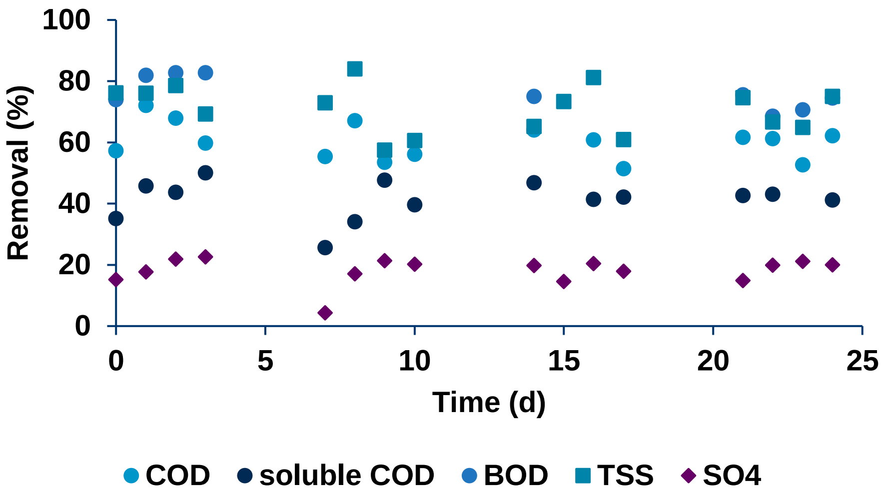

Figure 11. Pollutant removal in the AnMBR between Jun.-July 2022, corresponding to the start-up period.

Table 22. Averaged pollutant removals and their standard deviation between Jun-July 2022, corresponding to the start-up period.

	COD	soluble COD	BOD	TSS	SO4
Average removals (%) and standard deviation	60±6	41±6	76±5	71±8	18±4

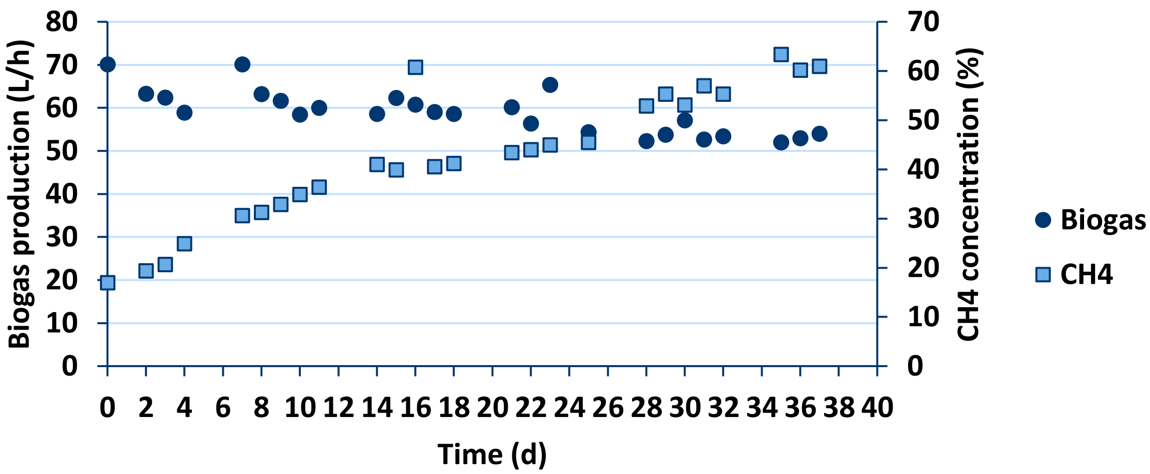

Figure 12. Biogas/methane content in the AnMBR between Jun-July 2022, corresponding to the start-up period.

Solids management in the AnMBR is of vital importance, as these must be retained in the UASB reactor for as long as possible to go through hydrolysis followed by the 3 other stages of anaerobic digestion and ultimately result in biogas production. Further, the solids should not find their way to the UF to avoid fouling issues. The total solids concentration in the UASB is being carefully monitored (Table 28) to help inform the reactor stability but also when the reactor needs to be desludged. So far, the UASB has not yet been desludged, which is one of the key advantages of the system due to the very low sludge production.

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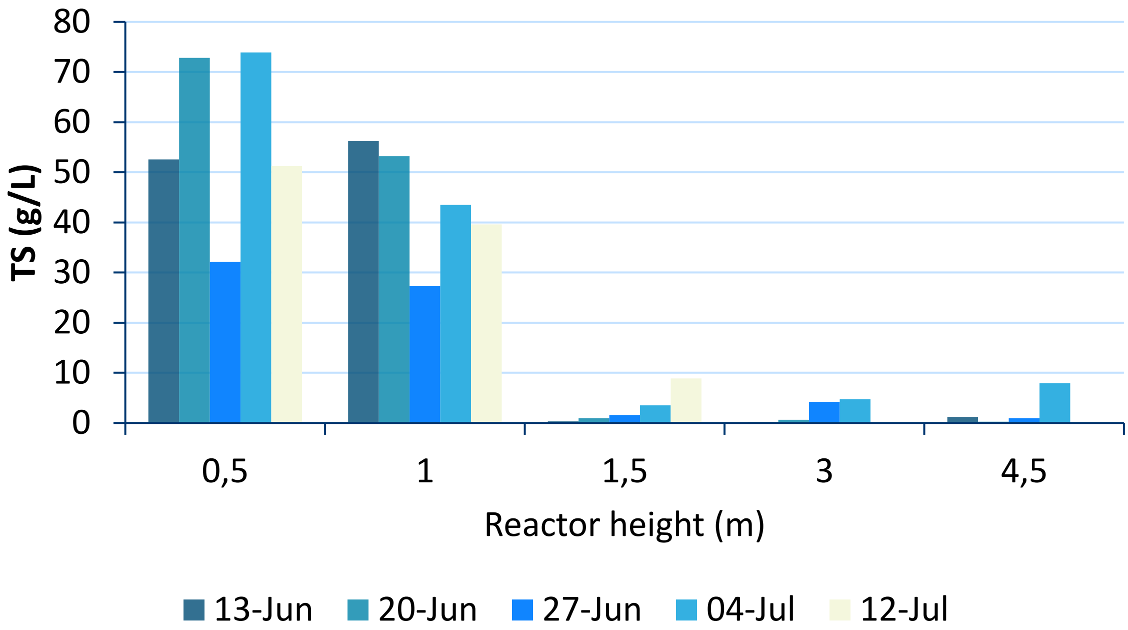

Figure 13. Total solids concentration in the UASB reactor for monitoring the sludge blanket.

The AnMBR operational efficiency achieved in this study was comparable to previous studies with variable influent municipal wastewater values for COD of 221-455 mg/L and TSS of 45-479 mg/L (Martin Garcia et al., 2013; Shin et al., 2014). The removal rates achieved for the COD and BOD_5 were still lower when compared to Wang et al. (2018), which obtained 83 ± 7% and 90 ± 6%, respectively, but similar values are expected once the AnMBR reaches stable operation. According to Ribera-Pi et al. (2020) a granular sludge inoculated AnMBR also achieved an sCOD removal of 43 ± 15%, also similar to this study's results. The removal efficiency of a self-forming hollow fibre dynamic membrane, analysed by Isik et al. (2019), was only around 42% and 34% for TSS and VSS. The similar reactors design of this study to previous studies emphasise the validity of the results and work performed. The operational temperature range was also similar to previous studies - Gouveia et al. (2015) operated at 18 ± 2°C and Wang et al. (2018) at 16.3 ± 3.7°C.

Regardless of the high COD influent in the systems, the methane yield reported was considered average. This was mainly because no solids could escape the system and hydrolysis was maximised during operation, which in turn ensured methane yields were high. In a study by (Gouveia et al., 2015), a municipal wastewater fed and pilot-scale AnMBR which operated at a similar temperature of 18°C and a lower COD of 74-225 mg/L produced a methane yield of around 0.16-0.31 L CH_4/g COD removed, which is comparable to this study. Similarly, two additional AnMBRs from the study by Ribera-Pi et al. (2020) operating at a lower temperature of 9.7 ± 2.4°C, had methane yields of 0.18-0.20 L CH_4/g COD removed.

3.1.8. Comparison of baseline situation and NextGen KPIs

The existing Spernal WWTP was the baseline case to which the NextGen Spernal demonstrators were compared.

The baseline case (Table 23):

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The Spernal WWTP is a medium sized plant treating an average daily flow of 27 ML/d to a 10 mg BOD/L, 25 mg TSS/L, 5-10 mg NH4/L and 2 mg P/L standard. The plant includes a preliminary treatment (6 mm screening and grit removal), conventional primary settlement tanks with iron dosing for P removal, secondary treatment comprising trickling filters for 33% and activated sludge for 66% of the flow, and tertiary sand filters.

Effluent from the plant has COD of 44.6 ± 11.5 mg/L, BOD of 3.6 ± 2.7 mg/L, TSS of 9.8 ± 6.8 mg/L, a total nitrogen (TN) content of 34.5 ± 5.18 mg/L, and a total phosphorous (TP) of 1.18 ± 0.3 mg/L. Microorganism concentrations in the influent and effluent are not shown and not regularly measured. The overall quality of both influent and effluent is better during the winter period.

Around 14.62 ton/day (1.061 kg VS/m^3.d) of sludge from the primary settlement tanks is treated by anaerobic digestion process. It produces about 13 156 m^3/day of biogas, which contains 40.2-63.7% methane (average 53.6%). The total methane gas production ranges from 216.4-999.9 m^3 CH4/kg VS (average 507.25 m^3 CH4/kg VS). Dewatered sludge (0.297 ton/day) is reused for farmlands and industries.

Table 23. Base case Spernal WWTP flow rates and standard influent and effluent parameters.

Parameter		Units	Mean value	Standard deviation	Measurement frequency	Summer mean value	Standard deviation	Winter mean value	Standard deviation	Considered years for the analysis
Influent	Flowrate	m^3/h	1 267	447	Daily	1114	344	1422	484	2018
Effluent	Flowrate	m^3/h	1 097	324.7	Daily	921.4	195.8	128	330.7	2018
Influent to the Spernal WWTP	COD	mg O_2/L	861.2	520.8	Twice per month	947.7	604.5	759	405.1	2018
	BOD_5	mg O_2/L	276.1	172.3	Twice per month	322.7	192.8	221.1	132.3	2018
	TSS	mg/L	515.2	300.6	Twice per month	536.9	358.3	489.6	228.9	2018
	TN	mg N/L	32.6	7.1	twice per month	34.7	4.3	30	9	2018
	NH4-N	mg N/L	31.0	8.2	Twice per month	34.2	4.6	27.2	10.0	2018
	TP	mg P/L	7.5	3.3	Twice per month	8.46	3.5	6.3	2.9	2018
Effluent from the Spernal WWTP	COD	mg O_2/L	44.6	11.5	Twice per month	43.69	11.1	45.7	12.4	2018
	BOD_5	mg O_2/L	3.6	2.7	Twice per month	4.2	2.7	2.9	2.6	2018
	TSS	mg/L	9.8	6.9	Twice per month	7.2	3.6	12.8	8.6	2018
	TN	mg N/L	34.5	5.2	Twice per month	34.1	5.6	35.0	4.9	2018
	NH4-N	mg N/L	2.4	1.1	Twice per month	2.0	1.0	2.8	1.1	2018
	TP	mg P /L	1.2	0.3	Twice per month	1.2	0.3	1.1	0.3	2018

The effluent from the Spernal baseline case is characterised in Table 24, and compared with the effluent from the combined NextGen technologies tested, such as the effluent from the IEX system (details about the IEX technology are provided in *D1.5 New approaches and best practices closing the materials cycle in the water sector* specifically for nutrient recovery technologies). The effluent quality from NextGen has a significantly higher quality and lower pollutant concentrations, (specially nutrients) compared with base case (Table 24).

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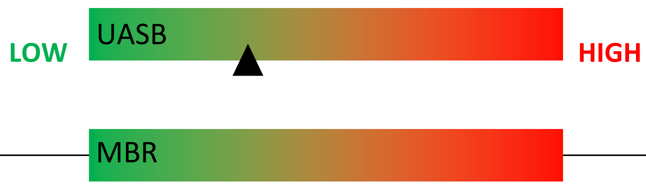
Table 24. Effluent quality – potential water for re-use produced in the base case and NextGen.

Parameter		Units	Mean value	Standard deviation	Measurement frequency
Base case Influent	Flowrate	m^3/h	1 267	447	Daily
Base case Effluent	Flowrate	m^3/h	1 097	324.7	Daily
Effluent from the Spernal WWTP	COD	mg O_2/L	44.6	11.5	Twice per month
	BOD_5	mg O_2/L	3.6	2.7	Twice per month
	TSS	mg/L	9.8	6.9	Twice per month
	TN	mg N/L	34.5	5.2	Twice per month
	NH4-N	mg N/L	2.4	1.1	Twice per month
	TP	mg P /L	1.2	0.3	Twice per month
	E. coli	CFU/100 mL	Not routinely measured		
	Total Coliform	CFU/100 mL	Not routinely measured		
	Faecal Coliform	CFU/100 mL	Not routinely measured		
	Legionella spp.	CFU/L	Not routinely measured		
	Intestinal Nematodes	egg/10L	Not routinely measured		
Effluent from NextGen (after all processes including IEX)	COD	mg O_2/L	<70	19	Daily
	BOD_5	mg O_2/L	<3	10	Daily
	TSS	mg/L	< 1		Daily
	TN	mg N/L	< 1		Daily
	NH4-N	mg N/L	< 2		Daily
	TP	mg P /L	< 1		Daily
	E. coli	CFU/100 mL	Still being determined but <3 350		Monthly
	Total Coliform	CFU/100 mL	Still being determined but <8 700		Monthly
	Faecal Coliform	CFU/100 mL	Still being determined but <4 600		Monthly
	Legionella spp.	CFU/L	Not determined		
	Intestinal Nematodes	egg/10L	Not determined		

3.1.9. Lessons learned

Required competence



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- Which knowledge is required to operate the plant?
    - UASB: Biological processes (aerobic effluent treatment processes and anaerobic sludge treatment processes) are widely used and understood by utilities. Operation of the UASB differs slightly from operation of widely used activated sludge plants and anaerobic digesters.
    - MBR: UF membranes are a complex piece of equipment, however, operation is largely automated and water utilities are familiar with operating the e.g. aerobic MBRs.
- What kind of training is necessary?
    - UASB: Key operational set points - up flow velocity, sludge blanket levels
    - UASB: Key performance metrics - biogas yields, sulphide level
    - MBR: Principles of operation - e.g. membrane flux rate
    - MBR: Cleaning requirements - scour, back pulse and chemical

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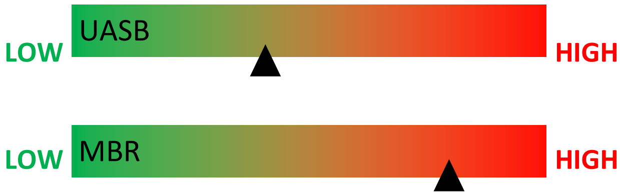
<tr><td>Maintenance</td><td></td></tr>
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- Frequency of plant maintenance per month or per year
    - UASB: Monthly
    - MBR: Regular (weekly) chemical cleans (as per design, might not be needed, but installed by commercial company)
- Duration of a normal maintenance procedure
    - UASB: 1 day/month
    - MBR: 2h/week
- Duration of active process control per day (manual process control, unforeseen events)
    - UASB: 2h/day
    - MBR: 1h/day
- Are external experts required to conduct the maintenance procedure?
    - UASB: No
    - MBR: No

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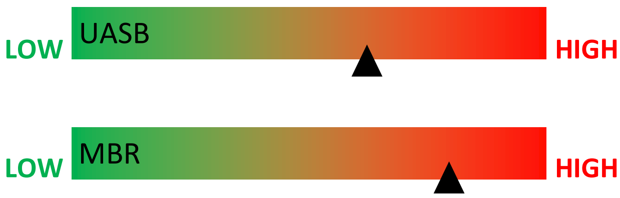
<tr><td>Technological risks</td><td></td></tr>
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- Reasons for downtimes or technical risks
    - UASB: Septicity – sulphate reducing bacteria affecting biogas yield and causing elevated H2S concentration in effluent – reseed required
    - UASB: Mechanical failures (compressor)
    - UASB: Blockage of inlet feed

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- MBR: Membrane leak
- Frequency of plant downtimes per year
  - UASB: 3 issues in 1 year – septicity of the influent, blockage and mechanical failure of compressor
  - MBR: 1 issue
- Duration of plant downtimes
  - UASB: 3 months
  - MBR: 3 months
- Are external experts required to restart the plant?
  - UASB: Yes
  - MBR: No
- Which measures can avoid such downtimes?
  - UASB: Routine maintenance, better management of inlet conditions
  - MBR: Membrane leak was a manufacturing or commissioning issue

3.1.10. Best practice guidelines for operating the technology

- What is important to consider during the construction of the plant?
  - Working with commercial suppliers was favourable but integrating the different technologies as a single flowsheet was challenging.
  - Health and safety considerations dealing with biogas and H_2S
- What is crucial for the start-up of the plant?
  - Having a fresh influent
  - Understanding sulphate fate
  - Having nitrogen gas available to sparge the membrane whilst biogas production is ramping up
- Which parameters are crucial for the optimisation of the production process?
  - Having a fresh influent
  - Organic loads and hydraulic retention time
  - Solids management
  - Membrane flux, sparging and cleaning routines
- Which ranges for the crucial parameters delivered the best removal and production results?
  - Influent feed with a positive (i.e., > 0mV) oxidation reduction potential and no presence of sulphide, UASB operation with COD loading rates >0.4 kg COD/m^3.day.

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3.2. Membrane bioreactor (MBR) in Athens (GR)

Authors: Klio Monokrousou (NTUA), Christos Makropoulos (NTUA), Giorgos Katsouras (EYDAP), Nikolaos Tsalas (EYDAP), Nikos Tazes (CHEMITEC), Konstantinos Tsimnadis (Municipality of Athens)

3.2.1. Description of the demo site

Athens is a city of 4 million citizens which is experiencing great urbanisation and the emergence of water scarcity issues. The Athens demo application is located in an area called Athens Plant Nursery, which is part of the Goudi Park, an area undergoing redevelopment and regeneration to become one of the key metropolitan parks of the capital. The mixed-use area in the heart of Athens, comprises urban green and urban agriculture spaces as well as administration and residential uses. The regeneration is an effort to boost both the local economy and improve quality of life for the citizens of the Attica Region.

The Plant Nursery belongs to the Municipality of Athens and covers an area of approximately 96 acres (or 0.39 km^2), 40 acres (0.16 km^2) of which are used in the production, development and maintenance of the plants, while the rest are used for general purposes, such as administration building and offices of the Municipality of Athens. The nursery supplies all urban parks and green spaces of Athens with plant material and uses potable water from Athens's Water Supply and Sewerage Company (EYDAP) for its irrigation. Furthermore, the nursery is the staging area for all of the pruning waste from all of Athens' urban green spaces. The green waste is not treated, only stored on site. Part of the green waste is eventually transferred to the Athens landfill. At the same time, the nursery uses fertilizers supplied by the local market. With regards to energy needs, the nursery uses electrical energy from the urban network and petrol oil for heating. Athens is seeking alternative water sources to achieve environmental, social and financial benefits to address the water scarcity matters through autonomous and decentralised water systems.

3.2.2. Motivation for implementing circular economy solutions in the water sector

The summers in Athens are hot and dry. Recent studies show an increasing tendency towards drier conditions, with increased variability of extreme rainfall events. Overall precipitation is expected to decrease as longer dry spells and reduced rainfall intensity has been observed. Temperatures are projected to increase in the Athens area on the order of 6.5-7°C by 2100, according to the worst climate change scenario based on the selected regional climate model developed in the Regional Adaptation Action Plan for Climate Change of Attica (RePACC of Attica, 2020). According to the estimations in this report, particularly important is also the projected increase in the average annual number of days with temperatures >35°C, up to 15-19 days for the near future by 2050 and over 22-55 days by 2100 in the urban areas of Attica. With the longer, hotter, drier summers, green areas are more important than ever to reduce the urban heat island effect. Lush green parks also create a positive environment for both the citizens and the local wildlife. Access to blue green urban spaces, containing both urban green vegetation and water bodies, has positive effects on the mental and physical health of urban

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citizens. The green spaces also help provide homes for wildlife. However, green areas require both water and nutrients to remain healthy and vibrant. Athens currently lacks adequate nutrient-rich soil, and the reduced rainfall and drier conditions mean more irrigation is necessary to keep green areas lush.

This situation has led to an increased interest to explore alternative solutions to reduce waste and resource usage. The dominant behaviour of 'take-make-consume-dispose', which assumes that resources are abundant, available, and competitive to dispose of, needs to be eliminated, and 'circular economy' principles and technological innovation should be embraced.

It is therefore essential to design a new circular water management strategy that considers the different elements in the water cycle and maximises their efficient usage. Within the context of the urban water cycle, the concept of water reuse and avoiding the costly and energy intensive transportation of treated water from centralised treatment plants, configurations of flexibility and autonomy of water resource in urban environments have become more attractive.

A technology that can combine flexible and decentralised wastewater treatment as well as advanced treatment technologies is called sewer mining (SM). SM technology was originally pioneered in Australia in 2006 and was first tested successfully in Greece in an FP7 project called Dessin in 2015.

In the NextGen project, further and more holistic investigation of the larger scale sewer mining hybrid membrane bioreactor/ultraviolet disinfection (MBR/UV) system and its applicability in a real-world urban environment was undertaken. Wastewater was actually extracted from local sewers, treated at the point of demand and reused for irrigation in water-stressed green areas. Thus, after implementation and testing of this technology, results prove the high quality and stability of the effluent water. Furthermore, this solution is in line with the Athens Resilient Strategy for a circular approach to water services by 2030.

The main benefits of the SM technology are as follows:

- ✓ requires limited space (small footprint)
- ✓ reduces waste and increases availability of resources
- ✓ saves energy, as water is reused at the point of demand
- ✓ proves to be an autonomous, decentralised resource recovery system
- ✓ transforms treated wastewater (a waste) into supply (a resource)
- ✓ is suitable for real world, dense urban environments

3.2.3. Actions and CS objectives

Table 25. Actions and objectives of the Athens case study.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
# 8 Athens, (GR) Location:	Sub-Task 1.2.4	Sewer mining modular unit (MBR/UV disinfection)	Test and optimise a flexible and decentralised	TRL 6 → 8	Water produced 25 m^3/d	Reclaimed water for urban green irrigation and

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Athens Plant Nursery			wastewater treatment system that produces irrigation water from sewage wastewater locally at the point of demand.			other non-potable uses at the point of demand.

3.2.4. Unique selling points

The implemented solutions work to replace existing value chains (drinking water and fertiliser) with upcycled waste chains (green waste, wastewater, and sludge) to create a circular and sustainable solution for Athens' green spaces.

Unique selling points for the implementation of a sewer mining unit are:

- ✓ Removal rates of COD and TSS are higher than 90%, suggesting that MBR is a very safe technology due to the very satisfactory operational stability and the high performance it provides.
- ✓ High quality water produced meets all national and international criteria for unrestricted irrigation and urban use.
- ✓ The treatment process achieves complete elimination of organic carbon and significant reduction of pathogens (total coliform & E. coli) due to MBR filtration process, without addition of chemicals which avoids production of secondary pollutants.
- ✓ Transmembrane pressure (TMP) remains steady at low values, proving that the combination of backflushing with maintenance cleaning is very effective.
- ✓ UV disinfection unit showed great performance in the treatment process.

As general benefits and selling points:

- ✓ The citizens of Athens shall benefit from greener parks and spaces.
- ✓ Blue green spaces have a positive effect on human health and wellbeing.
- ✓ Green areas have positive effects on climate change resiliency and help reduce urban island effects, making the plant nursery and similar green areas increasingly important in urban planning.
- ✓ Circular solutions that produce valuable resources from waste help promote a shift in people's mindsets regarding the need for a transition to circular economy.

3.2.5. Principal characteristics of the technology

The city of Athens operates a plant nursery which supplies all of the plants for the urban parks and green spaces in Athens. Until NextGen, they had been irrigating the nursery with potable water, brought in by EYDAP from literally the other side of the country (more than 250 km away) at great cost.

To address this matter, a modular sewer mining unit as an innovative water reuse system has been installed. In fact, the sewer mining technology is a wastewater treatment station.

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The main principle behind this technology is that wastewater is extracted from local sewers, is treated directly on site and is reused locally at the point of demand or is stock reserved for when it is needed (Figure 14). The treatment residuals could go back to the sewer network to be treated by a regular wastewater treatment plant or could be collected (like in the specific case) to treat them locally on site and, when merged with green waste from pruning, transform them into an eco-friendly fertilizer (compost).

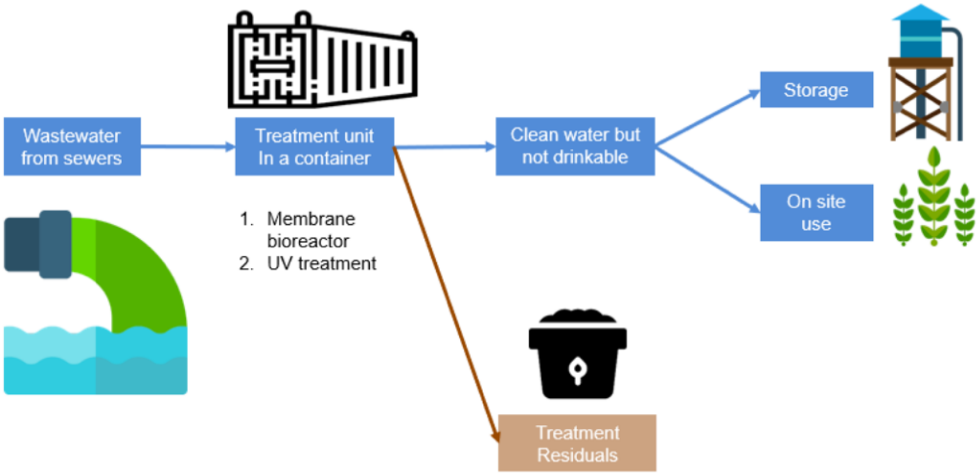

Figure 14. Overview of the Sewer Mining concept.

In this respect, the Athens case focuses on producing about 25 m3/day of recycled water from wastewater for urban green irrigation and potentially other non-potable uses.

Thus, a circular, decentralised, and innovative pilot system has been designed, implemented, tested and optimised with regard to water reuse schemes in urban environments with water scarcity issues. As illustrated in Figure 14, wastewater is mined from local sewers, through a small, prefabricated pumping station, then stored in a buffer tank and sent for treatment in the container to be reused for irrigation purposes at the point of demand. The mobile container treatment unit consists of a membrane bioreactor unit (MBR) along with a UV disinfection unit.

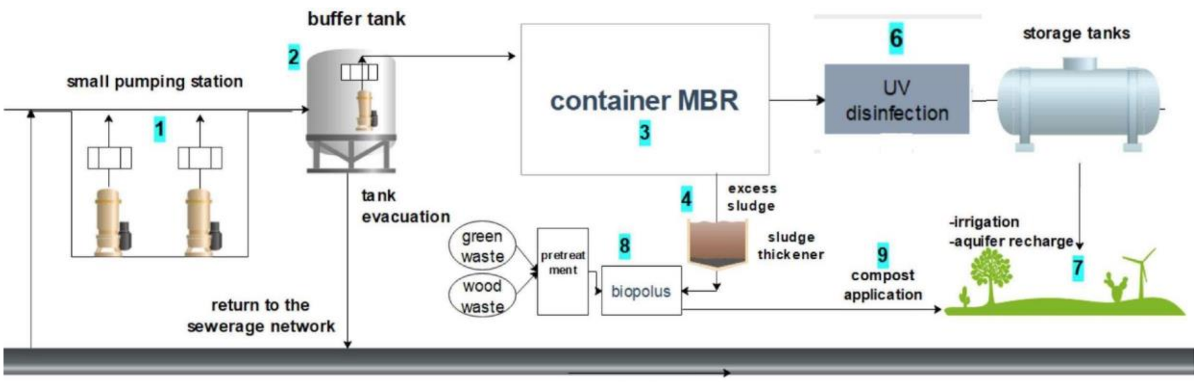

Figure 15. Flow scheme of the water and material recovery.

The hybrid MBR/UV unit operation was commenced in April 2021. More specifically, the

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sewage is extracted from ~4 meters below the surface using two pumps working alternately to fill a buffer tank. Subsequently, the sewer mining unit is fed with wastewater through a submersible pump installed inside the buffer tank. The raw sewage from the buffer tank is transferred and screened while flowing through a continuously rotating self-cleaning screen filter, and its flow is constantly measured with an electromagnetic flowmeter. The screenings (fine particulates) that are brushed away are disposed of in a screenings bin or included in the compost produced later in the process.

Figure 16.Overview of the sewer mining unit and the control room installed in the nursery.

The screened sewage is temporarily stored in a buffer tank of filtered wastewater which is attached to a denitrification tank through a bottom window. Inside the denitrification tank, anaerobic microorganisms turn nitrates to nitrogen gas, which naturally leaves the system. A mixer in the denitrification tank helps homogenise the mixture and keep the microorganisms suspended and continuous contact with it. The denitrification tank is connected to the nitrification or aeration tank through a bottom window.

An extra tank, which can function as a second nitrification or denitrification tank, depending on the systems’ needs, also exists. It can be connected by turning on or off the air flow through the aeration tank air inlet pipe.

Subsequently, the biologically treated wastewater is transferred to the membrane tank. Membrane modules produce about 1 m^3/h of permeate water, meaning the remaining 4 m^3/h overflows through the tank’s top window to the deoxygenation tank, operating under anaerobic conditions, before the mixture enters the denitrification tank once again through a bottom window.

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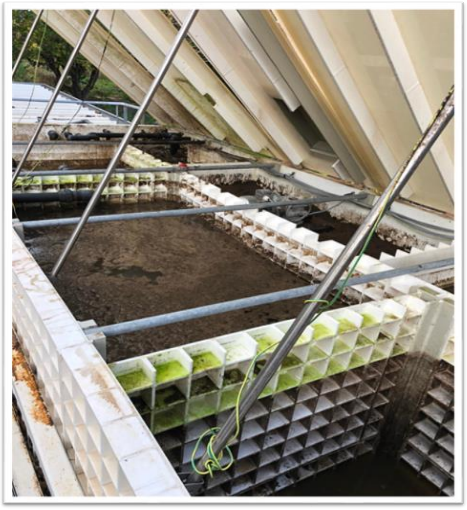

Figure 17. Various tanks of the treatment processes in the SM unit.

Figure 18. View of the interior of the container of the local control room.

Part of the excess sludge produced is transferred to the thickening tank, after which it flows to the dewatering bag filters to be thickened and used for the compost product.
The permeate overflows, passes through the UV disinfection unit, and the final disinfected product flows naturally into the irrigation storage tank.
The whole process is monitored through specific sensors (tank level, pH meters, Mixed Liquor Suspended Solids (SS) – Mixed Liquor Suspended Solids (MLSS) sensors, dissolved oxygen probes, etc.) and is automated using pneumatic actuated valves controlled by a PLC unit (Figure 19). An external overview of the sewer mining unit (on the right) and the control room (on the left) are illustrated in Figure 17 and Figure 18.
Additionally, a series of laboratory analyses provided further evaluation of the performance of the unit and were used for cross validating the sensor measurements. The laboratory analyses occurred twice a week during start-up and then a weekly monitoring plan was implemented to regularly collect and analyse a series of raw and treated wastewater samples. Those measurements included chemical oxygen demand (COD), mixed liquor suspended solids (MLSS), biochemical oxygen demand (BOD_5), total phosphorus (TP), total nitrogen (TN), ammoniacal nitrogen (NH_3-N), nitrate nitrogen (NO_3-N), total coliforms (TC), faecal coliforms

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(FC) and *Escherichia coli* (EC). Analyses were conducted according to the standard methods of the American Public Health Association.

The monitoring process consists of sampling from 6 distinct points of the pilot unit. Weekly composite samples of the raw sewage filtered inlet, membrane tank, denitrification tank, permeate tank and after UV disinfection were collected. The parameters monitored were COD, BOD_5, TP, TN, NH_3NH4-N, NO_3-N, TC, FC, pH, conductivity, dissolved oxygen and transmembrane pressure (TMP). All analyses were conducted according to standard methods (APHA et al., 2012).

Figure 19. PLC overview.

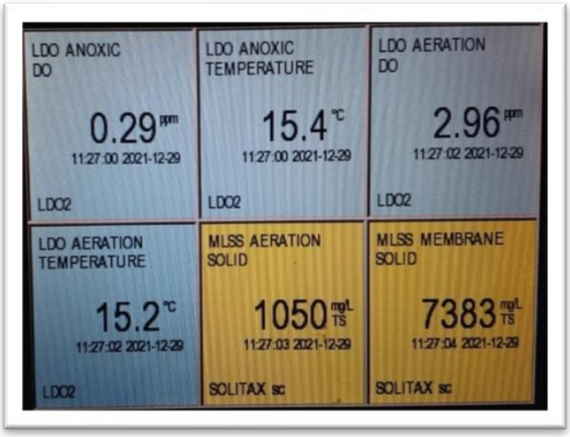

Figure 20. Online sensors overview.

3.2.6. Technology implementation requirements

Regarding the pumping station, sewage is extracted through two pumps that work alternately, which avoids their constant operation and increases the life expectancy of the pumps.

To reach high performance in the treatment process, a constant dissolved oxygen concentration of 2–3 mg/L is maintained inside the nitrification tank; this is achieved by supplying air through the diffusers of the blower to the aeration tank. A dissolved oxygen meter controls the blowers' air flow output using a variable frequency drive. The air flow pressure and temperature of the second (de)nitrification tank are monitored constantly to ensure the operational stability of the system.

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Afterwards, biological treatment of wastewater is performed, and the effluent is transferred in the membrane tank, where a constant flowrate of 5 m3/h should be maintained. Membrane modules should produce about 1 m3/h of permeate water so the remaining 4 m3/h overflows to the deoxygenation tank before the mixture enters the denitrification tank again. As for the excess sludge that is produced and transferred to the thickening tank, the MLSS should be kept constant between 7 000 and 10 500 mg/L with daily removal of excess sludge, therefore MLSS is constantly measured online. The permeate produced by the membranes is pumped into the backflush tank to be used during the backflush sequence. During this sequence, 1.4 m3 of permeate is pumped inversely from the backflush tank through the inside of the membranes to clean their surface and dissolve the cake layer that is formed.

The ultrafiltration membranes achieve a better filtration of the biologically treated wastewater, removing all suspended solids, colloids, bacteria and viruses. Additionally, a chemically enhanced backflush sequence occurs once per day.

Table 26. Required specifications for influent water quality of the MBR in the Athens case study.

Parameter	Units	Min	Max	Average	Reference
COD	mg O2/L	330	490	410	Chon et al., 2012; Dialynas & Diamadopoulos, 2009; Plevri et al., 2016; Yang et al., 2009
BOD5	mg O2/L	140	210	202	
TSS	mg/L	150	220	183	
Total N	mg/L	124	200	164	
Total P	mg/L	9.6	10.9	10.3	

3.2.7. Results obtained

The pilot unit has been operational since April 2021 and here we present the results for 12 months (07/05/2021 to 18/05/2022). The capacity of the unit was set to 25 m^3 of treated wastewater per day.

The unit has the innovative advantage of an automated ICT system with pneumatic actuated valves controlled by a PLC unit, which allows continuous control and monitoring of the sewer mining unit by uploading data to an online system. The quality of the process and the effluent is controlled by a series of online sensors installed at several key points of the unit which provide perpetual information about the integrity of the operation. Conductivity meters were installed in the inlet and permeate tank, pH sensors in the membrane tank, a turbidity sensor in the permeate tank, an MLSS sensor in the membrane tank, a DO sensor in the aeration tank, and finally a nitrate and ammonium sensor in both the anoxic and aeration tanks.

The unit started its full operation in mid-April 2021. The performance of the unit and pumping station has shown great stability. The hybrid MBR/UV had a start-up period of approximately 5-6 weeks. Figure 21 illustrates the start-up period along with the period of steady state conditions for COD concentrations and removal rate. It is evident that even during start-up, the removal rates are higher than 90%, which shows that the MBR technology is a very safe technology to use due to the great stability it provides. The average influent COD (inlet) was 443 ± 168 mg/l while the average effluent COD (outlet) was low 24.2 ± 4.1 mg/l, due to the very high removal averaging around 90-95%.

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The average influent BOD_5 (inlet) was 202 ±73 mg/l while the average effluent BOD_5 (outlet) had concentrations 8.6 ± 2.4 mg/l (Figure 22), lower than 10 mg/l for 80% of the samples (Table 27).

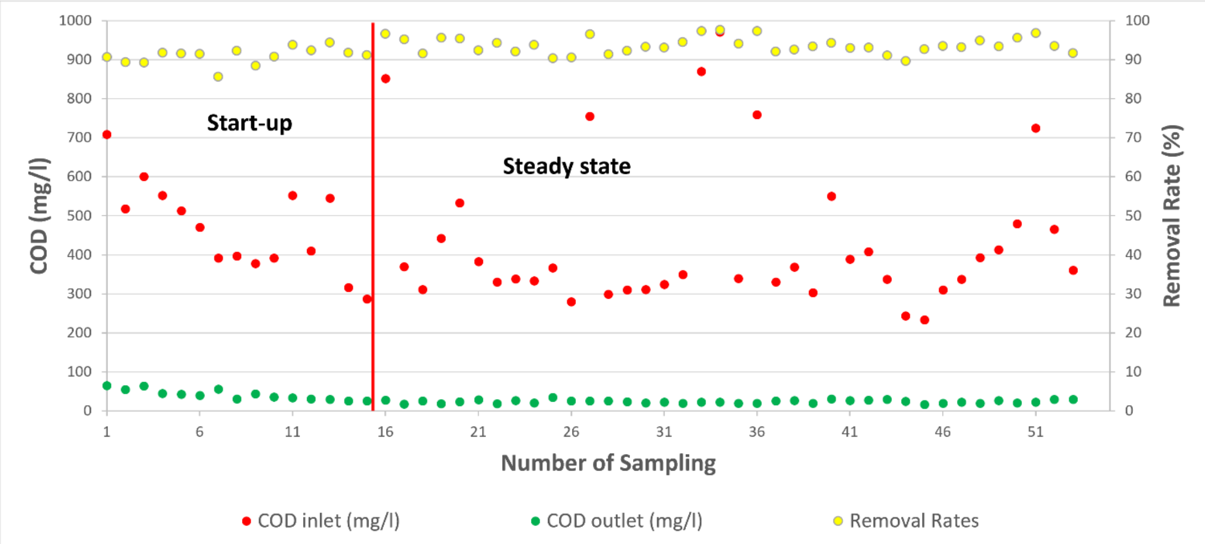

Figure 21. Inlet & outlet COD concentration and removal rate during the start-up and steady state periods.

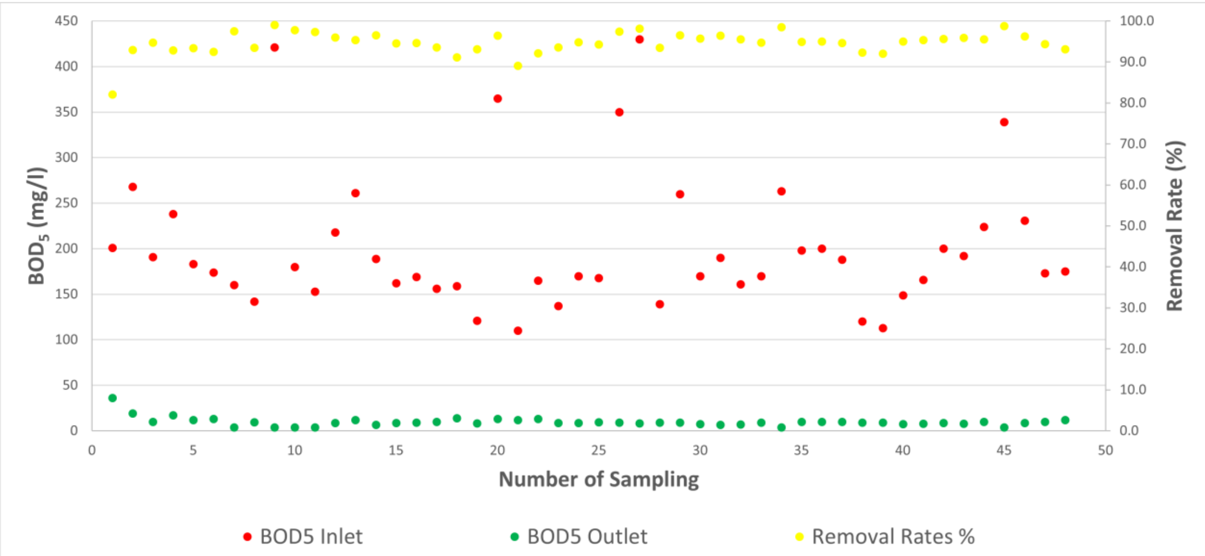

Figure 22. Inlet & outlet BOD5 concentration and removal rate during the start-up and steady state periods.

The first evidence of nitrification appeared at around week 5 (sampling No 14), when a sharp increase in the effluent nitrate concentrations from near detection limit to higher than 15 mg/l was observed, which coincided with sharp decreases in ammonia concentrations (Figure 23). Figure 23 illustrates the concentrations of the NH_4-N of the inlet and the outlet. The average influent ammonium (inlet) was 51 ±10 mg/l while the average effluent ammonium (outlet) was 0.2 ± 0.19 mg/l, which is under the limit value of 2 mg/l set in the Greek legislation for urban reuse and/or groundwater recharge.

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Also, the nitrification started after week 5 when the effluent ammoniacal nitrogen concentrations started reaching zero. After the start-up, a monitoring plan was implemented to regularly collect and analyse a series of raw and treated wastewater samples. The entire MBR/UV operation showed great stability in terms of constant operation as well as effluent water quality.

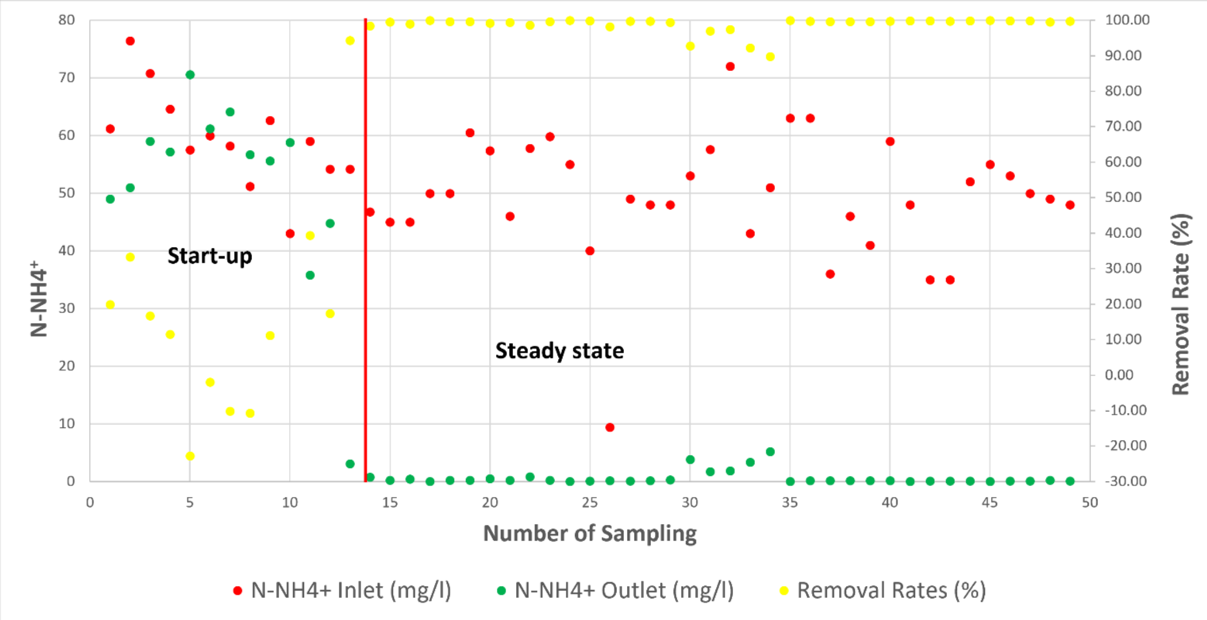

Figure 23. Inlet and outlet ammonium concentration and removal rate during the start-up and steady state periods.

Figure 24 presents the TSS of the inlet and outlet, and the MLSS concentration inside the MBR tank as well as the online measurements of the installed probe. The average influent TSS (inlet) was 147 mg/l while the average effluent TSS (outlet) was under the limit value of 2 mg/l for 80% of samples, in accordance with the aforementioned Greek legislation. The analyses showed effluent TSS concentrations reached zero, and the installed probe provided data which fit with the laboratory measurements. There are two operational periods: the start-up period and the steady state period. The steady state is defined as the period with constant MLSS concentration, steady removal rates, and initiation of nitrification.

The steadiness of the qualitative values (i.e. TSS, COD, BOD_5, turbidity) in the permeate flow during the operational period proved that the backflushing mode and the maintenance cleaning were very successful in maintaining the integrity of the membrane.

As illustrated in Figure 24, it is evident that the unit operated at values of MLSS over 8000 mg/L with adequate stability. Cross validation with the lab measurements revealed that the sensors provided reliable data. The accurate sensor measurements are noteworthy, as they allow remote control of the unit which provides safety measures such as alarm conditions and – if needed - ultimately to unit shutdown when key values exceed the programmed upper threshold.

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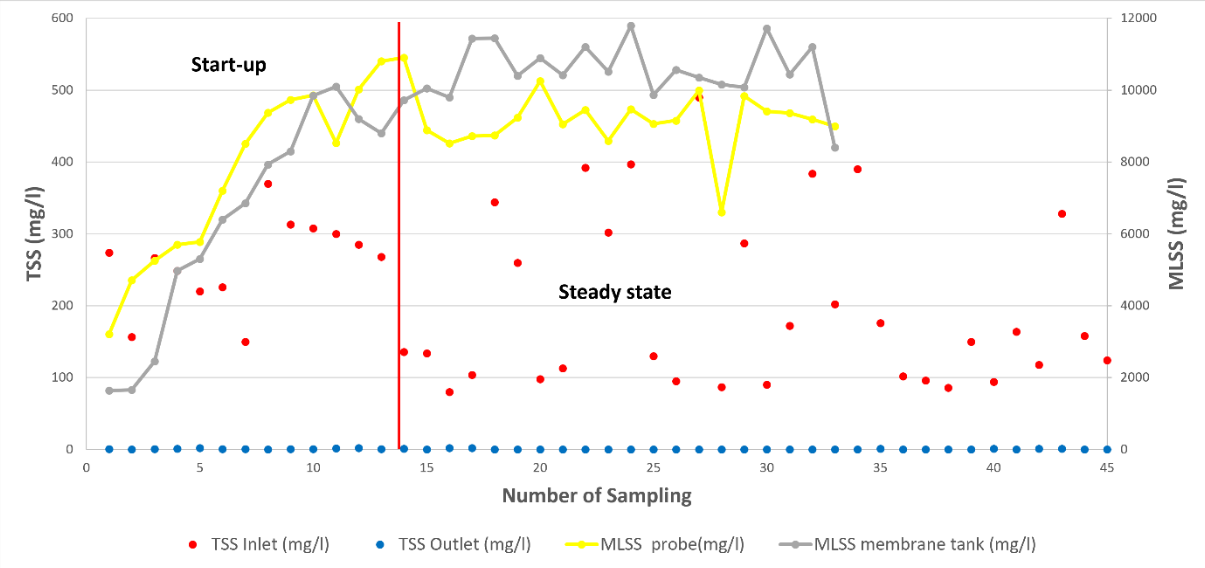

Figure 24. Inlet and outlet TSS concentration and MBR performance in terms of TSS removal.

Turbidity throughout the examination period (lab analyses and online data from the sensor) showed that most values were below 2 NTU, with the average value around 0 NTU.

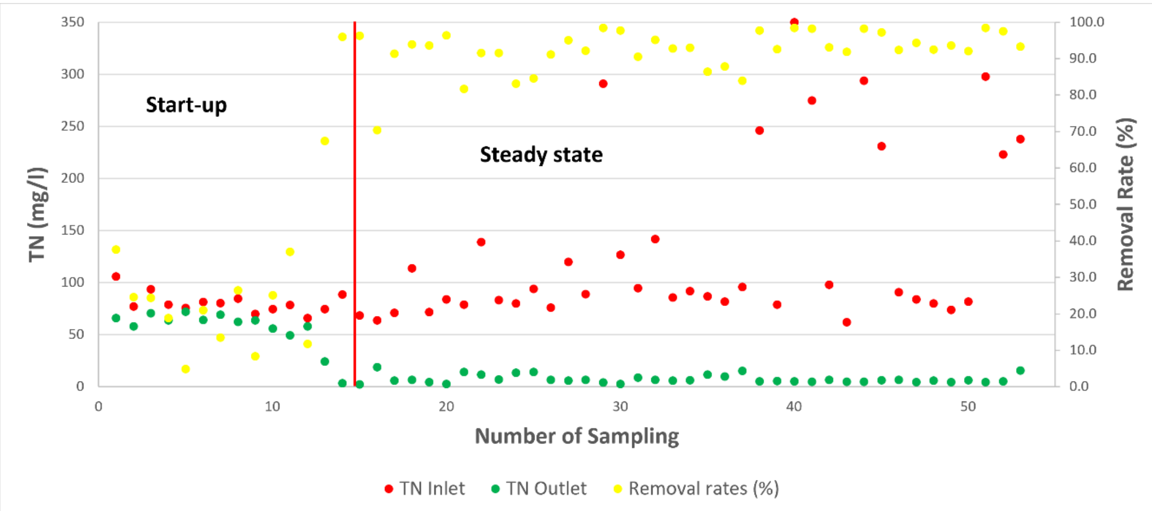

Figure 25. Inlet and outlet TN concentration.

Total nitrogen (TN) and total phosphorus (TP) influent and effluent concentrations were monitored during the experimental period to evaluate the removal of nutrients. The average influent TN (inlet) was 118 ± 73 mg/l while the average effluent TN (outlet) was 5.5 ± 1.4 mg/l, which is under the limit value of 15 mg/l in accordance with the Greek legislation (Figure 25). Table 27 summarizes the aggregated results for the quality characteristics of the hybrid MBR/UV effluent of the experimental system along with the limit values of the Greek National legislation regarding wastewater reuse for unrestricted irrigation and urban use (JMD 145116/2011).

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Table 27. Performance of the Hybrid MBR/UV pilot system (concentrations in mg/L, TC, FC, EC in cfu/100 mL, turbidity in NTU, Conductivity in µS/cm).

Parameters	Influent[1]	Effluent after UV disinfection	Legislation limits[2]
TSS	147 (average)	≤ 2 for 80% of samples	≤ 2 for 80% of samples [5] ≤ 10 for 80% of samples [4]
BOD_5	202 ± 73 [3]	8.6 ± 2.4 [3] ≤ 10 for 87% of samples	≤ 10 for 80% of samples [4,5]
COD	443 ± 168 [3]	24.2 ± 4.1 [3]	-
TN	118 ± 73 [3]	5.5 ± 1.4 [3]	≤ 15 [4,5]
NH_4-N	51 ± 10 [3]	0.2 ± 0.19 [3]	≤ 2 [4,5]
TP	17.8 (average)	1.57 (average)	-
Turbidity	-	0 (median)	≤ 2 (median) [4,5]
Conductivity	1 0681068 ± 76 [3]	667 ± 50 [3]	-
pH	6.9 ± 0.2 [3]	7 ± 0.3 [3]	-
TC	> 10 [6]	≤ 20 for 95% of samples	≤ 2 for 80% of samples [5] ≤ 20 for 95% of samples [5]
FC	> 10 [6]	1.5 (average)	-
EC	> 10 [6]	≤ 5 for 97.4% of samples	≤ 5 for 80% of samples [4] ≤ 50 for 95% of samples [4]

[1] Refer to filtered wastewater; [2] refer to Greek legislation regarding wastewater reuse Joint Ministerial Decision 354/8-3-2011); [3] average ± standard deviation; [4] refer to the limit values set in the Greek legislation for wastewater reuse for unrestricted irrigation and/or industrial reuse; [5] refer to the limit values set in the Greek legislation for urban reuse and/or groundwater recharge; [6] refer to the limit value set in the Greek legislation for every type of reuse for WWTPs with a population equivalent greater than 100,000.

MBR membranes achieved a significant decrease of microorganism concentration, varying from 4 to 8 log units, mainly through size exclusion. The parameters that were selected as representative indicators and thus were regularly monitored in the MBR permeate and UV effluent, were total and fecal coliforms (TC and FC) and *E.coli* (EC). These parameters were chosen because they are characteristic indicators for the existence of other microorganisms. More specifically, a decreased concentration of coliforms in general reveals absence of other microorganisms, and fecal coliforms have additionally been correlated with the existence of fresh fecal matter, while the decrease of *E. coli* is related to virus absence. *E. coli* after UV disinfection had an average value of 2.42 cfu/100ml, which was below the limit of 5 cfu/100ml for 97.4% of all the samples, the limit that is set in the Greek legislation for wastewater reuse for unrestricted irrigation and/or industrial reuse (Table 27;

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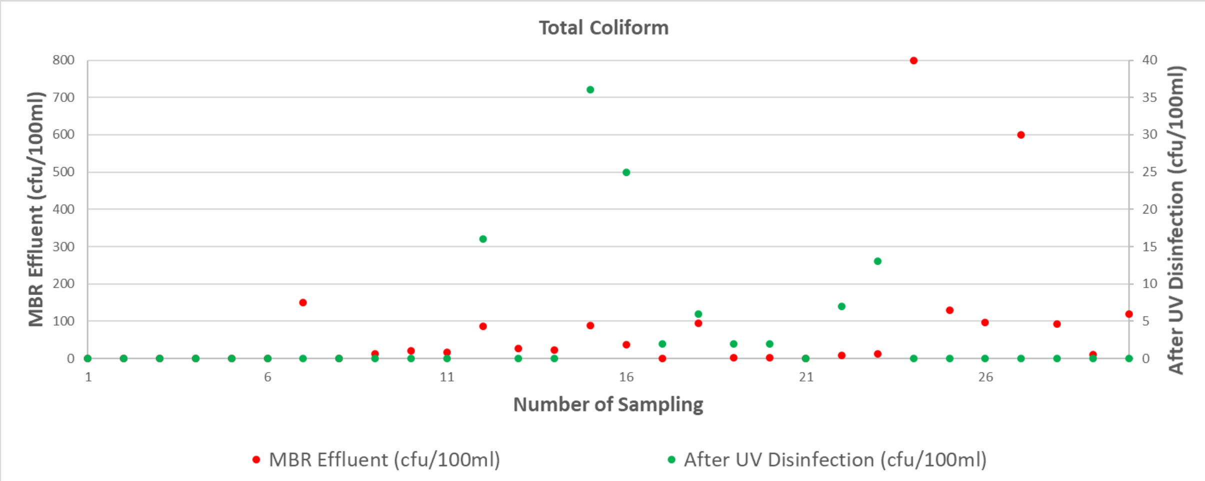

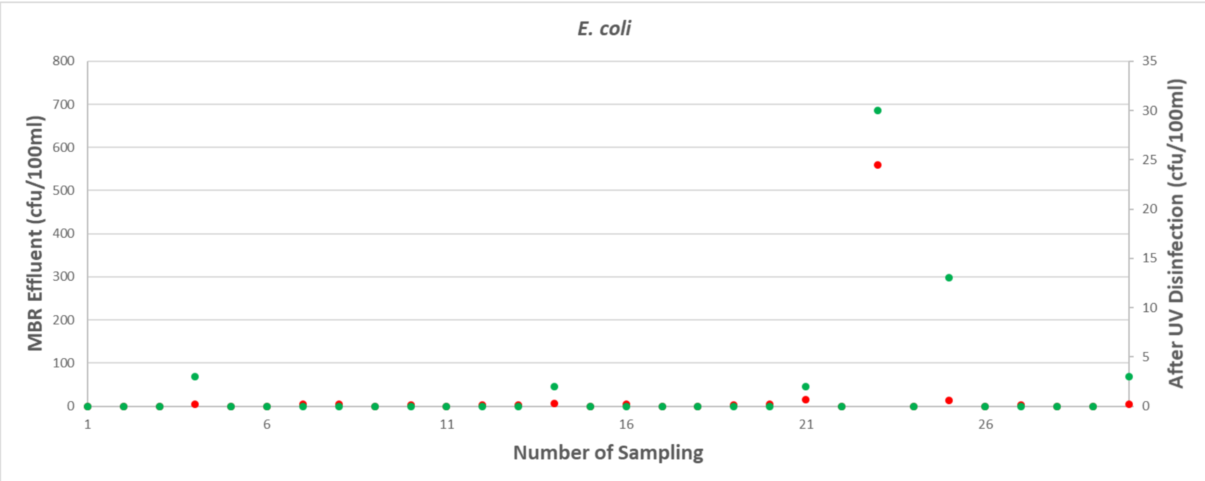

Figure 26). FC after UV disinfection were below the limit of detection of the analytical method (3 cfu/100ml) which, together with the *E. coli* concentrations, indicates that the membrane remained intact during the operational period. The TC content of MBR effluent was rather low, with values range below 200 cfu/100 mL with few exceptions (

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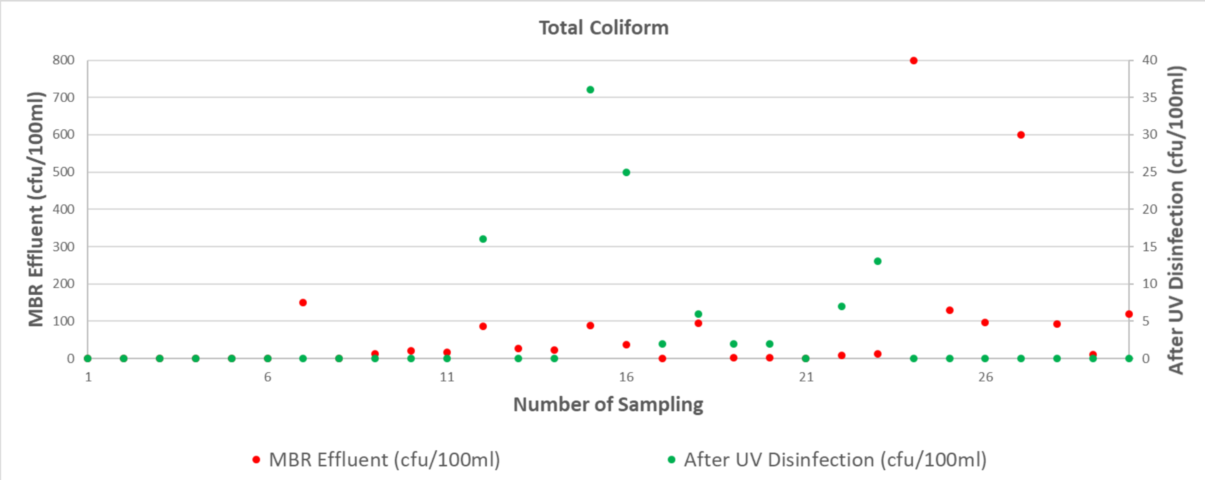

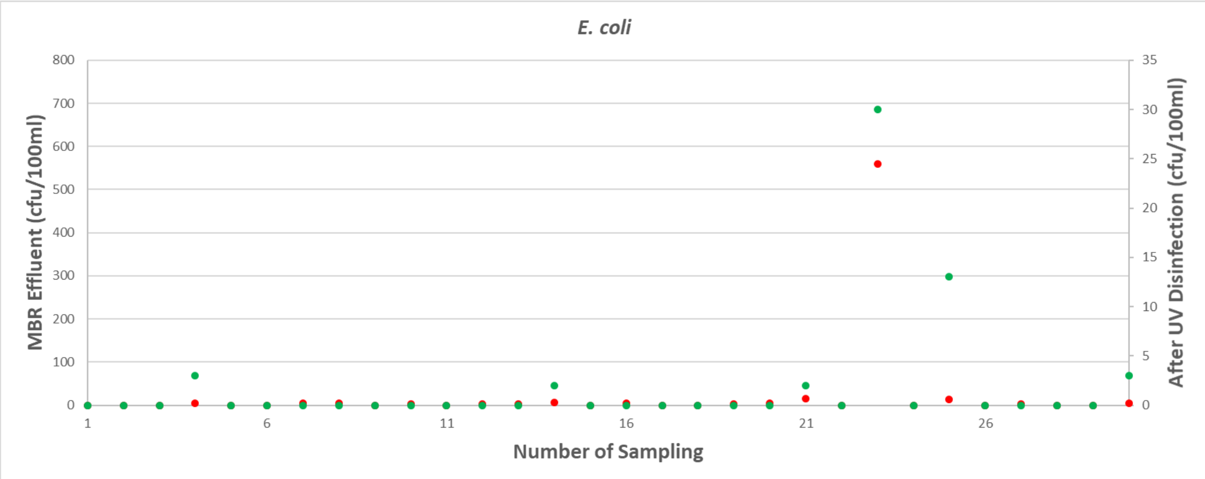

Figure 26).

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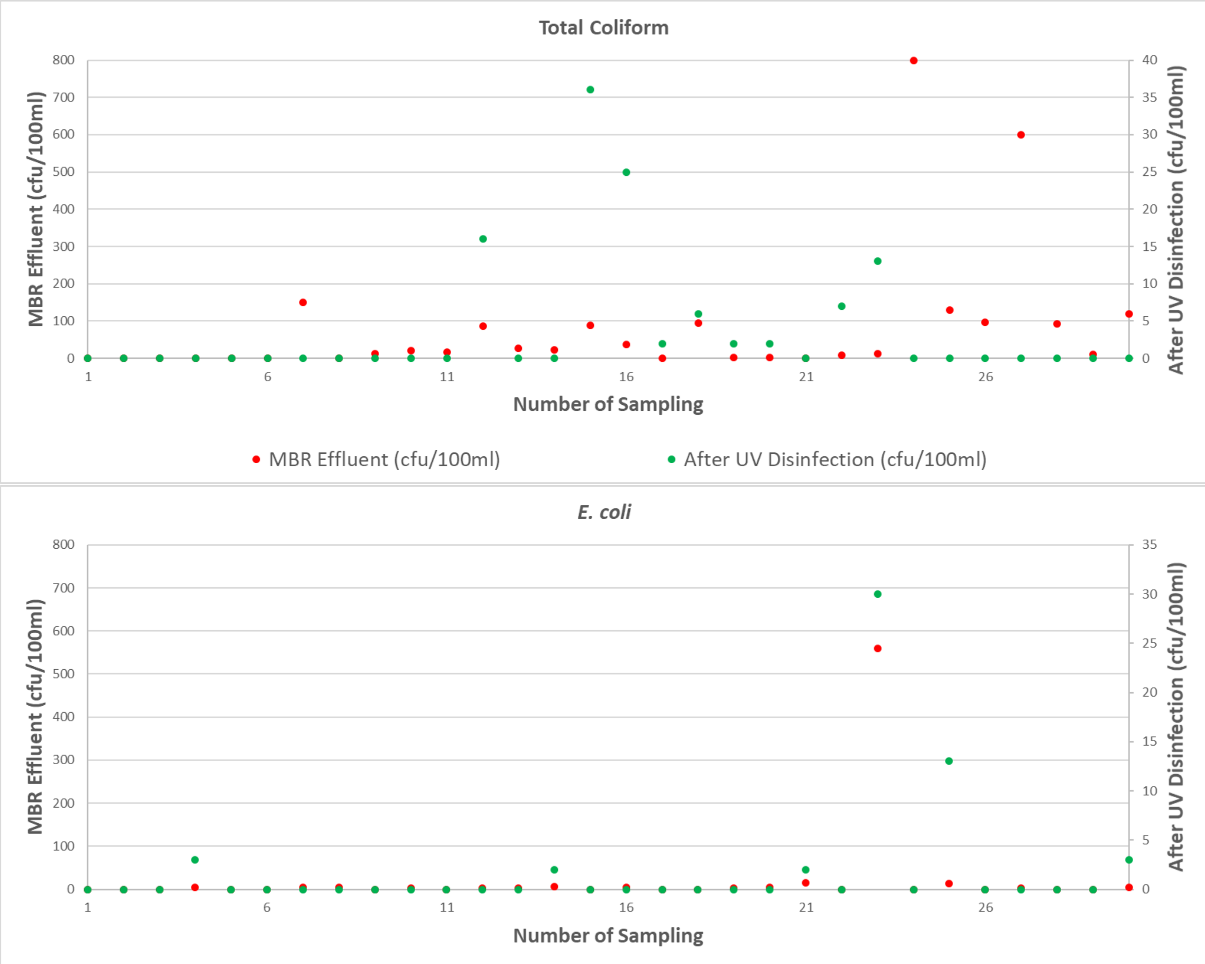

Figure 26. MBR effluent and UV disinfection for Total Coliform and E. coli.

The aforementioned results are evidence that UV disinfection unit performs well, and the dose of 60 l/min is enough to remove all pathogens and produce safe water for any kind of reuse, as it meets even the strictest criteria.

In conclusion, except for the start-up period of 5-6 weeks, the overall operation of the system shows great stability. The combination of the aeration tank along with the MBR filtration was very successful for the removal of all the biodegradable COD. Its automation enables it to operate autonomously without the need for daily monitoring.

3.2.8. Comparison of baseline situation and NextGen KPIs

Before the implementation of NextGen in the baseline scenario, the municipality of Athens had been irrigating the nursery with potable water, brought in by EYDAP from more than 250Km away at great cost.

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The results of NextGen project lead to the conclusion that the installed MBR/UV pilot unit can produce water of excellent quality in line with the standards specified in the Greek National legislation regarding wastewater reuse for unrestricted irrigation and urban reuse.
In addition, the experimental results support the conclusion that the application of sewer mining practice through the implementation of an on-site compact treatment system (consisting of a *pre-treatment unit* followed by a *membrane bioreactor* and a *UV disinfection unit*) can reliably meet all the national and international criteria set for all types of non-potable wastewater reuse at a rather moderate cost (see D2.2).
Such a dual membrane scheme in the context of a sewer mining application has proven to be a viable solution for water reuse in combination with fresh water saving in highly urbanised, space-limited environments.
NextGen's unit proved that it is an advanced solution for implementing decentralised wastewater treatment water reuse at the point of demand. Considering that future European regulations could include more priority pollutants as well as the gradual decrease in Environmental Quality Standards values, the importance of technologies, such as the MBR/UV, which can meet those criteria should not be overlooked. The unique value of this particular unit is the fact that it addresses real world water scarcity issues in a dense urban environment, by transforming treated wastewater (a waste) into supply (a resource).
The key impact of the SM technology is the transition from the linear model to the circular economy approach.

3.2.9. Lessons learned

At the case study in Athens, three different interconnected technologies were implemented. The interaction of the single technical units is complex and has to be considered in the system design. The system design, the installation, system control and automation of the technical units worked well and only minimal optimisation was necessary.
However, as with many other innovative processes, numerous unexpected problems also occurred, some of which were or are very time-consuming to deal with. Therefore, it is important to have employees who are inventive and capable of multitasking, and technology suppliers wgi are available for a longer time periods even after the commissioning of the system.
In the following table, more details about the lessons learned are presented specifically for the sewer mining modular unit (MBR/UV disinfection).

Required competence	LOW		HIGH

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For the SM unit, the local operator needs to be trained to use the PLC system and monitor specific parameters. Below there is a list of the main parameters that are monitored online both locally and remotely:

- Levels of tanks (cm)
- Dissolved oxygen (mg/L)
- Flow (L/h)
- Pressure (mbar)
- MLSS solid membrane (mg/L)
- Total consumption of electric energy (kWh)

A basic training is needed for the local operator to know which parameters and aspects should be monitored in the daily operation. However, one needs to be familiar with the implemented technologies and the background knowledge behind the processes in order to address any unexpected events. The SM configuration works automatically, with alarms and automations that can be monitored remotely online.

Knowledge on how to read the PLC parameters is necessary in order to monitor and operate the unit both locally and remotely. Furthermore, knowledge of the expected values in the tanks' levels and the quality parameters of the treatment unit is required.

Maintenance	LOW  HIGH

The chemically enhanced backflush sequence occurs once per day automatically, during which sodium hypochlorite and citric acid solutions are added to the backflush sequence. The plant maintenance is performed once a month by checking whether these chemicals need to be added manually in the particular tanks. The normal maintenance procedure lasts for about 1 hour.

Of course, there are certain unforeseen events that have occurred during the testing and operational period (overheating and stoppage of the unit motor, fault in an online sensor, burn of the UV lamp, etc.).

Normally there are no external experts required to conduct the maintenance procedure: however, in unexpected events there might be the need to call an electrician or a mechanical engineer to solve the matter.

Technological risks	LOW  HIGH

The main reasons for downtimes of the unit were a breakdown of the motor, an issue in the flutter of the pumping station, and a flood event due to extreme rain.

These downtimes events occur about 3-4 per year and normally 2-3 days are needed to fix the specific problem: in some situations, the issue was addressed immediately within the same day.

Typically, the restart is performed by the local operator or the partners of the project, but occasionally there would be an external expert.

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In order to avoid such downtimes, regular maintenance and monitoring of the various elements of the system is necessary, to prevent such unexpected events.

3.2.10. Best practice guidelines for operating the technology

Important aspects to consider during the design and construction of the plant:

- ✓ First, a sewage network that passes from a close distance from the proposed space to install the SM unit needed to be identified. Also, some technical parameters of the manhole had to be met:
  - the height of the network until the ground surface had to be acceptable
  - the sewage supply according to the capacity of the SM unit
  - the quality characteristics of the wastewater
- ✓ Also, a potentially available power supply was needed to connect the configuration (pumping station and MBR/UV unit)
- ✓ For the construction, as the pumping station was prefabricated, access for a trunk/crane to transfer, unload and install the equipment into the ground was necessary.
- ✓ The plant required very limited space (all equipment fit into a container) and the pumping station as well as the buffer tanks could be installed underground, resulting into a small footprint.
- ✓ For the containers of the SM unit, a concreate base was required so that the equipment is secured steadily in the ground.
- ✓ The plants or garden that use the reclaimed water should be relatively close to the SM unit in order to reduce the energy cost during irrigation.
- ✓ Security of the units should be ensured; therefore a protected environment is preferable.

Crucial parameters for the optimisation of the production

During the testing period of the sewer mining unit, several matters occurred that were addressed to optimise the operation of the configuration. The key matters that were optimised are as follows:

- To increase energy efficiency, the motor of the unit was modified to operate intermittently. After testing, sampling and analysis, a scheme that achieves optimum performance of the MBR/UV system in terms of energy saving was identified: 10 min on – 4 min off. The energy savings were estimated to be about 15%.
- To improve UV disinfection unit efficiency, operation in manual mode (on-off) extended the life span of the UV system compared to operation in auto mode.

Table 28 the ranges for the crucial parameters which delivered the best removal and production results.

Table 28. Crucial operating parameters for the SM unit: ranges for the best results regarding the reclaimed water.

Parameter	Units	Min	Max
Sludge tank			

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Sludge level	cm	150	290
Aeration tank			
DO	mg/L	2	5
Level	cm	210	220
Denitrification tank			
Level	cm	210	220
Air flow pressure	mbar	-500	500
Membrane tank			
Level	cm	200	250
MLSS	mg/L	7 000	10 500
Volumetric Flow Rate	L/h	1 000	1 500

3.3.3. Metabolic network reactor (MNR) coupled to a Micro-Ecological Life Support System Alternative (MELiSSA) advanced separation systems (MF/RO) in La Trappe (NL)

Authors: Ralph Lindeboom (SEMiLLA-IPSTAR), Clara Plata (SEMiLLA- IPSTAR), Rob Suters (SEMiLLA- IPSTAR) and Istvan Kenyeres (BioPOLUS)

3.3.1. Description of the demo site

The La Trappe brewery and the abbey, 'Abdij Onze Lieve Vrouw van Koningshoeven' , both located in Berkel-Enschot, Noord-Brabant, The Netherlands have a vision: to live in harmony with nature. The aim for the coming decade is to deal with the different wastewaters generated on site, as well as make as much water and nutrients as possible available for reuse. Wastewater present on site are the industrial wastewater from the brewing process as well as the municipal wastewater from the visitor centre, the guest house, and the abbey.

The brewery and the cheese factory produce about 360 m^3/day of agro-industrial wastewater on site. The municipal wastewater originates from the ~22 monks continuously present on site (who also take showers), the average ~400 daily visitors to 'Het Proeflokaal" (restaurant), and the ~140 additional employees working for the brewery and on the land. In total, a municipal flow of 15-18 m^3/day is produced under nominal conditions (pre- and post-COVID 19).

Given the characteristics of the urine, black water and grey water sources at the abbey, the combined municipal wastewater is expected to be somewhere between untreated domestic sewage and concentrated black water in terms of water quality, with a relatively high concentration of TN due to a larger urine composition than average.

This average brewery and cheese factory wastewater characteristics will be included to allow a comparison with the domestic sewage composition in terms of nutrient recovery, especially since the flow rate is much larger at La Trappe comparing with the average industry (240-360 m^3/d). Brewery wastewater is usually characterized by a highly fluctuating pH (3-12) and a

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relatively high COD of 2-6 g L^{-1}, which to a large extent is biodegradable (Rao et al., 2007; Simate et al., 2011). Although the COD concentrations of the case study water are in line with concentrated blackwater or urine, in terms of nutrients, the water is more similar to diluted domestic sewage. Bacterial counts vary widely between 10^3-10^8 CFU/ 100 mL, but under normal circumstances, pathogenic bacteria are not present in beverage production.

Table 29. Overview of average brewery wastewater composition (Rao et al., 2007).

Parameter	Value
pH	3 – 12
Temperature (°C)	18 – 40
COD (mg/L)	2000 – 6000
BOD (mg/L)	1200 – 3600
COD:BOD ratio	1.667
VFA (mg/L)	1000 – 2500
Phosphates as PO_4 (mg/L)	10 – 50
TKN (mg/L)	25 – 80
TS (mg/L)	5100 – 8750
TSS (mg/L)	2901 – 3000
TDS (mg/L)	2020 – 5940

Cheese factory wastewater is similar to brewery wastewater, and is usually also characterized by a very high COD:N:P ratio, although it contains relatively more TN and fats compared to brewery wastewater (Prazeres et al., 2012; Simate et al., 2011) .
Many full scale anaerobic digesters are successfully operated on cheese factory and brewery wastewater, due to their relatively suitable COD:N:P ratio and relatively low sludge production in comparison to aerobic wastewater treatment alternatives (Prazeres et al., 2012; Simate et al., 2011). However, these systems always require a polishing treatment to meet discharge regulations in terms of nitrogen and phosphorus.

3.3.2. Motivation for implementing circular economy solutions in the water sector

Given the long-term goals of reducing the intake of water resources at the abbey, the BioPOLUS metabolic network reactor (MNR) was introduced and constructed at the start of the NextGen project. As the aim is very similar to the goals of the Micro-Ecological Life Support System Alternative (MELiSSA) consortium, this case study therefore focuses on finding the technological similarities between the two. The MELiSSA consortium is an international collaboration between academia that is established by the Eureopan Space Agency to develop closed loop regenerative life support systems. Long-term manned space missions require a very calculated approach towards the physical human requirements in terms of water, food, air and climate control, due to the difficulty and associated costs of sending a mass payload into space [1]. MELiSSA technology consists of an interconnected loop of bioreactors that convert black water, urine and kitchen waste via a liquefying compartment (C-I), a photoheterotrophic compartment (C-II), and the nitrifying compartment (C3) into food for the astronauts via photoautotrophic edible “algae” compartment (C-IVa) and the higher plants compartment (C4b) (Godia et al., 2002). The astronauts themselves are considered part of the engineered loop of bioreactors as the crew compartment (C-V).

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Is it technologically feasible to apply MELiSSA's technology to close the cycle and move towards a Zero Liquid Discharge abbey and brewery? The long-term aim is to use MELiSSA technologies for bottle washing, aeroponics, and aquaculture, so the potential of life support system engineering will also be tested within this case study.
In practice, the MNR is a biofilm reactor in which plants provide a part of the oxygen, reducing the energy use of the system in comparison to conventional activated sludge systems. It consists of a serial configuration of different reactor vessels with different DO levels, includes a nitrification-denitrification based nitrogen removal (and uptake by plants), and a chemical phosphate removal. The effluent of the system is treated with a dissolved air flotation followed by a microfiltration unit and a UV-based disinfection. Afterwards, the water is suitable for reuse as irrigation water and/or groundwater infiltration. Potential redundant water may be safely discharged to surface water.

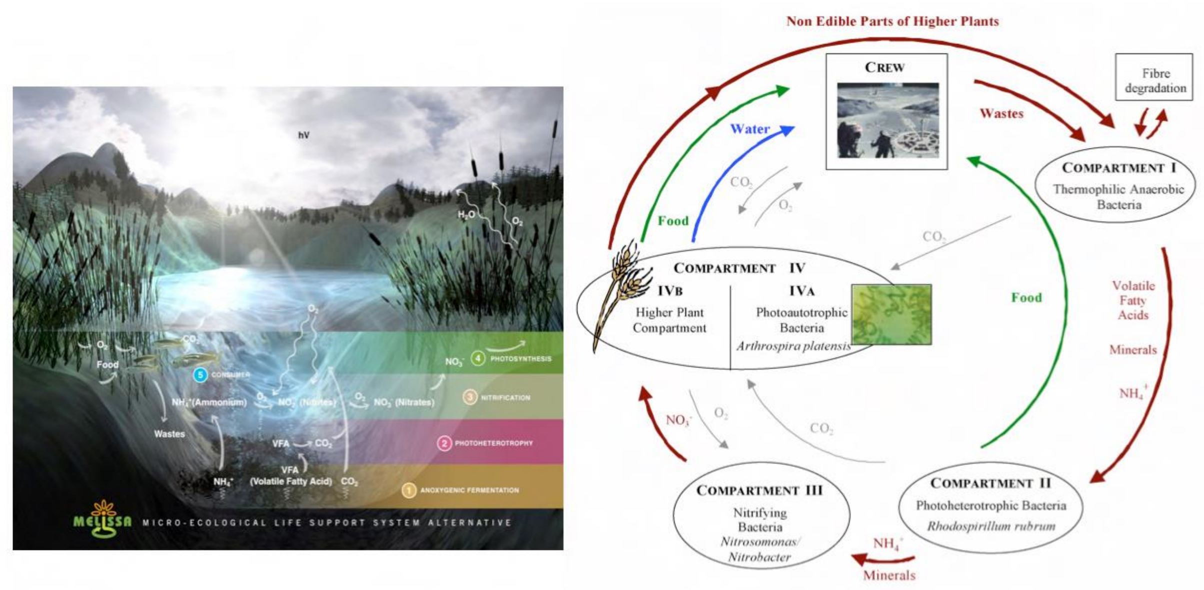

Figure 27. Overview of the Micro-Ecological Life Support System Alternative (MELiSSA) (Lasseur et al., 2010)

The benefits of the combined MNR MELiSSA (NF or RO) inspired membrane system are:

- ✓ **Fit-for-purpose quality suitable for direct reuse in the factory and abbey at various quality levels**

Due to the implementation of a multistage treatment train, the effluent after each stage could be considered for reuse purposes (Lindeboom et al., 2020). As the water use at the abbey grounds range from non-edible plant cultivation, to bottle washing water, to potable water, and to boiler feed water, each step offers opportunities to optimise the dimensions of post treatment to reach the required water quality. For example, for irrigation of non-edible plants, the presence of suspended solids and nutrients is not a major concern, while for potable water and boiler feed water, they should be avoided at all costs.

- ✓ **Reduced capital expenditure ('CapEx') and operating expenses ('OpEx) due to MNR removing main flux limitations in membrane system**

Since membrane surface area and operational pressure are key to reduce the total cost of ownership for membrane filtration systems, the pollutant load in the influent stream should be carefully analysed.

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Multiple foulants in the effluent are known to influence the performance of membrane filtration systems. Suspended solids typically cause pore clogging, or in the case of hollow fiber membranes, cause fiber clogging. Hardness ions can be a concern if higher recoveries are desired, due to the volumetric concentration factor and saturation index exceedance. Salinity increases the required operational pressure due to its effect on the osmotic pressure. Nutrient presence often leads to long-term operational concerns including biofilm formation. Designing a biological system to enhance the performance of membrane-based filtration of urine and grey water was proven to be effective (Lindeboom et al., 2020). Therefore, it is anticipated that the MNR could reduce the TCO or Total Cost of Ownership of membrane-based systems as well.

- ✓ **Integrated upcycling of brine for membrane-based treatment plant**

Upcycling brine will give the benefit to value it (nutrient rich, soiltreatment) and will increase the water reuse opportunity.

- ✓ **Demonstrate an aesthetically pleasing and integrated water treatment reuse concept which can be placed inside urban residential zones**

Wastewater treatment still isn’t ‘sexy’. While showing the possibilities of the Metabolic network reactor (MNR) coupled to a Micro-Ecological Life Support System Alternative (MELiSSA) advanced separation systems in practice it will stimulate the willingness to integrate it in a closer loop approach in urban residential zones.

Further reasons for implementing the membrane system include:

- ✓ **Increased nutrient recovery potential through use of concentrate in the MELiSSA-inspired photobioreactor**

The WWTP receiving the cheese and brewery wastewater profits from the reduced phosphate return load. Thus, a part of iron or aluminium salts often used for a conventional chemical removal might be saved due to the lower return load.

- ✓ **Decrease effluent quality fluctuations**

The influent composition of the membranes (the effluent produced by the MNR) still show fluctuations that would reduce the opportunities to reuse the water. Decreasing the fluctuations and by complementing the system with membranes, which are considered to be an absolute pathogen barrier, extra water safety measure is implemented.

3.3.3. Actions and CS objectives

Table 30. Actions and objectives of the case study in La Trappe.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
# 6 **La Trappe** **Location: La Trappe Brewery**	Sub-Task 1.2.6 Production of fit-for-purpose water in La Trappe	La Trappe brewery wastewater treatment plant	Metabolic network reactor (MNR - plant root enhanced fixed bed bioreactor) + MELiSSA advanced	MNR - plant root enhanc ed fixed bed bioreac	La Trappe brewery wastewate r treatment plant	Metabolic network reactor (MNR - plant root enhanced fixed bed bioreactor) + MELiSSA

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			separation systems (UF/RO or NF) to produce fit-for-purpose water	tor (TRL 7 → 9) +		advanced separation systems (UF/RO or NF) to produce fit-for-purpose water

3.3.4. Unique selling points

Unique selling points for the implementation of a combined MNR membrane system are:

- ✓ Fit-for-purpose quality suitable for direct reuse in the factory and abbey at various quality levels
- ✓ Reduced capex and operational expenses due to MNR removing main flux limitations in membrane system
- ✓ Integrated upcycling of brine
- ✓ Demonstrate an aesthetically pleasing and integrated water treatment reuse concept that can be placed inside urban residential zones

Unique selling points for MNR are:

- ✓ Aesthetically pleasing WWTP solution, housed in an enclosed structure which can be architecturally integrated into the built environment
- ✓ Small physical footprint
- ✓ Low energy use compared to activated sludge or membrane bioreactor systems

3.3.5. Principal characteristics of the technology

In the case study La Trappe, three different, interconnected technologies were implemented:

- Metabolic network reactor
- MELiSSA-inspired membrane systems
- MELISSA-inspired photobioreactor

In this report, the first two, which concern the water recovery system, are described. The MELiSSA-inspired photobioreactor technology is presented in *D1.5 New approaches and best practices closing the materials cycle in the water sector.*

Metabolic network reactor

MNR technology, developed and patented by the company Biopolus, uses integrated fixed film activated sludge (IFAS) water treatment technology. This technology, based on the Living Machine principle introduced by ecologist John Todd, makes use of the phenomenon that microbial biofilm develops on the roots of aquatic plants. Figure 2 shows how such a reactor is designed. The roots of the plants are growing inside tanks that can be submerged in the ground. The natural roots inside the tank are supplemented with artificial roots to maximize area for biofilm growth.

There are several advantages in using a metabolic network reactor. MNR technology has a small footprint, has the look and feel of a botanical garden, and can fit very nicely into curated architectural environments. It also uses approximately 30% less energy in the treatment

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process compared to traditional aerobic treatment processes. The reactor's treatment efficiency comes from the unique use of biofilm processes which are characterised by a large microbial biodiversity.

Figure 28. Pictures of the MNR at La Trappe.

MELiSSA-inspired membrane system

In previous work, an alternative non-sanitary five-stage treatment train for one "astronaut" was successfully developed based on years of MELiSSA experience in pilot systems and at the Concordia station in Antarctica (Lindeboom et al., 2020). This so-called Water Treatment Unit Breadboard (WTUB) successfully treated urine (1.2 L/d) through five stages: crystallisation, COD-removal, ammonification, nitrification and electrodialysis, before it was mixed with shower water (3.4 L/d) and passed through a ceramic nanofiltration and single-pass flat-sheet reversed osmosis (RO). Through smart integration, a biological pre-treatment system could reduce operational expenditure for advanced membrane systems (Lindeboom et al., 2020). This conclusion inspired the pilot case at La Trappe.

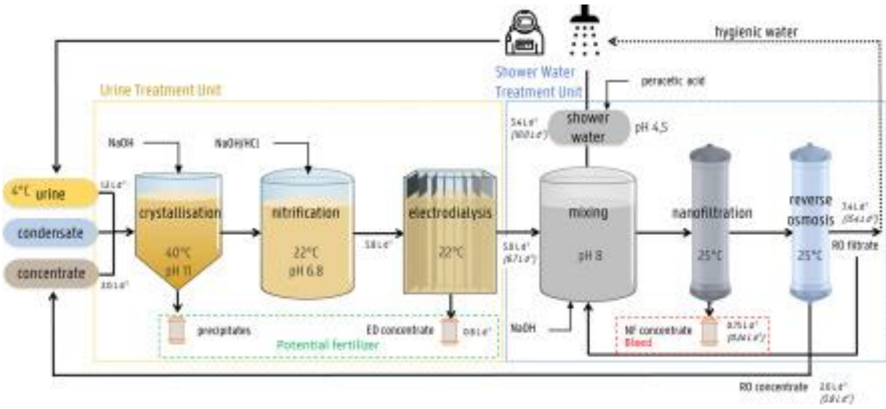

Figure 29. Flow scheme and picture of the WTUB (Lindeboom et al., 2020).

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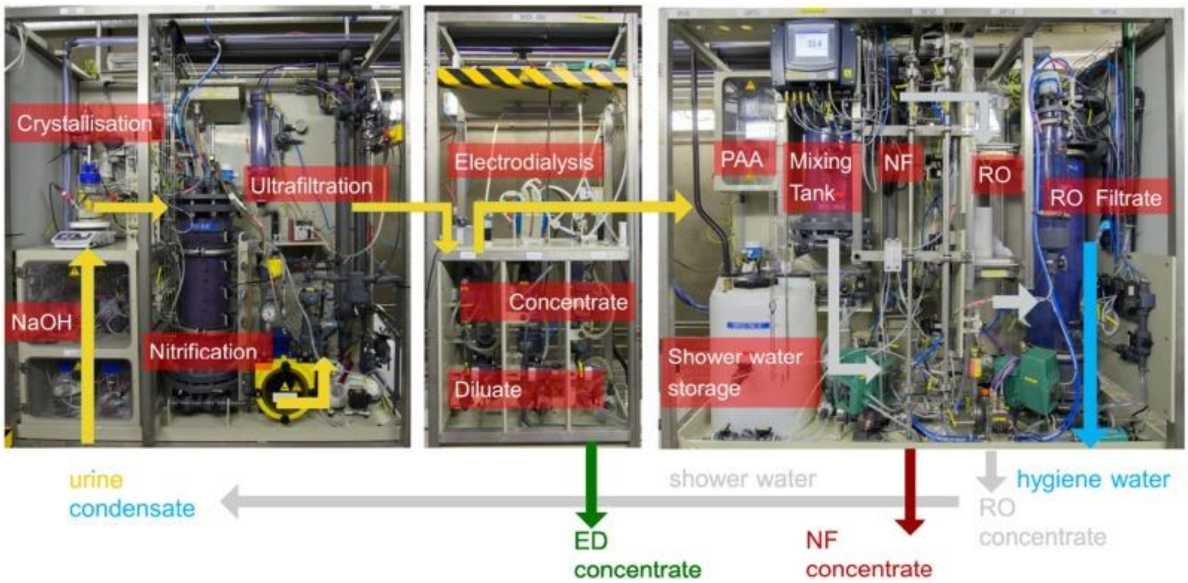

Figure 30. Pictures of the original WTUB which inspired the application at La Trappe (Lindeboom et al., 2020).

In the end, an ultrafiltration-reverse osmosis (UF/RO) unit of Firmus greywater systems (A MELiSSA partner) was tested off-site on raw brewery effluent, while a MELiSSA-inspired approach was chosen through the use of a Jotem nanofiltration (NF) system on MNR effluent.

3.3.6. Technology implementation requirements

The flow scheme of the La Trappe case study is given in Figure 31.

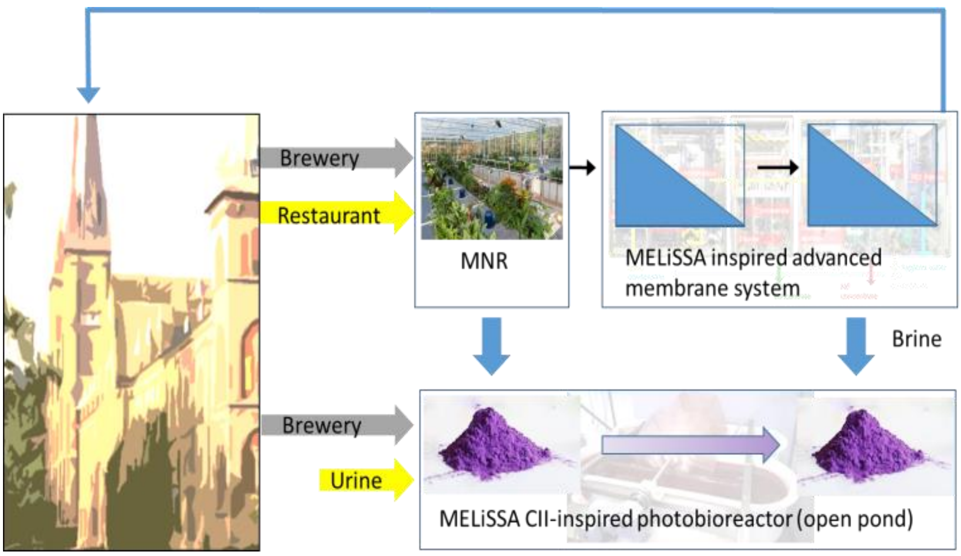

Figure 31. Flow scheme at La Trappe case study.

Metabolic network reactor
The MNR system at La Trappe was designed to treat the both the industrial wastewater from the brewing process as well as the municipal wastewater from the visitor centre, the guest house and the abbey. The system was designed with two treatment lines for the separate influents to avoid contamination of the process water with human waste.

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The system was designed to treat 360 m³ of industrial and 18 m³ of municipal wastewater per day. The effluent goals were set to enable the reclaimed water to be used for irrigation or to be released into the environment.

Effluent quantity and quality have large fluctuations due to the batch processes employed in the brewery. To accommodate these fluctuations and to even-out the loading of the system, a new buffering tank was built besides the existing one employed by the brewery. This additional tank was equipped with pH control system to neutralize the extremely high pH (>11) effluent from the Clean in Place (CIP) process. Dosing control was also implemented to supplement the wastewater with nutrients, as the preliminary measurements showed that the brewery wastewater was unbalanced in terms of C/N/P ratio (deficient in nitrogen and phosphorus), which can hinder biomass growth. For added flexibility, 4 of the 14 reactor cells were designed so they can be operated either as aerobic or anoxic zones, based on the influent.

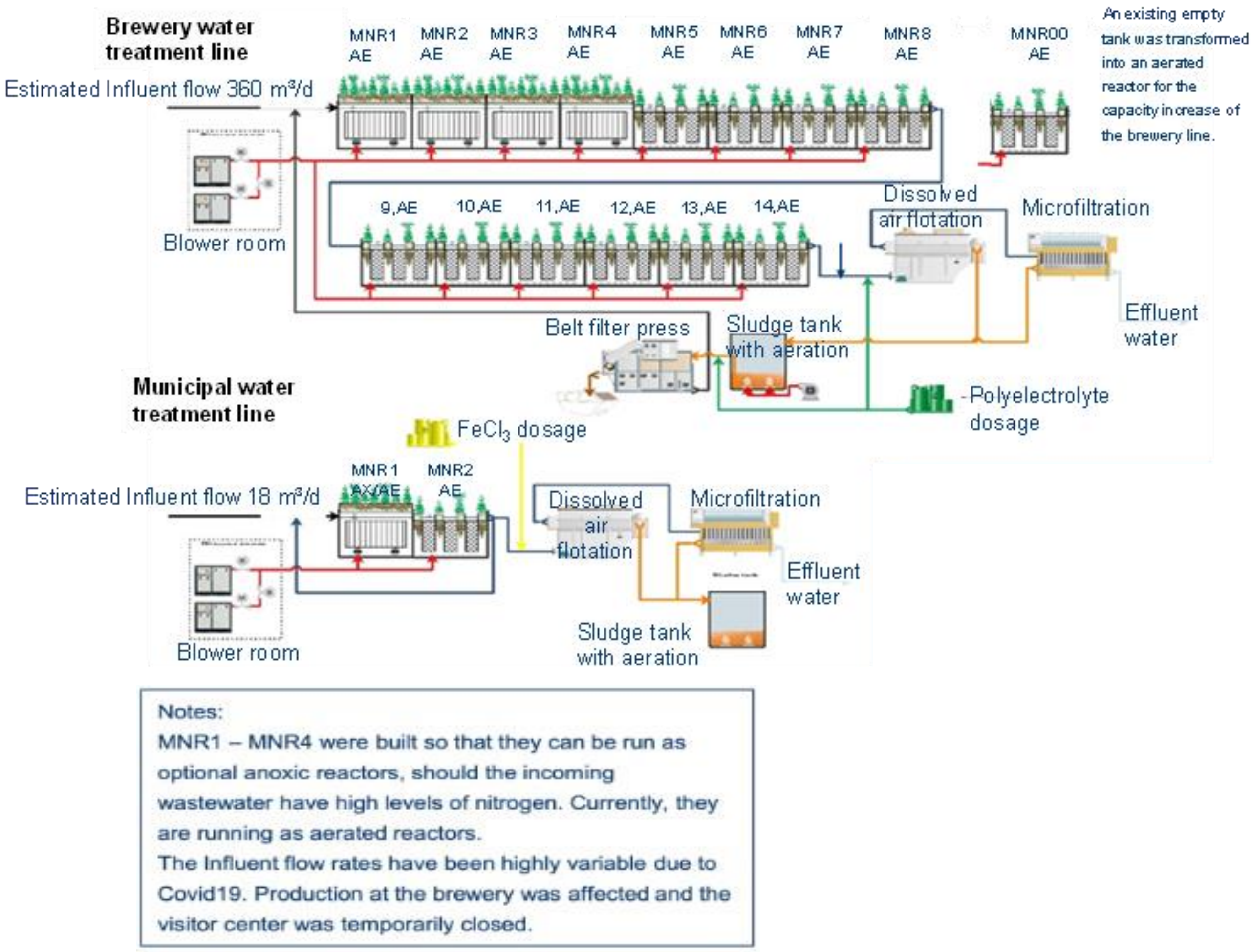

Figure 32. Diagram of the MNR.

The technical parameters of the system were determined based on the following expected influent parameters and discharge goals.

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Table 31. Requirements and operating conditions for the metabolic network reactor.

Influent concentrations		
Parameter	**Design**	**Units**
COD	3,080	mg/l
BOD	1,904	mg/l
NH_3-N	3.0	mg N/l
TN	34.5	mg N/l
TP	15.2	mg P/l
TSS	252	mg/l
Typical influent wastewater temperature	15-30	°C
pH	4-12	-
Average brewery wastewater flow	320	m^3/day
Maximum brewery wastewater flow	420	m^3/day
Average brewery wastewater flow	13.3	m^3/hr
Maximum brewery wastewater flow	32	m^3/hr
Municipal wastewater flow (with 400 visitor per day)	18	m^3/day
Average municipal wastewater flow	0.75	m^3/hr
Maximum municipal wastewater flow	2.25	m^3/hr
Effluent target		
Parameter	**Maximum**	**Units**
COD	125	mg/l
BOD	20	mg/l
NH_4-N	1	mg N/l
TP	0.3	mg P/l
TN	10	mg N/l
TSS	2	mg/l
pH	6-9	-
Technical parameters		
Denomination	**Design**	**Units**
Reactor volume – brewery	210	m^3
Reactor volume - municipal	30	m^3
Brewery		
Required average aeration capacity	550	m^3/h
Maximum aeration capacity	940	m^3/h
Municipal		
Required average aeration capacity	58	m^3/h
Maximum aeration capacity	100	m^3/h

MELiSSA-inspired membrane system

Membrane systems are designed for removing pollutants, but different pore sizes result in different removal efficiencies and fluxes, the latter of which is defined as litre per square meter of membrane surface area per hour. The UF/RO system was chosen as an option to treat raw brewery effluent directly, while the NF system focused on an integrated approach with the MNR system.

Parameter	Units	Consideration	Reference
UF/NF/RO			
Saturation index		To prevent scaling in the RO, hardness should be managed	

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		below SI<1	
TSS	mg/L	No strict requirement for UF, but should be completely removed for RO. For capillary NF, should be below 50 mg/L	
Pressure UF	mbar	Typical several hundreds of mbar	
Pressure NF	bar	~5 bar	
Pressure RO	bar	Operational pressure is needed to counter osmotic pressure and is thus dependent on salinity/type of membrane	

3.3.7. Results obtained

Metabolic Network Reactor

To evaluate the MNR, both practical results and simulation results have been acquired in NextGen.

Shortly after the start-up of the system in 2019, it was discovered that some sections of the aeration pipeline were inadequately sized and required enlargement. Parallel to this the brewery indicated that it was planning to upgrade its production and an increase in wastewater emission was foreseen. During the summer of 2019, the aeration system was upgraded with more powerful air blowers, a larger pipeline and an existing tank was converted to an additional MNR reactor.

When the system was restarted after the alterations, it was discovered that the brewery switched to using phosphoric acid for cleaning of the yeast tanks. This resulted in an influent with a much higher phosphorus content (which was originally measured to be deficient) and necessitated implementation of chemical phosphorus removal by dosing ferric chloride.

Additionally, a recurring problem with foaming was reported, which was not observed before the restart of the system. It was hypothesized that it was caused by excessive amount of protein in the wastewater, but the cause was never confirmed. To alleviate the problems caused by the foaming, several types of anti-foaming agents were tested, which resulted in increased COD loading of the system.

Due to the COVID situation, the municipal line never worked according to specifications and therefore the focus was shifted to the brewery line only. The beer production and therefore the brewery line itself was also stopped and restarted several times during this period. Normal operations resumed with a lower than anticipated load in 2021.

Unfortunately, due to the frequent restarts and changes implemented by the operator and the brewery, the reactor never stabilized during the duration of NextGen and discharge limits, in terms of N, P, COD and TSS were regularly exceeded.

The results that were obtained in the brewery line are presented in Table 32.

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Table 32. Results obtained in the brewery line at La Trappe case study.

Case study	Topic	Objectives		Key Parameters	Influent Range (mg/l)	Discharge Limits (mg/l)	Effluent Range (mg/l)
#6 La Trappe (NL)	Water	Successful operation of brewery MNR	Effluent is fit for irrigation use / aquifer recharge.	COD	453 – 3829	125	62 – 427
				Ammonium	0.08 – 4.6	1	0.01 – 8.3
				TN	4.9 – 47	10	4.8 – 24.1
				TP	4.5 – 26.1	0.3	1.8 – 17.8
				TSS	No Data	2	No Data
				Chloride	43 – 110	60	60 – 80
				Sulphate	20 – 103	60	62 – 159

To show the potential of this technology and to aide in the Life Cycle Cost (LCC) analysis, three flow scenarios were simulated - 150 / 300 / 450 m³ daily quantities. The assumption of the influent wastewater concentrations was updated based on measurements conducted by Waterboard De Dommel. Table 33 summarizes these new assumptions.

Table 33. Assumptions for the concentrations of the influent wastewater characteristics.

Parameter	Original	Updated	Unit
COD	3,080	3,725	mg/l
BOD	1,904	2,346	mg/l
NH_3-N	3.0	0.18	mgN/l
TN	34.5	46	mgN/l
TP	15.2	5.1	mgP/l
TSS	252	438	mg/l
Typical influent wastewater temperature	15-30	20	°C
pH	4-12	4-12	-

Based on these assumed conditions the effluent quality concentrations and operating parameters were calculated using the SUMO wastewater simulation software. The results are summarized at Table 34.

Table 34. Comparison of different scenarios for MNR operation for the treatment of the brewery wastewater.

Parameter	Unit	150 m³/d	350 m³/d	450 m³/d
Effluent concentrations				
COD	mg/l	84.3	84.8	90.1
BOD_5	mg/l	2.5	2.4	6.5
TSS	mg/l	3.1	3.9	4.2
TN	mg/l	1.5	2.1	2.3
NH_4-N	mg/l	0.0	0.4	0.2
NO_x-N	mg/l	0.0	0.0	0.0
TP	mg/l	0.2	0.3	0.2
PO_4-P	mg/l	0.1	0.1	0.0

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Technical parameters				
Aeration requirement	m^3/h	756	1,169	1,439
HRT	h	36	18	12
P source dosage	kg P/d	4.20	12.05	11.90
N source dosage	kg N/d	5.80	17.65	32.50
Sludge production (dry matter)	kg/d	182.5	462.7	756.5

MELiSSA-inspired membrane systems
As the operation of the MNR faced many delays, a UF/RO combination was used to show the potential of producing potable water from raw brewery effluent. 5 L of effluent was sent to the Firmus lab in France and using 2 membrane setups (UF and RO) from the MELiSSA community, the brewery effluent could be converted into potable water quality.

Ultrafiltration test

The membrane used was an ultrafiltration mineral membrane with a cut-off threshold of 150 kD. The filtration area was equal to 75 cm². The test was carried out in a "production" configuration with the following operating conditions:

- flow: 400 L/h, i.e., a flowspeed of 4 m/s,
- volume of product used: 3.7 liters of water prefiltered through a 150 µm cartridge,
- working pressure: 1 bar,
- duration of the test: 280 minutes,
- volume of permeate produced: 2.84 liters, and
- final concentration factor by volume: 4.3.

Figure 33 shows the evolution of the permeate flow as a function of the Volumetric Concentration Factor, the ratio of the initial volume to the final volume in the feed tank (VCF).

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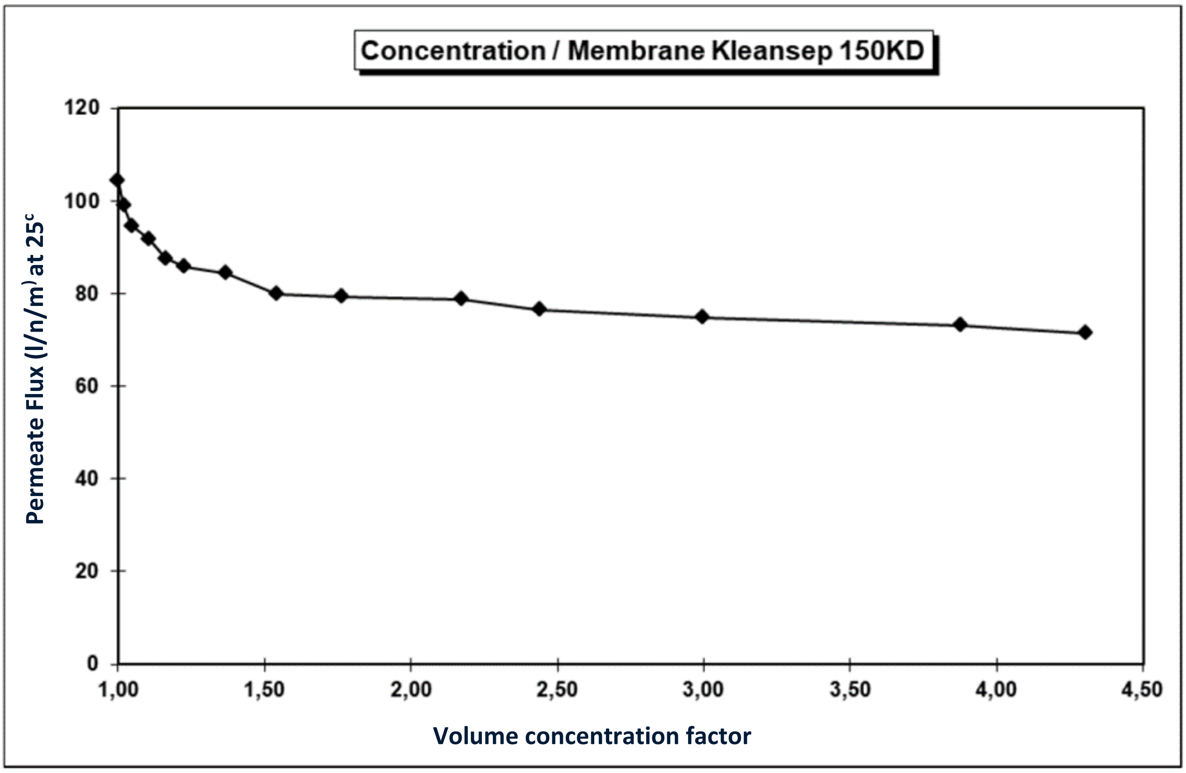

Figure 33. Permeate flow as a function of VCF.

For an applied pressure of 1 bar, the permeation flux was between 104 and 72.7 L/h.m² for a VCF ranging from 1 to 4.3.

Figure 34 visualises the evolution of the pressure as a function of the VCF.

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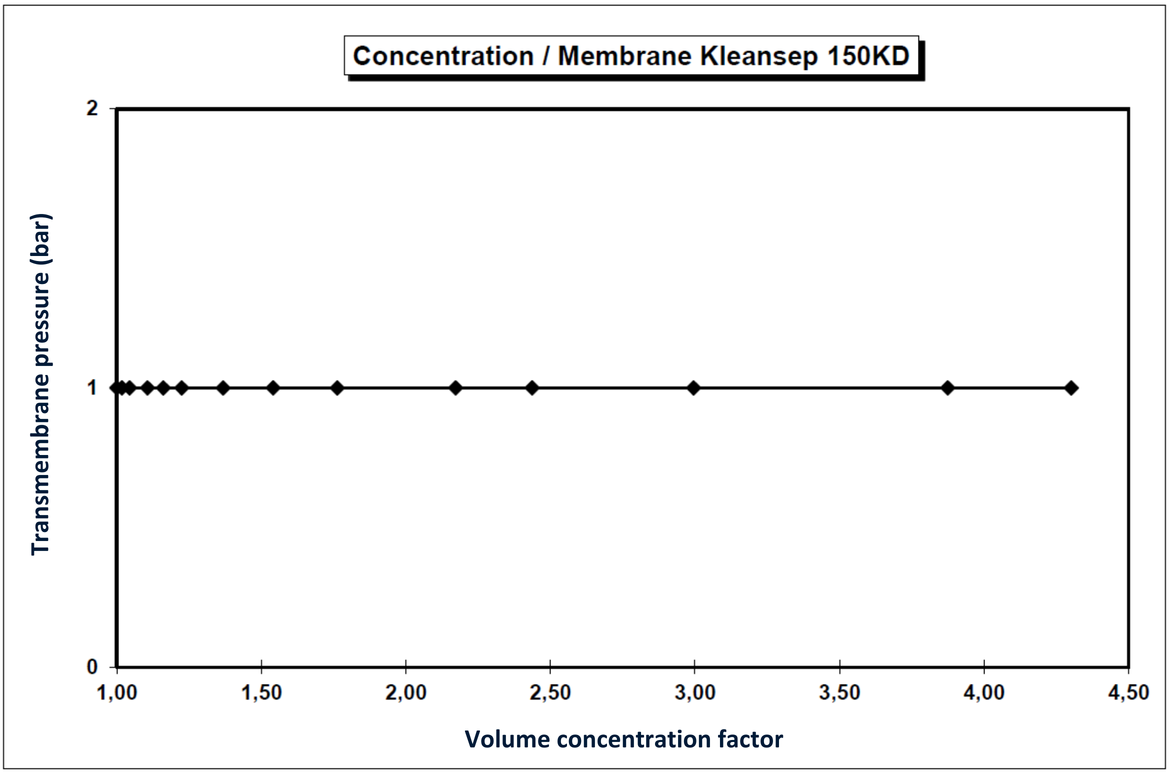

Figure 34.Transmembrane pressure as a function of the VCF.

The average flux measured during the test was equal to 84.9 L/h.m² for an applied pressure of 1 bar and a temperature between 24.8 and 25.8°C.

Table 35 summarizes the analytical results obtained for the ultrafiltration test.

Table 35. Analytical results of the ultrafiltration test. R initial - Initial retentate; R final - Final retentate at VCF 4.3; Averaged P – averaged permeate at VCF 4.3.

Sample	**Initial solution**	**Final retentate**	Averaged final permeate	**Retention (%)**	**Removal (%)**
Turbidity (NTU)	238	772	1.2	100	100
Conductivity (µS/cm)	2400	2350	2200	6.4	8.3
pH	11.5	11.2	11.4	-	-
COD (mg/L)	1761	3115	1834	41	20
$[Na^+]$ (mg/L)	664	705	606	14	30
$[K^+]$ (mg/L)	20	21	21	0.0	19
$[Mg^{2+}]$ (mg/L)	18	63	0.0	100	100
$[Ca^{2+}]$ (mg/L)	70	195	19	90	79
$[F^-]$ (mg/L)	15	13	13	2.5	34
$[Cl^-]$ (mg/L)	19	18	21	-17	17
$[Br^-]$ (mg/L)	3.3	2.8	2.5	20	41
$[NO_3^-]$ (mg/L)	3.1	2.9	2.8	2.4	30
$[PO_4^{3-}]$ (mg/L)	20	77	5.5	93	79
$[SO_4^{2-}]$ (mg/L)	9.8	11	9	22	31

Following the test, the membrane was rinsed with demineralized water and its flow rate was checked. The water flow after testing and rinsing was equal to 100.2 L/h.m² bar and 25°C,

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whereas it was equal to 210.6 L/h.m².bar and 25°C before the test. The loss of flow to water was 52.4 %.

The membrane was cleaned by circulating a soda solution at 10 g/L at a temperature of 50°C for 20 minutes at minimum pressure and for 10 minutes at 1 bar.

The water flow measured after this cleaning sequence was 151.8 L/h.m² bar at 25°C.

The membrane was then cleaned by circulating an acidic solution at 10 g/L at a temperature of 50°C for 15 minutes at minimum pressure and for 5 minutes at 1bar.

The water flow measured after this cleaning sequence was 207.9 L/h.m² bar at 25°C.

The obtained results during the tests under different water flows are presented in Table 36.

Table 36. Summary of the results of the different water flow tests.

	Before tests	**After test**	After cleaning with 1% NaOH at 50ºC	**After cleaning with 1% HCl at 50ºC**
Flow with demineralized water (L/h·m² at 1 bar and 25 ºC)	210.5	100.0	151.8	207.9

The cleaning implemented reinstated the initial characteristics of the membrane.

Reverse osmosis test

The ultrafiltration test produced enough permeate for the reverse osmosis step. The volume of permeate resulting from the ultrafiltration introduced into the driver was 500 ml.

The membrane used was a reverse osmosis membrane of type BW30 from Filmtec. The filtration area was equal to 28 cm². The test was carried out in a "concentration" configuration with the followingoperating conditions:

- flow: 108 L/h, i.e., a flowspeed of 2 m/s,
- volume of product used: 0.5 liters of permeate from the ultrafiltration test,
- working pressure: increasing from 20 to 26.5 bar,
- temperature: between 24°C and 24.8°C,
- duration of the test: 179 minutes,
- volume of permeate produced: 0.350 liters, and
- final concentration factor by volume: 3.33.

Figure 35 shows the evolution of the permeation flow as a function of the VCF.

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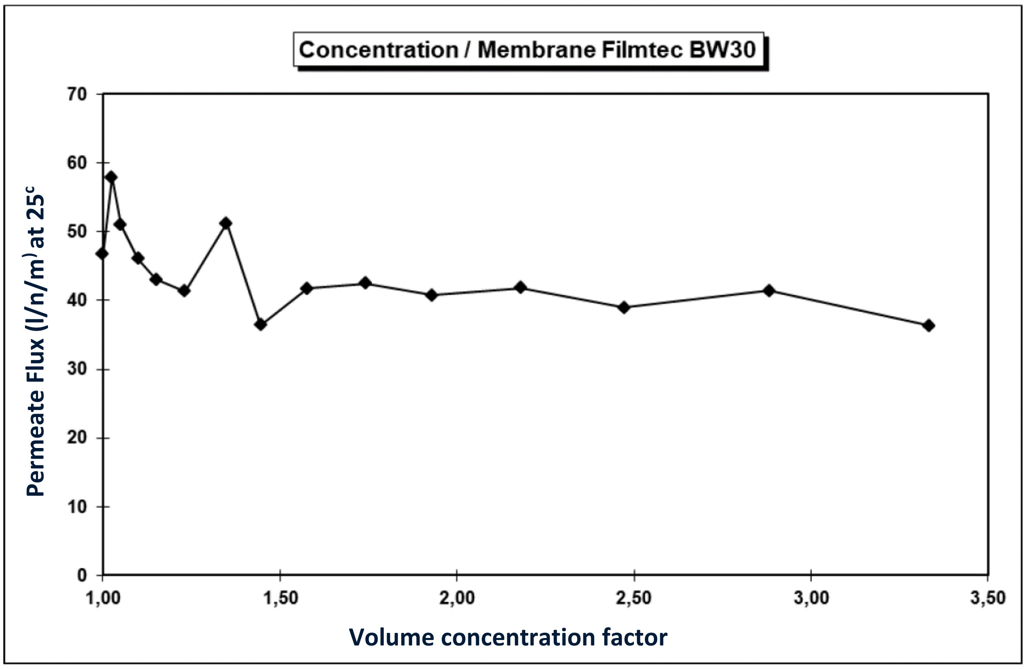

Figure 35. Permeation flow as a function of VCF.

During filtration the permeation rate is kept constant by gradually increasing the working pressure. The VCF increased from 1 to 3.33.

Figure 36 shows the evolution of the pressure as a function of the VCF.

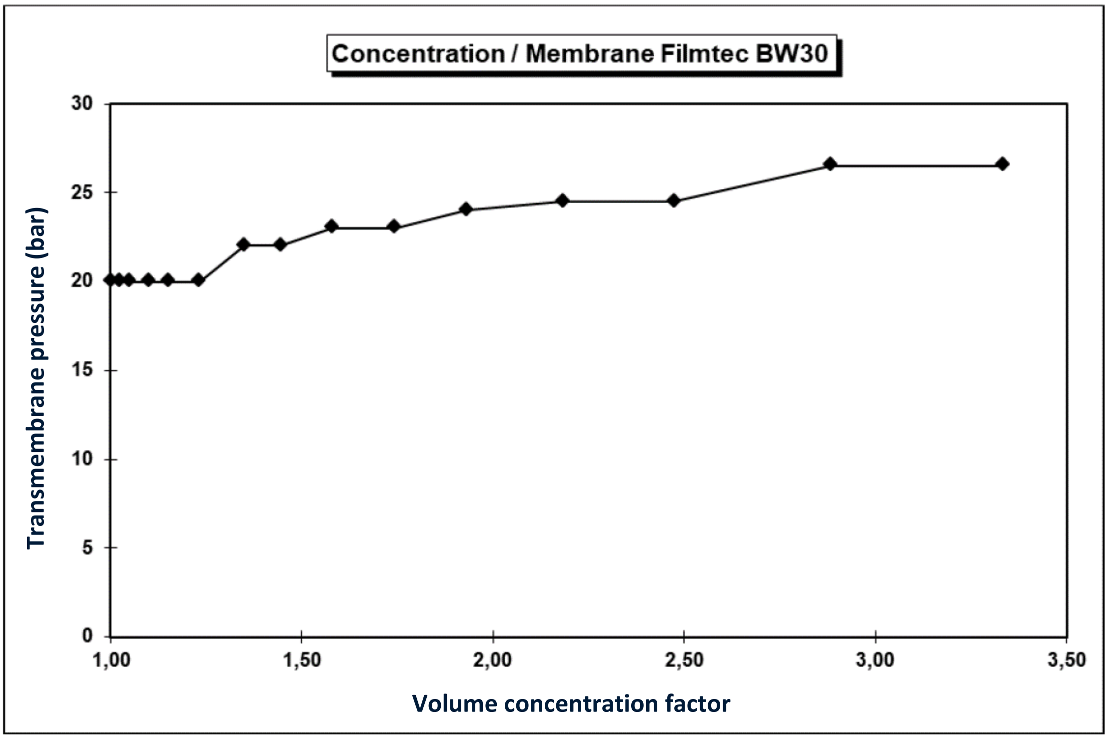

Figure 36. Transmembrane pressure as a function of the FCV.

In order to maintain a constant permeate flow around 40 L/h.m², the pressure was increased from 20 to 26.5 bar as the concentration increased.

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The average flux measured during the test was equal to 43.4 L/h.m², with an average pressure of 22.4 bar and a temperature between 24 and 24.8°C.

Table 37 summarizes the analytical results obtained for the reverse osmosis test with the BW30 membrane.

Table 37. Analytical results of the BW30 reverse osmosis test. R initial - Initial retentate; R final - Final retentate at VCF 4.3; Averaged P – averaged permeate at VCF 4.3.

Sample	**Initial solution**	**Final retentate**	Averaged final permeate	**Retention (%)**	**Removal (%)**
Turbidity (NTU)	1.2	258	0.88	100	25
Conductivity (µS/cm)	2200	5830	118	98	95
pH	11.4	11.6	10.5	-	-
COD (mg/L)	1834	5150	275	95	90
[Na^+] (mg/L)	606	2106	17	99	98
[K^+] (mg/L)	21	58	9.1	84	70
[Ca^{2+}] (mg/L)	19	62	0.47	99	98
[F^-] (mg/L)	14	51	0.32	99	98
[Cl^-] (mg/L)	21	57	7.5	87	75
[Br^-] (mg/L)	3.1	13	0.27	98	94
[NO_3^-] (mg/L)	3.0	9.8	0.30	97	93
[PO_4^{3-}] (mg/L)	5.5	2.4	0	100	100
[SO_4^{2-}] (mg/L)	12	29	0.64	98	96

Initial R: initial retentate
Final concentrate: final concentrate to VCF 3.33
Final average permeate: average permeate to VCF 3.33

The conductivity reduction rate was 95%. The turbidity reduction rate was 25%. The COD reduction is equal to 90%.

Following the test, the membrane was rinsed with demineralized water and its flow rate was checked. The water flow after testing and rinsing was equal to 36 L/h.m² at 10 bar and 25°C, whereas it was equal to 43 L/h.m² at 10 bar and 25°C before the test.

Table 38 summarizes the results of the various water flow tests.

Table 38. Results of the various water flow tests.

	Before testing	**After test and rinsing**
Flow with demineralized water (L/h·m² at 10 bar and 25 ºC)	43	36

A simple rinse with demineralized water made it possible to reinstate the characteristics of the membrane prior to testing.

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Conclusion Test Greywater systems **Firmus**

Ultrafiltration

Since the wastewater is loaded with suspended material, a prefiltration through a filter at 150 µm was required prior to ultrafiltration pre-treatment. The turbidity abatement rate was 100%. Ultrafiltration has no influence on conductivity and pH. The COD abatement rate was 20%, the COD concentration in the permeate was equal to 1834 mg/L compared with that of the raw effluent of 1761 mg/L.

The average permeation flux was 84 L/h.m², for a transmembrane pressure of 1 bar, a temperature between 24.8 and 25.7 °C and a final VCF of 4.3 (76.8% recovery). Chemical washing with soda and acid made it possible to recover the characteristics of the ultrafiltration membrane.

Reverse osmosis of ultrafiltered water

The conductivity reduction rate was 95%. The pH was not changed by reverse osmosis.

The COD abatement rate was 90%, the COD concentration in the permeate was equal to 275 mg/L compared with that of ultrafiltered water 1834 mg/L.

The average permeation flux was 44 L/h.m², for an average transmembrane pressure of 22.4 bar, a temperature between 24 and 24.8°C and a final VCF of 3.33 (70% recovery).

However, as the sample was relatively small, and no duration tests could be performed on-site with this equipment because of the COVID pandemic, no accurate estimation of fluxes and required surface area could be made.

Anyhow results looked promising.

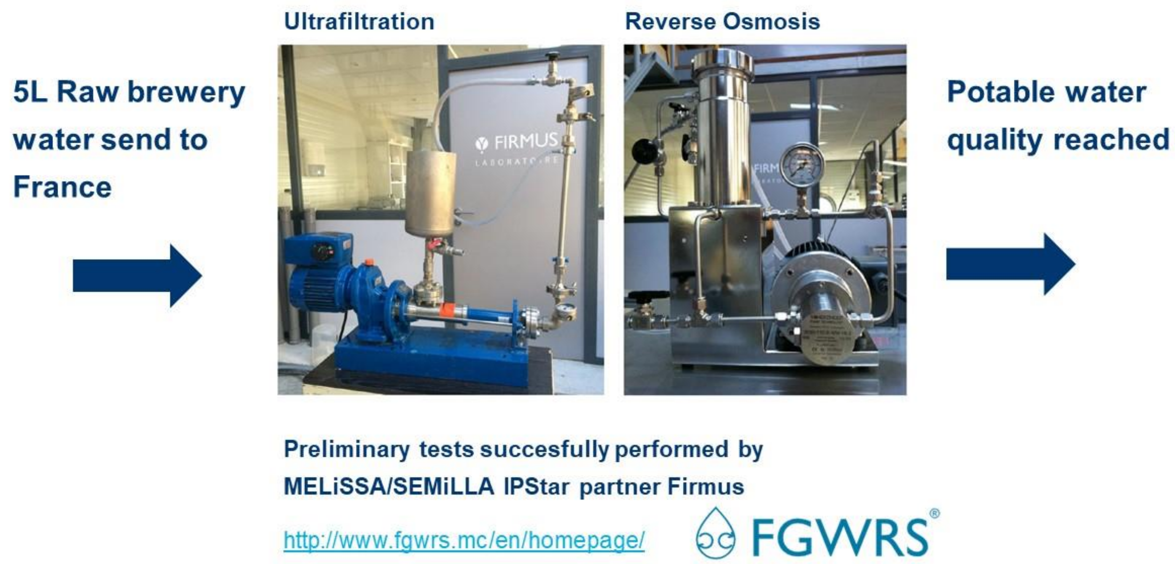

Figure 37. Overview of setup and water quality

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After this test the Jotem Smart box, a NanoFiltration system, was tested, with results depicted in Table 39. Due to the high TSS load in the effluent of the MNR and the limited control over the solid liquid separation (DAF/microfiltration), no duration tests could be performed.

Table 39. Results of the Jotem Smart Box test.

	Effluent	stdev	Permeate	stdev	Concentrate	stdev	Removal (%)
pH	8.0	0.1	8.0	0.2	8.0	0.2	**0%**
COD	226.9	121.1	11.2	3.8	238.9	113.2	**95%**
TN	5.7	4.8	4.1	0.9	7.8	2.8	**28%**
TP	4.1	3.7	0.4	0.4	3.7	2.9	**91%**
Cl-	88.9	34.6	86.9	30.6	84.8	32.1	**2%**
Hardness (Ca2+, Mg2+)	2.5	0.4	1.5	0.6	3.6	0.6	**41%**
CaCO3*	44.5		26.3		63.9		

3.3.8. Comparison of baseline situation and NextGen KPIs

Metabolic network reactor

Before the installation of the MNR system the effluent from the brewery was released into the public sewerage network of Tilburg. The treatment took place in the Tilburg municipal wastewater treatment plant, located approximately 9km from the brewery, at the opposite end of the city. The transport of high strength wastewater over long distances can cause issues in the sewer lines, such as deposition of solids and anaerobic decomposition resulting in emission of odors and corrosive gases.

According to information received from Waterboard De Dommel, the treatment cost of one person equivalent (p.e.) of COD (136 g/d or 49.56 kg/y) is 40 € annually. This figure does not include the cost of the pumping to the treatment plant and the cost of handling the resulting sewage sludge. According to industry standards, these items typically amount to a similar cost as the treatment itself.

<u>Baseline treatment cost calculation based on local waterboard standard:</u>

1 m3 brewery wastewater equals 3,725 gCOD/m3 x 136 gCOD/p.e./d = 27.4 p.e./m3/d

The cost of treating 1 p.e. of wastewater = 40 EUR/p.e./year = 0.11 EUR/p.e./d

The treatment cost of 1 m3 of brewery wastewater is calculated as follows:

27.4 p.e./m3/d x 0.11 EUR/p.e./d = **<u>3 EUR/m3</u>**

Note: This 3 EUR/m3 figures doesn't include the cost of the pumping to the treatment plant and the cost of handling for the resulting sewage sludge.

<u>MNR operating costs:</u> The total energy used to treat 1 m3 of brewery wastewater was calculated based on the installed motor power ratings, the average daily flows and the relevant daily run times as follows:

Average specific volumetric energy use: 3.25 kWh/m3

Average specific COD removal energy efficiency: 0.89 kWh/kg COD removed

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The distribution of the total energy use obtained during the operation of the MNR pilot plant is presented in Table 40.

Table 40. Distribution of total energy use.

Process step	Percentage %
Pre-treatment	0
Aeration	64
Pumping and mixing	15
Sludge separation and dewatering	14
Dosing and off gas treatment	7
TOTAL	**100**

Table 41. Obtained KPIs with the MNR pilot plant.

Topic	Objectives	KPI	Results
Water	Successful operation of brewery MNR Effluent is fit for irrigation use / aquifer recharge.	Water yield of the system (produced / collected)	99%
		Energy consumption (kWh/m^3 produced)	3.25
		Chemical consumption (kg / m^3 produced)	0.16 kg Urea / m^3 0.11 kg 75% Phosphoric-acid / m^3
		Quality: BOD and COD removal vs inlet flow to the system (%)	COD: 97.6% BOD: 99.7%
		Quality: SS and turbidity removal vs inlet flow to the system (%)	99%

The above data are based mainly on simulation results which were partially validated with data from relatively short-term undisturbed operation periods.

MELiSSA-inspired membrane system

Assuming stable operation of the MNR, high quality effluent could be produced. However, due to lower than expected MNR effluent water quality it was not possible to determine KPIs in terms of flux, energy consumption for the membrane systems. Quality parameters were at or above expectations after membrane filtration (See Table 42).

Table 42. Obtained results of the monitored parameters during the NextGen project at La Trappe.

Topic	Objectives	KPI	Results	
			Retention (%)	Reduction (%)
Water	Successful operation of the ultrafiltration test Effluent is fit for reuse in brewery wash	Turbidity (FNU)	100	100
		Conductivity (µS/cm)	6,4	8,4
		pH	-	-
		COD (mg/l)	41	20
		$[NA^+]$ (mg/l)	14	30

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	processes.	$[K^+]$ (mg/l)	0,0	19
		$[MG^{2+}]$ (mg/l)	100	100
		$[Ca^{2+}]$ (mg/l)	90	79
		[F] (mg/l)	2,4	34
		[Cl] (mg/l)	-17	17
		[Br] (mg/l)	10	41
		$[NO_3]$ (mg/l)	2,4	30
		$[PO_4^{3}]$ (mg/l)	93	79
		$[SO_{42}]$ (mg/l)	22	31
	Successful operation of reverse osmosis test with the BW30 membrane Effluent is fit for reuse in brewery wash processes	Turbidity (FNU)	100	25
		Conductivity (µS/cm)	98	95
		pH	-	-
		COD (mg/l)	95	90
		$[Na^+]$ (mg/l)	99	89
		$[K^+]$ (mg/l)	84	70
		$[Ca^{2+}]$ (mg/l)	99	98
		[F] (mg/l)	99	98
		[Cl] (mg/l)	87	75
		[Br] (mg/l)	98	94
		$[NO_3]$ (mg/l)	97	93
		$[PO_4^{3}]$ (mg/l)	100	100
		$[SO_{42}]$ (mg/l)	98	96

3.3.9. Lessons learned

At the La Trappe site, three different interconnected technologies were implemented. The interaction of the single technical units is complex and has to be considered in the system design. The system design, the installation, system control and automation of the technological units did not work well and all units had to be operated separately.
However, as with many other innovative processes, numerous unexpected problems also occurred here, some of whichwere or are very time-consuming to deal with. Therefore, it is important to have employees who are open to "new things,“ and technology suppliers are available for a longer time period even after the commissioning of the system. In the following tables, more details about the lessons learned are presented per technology.

MELiSSA-inspired membrane system

<table>
<tr><td>Required competence</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">Limited training is needed to provide plug and play knowledge which allows the production of good water quality. However, knowledge that is beyond the “standard” wastewater treatment knowledge is needed if stable long-term operation is desired:
• Constant changes in water quality require high level understanding of scaling, clogging and flux permeability in operation

Due to the innovative technology, open minded and solution-oriented personnel arebeneficial to have if installing such a technology. Currently, a daily manual process control and maintenance is conducted for at least 2 h/d but is expected to decrease in the future.</td></tr>
</table>

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Maintenance	LOW — HIGH (indicator near HIGH)
Although in theory the membrane system is operated at low recovery in a low maintenance mode, the changes in effluent MNR quality made this difficult. A manually operated settling tank was installed to prevent major upsets. This system had to be tuned daily. Under normal conditions the effort for maintenance and manual process control is a few hours per month. Due to unforeseen events, such wash out of small struvite crystals and clogging of pipes, the effort increased to be more than 2 h/d. Twice a year extensive maintenance work lasting around one week is required. In this case, the following steps are carried out: • Intensive investigation regarding wearing of plant components • Functional tests • Cleaning of plant components For this work, usually external experts support the maintenance workers. During the first three years of operation, the plant usually had two downtimes per month.	
Technological risks	LOW — HIGH (indicator near HIGH)
Nanofiltration is a well-established technology. However, the integration with a biological system requires a high-level understanding for the NF to work according to specifications.	

3.3.10. Best practice guidelines for operating the technology

Metabolic network reactor

Important aspects to consider during the design and construction of the plant:
Downscaling the MNR technology from large scale (tens of thousands of m^3/d capacities) municipal applications to a few hundred m^3/d highly fluctuating brewery wastewater in an industrial and decentralised environment needs extra care in the design and construction, especially in the following areas:

- Needs much higher level of automation as the operation and maintenance of these facilities is done by part time operators only. However, this will certainly increase investment costs.
- More attention should be paid to proper training, online support and remote supervision.
- The greenhouse structures to be used in this industrial environment should be carefully constructed out of proper materials, especially considering corrosion resistance and high humidity.

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- During the past years the unusually high summer temperatures indicated that the greenhouse structure which encloses the MNR planted reactors needs more and automated shading structures, typically used in agricultural greenhouses.
- The system should be better prepared for extremities in flow, composition and temperature, and a 2-stage buffering and equalization should be used (as originally was envisioned but not fully completed) with proper alarm and safety measures to protect the biology.

Crucial parameters for the optimisation of the production process:

- TSS: Better individual and preferably automated control of aeration in the separate reactor cascades can notably increase system flexibility
- Automated control to ensure suspended biomass concentrations in the reactors are low can help in energy optimization
- An automated process parameter control strategy could help follow the C:N:P ratio, monitoring of which is crucial
- Temperature: the typically 25-30°C wastewater from the brewery should first be used for thermal energy recovery, after which the temperature can be better kept in the 20-25°C range where biology and foaming is easier to control
- Unexpected changes in influent: the system should be better prepared to adapt to changes in the brewing technology (e.g. new cleaning processes, change in yeast usage, change in raw materials), meanwhile changes in beer production should be better communicated with wastewater treatment plant operator

<u>**MELiSSA-inspired membrane systems**</u>

Important aspects to consider during the design and construction of the plant:

- Choice between UF/RO or NF should be made once MNR produces stable effluent and industrial water quality requirement is known
- Suitable pore size should be chosen to enable low recovery
- High quality materials must be used for the system (corrosion resistant, etc.)
- Compliance with the country specific requirements for health and safety are necessary
- System should be flexible and scalable (also accessible for retrofitting work) and operation should be automated/remotely controlled to avoid complex operational task for the monks

Important aspects to consider during the start-up of the plant:

- The process water must be as free as possible of particles
- The chemical composition of the process water should be as constant as possible, and the flow rate should be sufficiently high to run the process properly
- A sampling plan should be considered, and the sampling must be documented

Crucial parameters for the optimisation of the production process:

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- Chemical composition of the MNR effluent (hardness, phosphate, and ammonium concentrations, TSS) should be aligned with operational pressure/flux and backwash cycle (Table 43).

Table 43. Crucial operating parameters for the MELiSSA inspired membrane system: ranges for the best results in NF.

Parameter	Units	Min	Max
Ca/Mg + PO_4-P feed	SI	**0**	**1**
NH_4-N feed	mg/L	**0**	**10**
TSS	mg/L	**<50**	
Recovery		**20 - 30%**	
Operational pressure		**<5 bar**	

3.4. Ultrafiltration (UF) and nanofiltration (NF) system with reverse osmosis (RO) regenerated membranes in Costa Brava (ES)

Authors: Queralt Plana and Mireia Plà (EUT)

3.4.1. Description of the demo site

In the case of the Costa Brava site, a pilot plant integrated with ultrafiltration (UF) and nanofiltration (NF) modules fitted with reverse osmosis (RO) regenerated membranes was installed in December 2019 at the wastewater treatment plant (WWTP) of Tossa de Mar. The pilot plant was placed after the sand filter of the tertiary treatment and operated for two years (2020-2021). During this period, this new system's operational conditions and the effluent quality obtained for private gardens' irrigation purposes were evaluated.

3.4.2. Motivation for implementing circular economy solutions in the water sector

Costa Brava is a region with high seasonal water demand and frequent water scarcity episodes, which can also cause saltwater intrusion. It is one of the first areas applying water reuse in Europe. In total, 14 full-scale tertiary treatments provide 4 Mm^3/year (2016) for agricultural irrigation, environmental uses, non-potable urban uses and, recently, indirect potable reuse.

The Tossa de Mar WWTP works with one-line tertiary treatment with an average flow rate of 7.4 m^3/h, ranging from 4.5 m^3/h during the winter period (values from 2018) to a maximum of 11 m^3/h reached in summer. Mainly during the summer period, both the number of tourists and the wastewater flow rate to be treated increases: thus, a part of the effluent from the secondary treatment is sequentially treated by its tertiary treatment (flocculation/coagulation, pre-chlorination, sand filtration and disinfection process with UV lamps and chlorination).

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Nowadays, the effluent from the tertiary system is used for agricultural irrigation and environmental and non-potable water uses. The water excesses flow to the sea. Due to the increase in water demand, especially during summer, improving the final quality of reclaimed water for broadening its application in more restrictive reuses such as private garden irrigation or indirect potable reuse is desired. The NextGen pilot plant pursues this goal.

3.4.3. Actions and CS objectives

Table 44. Actions and objectives of the Costa Brava case study.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
#2 Costa Brava (ES) **Location: Tossa de Mar**	**Sub-Task 1.2.2 Integration of recycled membranes in multi-quality/multi-purpose water reuse**	WWTP with a tertiary treatment integrated by a pre-chlorination treatment, a coagulation / flocculation process, a sand filter, and UV lamp treatment. Pilot plant from ZEROBRINE Project consists of ultrafiltration (UF) and nanofiltration (NF) modules that can treat up to 2 m^3/h of water.	Refurbishment and adaptation of the pilot plant from ZEROBRINE Project: ultrafiltration (UF) and nanofiltration (NF) modules are fitted with regenerated reverse osmosis (RO) membranes used as a final treatment of urban effluents in the WWTP of Tossa de Mar to obtain a reclaimed water for being used to irrigate private gardens.	TRL 5 → 7	Pilot plant which produces 2 m^3/h of reclaimed water	Reclaimed water (2 m^3/h) for private garden irrigation (RD 1620/2007, Spain) Theoretically: Indirect Potable Reuse by aquifers recharge
		Regenerated effluent from tertiary treatment is nowadays used for public garden irrigation		TRL 9		

3.4.4. Unique selling points

The unique selling points for the integration of recycled membranes in multi-quality/multi-purpose water reuse are:

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- ✓ Tailor made rejection yields (e.g. > 80% of emerging pollutants/priority substances; > 99% of microorganisms; > 95% of salts).
- ✓ Reduction of emerging/priority pollutants that reach aquatic systems.
- ✓ Reuse of a waste (end-of-life RO membranes) that is regenerated (regenerated RO membranes) and can be used in the water cycle as a circular economy concept.
- ✓ Production of reclaimed water with enough quality to be reused. Thus, reduction of the drinking water used for private garden irrigation.

3.4.5. Principal characteristics of the technology

Ultrafiltration (UF) and nanofiltration (NF) are membrane filtration processes whose purpose is to mainly remove suspended solids and organic matter and divalent ions from liquid effluents, respectively. The UF normally works at pressures of 1 – 5 bar (Jafarinejad, 2017) and 5 – 20 bar for NF (Charcosset, 2012). Also, they present zero or low monovalent ions rejection. In general terms, UF is able to efficiently separate colloidal particles, viruses and bacteria (Spivakov & Shkinev, 2005), but has low salt rejection (Calabrò & Basile, 2011). On the other hand, NF not only enables the separation of even smaller organic molecules, but also of inorganic salts. However, it is to note that NF membranes have low rejection of monovalent ions, high rejection of divalent ions and higher permeabilities compared to RO membranes (Wu et al., 2017).

As a function of the oxidation degree, regenerated end-of-life reverse osmosis (RO) membranes can operate as UF and NF modules. In this way, a waste can be reused in the water cycle, increasing their lifetime.

In the NextGen project, the pilot plant, located within a sea container of 20 feet (6.05 m), is fed with water from the sand filter of the tertiary treatment of Tossa de Mar WWTP. The pilot consists of a UF coupled to an NF module, fitted with regenerated RO membranes to produce reclaimed water of Quality 1.1 fixed in the *Real Decreto 1620/2007*. The pilot plant has an estimated production flow rate of 2,2 m^3/h. The water produced is disinfected by the online addition of sodium hypochlorite and is stored in a 10 m^3 tank. This tank is placed in an easily accessible area, where the water tank truck can pick it up and distribute it to the end-user sites.

The process consists of a 50 µm mesh filter to remove the coarse particulate matter. Next is the UF stage, where one module of a commercial membrane is installed. Finally, the NF stage with regenerated RO membranes occurs. A simplified diagram of the process is given in Figure 38. Figure 39 shows some images of the inside of the plant.

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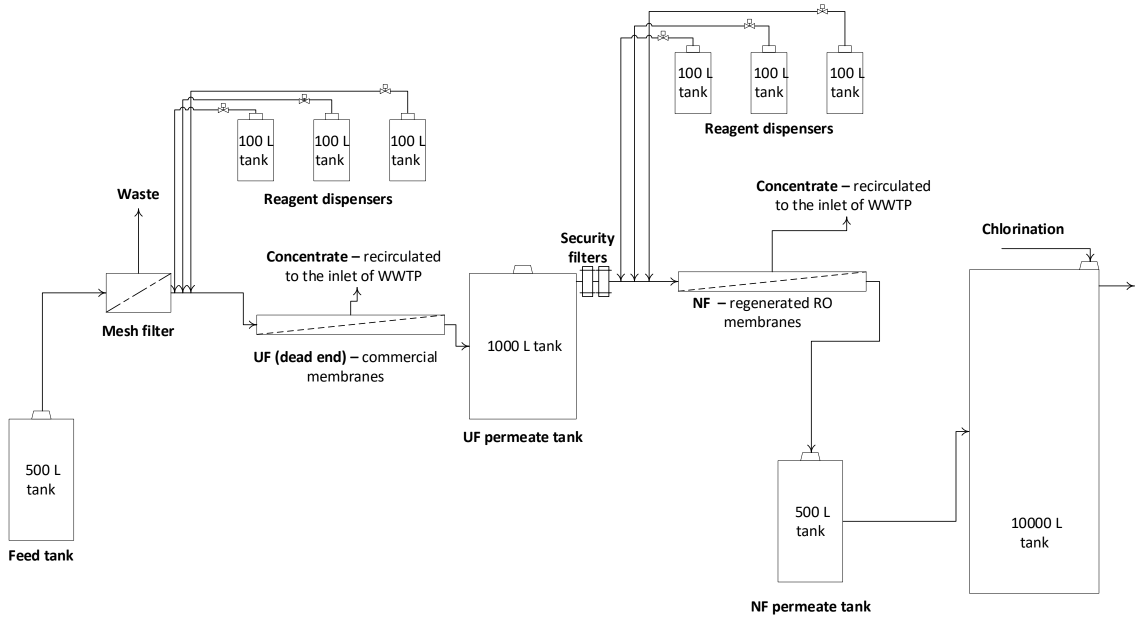
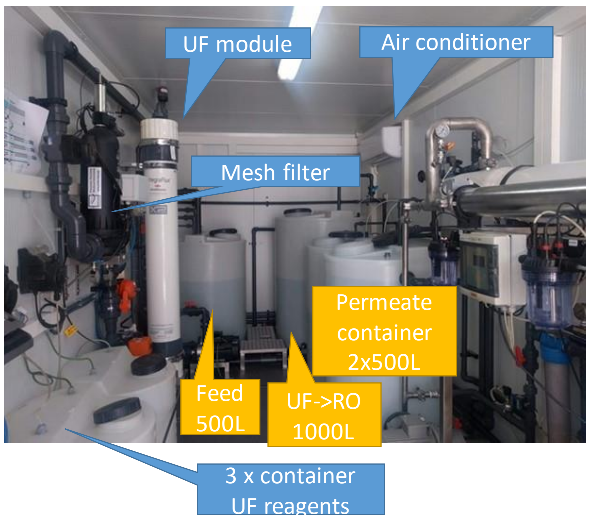


Figure 38. Simplified P&ID of the NextGen pilot plant.



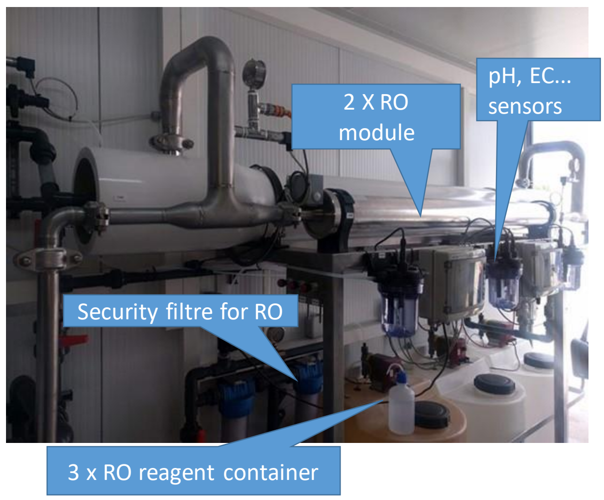


Figure 39. The general location of the pilot plant equipment.

Mesh filter

The function of the mesh filter is to protect the UF process. A 50 µm filter is currently used, but a 10 µm filter can also be installed. An automatic cleaning system is also incorporated, which is activated when a predetermined pressure differential is exceeded. The length of each cleaning step is 30 s, and a feed pressure of 4 bar and a flow rate of 5 m^3/h are required due to pump requirements.

Ultrafiltration

The module consists of a commercial membrane. Back-washes, CEBs and most UF stages are versatile and can be configured and automated using the software developed for the pilot plant. Cleaning-in-Place (CIP) is not automatic and is carried out using the feed tank (500 L). Moreover, there are 3 reagent dispensers for the Chemical Enhanced Backwashes (CEB) which use 3 tanks of 100 L each.

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Nanofiltration

The NF process is composed of two sequential modules, a recirculation pump which supplies a crossflow flowrate of 10 m^3/h, and 3 tanks (100 L each) for reagent dosage. After each run, the modules are automatically flushed and are fed by the permeate solution (2 x 500 L tanks). The system was configured by carrying out non-automatic CIPs. There also are 3 in line dosing systems (e.g., pH adjustment, anti-scaling reagent dosing, disinfection product) with 3 tanks of 100 L each.

3.4.6. Technology implementation requirements

Mesh filter

A mesh filter must be included at the beginning of the treatment to ensure that coarse solids do not reach the UF module to reduce the number of cleaning cycles and increase the length of the filtration cycles.

Ultrafiltration

UF cleaning should be performed periodically to ensure suitable operation. The following table summarize the most appropriated values of several parameters for the conventional UF.

Table 45. Required operating conditions of the commercial UF membranes.

Parameter	Units	Min	Max	Reference
Transmembrane pressure (TMP)	bar	-	2.1	(DuPont, 2019)
Temperature	ºC	1	40	(DuPont, 2019)
pH	upH	2	11	(DuPont, 2019)
Particle size	µm	0.03	0.5	(Spivakov & Shkinev, 2005)

Nanofiltration

Like the UF, NF cleaning c should be performed periodically to ensure suitable operation. The following table summarize the most appropriated values of several parameters for the commercial RO membranes. However, these may differ when operating regenerated RO membranes.

Table 46. Required operating conditions of the RO commercial membranes.

Parameter	Units	Min	Max	Reference
Turbidity	NTU		<1	NextGen D1.2
Pressure	atm	5	50	(DuPont, 2020)
Temperature	ºC	1	45	NextGen D1.2
pH	-	2	11	NextGen D1.2
SDI	-		5	(DuPont, 2020)
MFI 0.45	-		4	(DuPont, 2020)
Oil and grease	mg/L		0.1	(DuPont, 2020)

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Parameter	Units	Min	Max	Reference
TOC	mg/L		3	(DuPont, 2020)
COD	mg/L		10	(DuPont, 2020)
AOC	µg/L Ac-C		10	(DuPont, 2020)
BFR	pg/cm2 ATP		5	(DuPont, 2020)
Free chlorine	mg/L		0.1	(DuPont, 2020)
Ferrous iron	mg/L		4	(DuPont, 2020)
Ferric iron	mg/L		0.005	(DuPont, 2020)
Manganese	mg/L		0.005	(DuPont, 2020)
Aluminium	mg/L		0.005	(DuPont, 2020)

3.4.7. Results obtained

This section presents the results obtained over a year of the NextGen pilot plant operation. During this time, results of water quality (flow, conductivity, turbidity, pH, etc.), emerging pollutants (endocrine disruptors, medicines, etc.) and household products, among others, were recorded and employed to quantitatively assess the efficiency of the treatment through NF regenerated membranes. The efforts on monitoring compounds added to the common physicochemical parameters have been done regarding the intention to use regenerated water for aquifer recharge in Tossa de Mar in the future.
The emerging compounds have been selected according to the WatchList of 2018 and 2020, the Drinking Water Directive and also other literature publications related to the toxicity and effects to the human health. The list of the emerging compounds has been built and agreed with the Catalan Water Agency (ACA, from the Catalan acronym of Agència Catalana de l'Aigua) and the Health Department of the Catalan Government.

- **Water quality parameters**

The water quality parameters evaluated during the execution of the Costa Brava pilot plant were total suspended solids (TSS), total organic carbon (TOC), chemical oxygen demand (COD), total nitrogen (NT), total phosphorus (PT), the concentration of chlorides, phosphates, nitrates, nitrites and ammonium, and the total concentrations of calcium, magnesium, potassium, and sodium ion. Data was recorded from February 2021 to December 2021.
Figure 40 shows the parameters TSS, TOC, COD and chlorides in separate graphs. For all of them, the primary ordinate axis (left) shows the concentration recorded in mg/L, and the secondary ordinate axis (right) shows the tertiary treatment efficiency (%). Dark blue columns show the concentrate (sand filter effluent), and light blue columns show the permeate (effluent after nanofiltration treatment). The grey dots show the nanofiltration efficiency.
As shown in Figure 40, on the graphs (a), (b) and (c), the tertiary treatment efficiency was always around 80%. In some specific cases, and as shown in Figure 40 on the graph (c), there were decreases in COD removal at specific periods. For instance, from March to August 2021, 5 and 35% efficiencies are observed due to the limit of detection was at 50 mg/L and the efficiencies were estimated considering this limit. On the other hand, in September 2021, the

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analytical method was modified to quantify the low levels of COD. Since then, there was a significant increase in efficiency in the COD elimination, reaching more than 90% in December 2021. Thus, the latter efficiency removal was concluded to be the real efficiency.

The elimination of TSS (Figure 40, graph (a)) was around 80%. TSS concentrations in the nanofiltration effluent were 2.5 mg/L, satisfying the legislative standards established. TOC elimination was about 75% on average (influent concentrations were 1500 mg/L and after the treatment diminished to 300-400 mg/L).

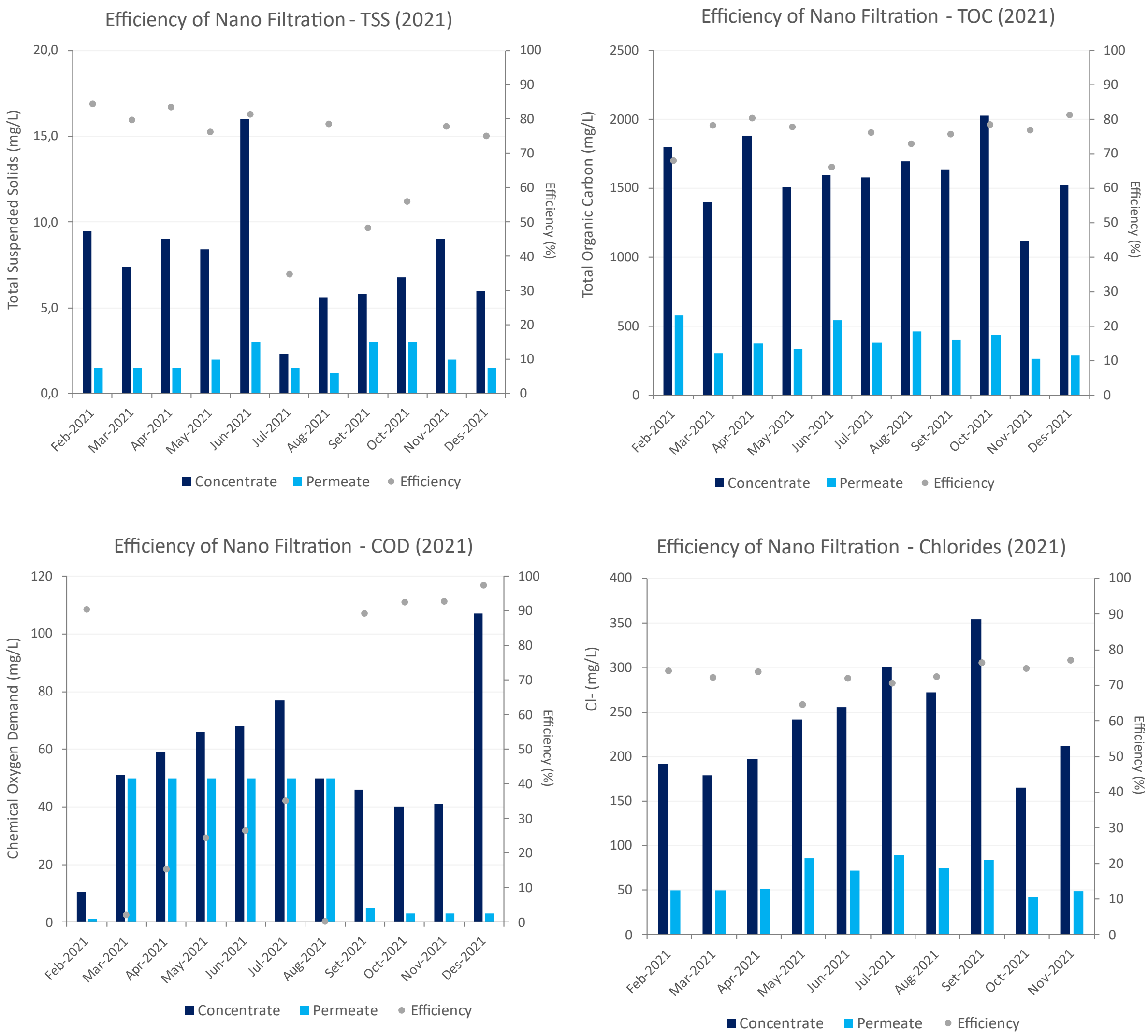

Figure 40. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of (a) TSS, (b) TOC, (c) COD and (d) chlorides during the pilot operation with regenerated end-of-life RO membranes.

The efficiency of chloride removal was also large (80%), satisfying the legislative standards established. Chloride concentrations at the effluent of the sand filter were between 150 and 350 mg/L: after NF, the concentrations were below 100 mg/L. In September 2021, there was an increase in chlorides (350 mg/L). However, the membrane-based system was able to maintain the efficiency producing low chloride concentration effluent (< 95 mg/L Cl^-).

Annex 1.A.1 Nanofiltration efficiency: Water quality parameters exhibits the water quality results obtained for total N, total P, phosphates, nitrates, nitrites, ammonium ions, calcium, magnesium, potassium, and sodium parameters.

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Sand filter effluent registered total nitrogen (TN) and total phosphorus concentrations around 20 mg/L and 1.5 to 7 mg/l, respectively. After NF, the concentrations were ~10 mg/L for TN and below 0.2 mg/L for TP, registering between 78% and 95% removal efficiency, respectively. The phosphate concentrations recorded at the outlet of the sand filter effluent ranged from 4 to 16 mg/L. Nevertheless, the concentrations in the NF effluent were stabile (between 0.2 and 1.2 mg/L), displaying a high phosphate removal (90 – 95%).
Like phosphates, TN and TP, the ammonia concentrations at the sand filter effluent fluctuated (from 25 to 80 mg/L). However, the concentration in the effluent of the NextGen system was constant (from 10 to 15 mg/L), obtaining removal efficiencies ranging from 75 to 80% of NH_4^+.
In addition, NF membrane (i.e. RO regenerated membranes) exhibited an average removal efficiency of 50% for nitrates and nitrites, being higher in some cases for nitrates (80 – 90%) compared to nitrites (50 – 65%).
Sand filter effluent had calcium and magnesium ion concentrations of 70 mg/L and 25 mg/L, respectively. The results showed that the removal efficiency of Ca^{2+} and Mg^{2+} was independent of their concentrations at the inlet of the NF since there was registered an elimination efficiency of almost 100% in all cases.
An irregularity in the sand filter effluent was registered in June for K^+, jumping from 20 mg/L to 190 mg/L. However, the tertiary treatment efficiency with regenerated NF membranes was stable, eliminating 80% of the K^+ on average.
The removal efficiency of Na^+ remains stable over time (approximately 80%) regardless of the quality at the inlet of the tertiary system (120 mg/L Na^+). The Na^+ concentrations at the outlet of the NF were stable, around 50 mg/L, reaching removal efficiencies between 75 and 80%.
Figure 41 displays the electrical conductivity (µS/cm) (considered as salt concentration) at the NF inlet and outlet throughout 2021. The system exhibited a stable conductivity elimination efficiency (between 70 and 80%).

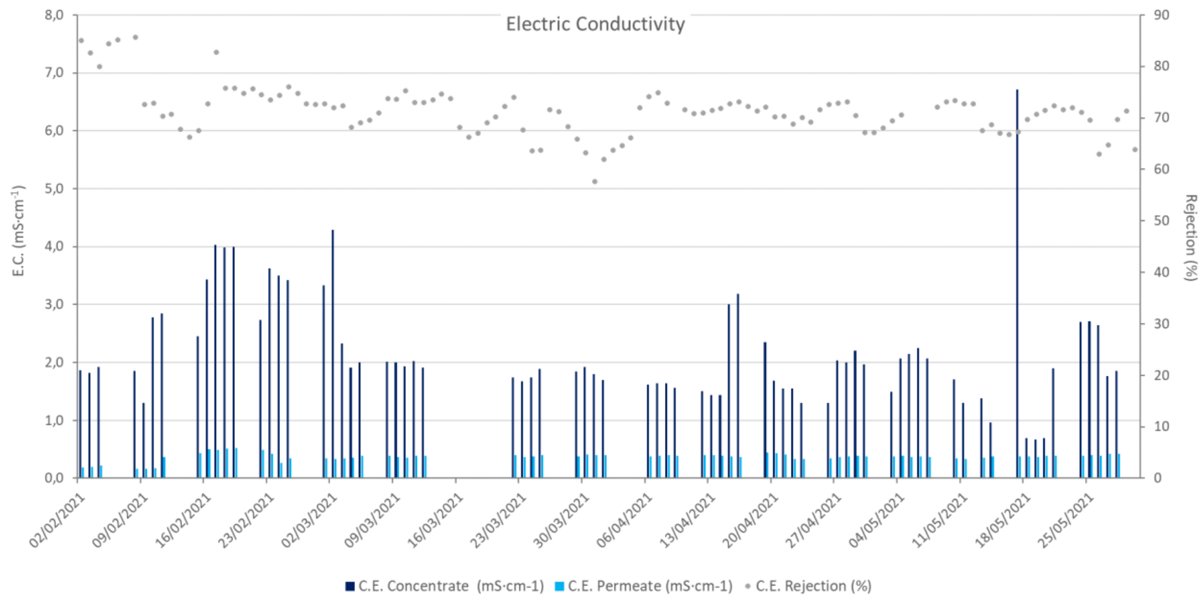

Figure 41. Electrical conductivity of the concentrate and permeate and the % rejection.

- **Endocrine disruptors**

Twenty-one endocrine disruptors present in the sand filter effluent and the NF permeate were been analysed, including progesterone, testosterone, bisphenol A and estrones E1, E2 and E3.

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The analyses were performed every 4 months (March, July, and November 2021). The results obtained in March are presented in this section (See Figure 42), whereas the results from July and November are provided in Annex 1.A.2 Nanofiltration efficiency: Endocrine disruptors.

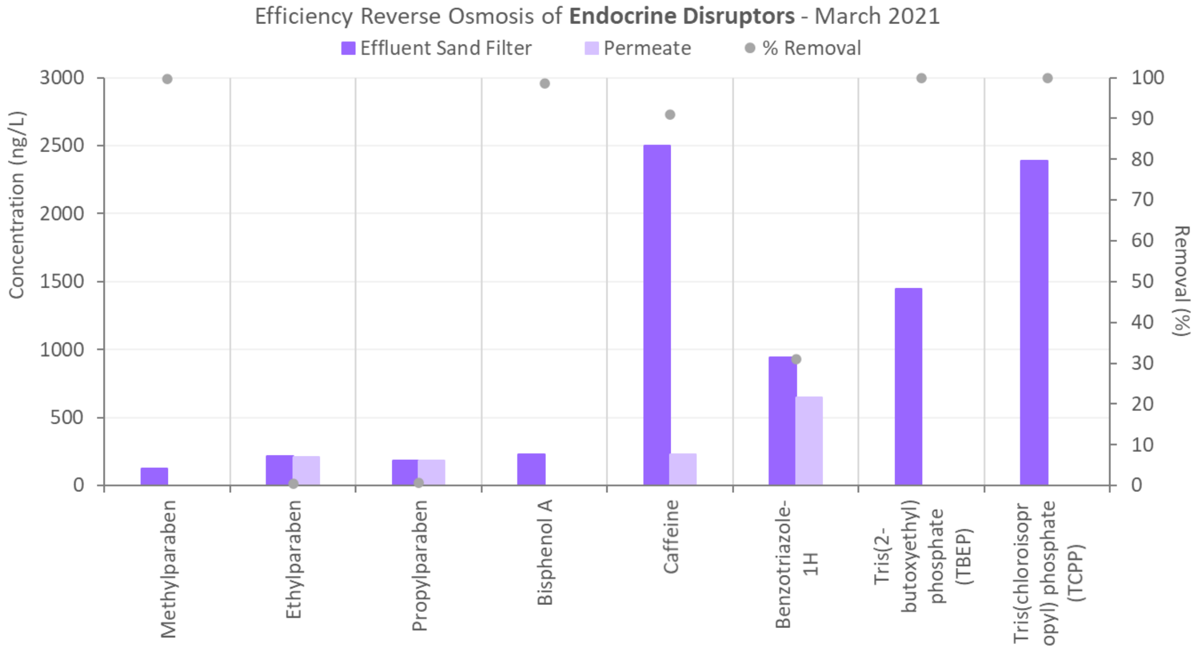

Figure 42. Endocrine disruptors detected at the outlet of the sand filter and their removal efficiency in March 2021.

All analyses always detected six endocrine disruptors (methylparaben, ethylparaben, propylparaben, caffeine and tris 2-butoxyethyl phosphate (TBEP)). Benzotriazole and tris-chloroisopropyl phosphate (TCPP) were occasionally detected.

In July 2021, the compounds with the highest concentrations were Caffeine (2500 ng/L), Benzotriazole (942.2 ng/L), and TBEP (1447.0 ng/L) and TCPP (2387.1 ng/L).

There is no clear relationship between seasonality and the endocrine disruptors detected. For instance, caffeine displayed high concentrations in both March and July but not November.

TCCP registered high concentrations in March, July, and November (2000 – 3000 ng/L). In all analyses, the NextGen system exhibited a removal capacity of approximately 100% (the concentration at the outlet was below the Limit of Detection – LOD).

Some endocrine disruptors, such as ethylparaben or propylparaben, exhibited concentrations between 30 and 180 ng/L, with only a slight removal efficiency (0.5 – 10%).

- **Pharmaceutical compounds**

Eighty-one pharmaceutical compounds were analysed at the sand filter effluent to observe the NF performance of the NextGen system in March, July, and November. Results from March are presented in this section (See Figure 43), whereas results from July and November are given in Annex 1.A.3 Nanofiltration efficiency: Pharmaceutical compounds.

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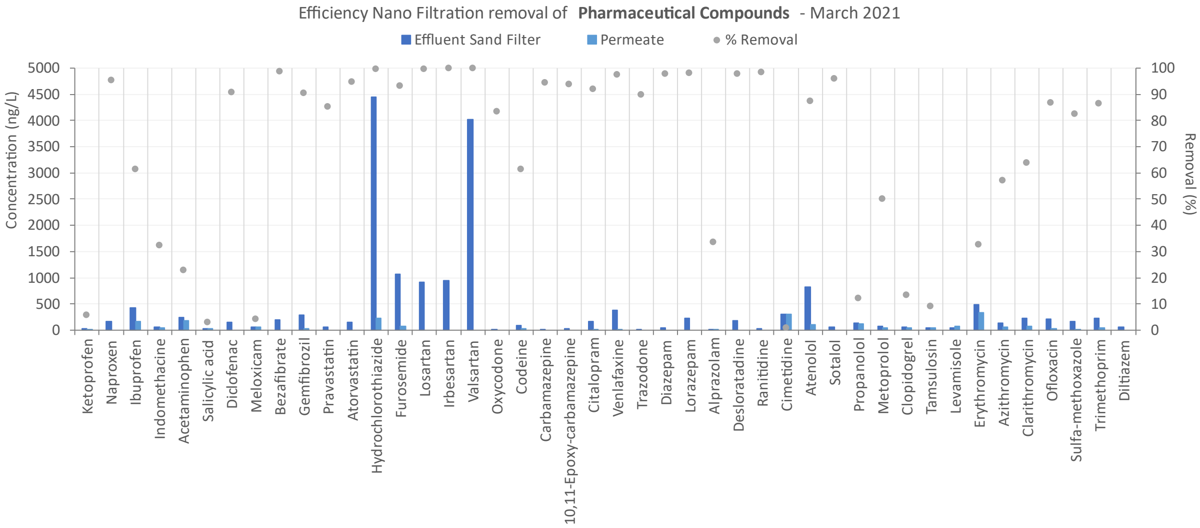

Figure 43. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the pharmaceutical compounds detected in March 2021.

High concentrations of Venlafaxine (4678 ng/L), Hydrochlorothiazide (4451 ng/L) and Valsartan (4019 ng/L) were detected at the sand filter effluent. After the NF, high removal was registered (90 – 95 %). For other compounds such as Erythromycin (495 ng/L), Ibuprofen (421 ng/L), Metoprolol (111 ng/L) or Codeine (81 ng/L), the mentioned influent concentrations were lower, thus a lower removal (i.e., 40 to 60%) was observed.

For compounds such as Ketoprofen (717.8 ng/L), Acetylsalicylic Acid (86 ng/L), Propranolol (139 ng/L) or Meloxicam (59.2 ng/L), the removal was low (around 10%), which could be related to the LOD of some compounds. For instance, Ketoprofen has a LOD of 21.3 ng/L. If the output value registered after NF is close to the LOD, it could interfere, giving lower efficiency values than expected.

Something similar happened with Acetylsalicylic Acid, which has a LOD of 1.2 ng/L. For high concentrations in the NF influent, removal of 85% was observed in July 2021. On the other hand, a low removal (less than 10%) was observed for concentrations close to the LOD (November 2021).

- **New pharmaceuticals**

In 2021, twelve new pharmaceuticals were added to the analysis. The most frequent detected compounds are Oxypurinol, Gabapentin, Valsartan Acid, and Tramadol (See Figure 44). A high removal efficiency was observed for most of the compounds detected in the NextGen influent (95 – 100%). Results from November are presented in this section, whereas results from March and July are depicted in Annex 1.A.4 Nanofiltration efficiency: New pharmaceuticals.

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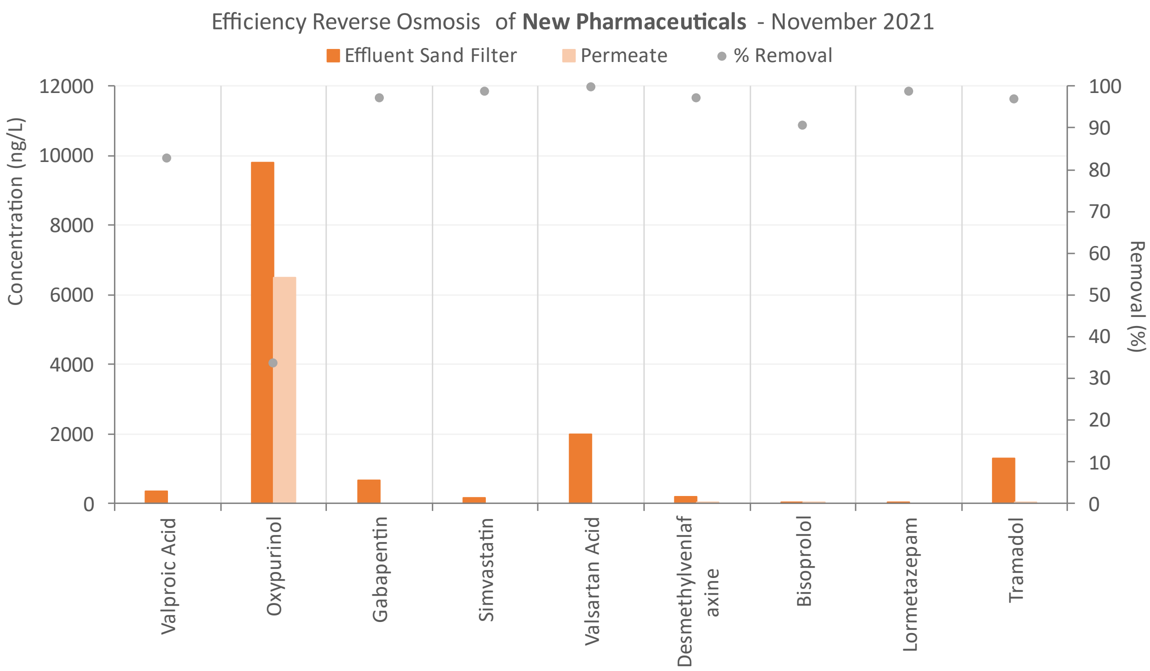

Figure 44. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the new pharmaceuticals detected in November 2021.

Compounds such as Bisoprolol and Lormetazepam had low concentrations (from 20 to 40 ng/L), close to their LOD.

The highest concentrations found were Oxypurinol (3000 to 10000 ng/L), Gabapentin (1000 to 2000 ng/L) and Valsartan Acid (500 to 4500 ng/L). Oxypurinol exhibited a high removal range (from 35 to 80%). The Oxypurinol molecule can easily pass through the regenerated membrane structure, therefore the removal could be related either to the depletion of the membrane or the creation of preferential pathways. On the other hand, Gabapentin and Valsartan Acid registered better removal efficiencies (85 – 95%).

Proper maintenance and periodic cleaning of the membranes unquestionably improve this complex compound removal (recorded removal values around 80% in March 2021).

- **Pesticides and herbicides**

The NextGen project analysed eighty-one herbicides and pesticides (results from March are presented in this section, whereas the July and November figures are depicted in Annex 1.A.5 Nanofiltration efficiency: Pesticides and herbicides). The compounds detected with higher concentrations were AMPA (3290 ng/L), Diuron (2056 ng/L), Imidacloprid (1146.1 ng/L), Tert-butyl (1058 ng/L), Thiamethoxam (405.8 ng/L), 2,4-D (384 ng/L), MCPA (260 ng/L), Glyphosate (200.0 ng/L), and Mecoprop (70 ng/L).

Although the concentrations in some cases were elevated, the removal efficiency of the NextGen system is high (90 – 95%). Figure 45 shows Diuron is the herbicide with the highest concentration in the sand filter effluent. NextGen's NF system removes 95% of diuron in the outlet. The same is true occurs for AMPA or 2,4-D, NF is effective ateliminating those compounds (98%). The removal of pesticides is crucial, given their toxic nature. Diuron, for instance, is applied to control invasive plants, is considered harmful to humans and is persistent in soil.

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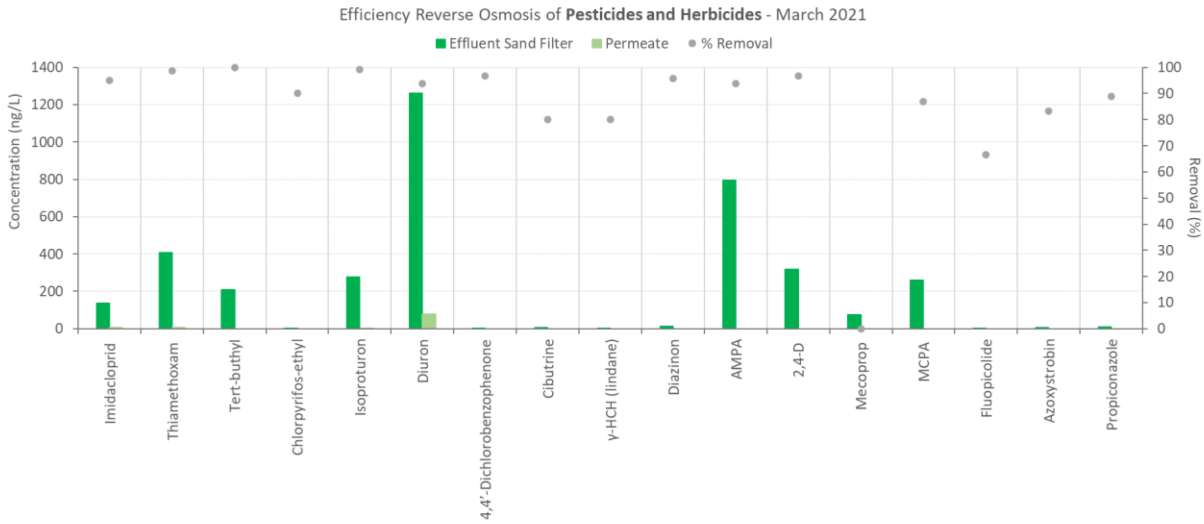

Figure 45. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the pesticides and herbicides detected in March 2021.

Chlorpyrifos was detected in all samples. It is a powerful insecticide, usage of which was limited in 2015 and finally banned in 2020. The danger of this pesticide is related to its significant persistence in river and sea environments, which not only preventthe insect fauna proliferation but also affects other families of biota, such as crustaceans and fishes.

- **Household products**

Four household products were detected in 2021: Sucralose, Acesulfame, Paraxanthine and N, N-diethyl-meta-toluamide (DEET). Sucralose and Acesulfame are two synthetic calorie-free sugar substitutes (artificial sweeteners). Paraxanthine is a major metabolite of caffeine in humans. Shortly after ingestion, caffeine is metabolized into Paraxanthine. These three compounds were observed in all analyses performed in 2021 (July results are presented in this section, March and November figures are depicted in Annex 1.A.6 Nanofiltration efficiency: Household products). The last compound (DEET) was only detected in the summer (July 2021), as DEET is widely used in household mosquito repellent (See Figure 46).

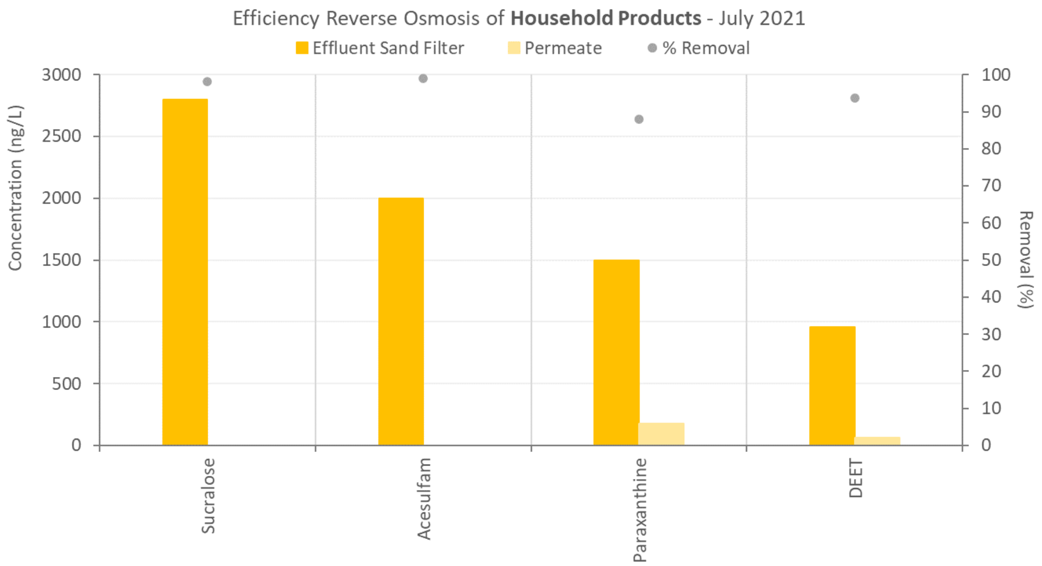

Figure 46. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the household products detected in July 2021.

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The compound with the highest concentrations is Sucralose (up to 7200 ng/L at the sand filter effluent) (See Figure 46 and Annex 1.A.6 Nanofiltration efficiency: Household products). In all cases, the NF removal capacity for this compound was 99%. For Acesulfame and Paraxanthine, the results were similar. Although the concentrations of those compounds after the sand filter were low, the removal capacity of the NextGen system was very high, reaching 99% for Acesulfame and DEET in July and November 2021.

- **Benzotriazole compounds**

Three Benzotriazole compounds were analysed: 5-Chloro-1H-Benzotriazole (CIBTR), 4-Methyl-1H-Benzotriazole (4-TTR) + 1H-Benzotriazole (5-TTR), and 5-6-Dimethyl-1H-Benzotriazole (XTR). 4-TTR + 5-TTR was found at the highest concentrations in all cases. Figure 47 shows the sand filter effluent concentrations recorded during July 2021 (1200 ng/L). The NextGen system did not demonstrate a high removal capacity of this compound (removal efficiency between 10 and 30%) (See also Annex 1.A.7 Nanofiltration efficiency: Benzotriazole compounds).

CIBTR and XTR were present at low concentrations after the sand filter (6 to 9 ng/L and 13 to 74 ng/L, respectively). The removal efficiency of the NextGen system is 35 and 80%, respectively. However, we cannot wholly assume these values are correct because they are close to the LOD and therefore possibly related to analytical errors.

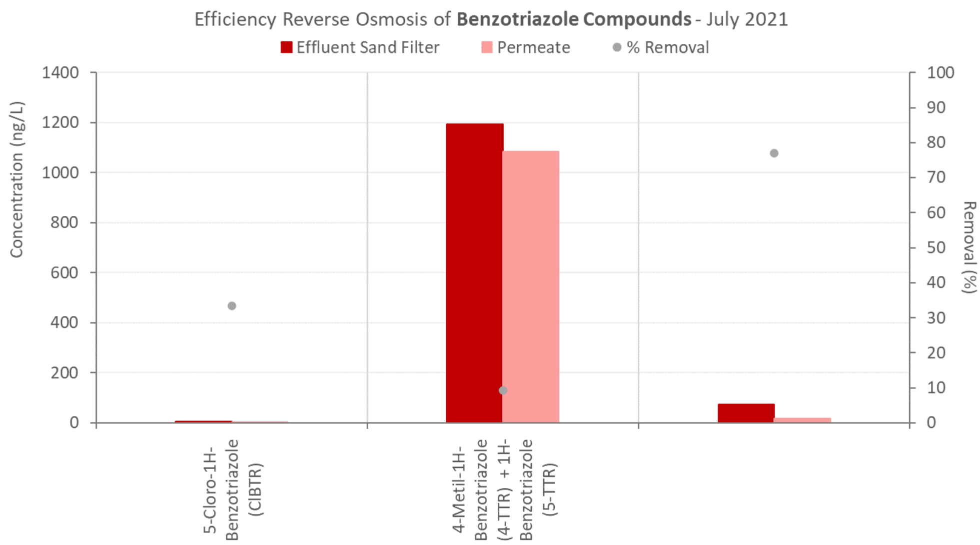

Figure 47. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the benzotriazole compounds detected in July 2021.

3.4.8. Comparison of baseline situation and NextGen KPIs

At the Tossa de Mar WWTP, tertiary treatment is currently in operation. This tertiary treatment consists of flocculation/coagulation, pre-chlorination, sand filtration and disinfection process with UV lamps and chlorination. The treated water, which meets the limits of RD1620/2007 for public use, is distributed for agricultural irrigation and environmental and non-potable water uses (i.e. public irrigation). As presented in previous sections, the objective of the NextGen pilot plant was to improve the water quality in the effluent using a membrane system to meet the limits of RD1620/2007 for private uses, which

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are more restrictive than the limits for public purposes. In this section, the baseline scenario is considered, as the water quality at the outlet of the sand filter of the current tertiary treatment at the Tossa de Mar WWTP and the outlet of the membrane-based treatment as the NextGen system.

The plant installed on the Costa Brava demo site within the framework of the NextGen project gave excellent results. It has been proven to remove contaminants of high toxicity, both for the environment and for human health. The increase in water quality during the application of the NF system was noticeable, since all the water quality values at the outlet improved. General KPIs obtained during the NextGen project are presented at Table 47. It is possible to observe that the water quality at the outlet of the NextGen pilot plant is improved and meets the RD1620/2007 for private uses in terms of turbidity, TSS, E. coli and intestinal nematodes (See also Table 47 for further details on the baseline and NextGen systems outlets).Compared to the current tertiary treatment, the NextGen pilot plant was also able to remove about 80% of the emerging compounds (EC). Although their removal is currently not a legislative requirement, the published surface water Watchlist (WL) under the Water Framework Directive (WFD) presents the toxicity levels. Comparing the obtained results with the Watchlist toxicity levels, the effluent concentrations of the monitored EC are below the mentioned levels (see detailed information in previous sections).

Table 47. General KPIs for baseline scenario and NextGen system for the Costa Brava case study.

Topic	Objectives	Specific Key Performance Indicator (KPI)	Current value	NextGen values
Wastewater treatment and reuse	To increase the production of reclaimed water for private garden irrigation	Water yield of the system [% of reclaimed water produced for private garden irrigation]	0 %	70-80%
	To reduce the salinity of the effluent	Salt rejection yield [% salt removal vs inlet flow]	0 %	75%
	To reduce the content of trace organic compounds (TrOCs) of the reclaimed water	Global removal yield for several priority/emergent pollutants [%]	0 %	80 %
	To reduce the TSS and turbidity of the effluent	TSS and turbidity removal yield vs inlet flow to the system [%]	40 %	> 95 %
	To reduce the pathogen content of the effluent	*[E. coli]* final effluent [CFU/100mL]	1	0
		[Intestinal nematodes] final effluent [egg/10L]	1	≤ 1
		[Legionella spp.] final effluent [CFU/100mL]	< 100	< 100
Energy	To reduce electricity consumption of the NextGen UF & NF processes compared with conventional NF membranes (current value)	Electricity consumption [kWh/m^3 reclaimed water]	2 kWh/m^3 (Garcia-Ivars et al., 2017)	0.9 – 1 kWh/m^3
Materials	Evaluation of the viability of the RO recycled membranes compared to	Flux [l m^{-2} h^{-1}] related to transmembrane pressure [bar]	13 lm^{2}h/bar (Garcia-Ivars et al., 2017)	13 lm^{2}h/bar

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	the commercial membranes (current value)	Salt rejection [%] compared to a commercial membrane of the same type	> 97% (NF270)	> 75%

Table 48. Monitored KPIs of the baseline scenario and at the outlet of the NextGen pilot plant at the Costa Brava case study.

	Parameters (units)	Average			Measurement frequency	Years
		All values	Summer values	Winter values		
Current tertiary treatment effluent	Flow rate (m^3/h)	1.40	1.40	1.40	Daily	2021
	COD (mg O_2 /l)	55.95	10.29	13.00	Monthly	2021
	pH (upH)	7.47	7.33	7.65		
	EC (µS/cm)	1615.64	1627.75	1573.67		
	TSS (mg/L)	8.72	9.05	7.63		
	Turbidity (NTU)	7.04	7.65	7.04		
	NH_4^+ (mg N/L)	44.60	32.00	71.00		
	NO_3^- (mg N/L)	2.59	3.35	2.75		
	NO_2^- (mg N/L)	12.40	19.78	3.00		
	Total N (mg N/L)	29.92	25.16	58.50		
	Total P (mg P/L)	8.97	10.70	4.94		
	Br^- (mg/L)	0.33	0.30	0.30		
	Cl^- (mg/L)	237.00	267.75	202.00		
	PO_4^{3-} (mg/L)	8.86	7.45	11.60		
	Ca^{2+} (mg/L)	61.20	64.75	58.00		
	Mg^{2+} (mg/L)	15.30	15.75	14.50		
	K^+ (mg/L)	39.00	65.50	21.00		
	Na^+ (mg/L)	153.20	151.00	146.00		
	E. Coli (CFU/100 mL)				Not measured	
	Legionella spp (CFU/L)					
	Intestinal nematodes (egg/10L)					
	Coliphages (ufp/mL)					
	Clostridium perfringens (ufc/100 mL)					
	Benzotriazole-H (ng/L)	755.7	621.4	763.70	Monthly	2021
	Caffeine (ng/L)	3645	2953.3	3722.5		
	AMPA (ng/L)	1889	1943.8	1801.5		
	2,4-D (ng/L)	142	111.8	155.3	Monthly	2021
	Azithromycin (ng/L)	168	79.9	277.2		
	Venlafaxine (ng/L)	332	371	270		
	Parameters (units)	**Average**			**Measurement frequency**	**Years**
		All values	**Summer values**	**Winter values**		
NEXTGEN Effluent	Flow rate (m^3/h)	1.07	1.07	1.07	Daily	2021
	COD (mg O_2 /l)	28.64	38.75	1.00	Monthly	2021
	pH (upH)	7.22	7.23	7.40		
	EC (µS/cm)	395.91	445.00	389.33		
	TSS (mg/L)	2.03	2.11	1.50		
	Turbidity (NTU)	0.33	0.33	0.30		
	NH_4^+ (mg N/L)	12.84	11.63	17.50		

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	NO_3^- (mg N/L)	1.83	2.60	1.25		
	NO_2^- (mg N/L)	5.45	8.08	1.55		
	Total N (mg N/L)	10.20	9.79	15.00		
	Total P (mg P/L)	1.90	2.59	0.15		
	Br^- (mg/L)	0.25	0.25	0.20		
	Cl^- (mg/L)	64.90	80.50	49.50		
	PO_4^{3-} (mg/L)	0.59	0.45	1.15		
	Ca^{2+} (mg/L)	2.40	3.30	1.35		
	Mg^{2+} (mg/L)	0.74	0.93	0.50		
	K^+ (mg/L)	11.03	19.58	4.90		
	Na^+ (mg/L)	44.29	48.73	37.50		
	E. Coli (CFU/100 mL)	0	0	0	Bimonthly	2021
	Legionella spp (CFU/L)	0	0	0		
	Intestinal nematodes (egg/10L)	<1	<1	<1		
	Coliphages (ufp/mL)	<1	<1	<1		
	Clostridium perfringens (ufc/100 mL)	0	0	0		
	Benzotriazole-H (ng/L)	544	420.1	636.8	Monthly	2021
	Caffeine (ng/L)	333	386.2	312.2		
	AMPA (ng/L)	78	103.0	65.0		
	2,4-D (ng/L)	19	<10	<10	Monthly	2021
	Azithromycin (ng/L)	81	<10.3	81.1		
	Venlafaxine (ng/L)	10	<1.2	9.5		

Regarding physicochemical parameters, it has been observed that NextGen effluent values were lower than the values from the baseline scenario (i.e. outlet of the sand filter). Also, for most of the components, except for ammonium, TN and phosphates, the summer concentrations were significantly higher than winter concentrations. This might be due to the tourist season which triples the population in the town.

Most of the parameter concentrations satisfying the limits not only for private uses but also for indirect potable reuse (i.e. aquifer recharge). However, ammonium concentrations at the outlet of the NextGen system are still above 10 mg/L (limit fixed by Quality 5.1 at the RD1620/2007 for aquifer recharge) which is toxic to organisms and may degrade the water quality of the aquifer (Mohd Kamal et al., 2017). In addition, ammonium under reducing conditions cannot be oxidized to nitrate and it will remain as ammonium or nitrogen gas. Therefore, in order to pursue indirect potable reuse, the secondary treatment must be improved or include a tertiary treatment step on absortion to increase nitrogen removal from the wastewater.

Surprisingly, average COD concentrations at the effluent of the NextGen system are high, especially in the summer. Until September 2021, the LOD for COD was at 50 mg/L, and the lab method had to be adapted to reach lower levels of COD, which explains the high COD concentrations.

In microbiological terms, no microorganisms were found in the NextGen effluent, and the values comply with the current legislation, i.e. RD 1620/2007. These microbiological parameters have not been monitored at the inlet of the NextGen system since the baseline treatment does not intend to remove microbiological pathogens.

Additionally, it was possible to produce the same flux of treated water (i.e. 13 LMH) with a similar recovery for commercial and regenerated RO membranes (i.e. 70-75%) at a lower transmembrane pressure (TMP). In this case, the TMP for generated RO membranes was

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between 7 and 8 bar, whereas in the preliminary tests with commercial RO membranes, the TMP was between 11 and 12 bar. Thus, it is translated to less energy consumption (i.e. between 0.9 and 1 kWh/m^3 instead of 2 kWh/m^3).
The regenerated water, meeting the legislation has been distributed to three private users to irrigate their gardens. Due to the low mineral concentrations of the reclaimed water, some mineralization was needed.

3.4.9. Lessons learned

<table>
<tr><td>Required competence</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">To operate a membrane-based treatment such the one tested in the CS, specific knowledge about the following systems is required:
- Membrane filtration process
- Membrane cleaning and maintenance
- Monitoring and control the plant
- SCADA system to operate the plant
A basic training is needed to provide the required knowledge to the operator to understand the process as well as to operate it and solve problems encountered during operation. Specific knowledge of the SCADA system is needed to start up and operate the plant on site as well as remotely.</td></tr>
<tr><td>Maintenance</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">Backwashing occur automatically when the TMP is increasing, or the flux is decreasing, as both mean the membrane is clogging. Basic chemical cleanings can also be launched manually once/twice per week. During these cleaning sequences, sodium hypochlorite and chlorohydric acid are used. These cleanings are meant to remove surface deposited material. However, it is recommended to perform a deep cleaning (CIP) every 4-6 months in order to remove more encrusted material and recover initial membrane characteristics and performance.

A daily check is performed, which can take 1-2h/day for a trained operator to do a general control during normal operating conditions. Although the CIP is performed automatically, it has to be launched manually. Thus, it requires extra time for performing and supervising the action.

Generally, no experts are required for system maintenance. However, external expertise might be needed for major issues regarding electricity, mechanics, or membrane renewal.</td></tr>
<tr><td>Technological risks</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">The main reason for the downtime periods of the membrane-based treatment has been the need for a CIP. This type of downtime was experienced 2-3 times in a year. These downtimes are due to the membrane clogging, producing unstable measurements, an</td></tr>
</table>

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increase of the TMP, and an increase of the automatic cleaning frequency. To minimize the impact of and need for an intensive cleaning, accurate monitoring of the system and performing preventative CIPs when deterioration of membrane performance is determined or after a pre-determined operation time (for example, after 120 or 150 days) is recommended.

3.4.10. Best practice guidelines for operating the technology

Important points to consider during the design and the construction of the plant:

- Installation of a prefilter to remove bigger particles and optimize the operation of UF and regenerated RO membranes (minimizing membrane clogging).
- Need for a high-pressure installation, including appropriate equipment, material, and instrumentation.
- The feed pumps must be properly dimensioned according to the flow and the pressure required by the treatment.
- A chlorination unit is required before the reclaimed water distribution to ensure the minimum free chloride concentration of 0.2 mg/L and no proliferation of microbiological pathogens.
- Water mineralization is needed before the use of the reclaimed water in order to avoid soil deterioration
- A storage tank is required to collect the reclaimed water prior to its distribution.
- The installation needs to comply with the local/state legislation regarding hygiene, security and health safety.

Important aspects to consider during the start-up of the plant:

- Although the valves are controlled automatically, checking that the valves are opened as required is necessary prior to starting-up the plant. Possible to start-up the system as a manual mode to check the operation of the units and its connections.
- Verification of chemical availability and their installation will prevent leakage during operation. Check any leakage in the system.

Crucial parameters for the optimization of the production process:

- For the UF membrane: pressure, temperature, pH, and particle size. The ranges of these parameters are presented in Table 45.
- For the regenerated end-of-life RO membrane (with a pore similar to NF): pressure, temperature, pH, turbidity and silt density index SDI are the key parameters. Also, other physicochemical parameters are suggested (See Table 46).

3.5. Decentralised membrane treatment in Gotland (SE)

Authors: Staffan Filipsson and Fredrik Hedman (ivl)

3.5.1. Description of the demo site

Storsudret on the island Gotland in the Baltic Sea (Sweden) is a region where the transition to a more sustainable water cycle is taking place. The aim is to demonstrate how the overall water availability can be increased by using a circular economy approach with use of local,

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energy efficient, small scale innovative systems. The location of the case study area (110 km^2) has been chosen carefully. The main prerequisite advantages of the location is that it is geographically very well defined (it's a peninsula), there is a well-established and active NGO (Forum Östersjön), there is a great need for fresh water, and it is very challenging hydrology with a flat landscape and tin soil layers that has a low capacity for storage of water, see Figure 48.

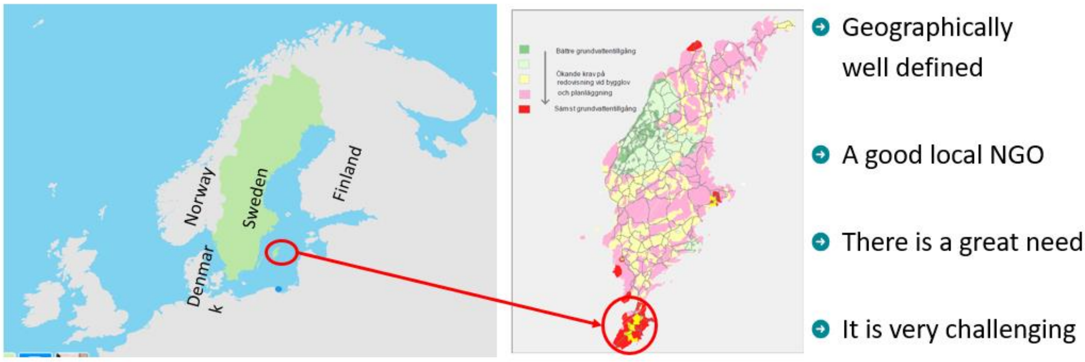

Figure 48. The location of the case study area has been chosen carefully. It is geographical very well defined, there is a well-established and active NGO, there is a great need for fresh-water, and it is a very challenging location.

To achieve sustainable water supply systems in line with the circular economy approach, innovative, alternative, local water sources have been found through the installation of different innovative systems. A unique membrane system that recovers sewage without biological pre-treatment has been installed, a large-scale water storage system based on real-time collected data has been planned in detail, and the automatic floodgate that will regulate the lake has been constructed and programmed. The floodgate is ready to be installed directly after permission from the Swedish land and environmental court has been given.

In addition to the innovative systems for water supply, calculations show the potential of expanding the test bed to a large-scale system which could contribute to Gotland's water supply with a circular economy approach.

Another important part of the case study is the involvement of stakeholders such as the organizations involved in the project, the county administrative board, and the residents of Storsudret.

The Gotland case study consists of the following main parts:

- Local support
- Establishment of water balance based on real-time and online monitoring
- Detailed planning and construction of an innovative system for rainwater harvesting and storage
- Planning, construction, installation and operation of a highly innovative system for direct reuse of sewage based on two membrane technologies
- Overall design of a pilot-scale system and full-scale system for the introduction of a sustainable water supply at Gotland

For rainwater harvesting and storage, an automatic floodgate for the regulation of a lake has been constructed and programmed for real time control based on the real-time sensors.

By use of a systematic approach, e.g by use of x-ray sensor on a helicopter, it has also been shown how groundwater reservoirs can be discovered and how those discovered reservoirs can be evaluated in more detail by a follow-up through different kinds of measurements on the ground. These ground water shall contain a certain volume of water for new construction

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areas, so that the need for extensive piping infrastructure associated with high investment costs can be minimized or avoided.

For reuse of wastewater, two innovative technologies for direct treatment of sewage which will be powered by solar energy have been set up and operated at pilot-scale.

On the basis of real-time, online measurements, it has been confirmed that even an area with very limited water storage and water supply possibilities should be able to develop into a net producer of freshwater. Based on the findings from the case study, a comprehensive basis for a conceptual design of a full-scale application of 500 000 m^3/year has been developed. The water can be used for irrigation or for drinking water supply and indicates that an area that currently has very limited possibilities for water supply could be transformed into a net producer of fresh water, producing enough for both the local area and exporting to surrounding areas.

3.5.2. Motivation for implementing circular economy solutions in the water sector

The need for alternative water supply solutions at Gotland is related to increased population, increased tourism, increased need for irrigation, and the effects of climate change, which gives longer cultivation seasons and a higher risk for droughts during summer. In addition, the lack of snowmelt during springtime provides less replenishment of groundwater. Due to the flat landscape, relatively few lakes, the tin soil and the solid lime rock underneath, the possibilities for storing water from the wet winter to the dry summer is highly limited. This is especially true for the peninsula Storsudret, which is probably the most challenging part of Sweden in terms of water supply.

The solution, so far, has been to invest in a larger desalination plant 45 kilometers north of Storsudret. The freshwater produced by the desalination plant becomes sewage after use. However, the wastewater treatment plant at Storsudret is not online, therefore the sewage is pumped 25 km north to a centralized WWTP, and then returned to the sea, where it mixes with chlorides which must be separated prior to processing in the desalination plant. If the sewage could be reused prior to being mixed with chlorides, the energy required for desalination would decrease. In addition, energy for long distance pumping could also be reduced if the sewage could be treated closer to where it is produced. Therefore, development of an energy efficient and local, direct reuse of sewage is highly attractive.

The aim of the case study Gotland at testbed Storsudret is to show how a region with low ability to store water for the long, dry summer season could be a net producer of fresh water. The testbed will demonstrate how water could be collected, stored, reused, and infiltrated to feed the municipal water supply system, and be reused in real estate and irrigation of crops and grass (Figure 49).

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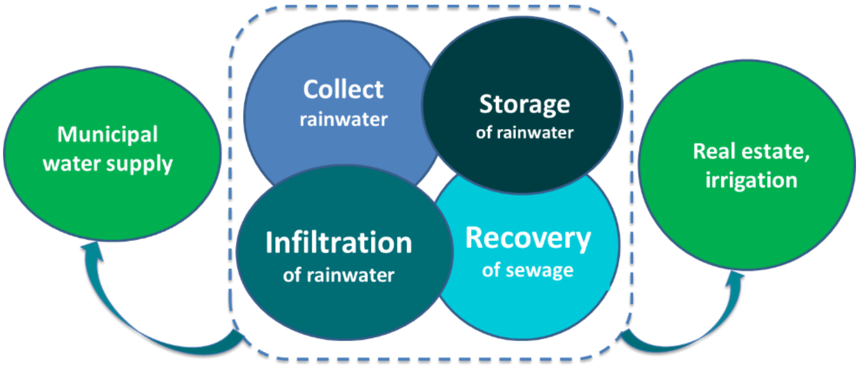

Figure 49. The aim of the Gotland case study that will demonstrate how water could be collected, stored, reused and infiltrated for feeding the municipal water supply system, real estate and farm irrigation.

3.5.3. Actions and CS objectives

Table 49. Actions and objectives of the case study in Gotland.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
# 7 Gotland Location: The peninsula Storsudret	Sub-Task 1.2.1 Demonstration of integrated management of alternative water sources	No control of water balance	Real time measurements of the water balance; precipitation, flow in ditches, surface- and groundwater levels.	8	>2 000 000 000 m3/year	The measurement have shown that the need for water supply (400 000 m3/year) could be met without import of desalinated water
		Rainwater flushing out to sea through a ditch	Innovative floodgate for storage of rainwater in a lake	8		
		Sewage pumped 45 kilometres to a conventional biological WWTP and disposed to the sea. Desalinated tap water pumped the reversed direction.	Direct membrane filtration of sewage	6	1 m3/h	Reused wastewater for technical applications or for further treatment by reverse osmosis to a drinkable quality. Concentrate remaining for conventional treatment 1/5 of origin volume.

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3.5.4. Unique selling points

- The use of a unique measurement system based on real-time sensors for precipitation, waterflow in ditches and ground- and surface water levels **has clearly demonstrated the potential for introducing a local and sustainable e water supply controlled by the same advanced measurement system.**.
- The obtained results from the unique measurement system clearly shows that **the installation of an innovative automatic floodgate will increase the natural storage of water from winter to the dry summer season.**
- **The pilot demonstration of membrane filtration of municipal sewage that is not pre-treated by a conventional WWTP** has shown that the use of a decentralised water reclamation system producing water at drinking water quality levels is a realistic way forward to the introduction of circular water supply systems.
- **The pilot demonstration of water reuse from sewage also shows an increased potential for energy and nutrient recovery from municipal wastewater.** Optimisation including all the relevant actors (government as potential resource managers and citizens as producers and receptors)

3.5.5. Principal characteristics of the technology

The overall ambition of future wastewater management is to turn today's linear wastewater treatment plants into production units for energy, fertilisers and fresh water that fits into the circular economy. The sewage will no longer be seen as waste but rather as a resource, a raw material (see Figure 50).

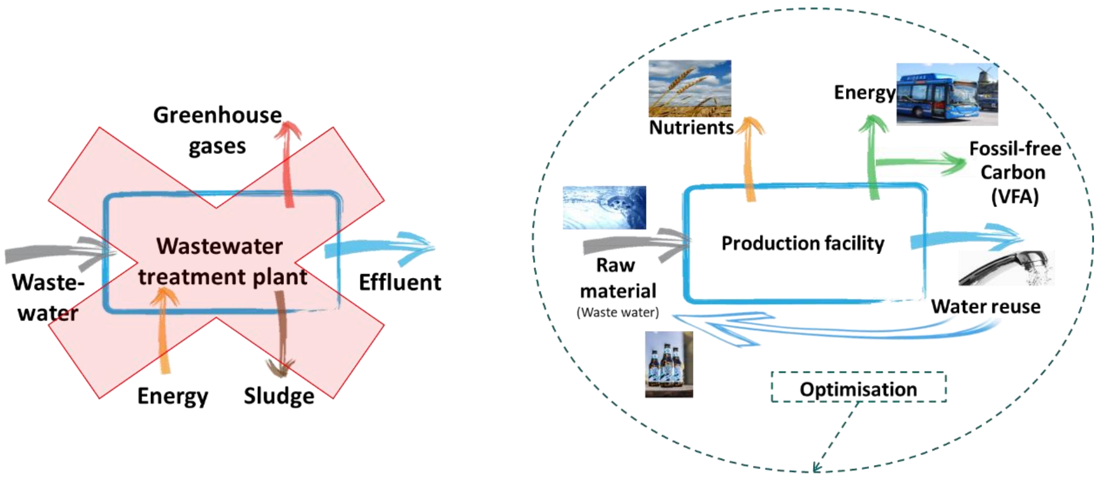

Figure 50. Today´s WWTP will be turned into production units in the circular economy that produces fossil free fertilizers, fossil free energy and fresh water.

Today, sewage from the case study area Storsudret is pumped 45 kilometers north to a conventional centralized wastewater treatment plant (WWTP). The treated wastewater is disposed in the Baltic Sea where it is mixed with chloride ions. 18 kilometers south of the WWTP a desalination plant separates the chlorides and produces a recovered water that is pumped in the opposite direction (south) back to Storsudret as drinking water. This route and

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the processes involved (pumping of sewage, wastewater treatment, mixing with seawater, desalination, pumping of drinking water (Figure 52)) is estimated to consume 10,5 kWh/m^3.
The innovative NextGen membrane system is based on direct recovery of sewage, without pre-treatment by conventional biological treatment (Figure 51). There are two main advantages of this solution (Figure 52):
1) The water can be reused locally where it is produced and where it is needed. Long distance pumping of large volumes of sewage and drinking water can be avoided.
2) Since the direct treatment of sewage has the advantage of not using conventional aerated biological step, which is converting carbon to CO2, one of the main targets for the direct membrane filtration is to increase the amount of carbon available to produce fossil free energy (biogas). The small concentrate stream that remains after separation of water has a much higher energy content, which also enables more efficient conversion and increases the possibility to recover nutrients. A more concentrated sewage can be treated by anaerobic technologies (e.g. UASB) which consumes less energy (electricity) and produces fossil free methane gas. In addition, a more concentrated sewage also increases the possibilities for recovery of fossil free fertilizers (phosphate and ammonia/nitrates).

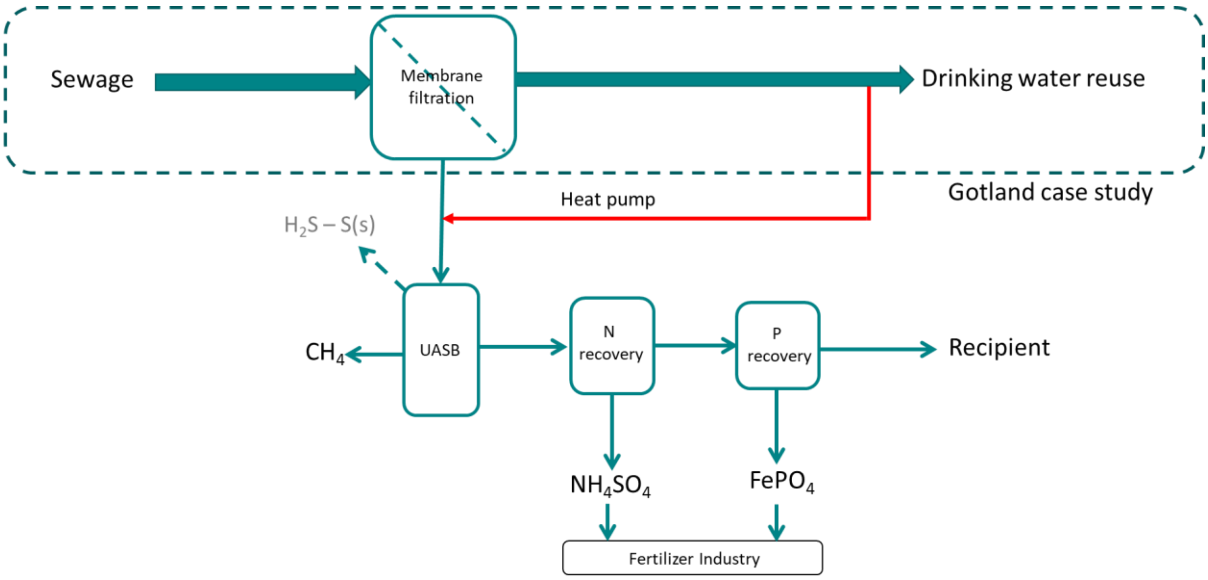

Figure 51. The principle of reuse of water from sewage, placed before conventional microbiological WWTP. The reused water is separated from the organics and salts that will remain in the concentrate at 1/5 of the original volume. The concentrate will serve as a raw material for fossil free energy (methane gas) and nutrients (fossil-free phosphate and nitrogen).

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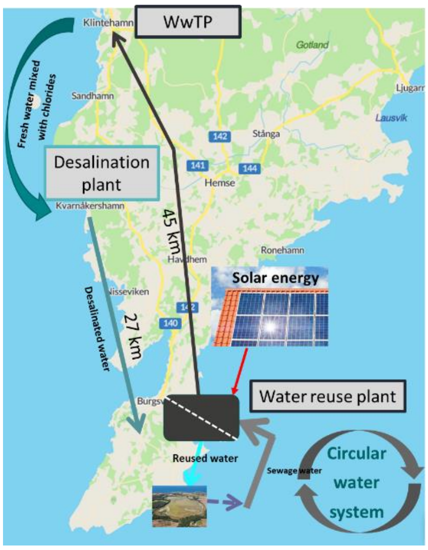

Figure 52. The concept of local water reuse by direct treatment of sewage as a complement to water supply by a centralized desalination plant.

The main challenge of direct reuse of sewage is the risk of membrane fouling. The pilot plant has therefore been designed to minimise the risk for biofouling of the ultrafiltration step and the risk for scaling of the reverse osmosis step.
The demonstration of recovery of wastewater was run at two different pilot plants. The first one was placed in Visby WWTP after conventional biological treatment for running of pre-tests. It was followed by a demonstration of water reuse at Storsudret, which studied direct membrane filtration of untreated sewage.

<u>Pilot tests in Visby</u>
The tests in Visby were performed with an ultrafiltration pilot (UF) which was rented from Björks Rostfria AB. The UF unit of type IntegraPac IP-51XP from DuPont Water Solutions was put into operation during in November 2019. The UF unit consisted of PVDF hollow fiber membranes of the "dead-end" type with a nominal pore size of 0.03 µm and a membrane surface of 51 m^2. The UF pilot was connected to outgoing water from Visby ARV as tertiary treatment step for water reuse (Figure 53). Although the pilot plant could be run in continuous operation, the UF filters clogged relatively quickly due to high particulate levels in the water. In March 2020, a drum filter (NP T1203) with a mesh size of 30 µm from NP-Innovation AB was therefore installed. With this configuration, the pilot plant has been in operation until trials were completed and the plant was shut down at the end of August 2020. The operation gathered valuable information and served as a reference for the design of the demonstration plant in Burgsvik for direct potable reuse.

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Figure 53. The pilot plant in Visby. On the left image and from left: drum-filter, ultrafiltration unit, buffer tank after UF. The right image depicts the reverse osmosis unit.

<u>Pilot tests at Storsudret for direct potable reuse</u>

The pilot plant for direct membrane filtration included modifications of the municipal wastewater treatment plant in Burgsvik at Storsudret (Figure 54). The ultrafiltration pilot consisted of a drum filter (20 µm) and ceramic ultrafiltration membranes (25 kDa). The ultrafiltration had a crossflow configuration with the possibility of back-pulsing, chemically enhanced backwashing (CEB) and cleaning in place (CIP) to maintain the flow.

Figure 54. The containers for the ultrafiltration and reverse osmosis for direct reuse of water from sewage in Burgsvik, Storsudret.

3.5.6. Technology implementation requirements

In this section only, the direct membrane filtration of sewage is presented. The groundwater and rainwater storage sections will be presented later in this report.

<u>Pilot tests in Visby</u>

The pilot plant for water recycling was initially planned to consist of a Nordic MBR pilot unit from Alfa Laval Nordic AB and an RO pilot provided by Region Gotland with a membrane from Toray (TMG20-400C).

After continuous problems with getting a stable operation in the MBR pilot, at the beginning of November 2019 it was decided to replace the MBR unit with a conventional UF unit (see previous section). Even after adapting the conventional UF, the pilot plant for recovery of wastewater after conventional biological treatment still had some initial difficulties, including particles in the feed. To mitigate this, a drum filter was installed as pre-treatment. This design was copied to the pilot for direct reuse of sewage, explained below and in Figure 55.

<u>Pilot tests in Burgsvik for direct reuse of sewage</u>

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Based on the results from those theses, a design for containers with pilot equipment was made. The equipment consisted of two membrane units (ultrafiltration and reverse osmosis) placed in two mobile containers at the now decommissioned WWTP in Burgsvik. The functions of the former WWTP is kept intact so it can provide flexible equipment for different types of pre-treatment before membrane filtration. The pumping station outside the former WWTP was adapted to provide the possibility of extracting representative wastewater for the pilot equipment. Similarly, the pumping station was adapted to receive the concentrate from the plants. The design in Visby with a drum filter as a pre-treatment step was copied at the plant at Storsudret for direct water reuse from sewage (Figure 55). The pilot was placed at the former WWTP in Burgsvik, Storsudret (Figure 56).

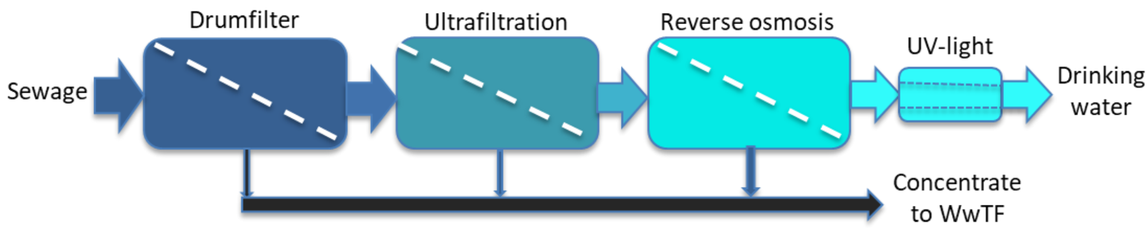

Figure 55. The setup of the membrane filtration units for both tertiary treatment of wastewater as well as for the direct reuse of sewage. For both plants, a drum filter was necessary as pre-treatment for removal of larger particles.

The initial main challenge for the pilot plant for direct water reuse was the supply of sewage from the pumping station, which caused several stops in pilot operation due to loss of water supply. The pumping station was modified to mitigate sedimentation, by filling it with concrete until the level of the connecting pipe to the new pumping station, after which a screen was mounted around the pump to reduce downtime caused by clogging of rags. The screen was rinsed once a week. A new pump and control system and piping was installed to fit the pilot plant.

Inside the WWTP, the existing screen for removal of larger debris was kept, after which the sewage was redirected from the MBBR directly to the sedimentation basin for removal of sludge. In the sedimentation tank the feed pump of the pilot plant was installed. The installation of the inlet pump in the sedimentation tank to some extent reduced the pre-sedimentation of sludge, but also offered a way to overcome some practical issues.

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Figure 56. The former WWTP Burgsvik, now serving as the pilot center in the case study.

3.5.7. Results obtained

Analysis of samples from the pilot tests in Visby

Apart from the initial difficulties with the MBR equipment and some adjustment of the UF plant design, the tests showed fairly low, but acceptable, capacity for the RO-pilot plant. During treatment of municipal wastewater, the risk for biofouling and scaling is always present. As seen from Table 50 the decrease of treatment capacity is approx. 50 % during the first 4 months, but quite stable in the last 5 months (from April until August).

The results of RO-permeate analysis are given in Table 51.

Table 50. The capacity of the RO-equipment during the test period from November 2019 to August 2020.

	Last day in	Recovery rate	Flux	Permeate flowrate
Year	month:	%	lmh	m^3/h
2019	November	93%	41	12
	December	89%	36	10
2020	January	84%	36	9.4
	February	67%	24	4.9
	March	80%	29	7.1
	April	78%	18	4.3
	May	72%	16	3.6
	June	65%	22	4.3
	July	67%	20	4
	August	68%	18	3.7

Table 51. The results of analysis of RO-permeate shows good results.

Parameter		Results for RO permeate (min/avarege/ max)	Limit for drinking water (SLVFS 2001:30)

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Microbiology			
Slow growing bacteria (Clostridium perfringens)	cfu/ml	39/199/1200	<5000
Coliform bacteria 35°C	number/100 ml	<1	<10
E. Coli (number/100ml)	number/100 ml	<1	<1
Odour at 20°C	-	No	No
Turbidity	FNU	0,1/0,13/0,18	0,5
Colour	mgPt/l	<5	15
Conductivity	mS/m	2,1/2,7/5,1	250
pH		7,5 - 9	
Nitrite NO2	mg/l	0,01/0,06/0,3	0,1
CODMn	mg/l	0,24/0,31/0,55	4
Ammonium	mg/l	0,014/0,075/0,24	0,5
Nitrate	mg/l	0,84/2,24/9,3	20
Fluoride	mg/l	<0,2	1,5
Chloride	mg/l	0,56/1,2/5	-/100
Sulphate	mg/l	1,7	-/100
PFAS 11	ng/l	0,78	90#
Benz(a)pyrene	µg/l	<0,01	0,01
Ca	mg/l	0,05/0,08/0.3	-/100
Fe	mg/l	0,001/0,002/0,003	-/0,1
Mg	mg/l	<0,1	-/30
Na	mg/l	2,2/3,5/11	-/100
Al	mg/l	0,001/0,001/0,002	-/0,1
As	mg/l	<0,00002	0,001
Cd	mg/l	<0,000004	0,005
Cr	mg/l	<0,00005	0,05
Mn	mg/l	0,00005/0,0001/0,0004	-/0,05
Sb	mg/l	<0,00002	0,005
B	mg/l	0,04/0,07/0,11	1
Se	mg/l	<0,005	0,01
Cu	mg/l	<0,00005	0,002
Pb	mg/l	<0,00001	0,01
Ni	mg/l	<0,0005/0,001/0,004	0,02
1,4-Dioxane	µg/l	<2	-
Pharmaceuticals	ng/l	<detection limit	-

, # Only recommended limits

Analysis of samples from the pilot tests in Burgsvikfor reuse of water from sewage

The direct membrane filtration of sewage for reclaimed water consists of two main steps: ultrafiltration (UF) followed by reverse osmosis (RO). Each technology was placed in a separate container at the demonstration site at the former WWTP in Burgsvik, Storsudret.

Ultrafiltration

From the initial tests with UF as tertiary treatment after the MBBR in the Visby WWTP, it was shown that the baseline scenario (only secondary treatment by MBBR and chemical precipitation) does not provide water fit for reuse applications. Results from the 8 months operation with UF after the conventional activated sludge biological treatment showed high

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initial recovery but gradually reduced from 93% to 65-68% due to the need for frequent backwashing and CIP procedures. Finally, the use of UF for direct treatment of sewage operated around 88% recovery, without any clear tendency to decline (Table 52).

Table 52. Comparison of recovery between baseline, UF after conventional biological treatment (CAS) in Visby, and direct membrane filtration of sewage in Burgsvik.

	Baseline	UF after CAS	Direct membrane filtration
Recovery, %	0	65-93	88

The results clearly show that the UF unit serves as an important pre-treatment step prior to RO by efficiently removing particles and larger molecules. As expected, ions and smaller molecules pass the UF membrane. Table 53 shows the result of the analysis before and after UF treatment. The results are in line with the expectations.

Table 53. Treatment of sewage, before and after direct UF filtration of sewage.

ELEMENT	SAMPLE	Before UF	After UF (permeate)	Reduction
Sampling Date		2022-04-21	2022-04-21	**(%)**
dissolved silicate as SiO2	mg/L	6.95	8.27	-19%
Dissolved silicate as SiO3	mg/L	8.8	10.5	-19%
Dissolved silicate as H2SiO3	mg/L	9.03	10.7	-18%
Al, aluminium	µg/L	43.7	<10	77%
As, arsenic	µg/L	1.61	1.74	-8%
Ba, barium	µg/L	21.2	19.4	8%
Ca, calcium	mg/L	90.4	90.1	0%
Cd, cadmium	µg/L	<0.05	<0.05	
Co, cobalt	µg/L	0.397	0.305	23%
Cr, chromium	µg/L	<0.9	<0.9	
Cu, copper	µg/L	11.7	4.42	62%
Fairy, iron	mg/L	0.281	0.0912	68%
Hg, mercury	µg/L	<0.02	<0.02	
K, potassium	mg/L	12.7	12.4	2%
Mg, magnesium	mg/L	14.5	14.5	0%
Mn, manganese	µg/L	27.3	25.6	6%
Mo, molybdenum	µg/L	1.59	1.41	11%
Na, sodium	mg/L	34.8	34.8	0%
Ni, nickels	µg/L	3.24	3.92	-21%
Pb, lead	µg/L	<0.5	<0.5	
V, vanadium	µg/L	0.389	0.41	-5%
Zn, zinc	µg/L	21.9	15.1	31%
P, phosphorus	µg/L	1260	929	26%
Sr, strontium	µg/L	334	332	1%
Cl, Chloride	mg/L		67.3	
COD-Cr	mg/L	64.7	36.9	43%
ammonia and ammonium as NH4	mg/L	15.4	13.1	15%
ammonia + ammonium nitrogen	mg/L	12	10.2	15%
total nitrogen	mg/L			

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Sulphate, SO4	mg/L	61.9	44.4	28%
total nitrogen	mg/L	11.4	12.5	-10%
TOC	mg/L	22.7	13.6	40%

Reverse osmosis

In order to produce a reused water with drinking water quality, the permeate from treatment by was further treated over reverse osmosis (RO). One example of the analysis of samples before and after treatment by UF is shown in Table 54.

Table 54. The chemical analysis of samples taken after UF (before RO) and after RO treatment.

ELEMENT	SAMPLE	After UF	After RO
Sampling Date		2022-04-21	2022-04-21
dissolved silicate as SiO2	mg/L	8.27	
Dissolved silicate as SiO3	mg/L	10.5	
Dissolved silicate as H2SiO3	mg/L	10.7	
Al, aluminium	µg/L	<10	<10
As, arsenic	µg/L	1.74	<0.5
Ba, barium	µg/L	19.4	<1
Ca, calcium	mg/L	90.1	<0.2
Cd, cadmium	µg/L	<0.05	<0.05
Co, cobalt	µg/L	0.305	<0.2
Cr, chromium	µg/L	<0.9	<0.9
Cu, copper	µg/L	4.42	<1
Fairy, iron	mg/L	0.0912	<0.01
Hg, mercury	µg/L	<0.02	<0.02
K, potassium	mg/L	12.4	<0.4
Mg, magnesium	mg/L	14.5	<0.2
Mn, the manga	µg/L	25.6	<0.9
Mo, molybdenum	µg/L	1.41	<0.5
Well, sodium	mg/L	34.8	1.15
You, nickels	µg/L	3.92	<0.6
Pb, lead	µg/L	<0.5	<0.5
V, vanadium	µg/L	0.41	<0.2
Zn, zinc	µg/L	15.1	<4
P, phosphorus	µg/L	929	<10
Sr, strontium	µg/L	332	
chloride	mg/L	67.3	
COD-Cr	mg/L	36.9	
ammonia and ammonium as NH4	mg/L	13.1	0.437
ammonia + ammonium nitrogen	mg/L	10.2	0.339
total nitrogen	mg/L		0.36
sulfate, SO4	mg/L	44.4	
total nitrogen	mg/L	12.5	
TOC	mg/L	13.6	<0.50
Ratio COD/TOC		2.713235	

Performance of the system (the combination of UF and RO)

Table 55 shows the overall performance of the sewage reuse system (UF+RO). The results are highly satisfying, especially for ammonia, which due to its small size is difficult to separate from water. The limit for ammonia in Swedish drinking water is 0,5 mg/l and the concentration

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in the RO permeate is 0,44 mg/l. All other parameters are also below the Swedish limits for drinking water.

Table 55. Overall performance of the sewage reuse system (UF+RO).

ELEMENT	SAMPLE	After UF	After RO	Redution
Sampling Date		2022-04-21	2022-04-21	(%)
Dissolved silicate as SiO2	mg/L	6.95		-
Dissolved silicate as SiO3	mg/L	8.8		-
Dissolved silicate as H2SiO3	mg/L	9.03		-
Al, aluminium	µg/L	43.7	<10	>77
As, arsenic	µg/L	1.61	<0.5	>69
Ba, barium	µg/L	21.2	<1	>95
Ca, calcium	mg/L	90.4	<0.2	>99
Cd, cadmium	µg/L	<0.05	<0.05	-
Co, cobalt	µg/L	0.397	<0.2	>50
Cr, chromium	µg/L	<0.9	<0.9	-
Cu, copper	µg/L	11.7	<1	>91
Fairy, iron	mg/L	0.281	<0.01	>96
Hg, mercury	µg/L	<0.02	<0.02	-
K, potassium	mg/L	12.7	<0.4	>97
Mg, magnesium	mg/L	14.5	<0.2	>99
Mn, mangan	µg/L	27.3	<0.9	>97
Mo, molybdenum	µg/L	1.59	<0.5	>69
Na, sodium	mg/L	34.8	1.15	>97
Ni, nickel	µg/L	3.24	<0.6	>81
Pb, lead	µg/L	<0.5	<0.5	-
V, vanadium	µg/L	0.389	<0.2	>49
Zn, zinc	µg/L	21.9	<4	>82
P, phosphorus	µg/L	1260	<10	>99
Sr, strontium	µg/L	334		-
Cl, Chloride	mg/L			-
COD-Cr	mg/L	64.7		-
ammonia and ammonium as NH4	mg/L	15.4	0.437	>97
ammonia + ammonium nitrogen	mg/L	12	0.339	>97
total nitrogen	mg/L		0.36	-
Sulphate, SO4	mg/L	61.9		-
Total nitrogen	mg/L	11.4		-
TOC	mg/L	22.7	<0.50	>98

Capacity of the pilots in Burgsvik for reuse of water from sewage

Ultrafiltration

As mentioned above, the main challenge for direct treatment of sewage by UF is to avoid biofouling of the membranes. Based on pre-tests, a method was set up and the results from long term capacity tests were promising. Figure 57 shows the capacity decrease after cleaning of the membranes by CIP. The initial permeate flow was 3,7 m^3/h but dropped to 2,2 m^3/h after a few hours. In the following hours the capacity drop was relatively stable until 1,9 m^3/h before a chemical enhanced backwashing (CEB) is made.

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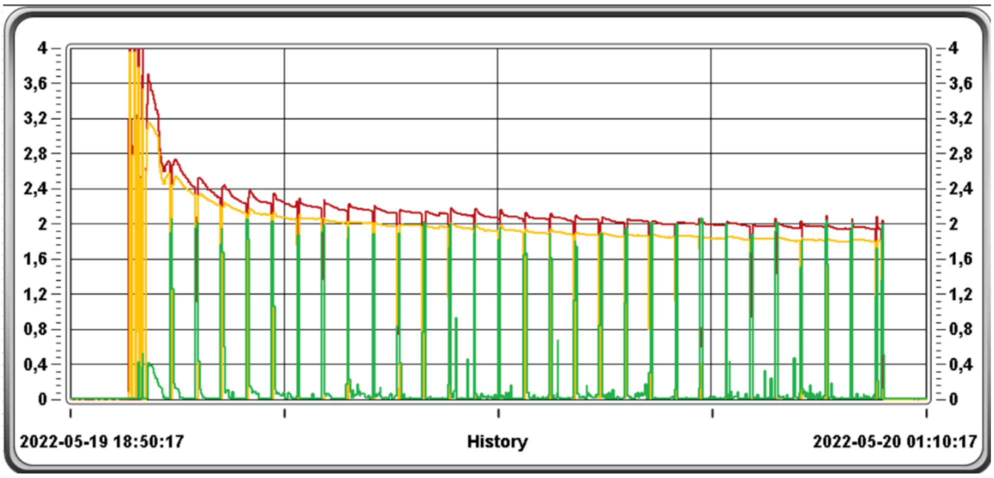

Figure 57. The capacity (flow rate m³ h-1) drop after CIP the 19:th of May..

After the CEB on 22.05.22, the initial capacity was not fully restored - the permeate flow was 2 m^3/h but dropped to 1,6 m^3/hafter approx. 6 hours. At that low flowrate, a new CEB was automatically started. In the following days the capacity drop showed a similar tendency (Figure 58). The same pattern was seen after the next CIP on the 30.05.22 (**Error! No s'ha trobat l'origen de la referència.**). The initial capacity after CIP was not met, and the capacity after CEB again was 2,0 m^3/h and dropped during a 6-hour period to 1,6 m^3/h until a new CEB was conducted.

The initial capacity (4 m^3/h) is recovered and drops to 1,6 m^3/h after 6 hours and a new CEB is made, Figure 58.

Due to different minor technical issues, the UF did not run continuously but operated in total for more than 1500 hours. At the end of August, the capacity is still the same as in May, which is highly promising for the concept (Figure 59).

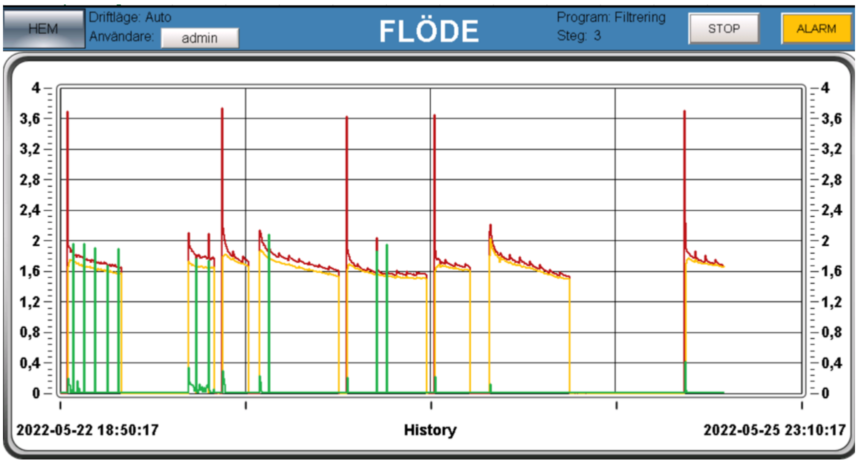

Figure 58. The flow rate (m3/h) of the ultrafiltration unit before and after CEBs.

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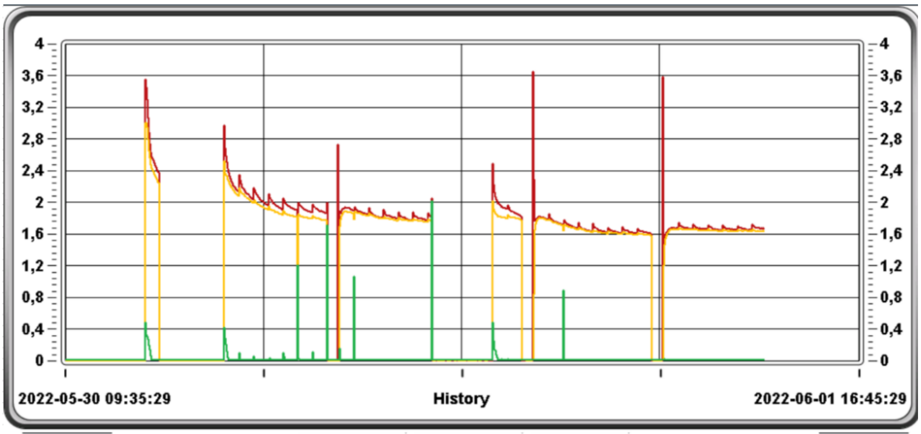

Figure 59. The flow rate (m^3/h) of the ultrafiltration unit after a CIP made the 31 May.

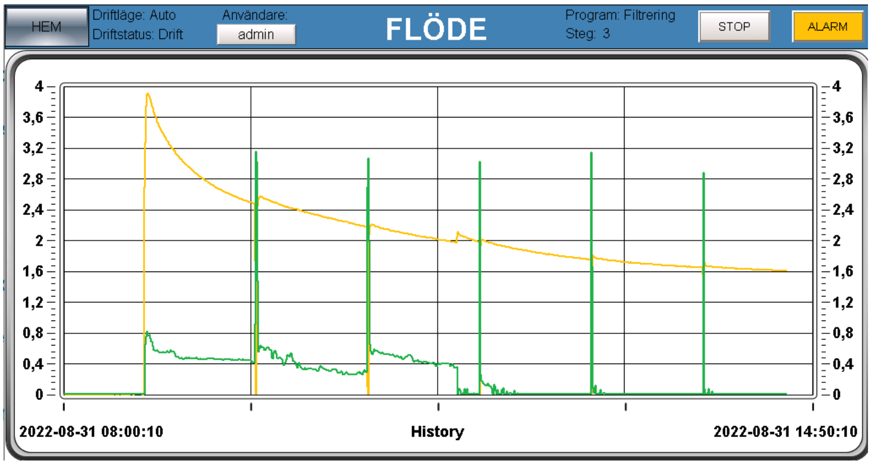

Figure 60. The flow rate (m3/h) of the ultrafiltration unit after a CIP the 31 of August. In the end of August, the capacity after CIP is still the same as in May (Figure 58).

Reverse osmosis

The capacity of the RO pilot plantin Burgsvik has been very stable. Figure 61 shows a representative capacity graph.

Figure 61. The capacity for RO treatment of UF permeate. The RO permeate flowrate is stable at 0.8 m^3/h which corresponds to a flux of 10 LMH.

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3.5.8. Comparison of baseline situation and NextGen KPIs

Without the NextGen solution for sewage treatment, no water would be reused. How much water could be recovered as a percentage of the treated flow is a key parameter for evaluating the direct potable reuse from municipal sewage. During the early pilot tests in Burgsvik, there was little impact related to a high recovery rate. This is positive since a higher recovery rate results in reuse of more wastewater for irrigation, infiltration to the groundwater water, or other uses. The tests indicate that the recovery rate for the UF RO combination could be at least 80 %. The key performance indicators (KPIs) for direct potable reuse are listed in table 8.3.1.

The higher the recovery rate, the smaller the concentrate volume. At a recovery rate of 80 % the retentate will be 20 % of the original sewage volume, which reduces energy for pumping the concentrate, improves the efficiency for biological treatment (e.g. by anaerobic USAB technology), and improves nutrient recovery efficiency. Anaerobic treatment of the concentrate is estimated to lower the energy consumption by > 50 % compared to conventional aerobic wastewater treatment. Additionally, the biogas yield should almost double. However, treatment of the membrane filtration concentrate was not part of the NextGen project and therefore no KPIs for this are given in tables 8.3.1 or 8.3.2. The KPIs for reused water quality compare the RO permeate quality with the Swedish drinking water standard.

Table 56. Specific KPIs for direct membrane filtration of sewage for water reuse.

Topic	Objectives	Specific Key Performance Indicator (KPI)	Current value	NextGen values
Direct reclamation of sewage	Direct treatment of sewage for water reuse to save energy for desalination and long-distance pumping	Water yield of the system [% of sewage volume reclaimed to a drinking water quality]	0 %	80 %
Costs	To reduce the cost for energy (electricity)	Cost for electricity related to water treatment and pumping of tap water [kWh/m^3 reclaimed water]	1,8 Euro/ m^3	<1,4 Euro/ m^3

Table 57. The KPIs for reused water quality. Analysis of RO permeate (reused sewage) compared to the Swedish drinking water standard. No analysed parameters have shown to be higher than the limits.

ELEMENT	SAMPLE	After RO	Limits for drinking water (SLVFS 2001:30)
Sampling Date		2022-04-21	

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dissolved silicate as SiO_2	mg/L		
Dissolved silicate as SiO_3	mg/L		
Dissolved silicate as H_2SiO_3	mg/L		
Al, aluminium	µg/L	<10	100
As, arsenic	µg/L	<0.5	1
Ba, barium	µg/L	<1	
Ca, calcium	mg/L	<0.2	100
Cd, cadmium	µg/L	<0.05	5
Co, cobalt	µg/L	<0.2	
Cr, chromium	µg/L	<0.9	50
Cu, copper	µg/L	<1	2
Fe, iron	mg/L	<0.01	0,1
Hg, mercury	µg/L	<0.02	
K, potassium	mg/L	<0.4	
Mg, magnesium	mg/L	<0.2	
Mn, the manga	µg/L	<0.9	50
Mo, molybdenum	µg/L	<0.5	
Na, sodium	mg/L	1.15	30
Ni, nickel	µg/L	<0.6	
Pb, lead	µg/L	<0.5	10
V, vanadium	µg/L	<0.2	
Zn, zinc	µg/L	<4	
P, phosphorus	µg/L	<10	
Sr, strontium	µg/L		
chloride	mg/L		
COD-Cr	mg/L		
ammonia and ammonium as NH_4	mg/L	0.437	0,5
ammonia + ammonium nitrogen	mg/L	0.339	
total nitrogen	mg/L	0.36	
sulfate, SO_4	mg/L		100
total nitrogen	mg/L		
TOC	mg/L	<0.50	

3.5.9. Lessons learned

Required competence	LOW  HIGH

- Further learning and optimisation and expert competence is required to run the plant.
- After optimisation, ordinary WWTP operators should be about to perform maintenance of the plant.
-

Maintenance	LOW  HIGH

- The running of the plant is still in the optimization phase and requires maintenance one day per week.
- Some weekly follow-up and maintenance by remote control will also be necessary after the optimization phase.

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- Many practical initial challenges have been overcome and the plant is currently running more continuously and smoothly, which indicates that it will be possible to run it without weekly maintenance. After optimization, the maintenance should be able to be run by the operating personal at the ordinary WWTP´s and every second week.

Technological risks	LOW ▲ HIGH

- The most frequent reasons for downtimes are related to break down of pumps and sensors that are not yet optimized. Currently in the optimization phase, the downtimes occur almost weekly.
- The duration of downtime varies, most often the duration is less than one day but sometimes there is a need for servicing the plant which normally occurs once a week. The service and restart are always made by own personnel (Region Gotland or IVL)
- During the current optimization phase, several measures have been made but still some remains and some new are discovered. All measures made aims to reduce the risk for downtimes and reduce the need for service and maintenance. There is an action list established that are followed up every second week and the list become shorter each month.
- Many practical initial challenges have been overcome and the plant is now running more continues and smooth which indicates that the downtimes in the near future will occur quite seldom.

3.5.10. Best practice guidelines for operating the technology

To design a membrane filtration system of non-pre-treated sewage, extensive pre-testing must be performed. The membrane filtration was studied in three master theses, and a pre-pilot equipment was developed and investigated in several repeated tests. Additionally, comprehensive planning of the equipment must be done, especially considering the equipment should be run by remote control and with only weekly physical service on site. The extent of the planning phase cannot be overemphasized.
Special attention to be paid to alarms and automatic shutdown in case of risk for damage. During the start-up and optimization phase, changes in the programming of the control system will also be extensive. Therefore, it is important that most parameters can easily be changed by remote control.
Much attention was paid to planning the main equipment (the UF and RO containers) but the demo-case initially struggled with the provision of sewage to the containers. There were issues with the inlet pump and the pre-sedimentation zone of the former WWTP was clogged by rags in the pumps. Another example was the relatively long retention time in the pilot system compared to the former full scale WWTP. This longer retention time resulted in anaerobic zones which resulted in sulfidic gas production. To summarize, early and extensive attention also to the pre-treatment steps is advised.

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No one single parameter is most important for avoiding biofouling of the UF membranes and scaling of the RO membranes. What has been observed is that the design and the process mode seem to be successful. The use of ceramic membranes for UF allows CEB of permeate, relatively powerful CIP, and relatively large channels for the concentrate/retentate. In addition, the ceramic membranes are more hydrophilic than the conventional membranes, which reduces the risk for fouling. Regarding the process parameters, it was shown that TMP was the most important parameter for minimizing the capacity lost for the UF membranes. The impact of TMP was 29 % closely followed by VRF (volume reduction factor) with 27 % impact. The crossflow rate had an impact rate of 21 % while Back-pulsing Frequency had an impact rate of 14. Run time had the least impacting Factor with a meagre of 7%. Since the crossflow has large impact on energy consumption and runtime on the risk for fouling, the order of the parameters' importance is advantageous for the continuing development of the process.

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4. Rainwater harvesting system

4.1 Innovative floodgate for storage of rainwater at Gotland (SE)

Authors: Staffan Filipsson and Fredrik Hedman (ivl)

4.1.1. Description of the demo site

The demo site is described in chapter 3.5.1.

4.1.2. Motivation for implementing circular economy solutions in the water sector

Please see chapter 3.5.2.

4.1.3. Actions and CS objectives

Please see 3.5.3.

4.1.4. Unique selling points

- Large volumes can be stored at small energy demand (one single solar panel)
- The technology is quite simple
- Relatively low investment cost for the technology
- It is a precautionary measure

4.1.5. Principal characteristics of the technology

The aim of establishing a water balance model based on data collected from the real-time sensors is not only for research on hydrology and ground water, but also to gain competence on how to control the water balance in an area with limited ability to store water from the wet winter to the dry summer. For this purpose, real-time, online data was used to model a control of the flow in a ditch which connects a larger lake to the Baltic Sea. Through using an automatic floodgate connected to the real-time sensor system, the water level in the lake can be actively controlled (Figure 62, left) so that rainwater can be kept on land without increasing the risk for flooding (Figure 62, right).

The automatic floodgate and the sensors for controlling the level, outflow, and inflow to the lake for natural storage of rainwater were located on the northwestern part of the case study area Storsudret (Figure 63).

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Figure 62. Active, real-time control of the water balance will keep water on land without increase the risk for flooding. To the right, flooding during springtime 2018.

Figure 63. The planned position of the automatic floodgate in the ditch that connects lake Mjölhatteträsk (in northwest) and the Baltic Sea.

4.1.6. Technology implementation requirements

During a normal year, an estimated volume of 70 million cubic meters (Mm^3) of rain falls on the surface of Storsudret. Of this volume, 20 Mm^3 remains after evaporation. The large ditches, in combination with the very thin soil depths, contributes to the stressed water situation at Storsudret. Shortly after rainfall, the soils and natural reservoirs are drained, including the areas that once were wetlands and could have contributed to the storage of water.

Mjölhatteträsk, which is on Storsudret's northwestern part just south of Burgsvik, is an example of how ditching carried out during the 1950s lowered the lake to make use of previously soaked areas such as arable land and grazing. In order to test the possibility of storing water in Mjölhatteträsk, discussions with the landowners who own the majority of the land around Mjölhatteträsk resulted in the idea to raise the level in three steps. The first step would be a regulation of the lake´s level 10 cm below the highest observed level (2.0 meter above the sea, MAS). At a second stage, the automatic floodgate should regulate the level of the lake at 2,0 MAS and l, after some successful years of demonstrating the automatic control of the lake´s level, the regulation will be made at 2.1 MAS.

However, a varied outflow without the possibility of flexible regulation would, during a longer precipitation period, elevate the risk of flooding on the surrounding land. Therefore, in order to eliminate this risk, the trench was outfitted with an automatic floodgate controlled by the level in Mjölhatteträsk. If the level starts to increase above the current maximum level, the dust cover should automatically open and drain immediately. If the in-flow to the lake occurs quickly, e.g. due to heavy rainfall or heavily snow melting over a longer period, the floodgate

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should be opened more than if the inflow to the lake is slow. The modelling of the automatic flood gate shall be gradually developed to minimize draining while minimizing the risk of flooding.
This model for controlling the water level could also be linked to the weather station data on precipitation to enable a faster response. This development of the modeling could be done through artificial intelligence (AI) where the model would teach itself to work as optimally and safely as possible. This is an example of a projects which could be run after the test bed was established. Linking the model to the weather forecasts could be another way to minimize the risk of flooding by opening the flood gate and lowering the lake's level as a more powerful precipitation area approach.

The main advantages of the system for storing water by use of an automatic floodgate by regulation of lake Mjölhatteträsk, as presented in the selling points, are:

- Large volumes can be stored at small energy demand (one single solar panel)
- The technology is quite simple
- Relatively low investment cost for the technology
- It is a precautionary measure

The main disadvantages that the case study Gotland observed were the following:

- Despite the fact that the regulation of the lake will take place 10 cm below the highest observed level of the lake, a ruling by the Swedish Land and Environment Court for the permit to install the floodgate is needed
- The procedure for a permit is time consuming
- The needed inventories of birds, frogs, ancient monument fish migration in the ditch etc are costly and time consuming

The disadvantages mentioned above are unlikely to be handled by a private landowner. Therefore, there is an overall aim establishing a national precedent through the court for future similar smart regulations of natural ponds (lakes) for storage of freshwater from winter to summer.

4.1.7. Results obtained

Based on the real-time data for establishing a water balance for lake Mjölhatteträsk via an analysis of the outflow of water from Mjölhatteträsk to the Baltic Sea during the spring period, during 20 March to 20 April 2019, Mjölhatteträsk's water level dropped by about 3000 m^3/day, which corresponds to about 100,000 m^3 total (Figure 64). Since no significant precipitation added water to the lake during this period, this represents a net decrease in the lake's volume. After that, the drain continues more slowly, at about 1500 m3/day between 20 April to 20 May, which corresponds to 45,000 m^3 total. After May 20, the flow almost completely stopped. In total, about 135,000 m^3 of water could probably be stored if the outflow was stopped from the latter part of March. After evaporation losses, this should correspond to more than 100 000 m^3. Similar analysis during springtime 2020 (Figure 65) and 2021 indicated similar volumes as during 2019.
However, a halted outflow without the simple possibility of flexible regulation would, at a longer precipitation period, risk flooding the surrounding land. Therefore, in order to

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eliminate this risk, the trench was provided with an automatic floodgate controlled by the level in Mjölhatteträsk. If the level starts to increase above the current maximum level, the dust cover should be opened automatically and be drained immediately. If the inflow occurs quickly due to heavy rainfall over a longer period, the dust door should be opened more than if the run-in is slow. The modelling of the automatic flood gate should be gradually developed to simultaneously minimize draining while minimizing the risk of flooding.
This model for controlling the water level could also be linked to the weather station data on precipitation to provide a faster response (Figure 66). In a separate, future project, this development of the modeling could be done through AI, where the model teaches itself to work as optimally and safely as possible. Linking the model to weather forecasts could be another way to minimize the risk of flooding by opening the flood gate and lowering the lake's level when a more powerful rainfall is foreseen.

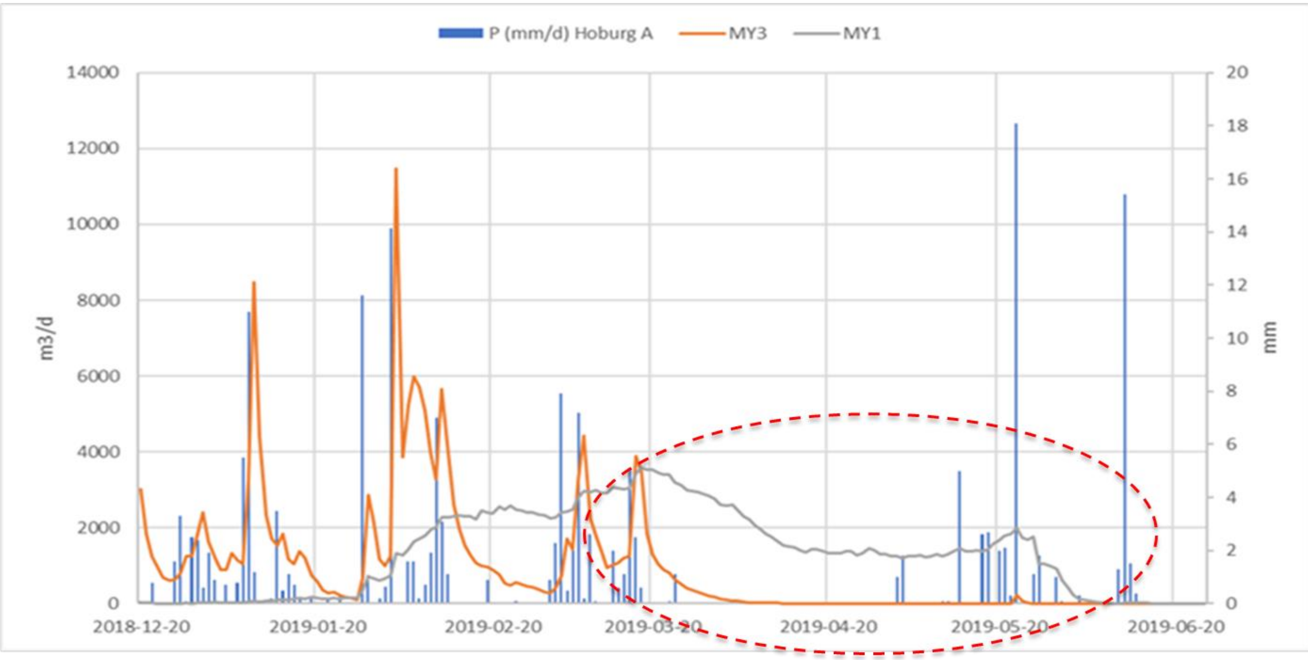

Figure 64. Draining of water from Mjölhatteträsk during the period March-June 2019. Blue bars represent precipitation, gray line is the measurement station MY1, which measures the outflow. The balance shows that if the drain was prevented, about 135,000 m3 of water (1800 m3 in average flow over 75 days) could be stored in the lake at today's maximum level. No precipitation fell during April, which is not representative of a normal year.

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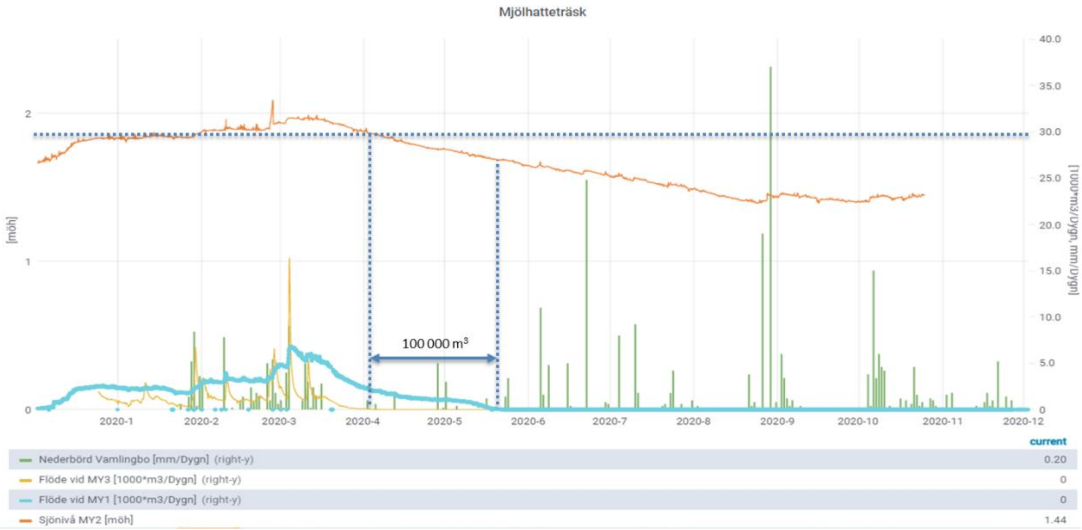

Figure 65. Draining of water from Mjölhatteträsk during the period December 2019-December 2020. Green bars represent precipitation, blue line is the measurement station MY1, measure the outflow. The balance shows that if the drain was prevented, about 100,000 m3 of water (2200 m3 in average flow over 45 days) could be stored in the lake at today's maximum level.

Based on the real time data information from the sensors MY1, MY2, MY3, the automatic floodgate was programed for safe storage of water in Mjölhatteträsk (Figure 66). The floodgate will not close before the surface level of the lake is 10 cm below the natural high-level (2,0 meter above the sea level). This will minimize the risk for flooding during periods of heavy rain or fast snow melting. The design and the placement of the floodgate is shown in Figure 67.

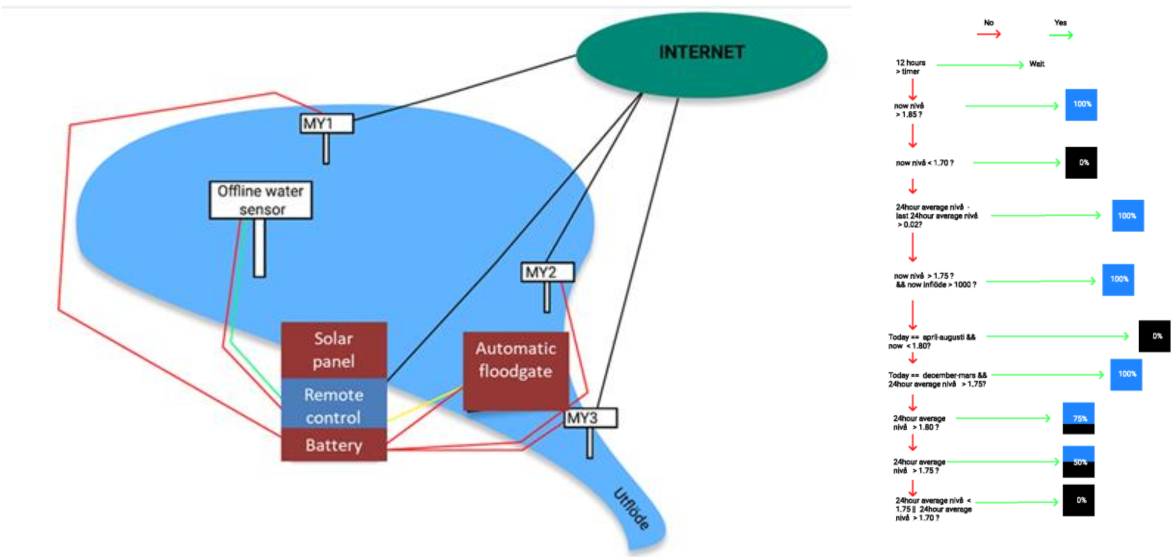

Figure 66. The programming of the automatic floodgate based on the 3 real-time sensors, MY1-MY3 for flowrate in inflow to the lake, the outflow and the actual surface level.

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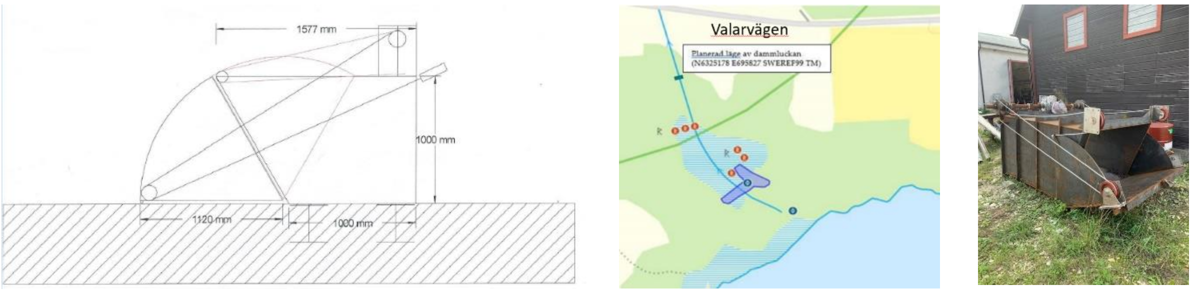

Figure 67. The design of the floodgate and the placement at the highest level of the outflowing ditch, between the lake and the sensor MY1 and north from several ancient monuments. To the right a picture of the floodgate, ready for installation.

In order to calculate the impact on the land areas that will be placed under the water level by the regulation 10 cm below the maximum natural level (Figure 68), a GIS model was developed for the area. The result of the GIS model is shown in Figure 69.

Figure 68. The picture on the left taken in January 2018 when large parts of Storsudret were under water after large amounts of precipitation. As can be seen partly from a comparison with the map image, and partly by studying the shoreline in the picture, it appears that high water levels in Mjölhatteträsk mean very limited flooded waterside areas.

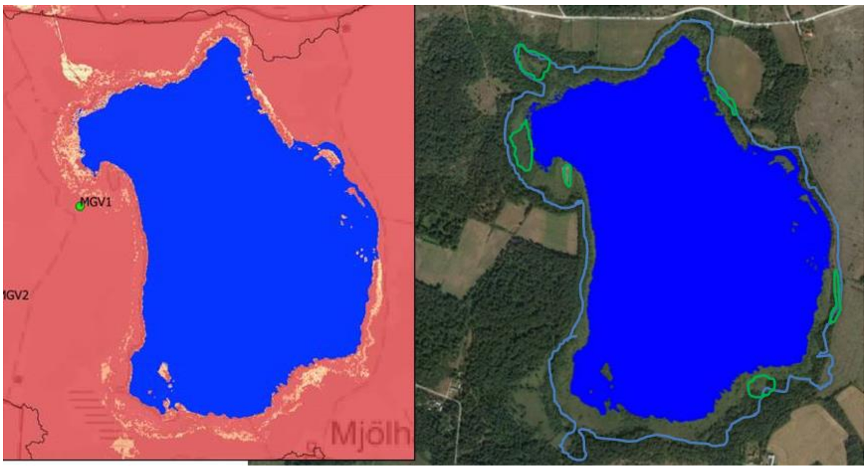

Figure 69. The affectedareas (green lines) by the regulation of the lake Mjölhattetrsäsk´s level between 1,8-1,9 meters above the sea level. The affected area is very limited in space and also time, mainly during April. In middle of May the evaporation has lowered the level to below 1,8 meters above the sea.

4.1.8. Comparison of baseline situation and NextGen KPIs

Mjölhatteträsk is an example of where a ditching carried out during the 1950s lowered the lake to make use of previously soaked areas for arable land and grazing. Here, modelling has

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shown that recreating the previous level (about 20 cm higher than today's maximum level) would mean that just over an additional 200 000 m^3 of water can be stored in the lake and would make a good contribution for a full-scale test bed that can produce 500 000 m^3 of water for Gotland's drinking water network.

To test the possibility of storing water in Mjölhatteträsk, discussions with the landowners who own the majority of the land around Mjölhatteträsk resulted in an idea to raise the level in two steps. A first increase of the level should be 10 cm (equivalent to 100 000 m^3 after evaporation losses), and a second step would increase the level by an additional 10 cm, whereby full storage capacity (200 000 m^3) would be obtained. Figure 70 shows how the shoreline would be affected by such an increase.

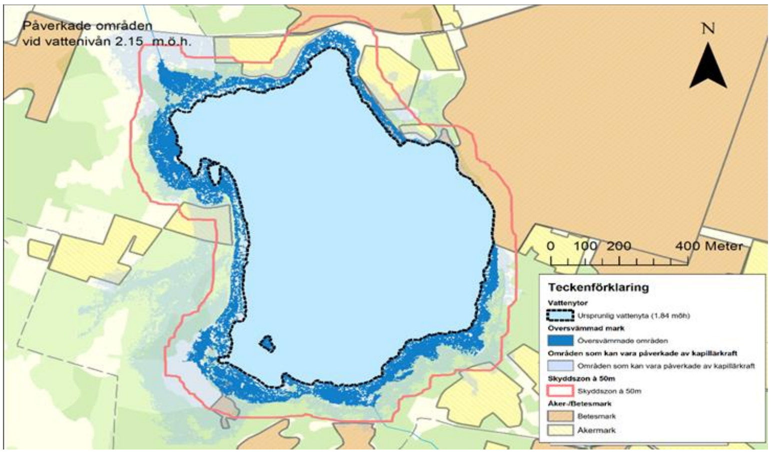

Figure 70. Dark blue marking shows the areas that will be put under water when raising Mjölhatteträsk by 20 cm. After which evaporation and withdrawal of water takes place during the spring and early summer, these parts will once again be dry.

During discussions with the County Administrative Board, it has emerged that this would require a permit from the Land and Environment Court. This is foreseen to take 1-2 years and therefore chosen to regulate the outflow only in such a way that the outflow is hindered by an automatic floodgate. The regulation will only be active when the natural maximum level has been reached and returned to a level 10 cm below the maximum level. In this way, according to Figure 64 and Figure 65, more than 100,000 m^3 should be able to be stored in the lake. As could be seen from the figure, without the floodgate, this volume of fresh water would have flowed into the Baltic Sea via the ditch. If additional precipitation risks raising the level above this natural (normal) maximum level, draining will take place via the automatically regulated floodgate.

Table 58. Specific key performance indicators (KPI) for the potential of local water supply by collection and storage of rainwater in lake Mjölhatteträsk by use of an automatic floodgate controlled by the real-time data management system.

Topic	Objectives	Specific Key Performance Indicator (KPI)	Current value	NextGen values
Rainwater harvesting and storage	To collect and store rainwater for irrigation and the municipal drinking water system.	Rainwater collected and stored [% of available water]	0 %	25 %
Energy	To reduce electricity consumption of the NextGen system compared with today´s situation	Electricity consumption for drinking water treatment and pumping [kWh/m^3 reclaimed water]	4,75 kWh/m^3	< 2 kWh/m^3

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Costs	To reduce the cost for energy (electricity)	Cost for Electricity related to water treatment and pumping of drinking water [kWh/m^3 reclaimed water]	0,8 Euro/ m^3	<0,33 Euro/ m^3

Regarding the water quality, most parameters for lake Mjölhatteträsk meet the KPIs for the water quality is the Swedish regulation for drinking water, SLVFS 2001:30 (Table 59). Except for arsenic, lake Mjölhatteträsk also shows good values and could be expected to serve as a drinking water reservoir. The value for DOC and TOC seems to be remarkable high and the parameter COD is not analyzed but could be expected to show values above the limits. Simple filtration tests show that the organic matter most likely could be filtered of e.g., by use of membrane filtration such as ultrafiltration (UF). The increased concentrations observed in September compared with the concentrations in July can likely be explained by concentration due to evaporation during the extraordinary warm and dry summer of 2018.

*Table 59. KPI for most of the quality related parameters, except for arsenic, in lake Mjölhatteträsk meet the KPIs for the water quality (which is the Swedish regulation for drinking water, SLVFS 2001:30). The value for DOC and TOC seems to be remarkably high and COD is not analysed but could be expected to show values above the limits. *Drinkable with remark; in red, over the limits.*

KPI	Units	Mjölhatteträsk MY2 (surface water) 2018-07-02	Mjölhatteträsk MY2 (surface water) 2018-09-05	Limits for drinking water (SLVFS 2001:30)
Cl	mg/l (mg/g)	36	44	100
Ca	mg/l	25	53	100
pH	upH	8.9	x	10.5
CE	mS/m	35	x	250
TOC (unfiltered)	mg/l	33	34	
DOC 0.45 µm	ug/l	32		
TN (unfiltered)	mg N/l (mg N/g)	2	2.6	
Ammonium NH4	mg N/l	0.16	0.62	0.5
Total phosphorus (TP)	mg P /l (mg P/g)	0.015	0.055	
NO2	mg N/L	<0.01	<0.01	0.1
NO3	mg N/L	0.007	<0.005	20
SO4	mg S/l	9.1	12	100
PO4	mg N/l	<0.01	<0.01	
P	mg/l	0.015	0.055	
Mn	mg/l	<0.05	0.017	0.,05
Fe	mg/l	0.008	0.044	0.1
Al	mg/l	0.013	0.03	0.1
Si	mg/l	7.8	7.4	
Na	mg/l	21	25	100
Mg	mg/l	17	23	30

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K	mg/l	4.2	6	
S	ug/l	11 000	16 000	
V	ug/l	0.76	1.4	
Cr	ug/l	0.12	0.27	50
Co	ug/l	0.11	0.12	
Ni	ug/l	1	1.3	20
Cu	ug/l	1	0.69	2
Zn	ug/l	1.3	2.1	
As	ug/l	1.6	2.9	1
Sr	ug/l	160	210	
Mo	ug/l	0.51	1.1	
Cd	ug/l	0.012	0.006	5
Ba	ug/l	9.3	19	
Pb	ug/l	0.43	0.8	10

4.1.9. Lessons learned

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<table>
<tr><td>Required competence</td><td>LOW  HIGH</td></tr>
<tr><td colspan="2">

- The real-time measurement system for the control of the automatic floodgate is up and running, but there is a need for competence to maintain and re-calibrate the system.
- The data collected is fed to the control system for the floodgate, which needs no extra competence.
- The mechanical part is also robust and will not require any specific competence when it is up and running.

</td></tr>
<tr><td>Maintenance</td><td>LOW  HIGH</td></tr>
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- The sensor stations for the control of the floodgate are powered by rechargeable batteries which need to be replaced every 4th month.
- A calculation shows that one solar panel should be enough for running the floodgate. If this is not fulfilled, there might be a need for replacement of the floodgate battery once or twice during the peak-flow season.
- A re-calibration of the sensor station should be performed every second year.
- The competence for running and maintaining the system is available in-house.
- During the first year´s peak-flow season (February-April) the floodgate will require a visual inspection once a week.

</td></tr>
<tr><td>Technological risks</td><td>LOW  HIGH</td></tr>
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- The main risk for downtimes are unexpected need for recharging batteries and physical damage of cables etc.
- After some initial, physical, challenges with the sensor MY2, the system for controlling the automatic floodgate has not had any downtimes.
- If a downtime is observed, there is a need to replace of batteries, cables etc which normally takes less than a week to organize. If the down-time event occurs during peak-flow, there might be a need for service within one or two days.
- Re-starting the sensor stations that control the automatic floodgate seldom requires any external personnel, but if mechanical issues occur, the need for external competence might be necessary.
- After the first season, the knowledge regarding maintenance of the floodgate will increase and result in less occurrences of down-time events.

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</table>

4.1.10. Best practice guidelines for operating the technology

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To store significant volumes of rainwater from winter to summer, measurements of the water balance have shown that the use of an automatic floodgate could prevent 100 000 m3 of water from being flushed to the sea. This can be achieved by regulating the water level in the lake after the natural maximum level has been reached and then returning it to 10 cm under the maximum level. This design of a system requires safety arrangements to avoid flooding when sudden, additional precipitation is at risk of raising the level above this natural (normal) maximum level. In such cases, draining would take place via the automatically regulated floodgate.
To minimize the risk for flooding, the control system consists of several measurement stations but also an algorithm which could foresee a sudden event with high inflow volumes. The most important safety arrangements are the following, which opens the floodgate fully:

- The level of the lake is increasing too fast,
- The weather station shows too large volumes of precipitation,
- The sensor that measures the inflow to the lake shows volumes that will increase risk of flooding, or
- An extra sensor, not connected to the overall data control system, could open the floodgate regardless of the data provided by the data control system.

During the first season, the inspection of the floodgate and the control system should be made at least once a week and even daily during high peak precipitation rates. Extra attention should be paid to the battery level (which is powered by the solar panel) and the physical condition of the floodgate. Ensuring that no larger rubbish, such as tree branches, sand etc. hinder the floodgate or the water flow in the ditch is critical.

Regarding time planning, be aware of the risk for unforeseen troubles related to permits by authorities. The communication with regarding the regulation of the lake with the county board was initiated two years before the planned installation. The advice from the county board was to not increase the level of the lake. Therefore, the design of an automatic floodgate was developed that could store water below the highest natural level of the lake. Such a plan should have been easily accepted by the authority, but it was not the case. As a result of this, Region Gotland will apply for a permanent permit at the Swedish land and environmental court, which is estimated to take approximately one year.

4.2 Alternative water sources at district level in Filton Airfield (UK)

Authors: Jungeun Kim and Jan Hoffman (UBATH)

4.2.1. Description of the demo site

The Filton Airfield site was purchased in 2015 and slated for development by YTL Development UK Ltd, a subsidiary of the multinational YTL Corporation. The £800 million scheme, a new suburb to be named Brabazon, will comprise more than 2,675 new homes and 62 acres of

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commercial space, as well as new schools, recreation spaces and health facilities (Figure 71). As the parent company of Wessex Water, YTL is set to place significant focus on the development's water management capability and is working with the University of Bath's Water Innovation and Research Centre (WIRC) to investigate and implement the waste-minimising circular economy practices it will need to appeal to planners and future residents. The large size of the development presents a unique opportunity to fully demonstrate and test these practices.

A masterplan for the site development is available, but further development and exploration of ideas for sustainable development are required. Within NextGen the water & energy management as part of this masterplan will be further developed and implemented. The investment project (construction starts 2018) includes a strategic surface water system (SSW), ensuring reliable drainage and allowing local use of captured rainwater and water reuse.

Specifically, during the NextGen project, rainwater harvesting (RWH) was selected as a promising urban water resource management method to reduce drinking water demand. Therefore, a feasibility study of the integration of a rainwater harvesting system in a Filton Airfield development scheme was conducted by demonstrating the drinking water savings and evaluating the applicability of local reuse of harvested rainwater. Details on the selected study site for the feability study are described in the following section.

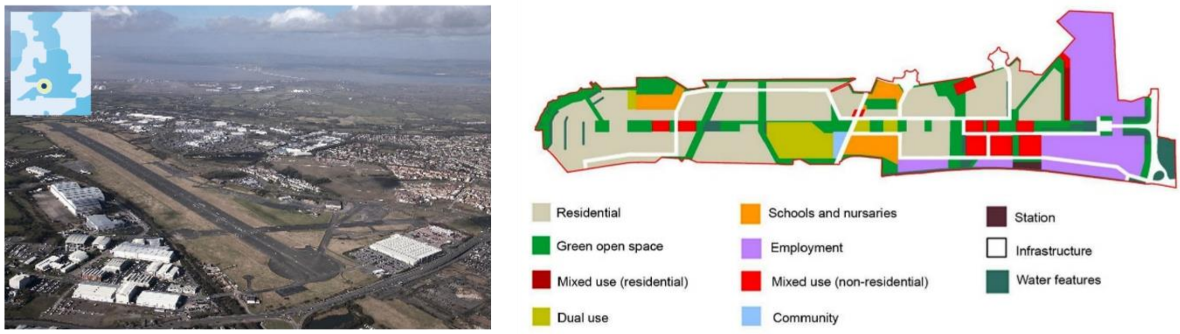

Figure 71. Location of Filton Airfield and Filton Airfield master plan.

Study site – Filton Airfield eastern infrastructure

The Brabazon Development is a mixed-use development located at the Filton Airfield site. The first phase of the development includes 278 housing units. This case study focussed on this first phase of the development with the intention that the results and findings from the research would provide a useful business case for YTL Developments in the future phases of the development. Figure 72 shows a simple plan for the Brabazon Development, with the location of the first phase indicated and named 'Hangar District'. In addtion, the existing three-bay Brabazon Hangar (Figure 72), which was built in 1946, will be transformed into a premier live entertainment venue with a capacity about 17 080 visitors, named as YTL Arena (YTL, 2021). The total roof area of the arena is about 30 000 m2: 8 500 m^2 (East), 13 000 m^2 (Centre) and 8500 m^2 (West).

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Figure 72. Filton Airfield eastern infrastructure development: residential "The Hangar District" and commercial "YTL Arena" areas.

4.2.2. Motivation for implementing circular economy solutions in the water sector

Although water supply in the Bristol area is sufficient, it is becoming a scarce resource on a national level, so the Filton development presents a key opportunity for nation-wide learning. The UK water sector's ambitions for the coming decades of reducing water consumption and halving the freshwater abstraction (UKWIR, 2022) to sustainable levels could benefit greatly from planned studies at the Filton development. Applying circular economy concepts could be one of the solutions to reducing water abstraction. By reusing water and collecting rainwater for non-potable purposes (toilet flushing, washing machine use, or in-garden hosepipes and sprinklers), the amount of water being taken from freshwater sources could be reduced. The water system developed at Brabazon will be focused on reusing water and the use of alternative water sources, such as the collected rainwater. In this way, the amount of freshwater abstracted from the environment can be reduced significantly.

As the Brabazon community will be newly built, it offers a great opportunity to create a different, future-proof water system. Plans include collecting rainwater from the huge roof of the YTL Arena, a new concert and events venue planned as part of the scheme, as well as from the roofs of the new homes. Because water demand is constant and rainfall is generally unpredictable, storage capacity will be created on and around the site, including in green spaces in the Filton area.

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The NextGen project aims to demonstrate circular economy approaches in mitigating current water consumption and improving self-sufficiency at a district level. The specific circular economy approaches for water solutions (Figure 73) are as follows:

- Explore alternative water resources
    - Rainwater harvesting – Residential and commercial reuse

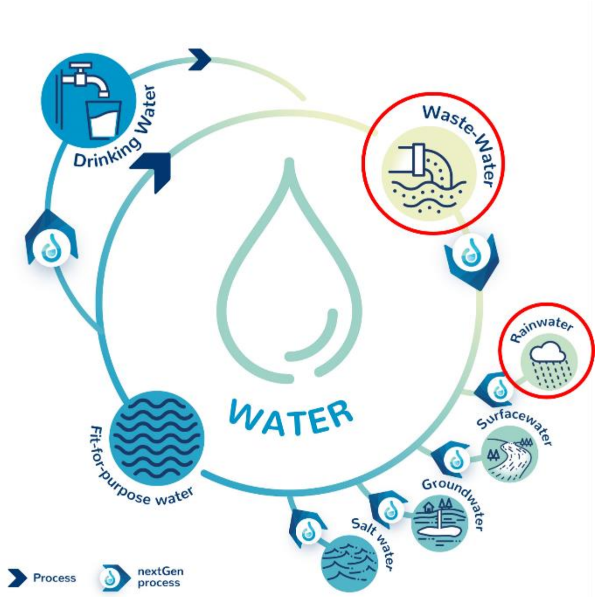

Figure 73. Positioning of Filton Airfield in the circular economy – Water.

4.2.3. Actions and CS objectives

Table 60. Actions and objectives of the case study in Filton Airfield.

Case Study number & name	Subtasks	Technology baseline	NextGen intervention in circular economy for water sector	TRL	Capacity	Quantifiable target
# 9 Filton Airfield Location: A former airfield in South Gloucestershire, north of Bristol	Sub-Task 1.2.7 Integrating alternative water sources at district level at Filton Airfield	- A former airfield in South Gloucestershire, north of Bristol, UK - YTL Developments will develop this former airfield into an attractive and sustainable area	Decentralized solutions for increased circularity in new housing districts	TRL 7 → 9	10 - 600 m^3 storage capacity, depending on applications (residential or commercial)	Urban water resource reuse for non-potable uses: water saving, %

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4.2.4. Benefit to end-users and beyond

In the frame of the Filton Airfield development, occupants, Wessex Water in the UK and YTL Developments (UK) Ltd are the main end-users/beneficiaries. In particular, YTL as a developer will lead an investigation of the acceptance of rainwater harvesting and reuse for non-potable purposes by authorities and industries. Therefore, the use of water circular solutions will add opportunities including marketing and public image.

The results drawn from the NextGen project will be recognised as a 'first showcase' for planners, developers, and designers to consider this approach for rainwater harvesting in Filton Airfield. Direct benefits that can be integrated for future research are as follows:

- Improvement of the applicability of a rainwater harvesting system at a small-, medium-, and large-scale levels
- Deeper understanding and providing a significant step towards local and water circular solutions for further study on the impact of site-specific conditions (i.e., urban densification and climate change) on other water resource management opportunities
- An evidence-based selection can be made for future design plan in a new housing district development

4.2.5. Methodology: Rainwater harvesting feasibility

Rainfall quality analysis

Rainwater samples across Filton Airfield were collected directly from atmospheric precipitation to assess the environment of the Filton Airfield and to provide insight into the quality of fresh rainwater as an alternative source for various applications.

There were five different sampling points (SP1-SP5) across the Filton Airfield (n = 25 samples). As shown in Figure 74, SP1 was located at the northwest of the Filton Road. SP2 and SP5 were located at the right side and the front of the east wing of the YTL Arena (YA), respectively. SP3 and SP4 were located at the behind of the west wing (near the used tanks) and the centre of the YA, respectively.

At this location, there is a local road with moderate traffic, whose distance from the YA varies between 0.5 km and 2 km. Commercial and residential areas are located to the east, northeast and northwest of the YA, Figure 74 (a). A sewage treatment plant and light industrial areas are located less than 10 km from the study area, but these are not shown in the figure. Figure 74 (b) shows prevailing winds in this area are from the southwest. Noteworthy is that the wind direction data during the sampling period were obtained from a weather station located 2.3 km from the Filton site (Weather underground, 2020).

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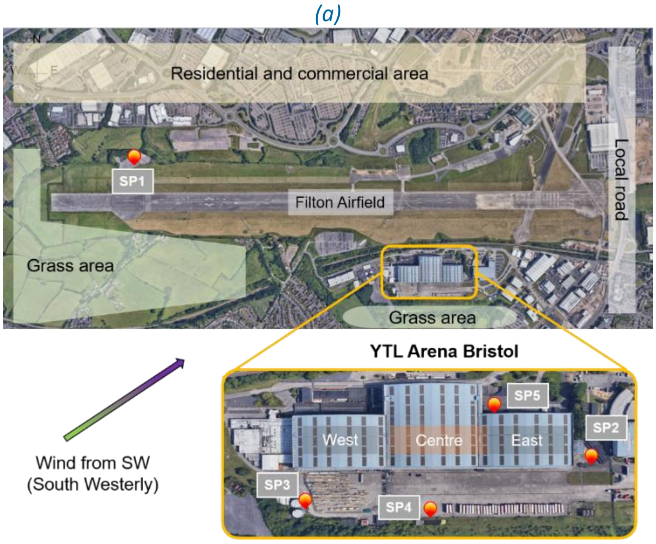
Weekly collection of rainwater samples was conducted, and the samples were kept in the cold room at 4˚C prior to analysis. The pH, electrical conductivity (EC, µS/cm),and total dissolved solids (TDS, mg/L) were measured on site using a pH/EC/TDS meter, while samples were sent to Wessex Water Scientific Centre for analysis of the other selected physiochemical and microbiological parameters according to the Standard Methods ISO 17025 (UKAS, 2020) as described in Table 82 in Annex 2. The physicochemical parameters analysed were turbidity (NTU), chemical oxygen demand (COD) and biochemical oxygen demand (BOD). In addition, nutrients, major ions and metals including total hardness, calcium hardness, magnesium hardness, alkalinity (HCO_3^-), ammonia (NH_4^-), nitrite (NO_2^-), nitrate (NO_3^-), chloride (Cl^-), sulphate (SO_4^{2-}), fluoride (F^-), calcium (Ca), potassium (K), magnesium (Mg), sodium (Na), iron (Fe), manganese (Mn), copper (Cu), chromium (Cr), cadmium (Cd), nickel (Ni), zinc (Zn), and lead (Pb), were determined using the methods described in Table 82 in Annex 2. The microbiological parameter (i.e. *E. coli*) was analysed by the membrane filtration method. Tap water was also analysed for the same parameters to compare the quality of both rainwater and tap water.

(a)



(b)

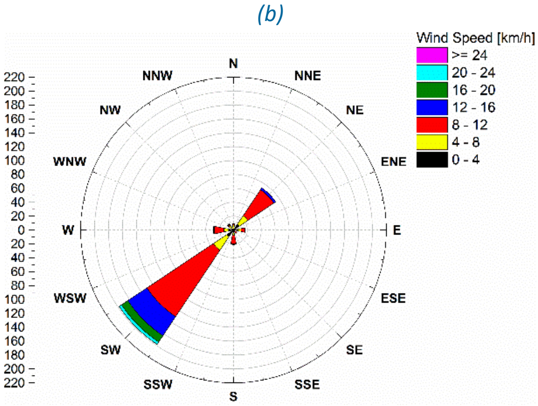


Figure 74. (a) Characteristics of the Filton Airfield area. Sampling points - SP1: at the end of the Filton Airfield, close to green area, SP2: the right side of the east wing of the arena, open area, SP3: at the behind of the west wing of the arena and near the used tanks, SP4: the behind of the arena, close to green area, and SP5: the front of the east wing, surrounded by small buildings) and (b) Wind direction data from Little Stoke Weather station (Distance from the arena: 2.3 km).

Water demand simulation – SIMDEUM

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SIMulation of water Demand, an End-Use Model (SIMDEUM), a MATLAB program developed by the KWR Water Research Institute, was used to produce residential demand profiles. SIMDEUM utilizes a '.SPG' file that contains pre-determined values and data supplied by the user to create '.stats' files which contain the water demand profile for up to a week-long period. Harvested rainwater is non-potable, therefore only water demand from toilet and washing machine usage was considered. Water demand is affected by seasonal weather, e.g., increased water usage for irrigation during summer months: however, SIMDEUM only provides demand profiles for periods of up to a week, thus the effect of seasonal weather on demand profiles is not accounted for. Despite this limitation, it should have a negligible effect on non-potable demand profiles, as they are not subject to variance due to seasonal weather. Since demand was simulated for a single week, the RWH model replicated the profile to match the length of the simulation. As the Filton Site is in development, precise data for the number of residents in each unit is not yet available. Without this data, accurate simulation of water demand is more difficult, even when the percentages of one-person, two-person and multi-person households are known (25.5%, 33.8% and 40.7% respectively). It should be noted that this does not necessarily reflect the actual number of residents in each unit. Furthermore, given the stage of development, the demographic information of residents is not available. It is assumed that there would be negligible bias of age, gender and employment for future Filton residents from the Dutch residents coded into SIMDEUM upon which the defaults are based. Therefore, the default values contained in the demo files were used and the composition of housing types was altered to reflect the balance of one person, two-person and multi-person households provided by YTL.

Water balance simulation – YAS and YBS models

In a typical RWH system (Figure 75), the roof of the building collects the precipitation which then flows into the rest of the system via guttering and downpipes. After being flushed and filtered from contaminants such as bacteria, the water enters a storage tank. Here, the water can be extracted when needed for the non-potable water demand of the house. If the tank overfills, excess water is spilt into the surroundings or existing stormwater drainage. If the tank cannot provide enough rainwater to meet demand, potable water will be withdrawn from the mains, ensuring the resident will always have access to immediate water. Although commercial and large-scale applications of RWH will have much larger variables, the process remains the same.

To assess the hydraulic performance of RWH systems in the YTL development, a generalized mass balance model was used for both centralized and decentralized RWH approaches. Inflow to the tank was calculated with Equation 1, where RC is the runoff coefficient and C*A* is the total area of the catchment surface. Runoff coefficient is a dimensionless factor that is used to convert the rainfall amounts to runoff. It represents the integrated effect of catchment losses. Consideration must be given to the type of surface, slope, degree of saturation and rainfall intensity when specifying the runoff coefficient for a given surface (Alim et al., 2020). The recommended runoff value for typical urban roofing used to determine the volumetric inflow is 0.95 (ASCE, 1996). The filter coefficient (FC) attempts to account for rainwater lost over the filter as harvested rainwater moves from the catchment area to the storage tank and was considered to be 0.9 (Ward et al., 2010a). It is assumed that the tank is covered, thus

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losses due to evaporation are negligible. The general balance for a RWH system is described by Equation 2.

$$Q_t = RC \cdot FC \cdot R_t \cdot CA$$ Equation 1

$$V_t = V_{t-1} + Q_t - S_t - Y_t$$ Equation 2

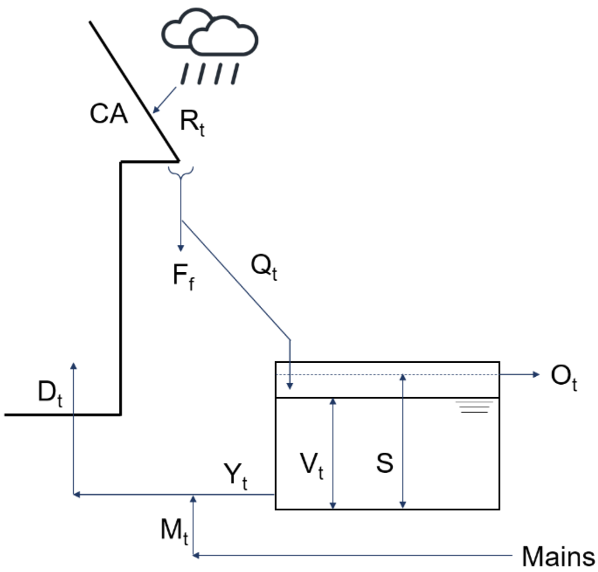

Figure 75. General configuration of a rainwater harvesting system. R_t = Rainfall (mm) during time interval, t; Y_t = Yield from store (m^3) during time interval, t; D_t = Demand (m^3) during time interval, t; V_t = Volume in store (m^3) during time interval, t; V_{t-1} = Volume of water in storage tank (m^3) on the previous time; Qt = Rainwater run-off (m^3) during time interval, t; M_t = Volume of water from the mains supply (m^3); S = Storage capacity (m3); O_t = Overflow (m^3); F_f = First Flush volume (mm); CA = Catchment area (m^2)

Figure 76 (a) and (b) show the yield after spillage (YAS) and yield before spillage (YBS) models for a RWH system developed by (Jenkins & Pearson, 1978). These models represent the extreme of the modelling assumptions relating to when harvested rainwater is used. In each case, three calculations are computed at each timestep as illustrated in Figure 77.

Starting with the YAS model, firstly, the total inflow into the tank is added to the stored volume at the previous time step. Secondly, the water volume that exceeds tank capacity (i.e., spillage) is calculated and subtracted. Finally, yield is then accounted for, providing the stored volume at the current timestep. This is represented below by Equation 3 and Equation 4 (Fewkes & Butler, 2000).

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} \end{cases}$$ Equation 3

$$V_t = \min \begin{cases} V_{t-1} + Q_t - Y_t \\ S - Y_t \end{cases}$$ Equation 4

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In both models, yield equals demand insofar as the demand does not exceed the stored tank volume. In the case where demand exceeds stored tank volume (i.e., the tank is fully drained), water from the mains is used to ensure demand is fully met. The YBS model follows the same computations as the YAS model except that yield is accounted for before excess rainwater is spilled. This is represented below by Equation 5 and Equation 6 (Fewkes & Butler, 2000).

$$Y_t = \min \begin{cases} D_t \\ V_{t-1} + Q_t \end{cases} \quad \text{Equation 5}$$

$$V_t = \min \begin{cases} V_{t-1} + Q_t - Y_t \\ S \end{cases} \quad \text{Equation 6}$$

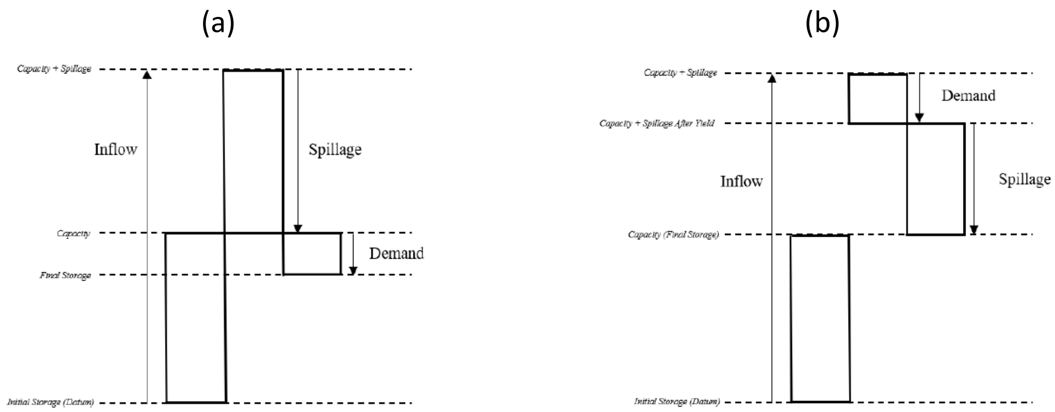

Figure 76. (a) YAS behavioural model with arrows denoting inflows and outflows to the tank and (b) YBS behavioural model with arrows denoting inflows and outflows to the tank.

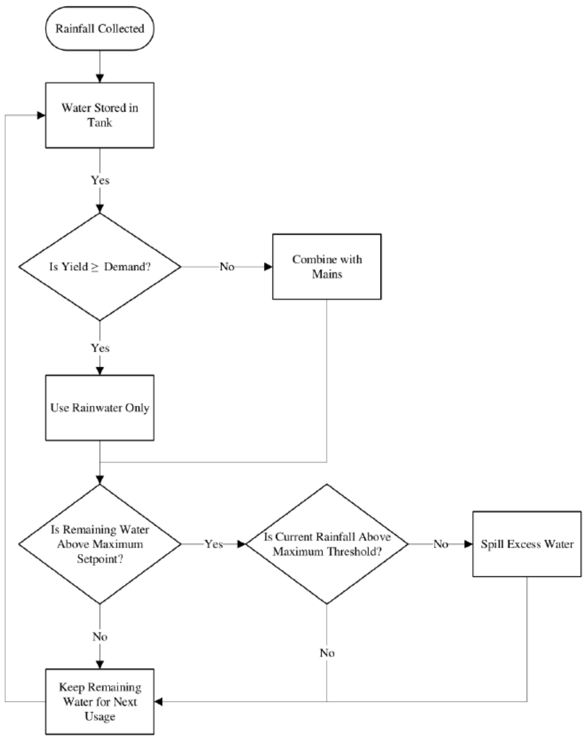

Figure 77. Flowchart displaying the computations executed at each timestep of the model.

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For toilet flushing demand within the YA, four different capacities were assumed to be met every functional day. An equal proportion of males and females was considered. For toilet use, half the males used urinals and the other half used toilet bowls. Toilet bowls were assumed to use 6 litres per flush, while the urinals used 3.6 litres per flush (Hills et al., 2002; Zadeh et al., 2013). The annual operational days was assumed to be 365 (Hills et al., 2002). An irrigation plan was assumed to be in operation when there is no rain from May to October for BP and FG. The volume of irrigation water was assumed to be 5 litres per square meter per day (Matos et al., 2013; Roebuck et al., 2011). Equations used to determine the water demand for each application can be found in Table 83 in Annex 2.

Description of RWH scenarios - catchment area and reuse application

Centralised and decentralised rainwater supply systems with different rainfall catchment scenarios were considered. It has to be noted here that rainfall catchment scenarios were changed and improved according to the study site development stage. The centralised system involves a rainwater harvesting system with a single rainwater storage tank, while the decentralised system involves multiple rainwater harvesting systems with multiple rainwater storate tanks which each system is connected to a small number of houses. Collected rainwater is used for non-potable purposes, including dishwasher, washing machine, irrigation and toilet flushing, depending on the scenarios (Table 61).

For scenario 1 (S1), a group of 23 houses was considered for the decentralized system with a roof surface of 1,495 m^2. At the early stage of the Brabazon development design plan, a total of 278 housing units were planned, but there was little information on the percentage of apartments and housings. So, a mean catchment area of 65 m^2 per unit was initially assumed. Whereas scenario 2 (S2) considered a centralized rainwater system that collects rainfall from a roof of the cantral hangar (13 000 m^2). It was assumed that the collected water is used for non-potable uses, including washing machine and toilet flushing. Thus, the annual demand for the decentralized (S1) and centralized (S2) systems amounted to 1 275 m^3 and 15 412 m^3, respectively. Although scenario 3 (S3) also considered a centralised rainwater collection from the roof of the cental hangar (13 000 m^2), water reuse in this scenario differs from scenarios 1 and 2 in that it considered only toilet flushing. Thus, the yearly demand without the washing machine was 12 652 m^3.

Table 61. Scenarios considered for rainwater harvesting systems in residential and commercial buildings.

Scenario (S)	Supply system	Catchment	Catchment area (m^2)	Water reuse (non-potable)	
Scenario 1 (S1)	Decentralized system	Roof of a group of 23 houses, 65 m^2/unit	1 495	WM, WC	23 houses per system
Scenario 2 (S2)	Centralised system	Central roof area of YTL Arena	10 000	WM, WC	278 houses
Scenario 3 (S3)	Centralised system	Central roof area of YTL Arena	10 000	WC	278 houses
Scenario 4 (S4)	Centralised system	Entire roof area of YTL Arena	30 000	WC, IR	YTL Arena, Filton golf course and Brabazon park

*WM - washing machine, IR - irrigation and WC - toilet flushing.

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Scenarios 1-3 used the collected rainwater for only domestic purposes while scenario 4 used the collected rainwater for commercial uses, including toilet flushing within YTL Arena and irrigation of both the Filton golf course and Brabazon park as described in Table 62. In this scenario, the entire roof of the YTL Arena (30 000 m^2) was assumed to be the catchment area for the centralised rainwater harvesting system.

Table 62. Water demand scenarios and values used for scenario 5.

Scenario			Unit	Value
Single use	YTL Arena (YA) toilet flushing (TF_{YA})	Visitors (TF_{YA1}, TF_{YA2}, TF_{YA3}, TF_{YA4})	Person/day	2 000, 5 000, 10 000, 20 000
		Toilet	L/flush	6
		Urinal	L/flush	3.6
		Frequency	Flush/capita/day	2
	Irrigation (IR_{BP} & IR_{FG})	Brabazon Park (BP) (IR_{BP1} & IR_{BP2})	ha	6 and 12
		Filton Golf Course (FG) (IR_{FG1} & IR_{FG2})	ha	23 and 46
		Frequency (May–October)	Irrigation/week	1
		Water use	L/m^2/day	5
Combined use	50%TF + 50%IR and 70%TF + 30%IR			

For scenario 4, there were sub-scenarios for water reuse applications. Figure 78 and Table 63 show the water demand scenarios and valuse used for four different water use scenarios: (a) toilet flushing within the YTL Arena (YA); (b) irrigation for the Brabazon Park (BP); (c) the Filton Golf Course (FG); and (d) a combination of toilet flushing and irrigation.

Figure 78. Location of water reuse applications, YTL Arena, Brabazon park and Filton golf course.

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Table 63. Demand characteristics for each scenario.

Scenario (S)		Water reuse (non-potable)		Water demand (m^3/year)	Water demand simulation methods
Scenario 1		WM, WC	23 houses per system	1 275	SIMDEUM simultion (refer to Section 5.1.2)
Scenario 2		WM, WC	278 houses	15 412	
Scenario 3		WC	278 houses	12 652	
Scenario 4	TF_{YA1}	WC	YTL Arena	8 030	Daily water balance simulation (refer to Section 5.1.3: a spreadsheet-based daily water balance model, YAS)
	TF_{YA2}			19 710	
	TF_{YA3}			39 420	
	TF_{YA4}			78 840	
	IR_{BP1}	IR	Golf course and Brabazon park	55 115	
	IR_{BP2}			110 230	
	IR_{FG1}			211 700	
	IR_{FG2}			423 035	
	50%TF_{YA4} + 50%IR_{BP2}	WC+IR	YTL Arena, Golf course and Brabazon park	94 535	
	70%TF_{YA4} + 30%IR_{BP2}			88 330	
	50%TF_{YA4} + 50%IR_{FG2}			182 135	
	70%TF_{YA4} + 30%IR_{FG2}			251 120	

Rainfall data collection and analysis

During the project, we tried different data and approaches for each scenario since real rainfall data in Filton was not available. Historical daily rainfall records of the Filton Airfield site were obtained from the UK Centre for Ecology & Hydrology and Weather Underground, which is an online platform where local weather information is available (Tanguy et al., 2016; Weather underground, 2020). Table 64 describes rainfall data used for each scenario.

Table 64 Description of collected rainfall data used for each scenario.

Scenario (S)	Historical rainfall data	Rainfall analysis
Scenario 1 (S1)	11-year, 1st January 2008 - 31st December 2018	Rainfall data was used to generate synthetic rainfall data
Scenario 2 (S2)		
Scenario 3 (S3)		
Scenario 4 (S4)	53-year, 1st January 1968 - 31st December 2020	Long period of historical rainfall data

Scenarios 1, 2 and 3

Throughout the preliminary stages of development, a placeholder approximation was used for daily rainfall, represented by the variable X, which was normally distributed around a mean of 10 mm. Once generated, X was appended to an array containing the previously generated values. Consequently, the tank volume model was run using this array of values to simulate rainfall. This approach to rainfall simulation was taken to ensure the tank volume model functioned as intended – once this was established, a more sophisticated and real-world approach to rainfall simulation was taken. A time series containing an 11-year-long set of daily

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rainfall values in the Bristol region for approximately 4000 consecutive days from the 1st of January 2008 until the 31st of December 2018 was used as an input to replace the rudimentary placeholder approximation described above. This approach allowed for the demonstration of the tank volume model with real-world, region-specific rainfall data.

Given that the RWH systems in urban settings are beginning to form part of a more holistic, decentralized approach to urban stormwater management systems, it is important to consider resilience and long-term applicability when optimizing design parameters (Valdez et al., 2016). Consequently, proposed RWH systems must be designed with the capacity to withstand and manage extreme events. Given the typical operational lifetime of a RWH system, an extreme event that occurs once in 30 years should be accounted for (Ghimire et al., 2019). An 11-year long historical set should not be used to simulate a once-in-30-year event due to the limitations of extrapolating a data set beyond a reasonable scope. Hence probabilistic modelling must be employed.

Weather events can be simulated by either deterministic or stochastic models. The word stochastic implies the presence of a random variable: e.g., stochastic variation occures when at least one of the elements is variable, and a stochastic process is one wherein the system incorporates an element of randomness, as opposed to a deterministic system, which does not. In a deterministic model, the values for the dependent variables of the system are entirely determined by the parameters of the model. In contrast, stochastic, or probabilistic, models include randomness in such a way that the outputs of the model take the form of probability distributions rather than discrete values (Rey, 2015). Rainfall is a complex phenomenon driven by multiple physical mechanisms acting at multiple spatial-temporal scales: thus, deterministic modelling holds limited practical value for the purpose of rainfall simulation (Hingray & Haha, 2005). More specifically, Hingray & Haha (2005), through an analysis of seven disaggregation models, showed that classic deterministic models lead to a significant underestimation of some important rainfall statistics, such as variation coefficient and extremes of 10-min rainfall amounts. Stochastic models have been the standard for several decades and the model outcomes are non-discretised (Rey, 2015). Instead, they are probability distributions, or probability density functions, which represent the inherent statistical properties of a phenomenon. Koutsoyiannis & Pachakis (1996) demonstrated the efficacy of such models at simulating rainfall by showing there to be no substantial difference in behaviour between a synthetic and historic rainfall time series. Kurothe et al. (1997) provides evidence to show that the intensity of daily rainfall levels is distributed exponentially if only wet days (days with rainfall) are considered.

Therefore, to allow for the modelling approach described by the flowchart in Figure 79, two assumptions were made. Firstly, daily rainfall levels were assumed to be exponentially distributed for wet days only. Secondly, the probability of a day without rainfall occurring was set to equal the total number of dry days divided by the total number of days in the time series. For the 11-year-long set of daily rainfall values, this probability was 0.47. With these two modelling assumptions, synthetic rainfall time series could be generated using the simulation steps described below.

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Firstly, the 11-year-long set of daily rainfall values (2008-2018) was manipulated by omitting all dry days from the data set to only include days with non-zero rainfall levels. The Kolmogorov-Smirnov test (KS test) is a distribution-fitting algorithm that quantifies the extent to which a dataset adheres to an empirical distribution. The KS test outputs the location and scale parameters for the probability distribution which most closely matches the dataset, as well as the p-value which indicates the probability that this pattern was due to a random sampling error. After the application of the KS test (distribution fit), the inherent statistical properties of the historical time series were represented by a probability distribution using the location and scale parameters. Subsequently, a Monte Carlo simulation was applied to yield different sets of rainfall data, or 'paths', of this stochastic process through iteration with a set of random variables, or 'state space', modelled based on the probability distribution produced in the previous step.

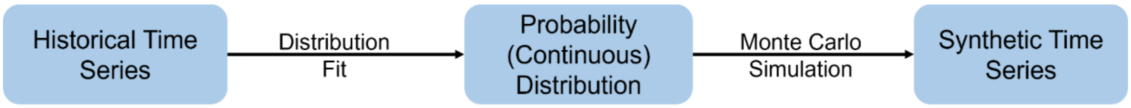

Figure 79. Flowchart displaying the process for generating synthetic rainfall data from a historical time series.

The efficacy of the distribution fitting and Monte Carlo simulations were analyzed to ensure that the inputs to the tank volume model were consistent with typical rainfall patterns of the North Bristol region, which encompasses Filton Airfield. Rainfall events, patterns and behaviors may be described by a plethora of metrics. Within the context of this enquiry, as it relates to the applicability of RWH systems to a development at Filton Airfield, five key metrics were identified as necessary components of a thorough comparison of synthetic and historical rainfall data. These were the distribution of rainfall event intensity, total annual rainfall, peak annual rainfall, seasonality, and periodicity. This analysis was comprised of a comparative analysis of rainfall data from between 2008 and 2018, with a year-long synthetic time series.

The distribution of rainfall events was assessed through a side-by-side, qualitative comparison depicted in Figure 80 (a) and (b). Both time series appear to be distributed exponentially – this was expected, since the synthetic time series displayed in Figure 80 (a) reflects the inherent statistical properties of the historical time series in Figure 80 (b). Given the assumption that rainfall levels for wet days were exponentially distributed, the KS test may be applied to yield the p-value, which was used to quantify the validity of this assumption. The KS test yielded a p-value of 0.027: thus, the probability that this pattern was due to a random sampling error was sufficiently low. The KS test provided the location and scale parameters of 0.254 and 3.85. These parameters describe an exponential distribution with the best possible fit to the historical data: the distribution in Figure 80 (b) is the best possible representation of the inherent statistical properties of the historical data insofar as it could be assumed that the historical data is distributed exponentially. This assumption is valid due to the p-value from the KS test, and consequently the synthetic time series accurately reflects the distribution of rainfall event intensity.

Annual rainfall averaged 706 mm per year over the 11-year period from 2008 to 2019, with a peak of 1 135 mm in 2012 and a low of 585 mm in 2010. This year-on-year variability was not apparent in the synthetic time series, since each set was based off the same probability

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distribution –only the random nature of the input variables results in variance. The overall average of mean annual rainfall for a set of ten synthetic time series was 729 mm, which is within ± 2.5% of the real-world figure. As expected, there was little year-on-year variance, with a peak of 743 mm and a low of 717 mm. The similarities in mean annual rainfall between historic and synthetic data demonstrate the general accuracy of the simulation: however, the lack of exceptionally wet years in the synthetic data (due to the low year-on-year variance) limits the applicability of such data. RWH system parameters need to be optimized with both typical and high-rainfall years, since this will have a direct effect on flood attenuation performance – the main cost saving benefit of RWH systems. Peak annual rainfall is the amount of rainfall experienced on the wettest day of a calendar year.

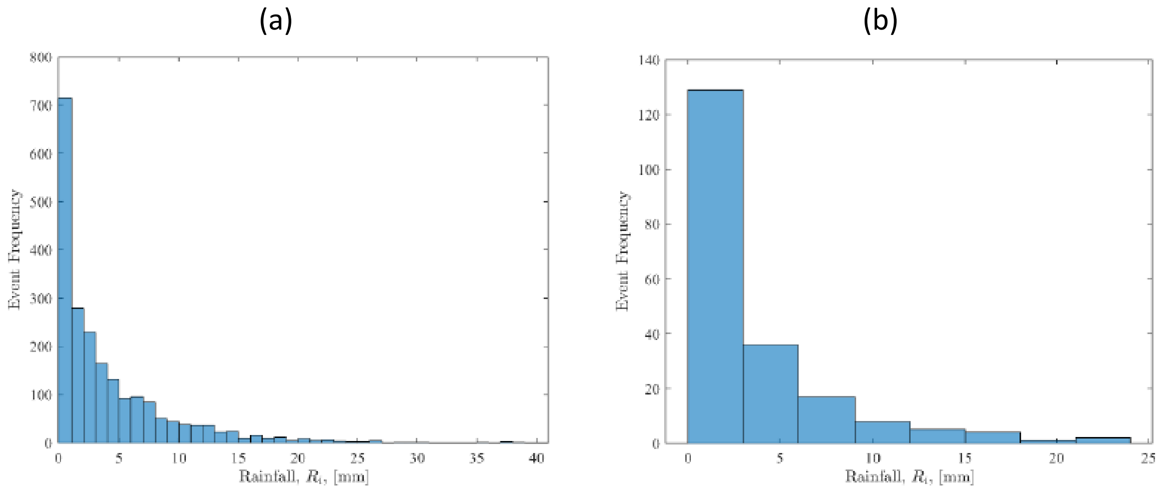

Figure 80. a) Histogram displaying the distribution of daily rainfall levels – excluding dry days – for Bristol from 1st January 2008 to 31st December 2018 and (b) histogram displaying the distribution of daily rainfall levels – excluding dry days – for a yearlong period that was generated stochastically based on the time series presented in Figure 80 (a).

In the synthetic time series, the peak annual rainfall was 29.5 mm and 24.6 mm as shown in Figure 81 (a) and (b) respectively. The peak annual rainfall for each of the other years was analyzed to ensure this discrepancy was not due to an abnormal year. From this, it was found that the mean peak annual rainfall in the historic time series was 24% greater than in the synthetic time series. Although the historical data may be closely approximated by an exponential distribution, it is not a perfect fit. This is the cause of discrepancies between peak annual rainfall values in historic and synthetic time series. This discrepancy was more pronounced when looking at extreme rainfall events. The rainfall values of common events were within ± 5% of each other for historic and synthetic time series: however, for extreme events this difference was significant since the adherence to exponentiality decreases as events become less frequent. The histogram of rainfall events in Figure 80 (b) shows this deviation from exponentiality at high rainfall values (greater than 15 mm). For this reason, a fitted exponential distribution will be unable to produce synthetic time series with similar peak annual rainfall values.

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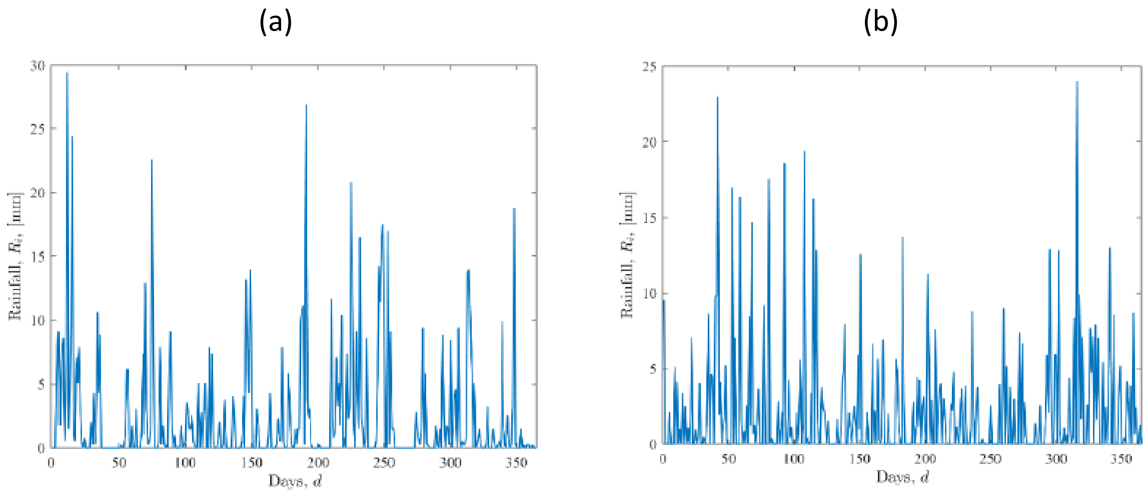

Figure 81. a) Daily rainfall levels for Bristol from 1st January 2018 to 31st December 2018 and (b) daily rainfall levels for a yearlong period that were generated stochastically based on a time series of rainfall values from 2008 to 2018.

Seasonal variance is a key characteristic of rainfall that affects the distribution of wet and dry months throughout the year. Figure 82 (a) contains the mean monthly rainfall from 2008 until 2019 and exhibits seasonal variance, with significantly wetter months from September to January and drier months from February to August. Although this data is specific to the Bristol region, this reduction in rainfall during the summer period is consistent with national rainfall data. Figure 82 (b) shows the mean monthly rainfall for data produced by the simulation, which does not account for seasonal variance, and as a result, the month-on-month variance does not exceed ± 3.5% from a mean of 66.8 mm.

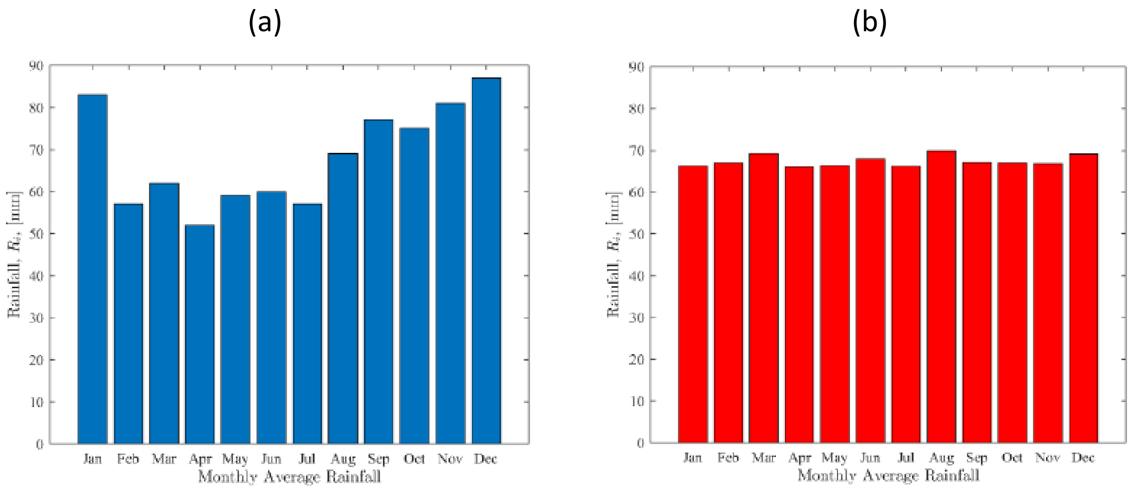

Figure 82. (a) Monthly average rainfall for the Bristol region from 2008 to 2019 and (b) monthly average rainfall for synthetic rainfall data produced by the simulation (11-year aggregates).

Thus, the simulation underestimates monthly rainfall totals from September to January and overestimates from February to August. This limitation has significant implications for the optimization of RWH system parameters – namely, it may lead to an underestimation of the overall tank volume, since parameters optimized using the synthetic data (Figure 80 (b), Figure 81 (b)) do not account for the high rainfall months from September to January. RWH systems that are optimized for an inflow from 66.8 mm of rainfall per month will likely be unable to manage greater inflows caused by the effect of seasonality on rainfall. As a metric, the periodicity of rainfall has important implications for the design and optimization of RWH

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systems, specifically the impact of periodicity on the reliability of storage systems (Afzal et al., 2016). As stated earlier in this report, the periodicity of rainfall is not accounted for due to an assumption made during modelling – specifically that a rainfall event has a 47% chance to occur on any given day. The longest annual dry periods were 18 days and 7 days for the 2018 data and the synthetic data, displayed in Figure 81 (a) and (b).

Moreover, inspection of these graphs shows dry periods were more sustained and frequent in the historical rainfall data compared to the synthetic data. This stark difference is a result of the aforementioned modelling assumption, as the probability of rainfall on any given day is a function of complex meteorological conditions and not a constant value of 47%. Since the simulation cannot accurately model dry periods, the RWH model will have a steadier influx of rainwater when operated using synthetic data. This feature will result in the artificial inflation of RWH system reliability, as the RWH tank is less likely to be empty. When operated with historical data, dry periods have a far more prominent effect on the dynamics of the tank water level, with a higher likelihood for an empty tank, necessitating mains water usage and consequently reducing performance. This difference in tank volume behavior for historic and synthetic rainfall data is demonstrated in Figure 83 (a) and (b), which report the tank volume over a month-long period for both historical and stochastic rainfall data with the centralized RWH system.

Evidently the tank volume in Figure 83 (b) does not accurately simulate the tank volume based on real world data due to the rainfall simulation method. Without accounting for periodicity, rainfall levels from the simulation are highly erratic and therefore so is the tank volume. Considering all of the above, historical rainfall data is best suited for RWH parameter optimization due to the limitations of the rainfall simulation in replicating the inherent statistical properties of the historical data.

(a) (b)

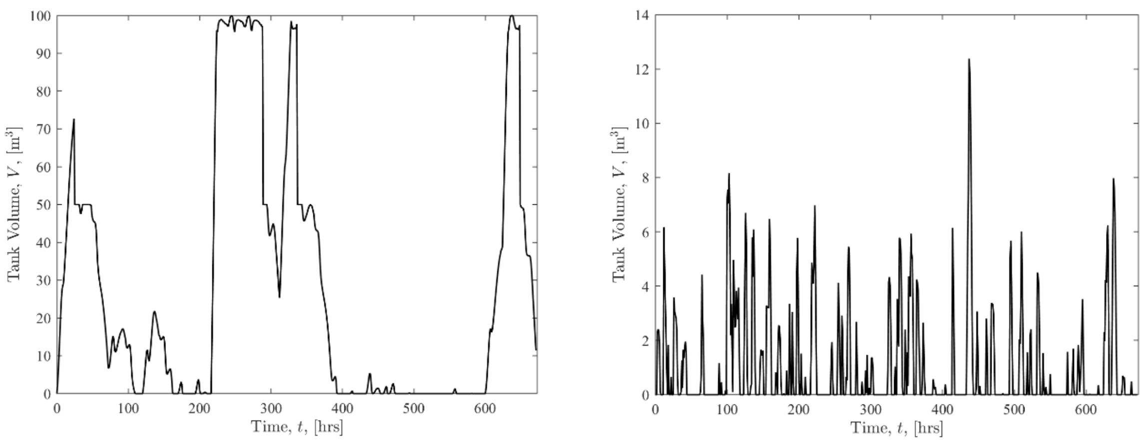

Figure 83. (a) Variance of tank volume for a month-long period with rainfall data from October 2018 with an hourly temporal scale and (b) variance of tank volume for a month-long period with synthetic rainfall data with an hourly temporal scale.

In summary, although probabilistic modelling encompasses possible extreme rainfall events not within the scope of an 11 year long data set, the synthetic data was inaccurate since the periodicity and seasonality of rainfall were not taken into account. RWH tank parameters were optimized with rainfall data from 2018, which is a typical year with mean annual rainfall of

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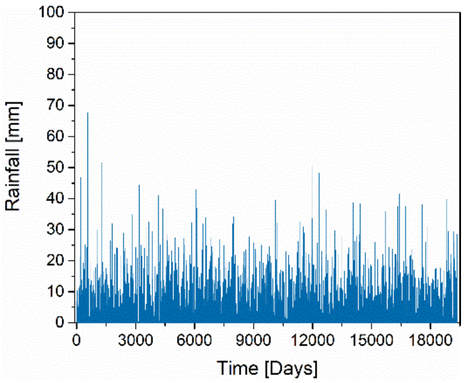
706 mm, within 2% of the mean. Subsequently, the optimized system was stress-tested using rainfall data from November 2009 (the wettest year of the available historical data, mean annual rainfall of 1 135 mm) to assess the resilience of the optimized system to adverse conditions.

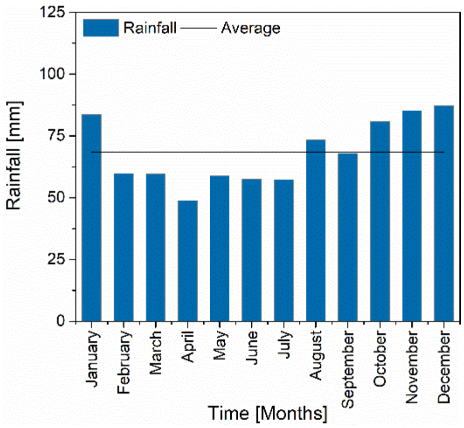
Scenarios 4

Historical daily rainfall data from 1 January 1968 to 31 December 2020 were gained from Tanguy et al. (2016) and Weather underground (2020). The average annual precipitation over this period was 820 mm. The daily and average monthly and annual precipitation trends for the Filton site are presented in Figure 84. The annual average rainfall amount was 811 mm, and the annual average rainy days was 128 days. Two years (2000 and 2012) received significant precipitation of 1 112 and 1 125 mm, while in 1973 and 2010 the average annual rainfall was 569 and 584 mm. These results correspond to the annual rainy days. The years 2000 and 2012 had 159 and 162 rainy days while in 1973 and 2010, there were 97 and 113 rainy days.

(a)



(b)



(c)

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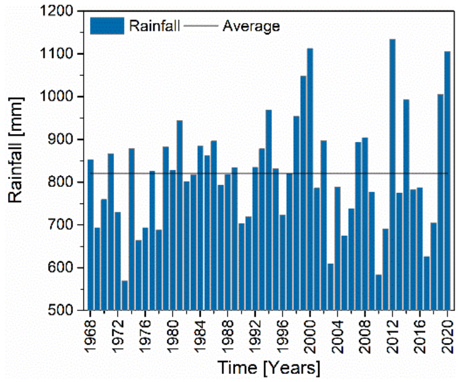

Figure 84. Historical rainfall data from 1 January 1968 to 31 December 2020 collected from the weather stations close to Filton Airfield (a) daily, (b) monthly and (c) yearly average rainfall variations.

Hydraulic performance indicators of RWH system

Water savings efficiency (WSE) is the percentage of non-potable demand that is met by harvested rainwater. Water savings efficiency quantifies the water conservation performance of RWH systems (Haque et al., 2016; Wallace et al., 2015). Water savings efficiency tends towards 100% when harvested rainwater can fully satisfy demand and it is defined according to Equation 7.

$$WSE, \% = \frac{\sum Y_t}{\sum D_t} \times 100\%$$ *Equation 7*

Stormwater capture efficiency (SCE) is the percentage of stormwater generated from the catchment which is used to satisfy non-potable water demand (S. Zhang & Guo, 2013). In essence, the SCE is identical to the water savings efficiency expect for spillage: storm capture accounts for spillage, whilst water savings does not, and thus SCE can be used to assess the effect of the RWH system on downstream drainage networks. It quantifies the runoff reduction performance and may be calculated through use of Equation 8 (Zhang et al., 2020).

$$SCE, \% = \frac{\sum Y_t}{\varphi A \sum H_t / 1000} \times 100\%$$ *Equation 8*

4.2.6. Results obtained

Rainfall quality analysis

Figure 85 presents the results of the following parameters: pH, conductivity, turbidity, total dissolved solids (TDS), total hardness, calcium, sodium, and *E. coli*. Moderate or marginal differences were observed between sampling points. The physiochemical and microbial characteristics of all raw rainwater samples can be found in Table 84 in Annex 2.

Rainwater pH ranged from 7.0 to 8.2, with a mean of 7.52, indicating rainwater of a neutral to alkaline nature. This is mainly because of basic components such as calcium and magnesium present in the soil dust (Kulshrestha et al., 2003) and no accumulation of acidic compounds in

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the rainwater due to the limited concentrations of nitrates and sulphates in the atmosphere (Table 85 in Annex 2).

Elsewhere, conductivity ranged between 8 and 62 μS/cm with an average of 25 μS/cm, representing a level much lower than that of irrigation and drinking water (700 and 400 μS/cm, respectively). In addition, both turbidity (0.09-0.6 NTU) and TDS (4.2-60 mg/L) satisfied the irrigation and drinking standard levels (<5 NTU for turbidity and 500 mg/L for TDS). Meanwhile, total hardness (TH) values showed the much lower values than the standard values of 460-500 mg/L $CaCO_3$. Overall, these results indicate that the free-fall rainwater in Filton area is clean and soft (Al-Khashman et al., 2017).

Furthermore, the effect of the marine environment on rainwater quality was also investigated. Table 65 shows the ratios of Cl, Ca, K and Mg to Na, and compares them to seawater ratios. All rainwater ratios were found to be higher than the seawater ratios. In addition, the non-sea salt fractions of Cl, Ca, K and Mg were95.7%, 95.5%, 91.7% and 28%, indicating that most components in the rainwater come from local contributions. The enrichment factor values further confirmed that these components originated from non-marine sources, such as natural and anthropogenic activities across the site (Herut et al., 2000; Kulshrestha et al., 2003).

E. coli (between 20 and 400 cfc/100 ml) was observed at lower concentrations than the irrigation water standards (< 1000 cfc/100 ml), but higher concentrations than the drinking water standards (0 cfc/100 ml). This indicates that rainwater collected directly from the atmosphere here appears to be applicable for a wide range of non-potable purposes, but not for potable purposes without additional treatment. All rainwater samples showed low content of metals (Fe, Mn, Cu, Cr, Cd, Ni, Zn and Pb) and met the recommended limit for irrigation and drinking water (**Error! No s'ha trobat l'origen de la referència.** in Annex 2). It has to be noted here that the main objective of the quality analysis was to understand the environment in Filton. Analysis of factors that influence harvested rainwater quality such as catchment materials, location, seasonality, and pollutant concentrations need to be further investigated.

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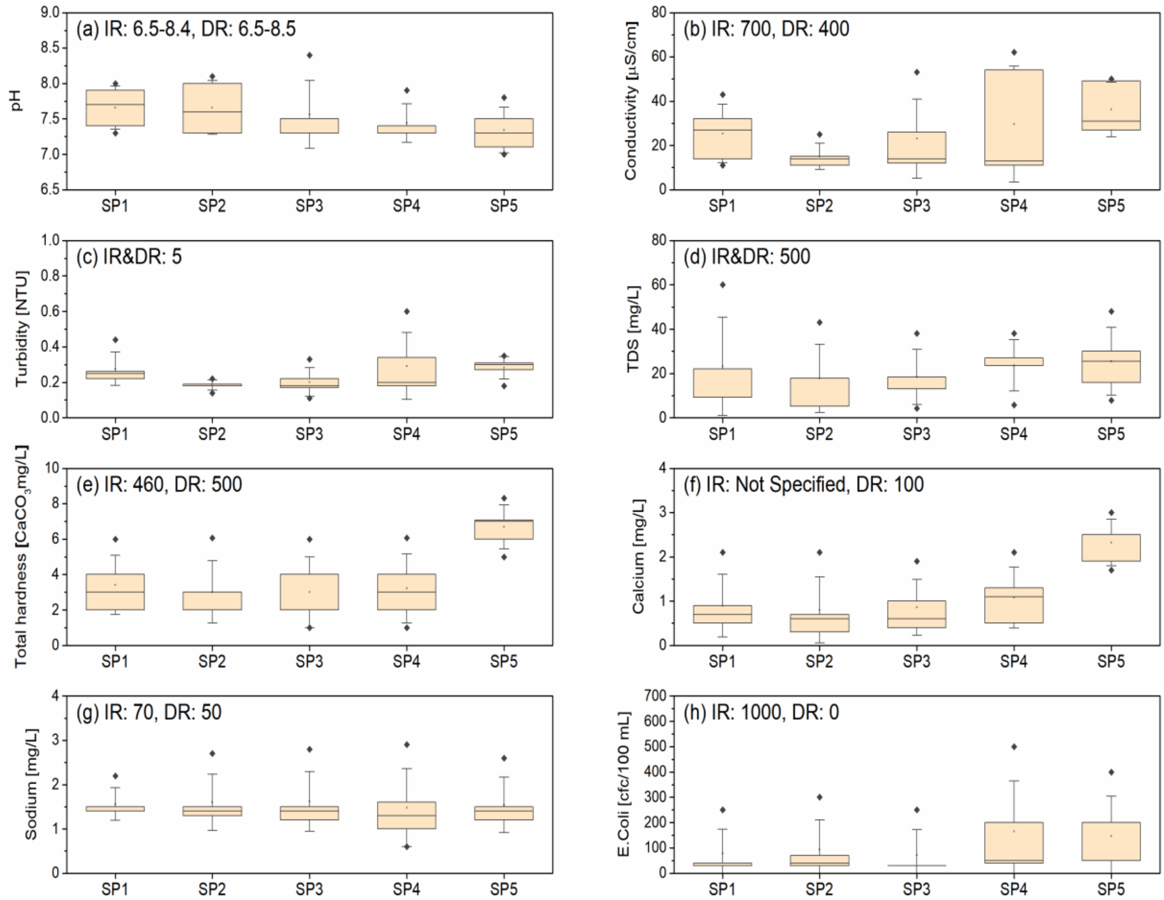

Figure 85. Physicochemical and microbial characteristics of free-fall rainwater collected from Filton Airfield. (a) pH, (b) conductivity, (c) turbidity, (d) total dissolved solids (TDS), (e) total hardness, (f) calcium, (g) sodium and (h) E. Coli. Five samples for each SP (n = 25 samples) were collected and are shown. IR: Irrigation water standards, DR: Drinking water standards.

Table 65. Evaluation of marine contributions to the samples via comparison of seawater ratios with rainwater components.

	Cl/Na	Ca/Na	K/Na	Mg/Na
Seawater ratios*	0.12	0.04	0.03	0.12
Ratios in rainwater	2.79	0.85	0.36	0.17
Sea salt fraction %	4.3%	4.5%	8.3%	71.9%
Non-sea salt fraction %	95.7%	95.5%	91.7%	28.1%
Enrichment factor**	23.2	21.2	12.0	1.4

*Sea water composition ratios obtained from Kulshrestha et al. (2003)
**Enrichment factor = Rainwater ratio/Seawater ratio

RWH system performance assessment

RWH system for residential application - scenarios 1, 2, and 3

Simulations were conducted to produce data that related storage fraction with water savings efficiency (WSE) and stormwater capture efficiency (SCE) as presented in Figure 86 (a) and (b). WSE approaches an upper limit of 70% as S_f increases, and SCE approaches an upper limit of 90% as S_f increases. To ensure consistency in the optimization approach, the setpoint was kept at 90% of the total tank volume to prevent it from being a limiting factor at the expense of flood attenuation performance. Since the storage fraction is a dimensionless quantity, it allows comparison of performance indicators despite differences in tank size. Figure 86 (a)

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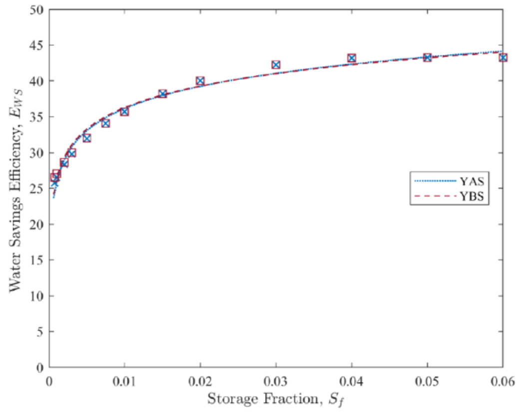
shows the WSE approaching a limit of 72%. For storage fractions in the range of 0.001 to 0.01, WSE increases sharply because tank volume is the limiting factor. In this range, small increases in storage fraction led to a large reduction of spillage volume throughout the year, since instances where the tank is full decrease. At some point, in the region where S_f = 0.01, the limited volume of harvested rainwater begins to dominate the relationship between S_f and WSE. Further increases in tank size cause minor reductions of spillage as few rainfall events can fill up the total capacity of the tank. With a S_f of 0.0075, a water savings efficiency of 36% is achieved.

(a)



(b)

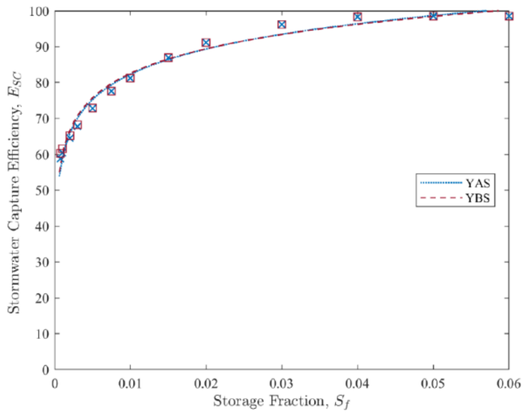


Figure 86. The variance of storage fraction with (a) water savings efficiency and (b) stormwater capture efficiency for a decentralized system (Scenario 1), YAS: yield after spillage and YBS: yield before spillage.

Multiple simulations of the centralized RWH system were conducted, yielding data which is reported in Figure 87 (a) and (b) relating storage fraction with WSE and SCE.

During the beginning of the optimization process, the setpoint was kept at 90% of the total tank volume to prevent it from being a limiting factor at the expense of flood attenuation performance. Figure 87 (a) shows WSE reaching a maximum of 45%. Despite sharp increases in WSE for low S_f values, there are diminishing returns for performance gains as S_f increases further. For the centralized system, an S_f of 0.05 equates to a tank with a capacity of 356 m^3. Although such a system is beyond financial and even physical possibility, it demonstrates that tank size is not the limiting factor for further improvements in WSE. There are two possible reasons for this: firstly, the insufficient supply of rainwater to the system relative to the expected demand; and secondly, a low setpoint causing large spillage volumes and therefore

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necessitating getting water from the mains to meet demand. Given that a setpoint of 90% was used for these initial simulations, the diminishing performance increases are likely due to the insufficient supply of rainwater, not tank sizing.

SCE data reported in Figure 87 (b) provides more evidence to support the conclusion that diminishing performance increases are due to a lack of available rainwater. An SCE of 91% is reached with an S_f of 0.02, meaning that 91% of all harvested rainwater is used to satisfy demand whereas only 9% leaves the system as spillage. Although the SCE is high, the corresponding water savings efficiency is only 40% - as a consequence, 60% of demand is met by the supply from the mains at a considerable expense.

In the centralised system, an S_f of 0.02 equates to a tank of volume 143 m^3. A centralised system at the Brabazon Hangar has the greatest potential to accommodate a single large tank. However, it is unlikely to yield a good return on investment if the supply of rainwater is insufficient. As emphasized throughout this report, the two most significant benefits of RWH systems are the non-potable water savings and flood attenuation. With a 143 m^3 tank, the reduced strain on the urban water system is beneficial, with only 601 m^3 of spillage for 6769 m^3 of harvested rainwater over a year-long period. Despite this, satisfying only 40% of non-potable demand is likely to be insufficient.

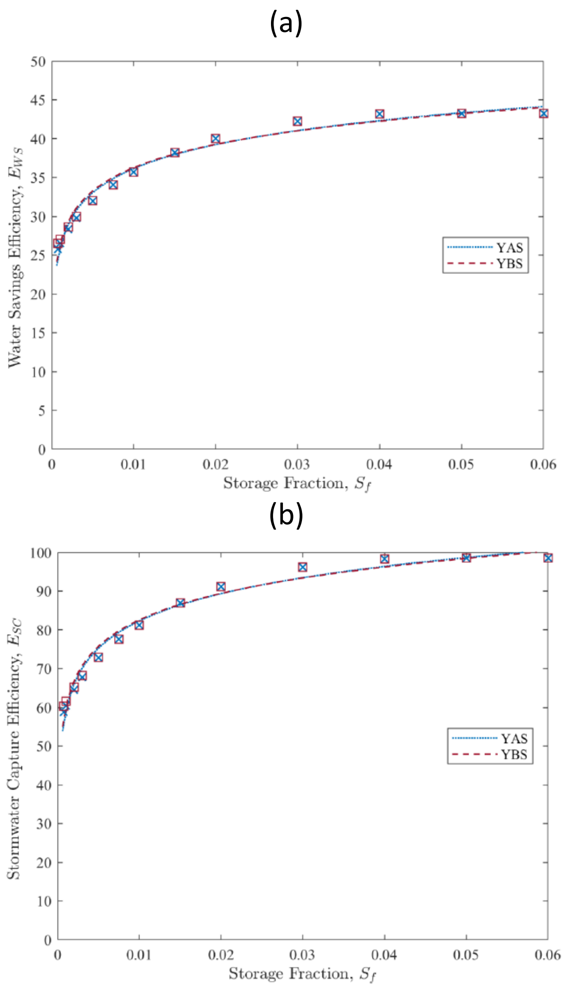

Figure 87. The variance of storage fraction with (a) water savings efficiency and (b) stormwater capture efficiency for a centralized system (Scenario 2), YAS: yield after spillage and YBS: yield before spillage.

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Results reported in Figure 87 show that the YAS and YBS algorithms produce results that are almost identical. There is some difference in performance at low storage fractions (between 0.0001 and 0.0025) where the model using the YBS algorithm yields a greater WSE and a greater SCE; however, the differences in WSE and SCE are 5% at most and decrease to 0% as S_f reaches 0.005.

Generally, the results produced by models using the YAS and YBS algorithms are significantly different at low tank volumes: a YAS model will give a conservative estimate of performance whilst a YBS model will give a liberal estimate (Ward et al., 2010b). However, as the temporal resolution of rainfall and demand data increases, the difference between YAS and YBS performance decreases. In the YBS algorithm, yield may be drawn from the spillage volume – this assumes that the spillage volume at each timestep is available to satisfy yield insofar as it occurs within the same timestep. This is a questionable assumption, since in real world systems, harvested rainwater will leave the system as spillage instantly if the tank is full. The validity of this assumption is poor for data with a large timesteps since the spillage volume has longer to accumulate, therefore it has greater potential to be used as yield. At smaller timesteps this potential is reduced and therefore the difference between the tank levels at the end of each timestep (due to the YAS and YBS models) is lessened. In this report, daily rainfall levels for 2018 were used in conjunction with hourly water demand volumes. To address the mismatch in temporal scale, the model averages the daily rainfall values equally across 24-hour long segments. By artificially reducing the timestep of the rainfall data by a factor of 1/24 to correspond to the hourly demand data, the difference between the tank levels (due to the YAS and YBS algorithms) at the end of each timestep is greatly reduced. At an hourly temporal scale, the models perform similarly, as evidenced in Figure 87.

To show the effect of an increased temporal scale on performance, Figure 88 reports the water savings efficiency for YAS and YBS models using daily demand and rainfall data. At low storage fractions (small tank volumes) the YBS model clearly outperforms the YAS model, with a water savings efficiency of 52.8% compared to 32.4% at a storage fraction of 0.15×10^{-3}. This 20.4% performance difference is significant and equates to a water savings of 3144 m^2 over the course of a year. Despite this saving, YAS performance sharply increases between storage fractions of 0.15×10^{-3} and 0.5×10^{-3}, eventually matching YBS performance at $S_f = 0.75 \times 10^{-3}$. Over this range there is an increased likelihood that the tank is full – this has a more adverse effect on a YAS system since the spillage volume is completely lost, whereas a YBS system can recoup some of the spillage volume as yield. Beyond $S_f = 0.75 \times 10^{-3}$ this effect diminishes, as tank size increases and thus the likelihood of a full tank is reduced, which reduces the propensity of large and frequent spillage volumes.

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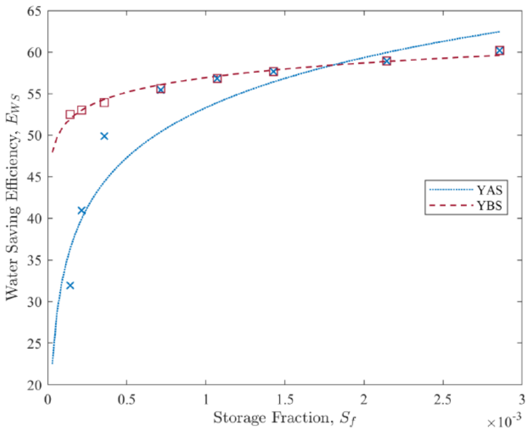

Figure 88. The variance of storage fraction with water savings efficiency for daily rainfall and demand data highlighting the effect of time step on YAS and YBS performance. The relationships between S_f and WSE for the YAS and YBS models are approximated by logarithmic functions with R^2 values of 0.88 and 0.97 respectively.

Although scenario 3 refers to the centralised system with a roof of the central YTL Arena, like scenario 2, the effect of storage fraction (S_f) on WSE and SCE was analysed only for toilet flushing purposes (Figure 89).

As expected, all three indicators increased with tank size. When demand consisted of only a toilet, the maximum WSE that could be achieved if all rainfall was utilized was 53.47%. For a storage fraction of 0.002 (14.14 m^3), WSE was close to maximum with 53.42% (Figure 89 (a)). This is due to only 9.66 m^3 of water spilling from the tank over the year. A storage fraction of 0.0015 (10.6 m^3) showed little change, with a WS efficiency between 53.14% and 52.85%. It is when a fraction of 0.001 (7.07 m^3) is used that WSE begins to quickly drop. Efficiency falls to between 51.69% and 50.71%. Whilst this may not seem significant, this is a loss between 217000 and 340000 L when compared to a fraction of 0.002. Any lower than 0.001 and the efficiency drops significantly, ruling out a tank size below 7 m^3. For SCE as shown in Figure 89 (b), a fraction of 0.001 also seemed to be the point at which the indicator begins to drop substantially. The SCE values dropped between 3.2% and 5%. This means a tank size of 7.07 m^3 could prevent up to 335 m^3 less rainwater reaching the stormwater drainage every year.

The optimum tank size, using the above performance indicators, lies between 7 m^3 and 10 m^3. Any higher than 10 m^3, the extra capital and operating costs of a larger storage tank will yield little benefit to the efficiency and reliability of the system. If smaller than 7 m^3, the performance will drastically decrease, and accuracy of results will become uncertain due to YAS and YBS differences. Using rainfall data from the stochastic model, the optimal size seems to be around 9 m^3.

(a)

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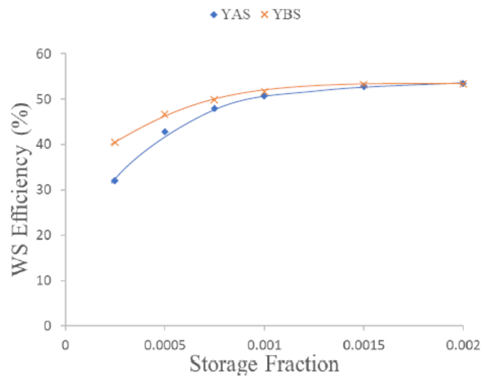

(b)

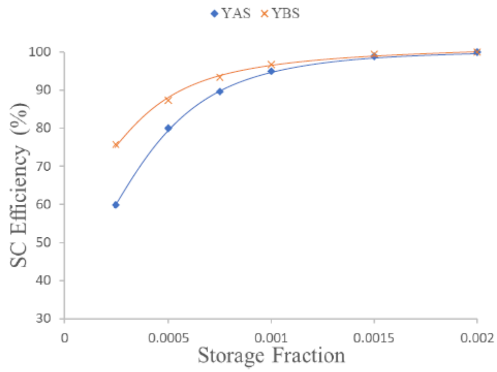

Figure 89. Performance indicators against storage fraction and water reuse only for toilet flushing within 278 housings (a) water savings efficiency and (b) stormwater capture efficiency (Scenario 3), YAS: yield after spillage and YBS: yield before spillage.

RWH system for commercial application - scenario *4*

Figure 90 (a) illustrates the impacts of the toilet flushing scenarios (TF_{YA1}, TF_{YA2}, TF_{YA3}, TF_{YA4}) on the WSE of the RWH system with the storage capacity varying from 100 to 2,000 m^3. For toilet flushing (TF_{YA1}, 22 m^3/day), when the storage capacity exceeded 800 m^3, the WSE of the RWH system remained constant, with a WSE of 98.3%. However, for a tank between 400 and 800 m^3, the WSE of the system was between 21.8% and 42% for TF_{YA3} and TF_{YA4} (108 - 216 m^3/day). However, for TF_{YA2} (54 m^3/day), when the storage size exceeded 1,800 m^3, the WSE of the RWH system was 79.8%.

For irrigation, the use of rainwater for different irrigation areas was assumed: 50% and 100% for the Brabazon Park (BP, IR_{BP1} and IR_{BP2}) and the Filton Golf course (FG, IR_{FG1} and IR_{FG2}). For a tank size of less than 800 m^3, the WSE of the system varied from 12.7% to 42% for $IR_{BP1,}$ showing the most sensitive to the storage capacity and followed by IR_{BP2}, IR_{FG1} and IR_{FG2}. However, when the storage size exceeded 800 m^3, the WSE of the RWH system remained constant between 7.2% and 14.1%, depending on the water demand (580-1 159 m^3/day) for IR_{FG1} and IR_{FG2} as shown in Figure 90 (b). Similarly, for IR_{BP1} and IR_{BP2} (151-302 m^3/day), the WSE of the RWH system for a 1,000 m^3 tank was between 25.7-46.1%. However, when considering the tank's infinite capacity, the WSE was between 33.7% and 67.4%, depending on the water demand. Although a higher WSE was achievable from the system with a large storage tank, such a large capacity would increase the installation costs (Umapathi et al., 2019), hence 1,000 m^3 is the maximum tank size which maximises the WSE of the system for this application.

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For the combined use of toilet flushing and the irrigation of BP (Figure 90 (c)), at a threshold value of 800 m^3, the WSE showed 24.1% and 25.6% for different ratios: 70:30 (242 m^3/day) and 50:50 (259 m^3/day), whereas for the combined use of toilet flushing and the irrigation of the FG, the storage capacity exceeded 600 m^3, and the WSE varied between 11.8% and 14.7%, depending on the water demand (499-688 m^3/day). These results suggest that the WSE of the RWH system is highly influenced by the water demand scenarios. They further suggest that the threshold value ranged from 400 to 1 000 m^3, depending on the water demand scenarios. As a result, a storage capacity of 400-1 000 m^3 can be perceived as the optimal size for all scenarios considered in this study.

The results in Figure 90 indicate that the WSE of the RWH system for this application can be enhanced by controlling the water demand scenarios, suggesting the importance of the water demand profile for the design and operational parameters of the RWH system. Larger rainwater storage volumes result in less overflow and more yield, hence a higher WSE of the RWH system. In contrast, smaller storage tanks limit the collection of rainwater, resulting in more overflow and less yield, hence a lower WSE of the RWH system. In this regard, the huge roof area of the arena requires a large storage tank, which could enhance the WSE of the RWH system and reduce consumption from the water mains, albeit at higher capital and operational costs (Silva et al., 2015; R. Wang & Zimmerman, 2015). In this analysis, the WSE of the RWH system with different water demand scenarios was evaluated using the historical rainfall data. These results affirm the significance of the water use profiles in the performance of the RWH system. However, changes in future rainfall patterns due to climate change need to be considered in the design and optimisation of the system, as the impacts of rainfall changes on the WSE of the RWH system are significant (S. Zhang et al., 2018).

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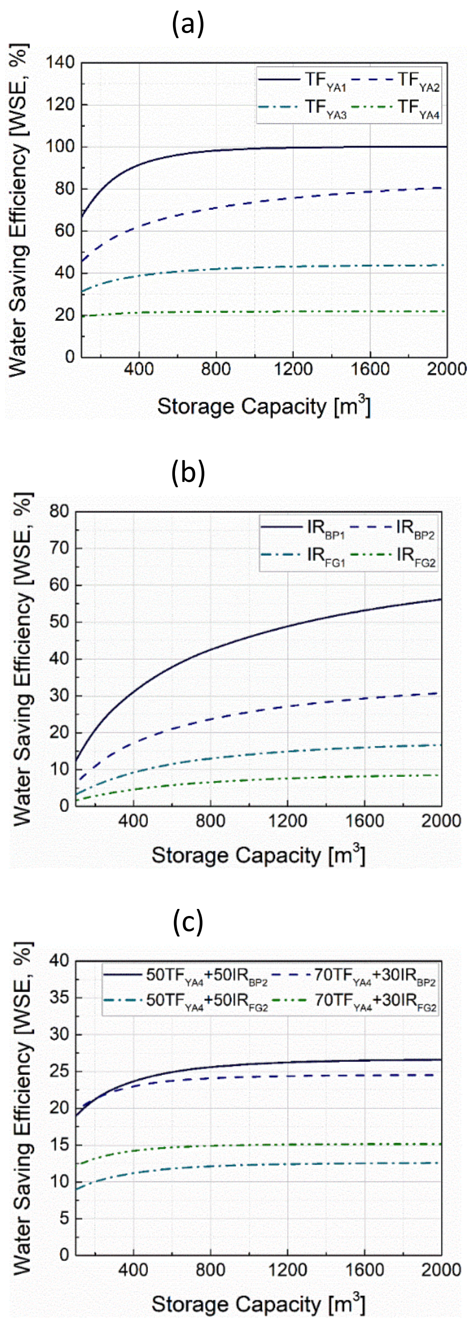

Figure 90. Variations of water saving efficiency values as a function of storage capacity for single and combined use scenarios (a) YA toilet flushing with varying numbers of visitors (b) irrigation: BP and FG and (c) combined use: YA toilet flushing + Irrigation.

4.2.7. Comparison of baseline situation and NextGen KPIs

In Filton Airfield, the NextGen technology for water reuse considered a rainwater harvesting system consisting of a catchment area, conveyance system, storage system, and distribution system. In terms of rainwater recovery, the relevant KPIs were: (1) the real rainfall measurement and (2) the amount for proper purposes. Table 86 in Annex 2 presents the real rainfall quantity analysis in Filton collected during the NextGen project (daily basis, started

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from September 2019) and rainfall data obtained from weather stations close to the Filton site. These data have been used to demonstrate a rainwater harvesting system in Filton Airfield. Thus, Table 66 further compares baseline situation and NextGen. The baseline situation refers to the existing cases implemented in the UK and has offered some solutions to determine the optimum storage capacity for utilising rainwater harvesting at residential or commercial buildings by taking into account optimizing variables, including cost, reliability, water saving efficiency, green roofs irrigation and runoff capture (An et al., 2015; Bocanegra-Martínez et al., 2014; Okoye et al., 2015; Ruso et al., 2019; Sample & Liu, 2014; Ward et al., 2012). It is important to note that more accurate results can be obtained if real rainfall data from Filton Airfield and future rainfall events become available on climate change. It is therefore expected that the findings drawn from this study will be compared with post-installation monitoring data on the actual performance of the RWH system within the YTL Arena and residential area in the near future, thus promoting the acceptance of RWH in urbanization schemes as a sustainable water management strategy.

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Table 66. Baseline and NextGen studies on rainwater harvesting case studies in the UK (RainHarvesting, 2019; Ward, 2007).

Building types	Name/Location/Completion	Application	Catchment Area [m^2]	Estimated usage [L/day]	Average annual rainfall [mm]	Tank Size [m^3]	Water Savings Potential [%]	PBP (yrs.)	Remark
RB	Social Housing Cheltenham/2013	TF	600	500	716	18	NA	NA	✓ 11 Houses and 2 flats ✓ Centralized Controls ✓ To reduce mains water consumption ✓ Client: Markey Construction for Cottsway Housing Association
	Browning's Close Social Housing/Gloucestershire/2012	TF	300	400	800	10	NA	NA	✓ 7 Houses ✓ To reduce environmental impact ✓ To achieve sustainable homes ✓ Client: Markey Construction for Cottsway Housing Association
	South West Eco Homes/Langport, Somerset/2006	TF, IR	792	1248	800	1.5	NA	24	✓ 12 Houses ✓ To reduce mains water consumption ✓ To reduce environmental impact ✓ To achieve sustainable homes
	Hanger District/Filton Airfield/Southwest	TF, IR	16288	30184	811	100	75	NA	✓ ~ 160 houses ✓ To reduce mains water consumption ✓ To achieve sustainable homes
CB	Frocester Cricket Club/Gloucestershire/2017	IR	412	NA	800	NA	NA	NA	✓ To reduce mains water consumption ✓ Client: Frocester Cricket Club

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Chesil Beach Visitor Centre/Dorset/2012	TF	200	333	800	4	NA	NA	✓ To reduce mains water consumption ✓ 5WCs and 2 urinals
Cheltenham West Fire Station/ Gloucestershire/2012	TF, CW	800	860	800	18	NA	NA	✓ To reduce mains water consumption ✓ Client: Glos. Fire & Resc ue Service
Dolygaer Mountain Centre, Merthyr Tydfil/2012	TF	171	626	1435	10	NA	NA	✓ To reduce mains water consumption ✓ Client: Mid Glamorgan Area Scout Council
Cardiff Bus Depot/Wales/2011	TF, CW	500	2450	1400	26	NA	NA	✓ To reduce mains water consumption ✓ 240 vehicles: all of whic h require washing on a regular basis. ✓ Client: Cardiff Bus
Adnams Distribution Centre/Southwold, Suffolk/2006	TF, CW	4,000	NA	550	35	NA	NA	✓ To reduce environment al impact ✓ Sustainable building de velopment ✓ Client: Adnams Brewer y
RSPB Education Centre Rainham Marshes/Essex/2006	TF	400	450	550	6	NA	NA	✓ To reduce mains water consumption sustainab le development ✓ Client: RSPB
Nant Yr Arian Visitor Centre/ Wales/2003	TF, BW	266	1050	1051	10	49%	8.3	✓ To reduce mains water consumption
YTL Arena/Filton Airfield	TF	13000	91866	811	100	21%	NA	✓ To reduce mains water consumption
	TF, IR	30000			600	10-42%	10-11	

RB: residential building, CB: commercial building, TF: toilet flushing, WM: washing machine, IR: irrigation, CW: car washing, BW: bike washing, PBP: payback period, NA: not available

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4.2.8. Lessons learned

Required competence	LOW ▲ HIGH
▪ Motivation, commitment, incentive and level of awareness are critical factors in the operation and maintenance of rainwater harvesting systems. ▪ Participatory training including a workshop on rainwater harvesting in the community and technical advice or the 'know how' will be provided to inter-connected social and technical aspects of urban water management systems.	
Maintenance	LOW ▲ HIGH
▪ **Rainwater harvesting system (50-year lifetime):** maintenance and replacement **(Roebuck et al., 2011; Roebuck & Ashley, 2007; R. Wang & Zimmerman, 2015)** ○ Inspection, reporting and information management — 2 year ○ Roof washing, cleaning inflow filters — 2 year ○ Tank inspection and disinfection — 1 year ○ Intermittent system maintenance (system flush, debris/sediment removal from tank) — 3 year ○ Pump replacement — 10 year ○ Minor fittings replacement — 10 year ○ Filter replacement — 15 year - *Also see Best practice guidelines for implementing the system below.*	
Technological risks	LOW ▲ HIGH
▪ Unpredictable rainfall – storage limits ▪ Regular maintenance – mosquitoes, algae growth and insects	

4.2.9. Best practice guidelines for operating the technology

- Rainwater harvesting system (for above ground tanks):
  - Roof
  - Gutter
  - First flush devices
  - Down pipe
  - Tank cover and screen
  - Storage tank
- The followings are the elements of the system and their design specifications that should be considered:
  - Considerations for selecting an appropriate location for rainwater tanks (BASIX, 2015; UWCS, 2018):

Considerations	Actions

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Roof area	- Most roof materials are acceptable for collecting rainwater unless otherwise the water is for drinking water purpose. - The minimum roof area: o 50% of the roof area – the larger the roof catchment area, the greater the potential for harvesting rainwater - Ensure that roof areas should be free from any overhanging vegetation and tree branches
Location on site	- Identification and consideration of the constraints of a particular location o e.g., boundary setbacks, neighbours, window views and easements, etc., depending on a property constraints plan. - Rainwater tanks should be located where the roof area catchment can be maximised. - Underground rainwater tanks can be considered to satisfy site constraints.

- **Maintenance of rainwater harvesting systems (UN, 2004):**

Elements	Actions	Frequency
Roof	- Wash off roof with water	- Check monthly and especially after long period of dry weather and heavy wind.
	- Replace rusted roofing.	- When needed.
	- Repaint (if rust is present) using lead-free paint.	- When needed.
Gutter	- Clean and washout bird droppings, leaves etc. with water.	- Check monthly and especially after a long period of dry weather and heavy wind.
	- Check and repair/replace gutters.	- When needed.
	- Install more guttering to increase rainwater collected.	- When possible.
	- Ensure guttering is slanted to ensure steady flow of water avoid pooling of water collection of dirt, debris, etc.	
Tank	- Cleaning	- Once a year
	- Check and repair leaks	- When needed.
	- Disinfect (e.g. chlorination and ultraviolet)	- When needed.
	- Cut nearby tree roots	- When needed.
	- Ensure lid is sturdy and secure to prevent leaves, animals and dirt.	- When needed.
Downpipe	- Repairing holes and replace if screen is fouled or blocked	- When needed.
	- Ensure there are no gaps where insects (e.g., mosquitoes and flies) can enter or exit.	- When needed.
	- Check and repair leaks at elbows.	- When needed.
Overflow	- Securely fasten mosquito screen over the end of the overflow pipe/valve.	- When needed.
	- Ensure there are no gaps where mosquitoes can be present.	- When needed.
	- Check and repair insect screen if damaged	- When needed.

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5. Aquifer storage systems

5.1 Aquifer storage and recovery systems in Westland (NL)

Authors: Jos Frijns, Sija Stofberg, Henk Krajenbrink, Dimitrios Bouziotas, Marcel Paalman, Klaasjan Raat (KWR)

5.1.1. Description of the demo site

In this document the results of the NextGen activities *sub-task 1.2.1 Demonstration of integrated management of alternative water sources* for the demo case (#3) *Westland Region* are described. For the transition towards a more circular water system in the Delfland region, an integrated assessment of performance of technologies and strategies is done. The scenarios include:

- rainwater harvesting through aquifer storage (Aquifer Storage Recovery or Water Banking)
- the reuse of municipal WWTP effluent for horticulture
- circular urban water management systems.

The Westland Region in the Province of South Holland, the Netherlands, includes dense urban and industrial areas and greenhouse horticulture complexes. Spanning in a total area of 410 km^2, the region is one of the most densely populated spaces in the Netherlands, with approximately 1.2 million inhabitants living and working in a total of ca. 0.5 million households and 40,000 businesses and industries.
Westland is well known for its greenhouse horticulture, where mainly vegetables (tomatoes, peppers, cucumbers etc., mostly on hydroponics), flowers and potted plants are grown. The geographical scope of NextGen's activities is Delfland (which is similar to the area of the Water Authority of Delfland) and contains the Westland horticulture area and other rural areas and part of the urban regions of Rotterdam, Delft and The Hague (Figure 91).

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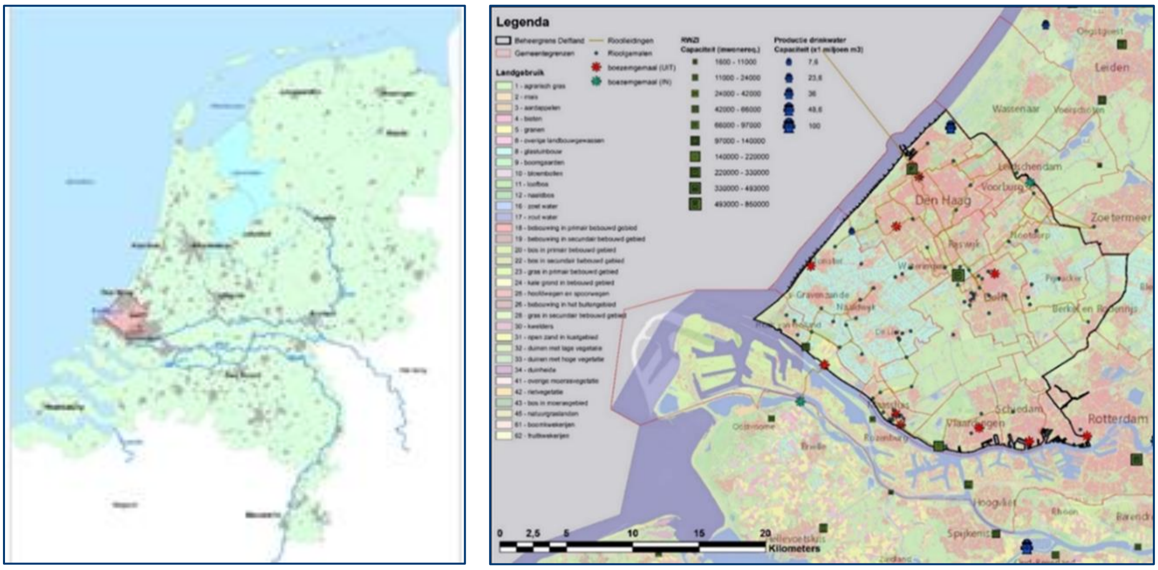

Figure 91. The Delfland area, including the Westland horticulture (blue), rural (green) and urban (red) areas.

The water system

The Delfland region consists mainly of lowland polder areas, with a narrow dune strip at the North Sea coast in the west. In the south, the region borders the Nieuwe Waterweg estuary. In the north and east, the region borders the regions of other Water Authorities that can be characterised as lowland polder areas as well. The area is mostly covered paved areas, including cities (of which The Hague, Rotterdam and Delft are the largest), greenhouses and industry. Unpaved areas mainly consist of pastures (some of which are considered nature areas as they are a habitat to birds) and the dunes. The Delfland region receives about 850 mm/year precipitation and has a yearly average precipitation surplus.

The surface water system of Delfland is characterised as a typical polder system, mainly consisting of drainage ditches and canals in which the levels are kept constant by pumping out the water, eventually discharging into the Nieuwe Waterweg or the sea, or supplying water from the Brielsemeer, which receives fresh water from the river, and is connected to Delfland with a pipeline. Pumping out water is necessary due to surface water level rise after precipitation events (rain storms) and groundwater seepage. Water supply is needed when water levels fall due to evapotranspiration (precipitation deficit), and in some cases also to prevent salinization of the surface water (due to brackish groundwater seepage).

The subsurface consists of several aquifers that are separated by clayey aquitards. The groundwater is brackish to saline as a result of marine transgressions in the past (geologic time scale). Therefore, the groundwater in the Delfland region is predominantly brackish/saline and is in the range of about 200 – 6000 mg Cl/L (about 1/3 of the salinity of sea water). In some parts of the region, brackish seepage towards the surface water occurs. Groundwater salinization is expected to increase in the future as a result of climate change, sea level rise and surface subsidence.

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Water management

Drinking water provision

Drinking water is provided by the drinking water companies ***Dunea*** and ***Evides***. Both produce drinking water from river water from outside the Delfland area. This water is temporary stored beneath the sandy dunes along the shore or into large water basins. The raw water is purified and transported as drinking water to the households, industries etc. In general, the drinking water is of high quality and is not chlorinated. The average total drinking water demand is 77.4 million m^3/y.

Urban water management and sewerage

In the urban areas (Rotterdam, The Hague, Delft), water level management is in place for flood prevention. Surplus of water during extreme rain events is quickly discharged through the sewage water system towards the rivers. The municipalities are responsible for the collection and discharge of stormwater and wastewater to wastewater treatment plants (WWTPs) in a mixed or separate sewer system.

Municipal wastewater treatment

The Delfland Water Authority operates four wastewater treatment plants (WWTPs) that treat and discharge the effluent in the river or sea: Houtrust in The Hague, Harnaschpolder in Midden-Delfland, Nieuwe Waterweg in Hoek van Holland, and Groote Lucht in Vlaardingen. The average total wastewater discharged is 129.6 million m^3/y.

Surface water management

To keep surface water levels constant, and to maintain a good surface water quality, water is discharged during periods of precipitation surplus and supplied during periods of precipitation deficit (usually during summer months). The responsible authority is Hoogheemraadschap van Delfland.

Regional water management

The Province of South Holland is responsible for water policy and the implementation of EU Directives (such as the Water Framework Directive, Groundwater Directive, Drinking Water Directive, etc) in a regional water programme. This programme also addresses policies regarding freshwater supply, flooding and water recreation.

Irrigation water for horticulture

The horticulture companies of Westland use between 3,000 – 10,000 m^3 water per ha per year, depending on the crops grown (in total about 20 Mm3/y). Vegetables such as tomatoes and peppers use about 10,000 m3 per ha per year. Precipitation is the main source of irrigation water. However, some crops demand more water than can be collected, and storage basins have a limited capacity, additional water is needed, even though water use is minimised by recirculation of irrigation water and recovery of transpired water. Therefore, additional irrigation water is produced from brackish/saline groundwater desalination by reverse

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osmosis (RO). The RO concentrate (brine) currently is discharged by infiltration into deeper brackish/saline aquifers. However, groundwater abstraction and desalination is not environmentally sustainable, causing land subsidence and groundwater salinization due to the brine discharged into aquifers. Currently, brine emissions regulations are under discussion, and as a result, alternative irrigation water sources are being considered, including drinking water, surface water, WWTP effluent, and (surface and subsurface) rainwater storage (Scholten, 2021).
There are 1291 greenhouse units in Westland in an area of 2431 ha. The leading entrepreneurial network in the Dutch greenhouse horticulture sector is Glastuinbouw Nederland.

State of play at the start of NextGen

Water uses in greenhouses
Horticulture uses rainwater (collected in shallow basins) for irrigation, but in times of shortages this is supplemented with brackish groundwater (desalinated by RO). The total yearly water demand is about 21.4 Mm^3, of which 17.6 Mm^3 is rainwater and 3.8 Mm^3 is desalinated groundwater. The horticultural companies prefer the use of rainwater as irrigation water sourced. The water quality criteria are high, as the sodium concentration in the irrigation water has to be below the 0.5 mmol Na/L (approximately 10 – 15 mg Na/L) to allow for recirculation of irrigation water. This means that in practice, rainwater is the only water source which satisfies these criteria without further treatment. Other water sources would have to be desalinated by reverse osmosis.

To harvest and collect the rainwater, the horticulture companies make use of water basins. The average size of the water basins is about 800 m^3/ha (= 80 mm/ha). As water demand of most crops is not constant over the year (peaking in summer, Figure 92), this means that only part of the annual rainfall (average 845 mm) can be effectively captured. However, in periods of rainwater shortage, the farmers use brackish/saline groundwater as an additional water source. This water is desalinated by reverse osmosis (RO). The freshwater fraction is used as irrigation water, whereas the membrane concentrate is discharged into a deeper aquifer. Depending on the background salt concentrations in the aquifer, this may lead to locally increased salt concentrations. The extraction of groundwater from the shallow aquifer is associated with salinization, as it can lead to upconing of deeper, more brackish groundwater (local salinization) as well as to increased groundwater flow inland from more brackish coastal groundwaters (regional salinization). The extraction of groundwater and discharge of membrane concentrate into the subsurface is from an environmental and political point of view under discussion, as salinization is undesirable.
As an alternative, ***Aquifer Storage Recovery (ASR) systems*** can temporarily store the excess of rainwater (winter) in an aquifer so that it can be recovered in the summer period as irrigation water. Besides a pilot study, no ASR systems are currently installed in Westland.

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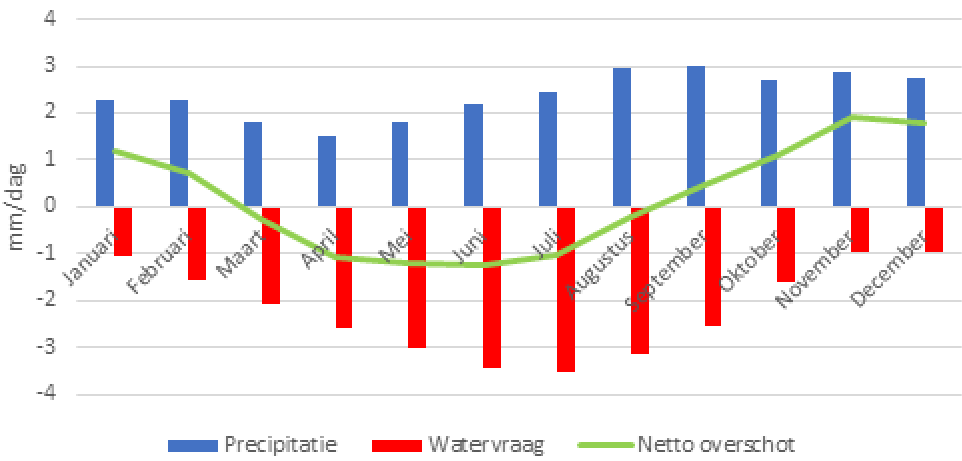

Figure 92. Precipitation (blue) and water demand (red) for the horticultural sector in the Westland region in mm per day, divided over the months in an average year. The green line is the difference between precipitation and demand.

Due to the large greenhouse areas and limited space in the rainwater collection basins, large rainfall events often result in basin overflow into the surface water. For the Delfland Water Authority, it becomes increasingly difficult to prevent flood risk. One of the measures they implemented is the RainlevelR programme. Horticultural companies that participate in the RainlevelR voluntarily discharge basin water into the surface water before a rainfall event occurs, to provide storage space for the coming rainfall event. At the moment a relatively small number of companies participates in this collaboration, but the authorities aim for an 80% participation rate in the future.

Water recycling and wastewater treatment in greenhouses

Inside the greenhouses, water is recirculated, evaporated water is condensed, and emission of nutrients and pesticides is minimised. The water use in the horticulture greenhouses is very efficient. About 85% of the horticulturalists cultivate crops on substrate water basis. The roots of the plants are 'connected' with the water system of the substrate cultivation. The irrigation water is recirculated continuously, nutrients are added when required and the water is disinfected by UV radiation. The water is drained when sodium concentrations exceed the limit of 0.5 mmol Na/L.

The surface water quality in especially the Westland horticulture region is poor and polluted with too many nutrients and pesticides (also called plant production products (PPPs). In order to improve the water quality, the horticulture farmers are obliged by law (from 2018 with 1-1-2021 as deadline for collectives) to purify the drain water to achieve a reduction in the emission of pesticides by at least 95% (and a near to zero emission target of nutrients and pesticides in 2027). Some horticulture companies will use activated carbon as single treatment to remove some specific organic trace compounds, or carbon coupled to Activated Oxidation Process (AOP) UV/O_3UV/O_3(see Figure 93).The horticulturalists can either treat their wastewater themselves, combine treatment in collaboration with other greenhouses (e.g. de Vlot), or as part of the collective treatment at a municipal WWTP. In 2020 initiatives were taken to install an additional treatment step (O_3) at WWTP Nieuwe Waterweg (Hoek van

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Holland) at a collective wastewater treatment facility for Westland horticulture, but this is currently under discussion (related to bromate formation during ozonation).

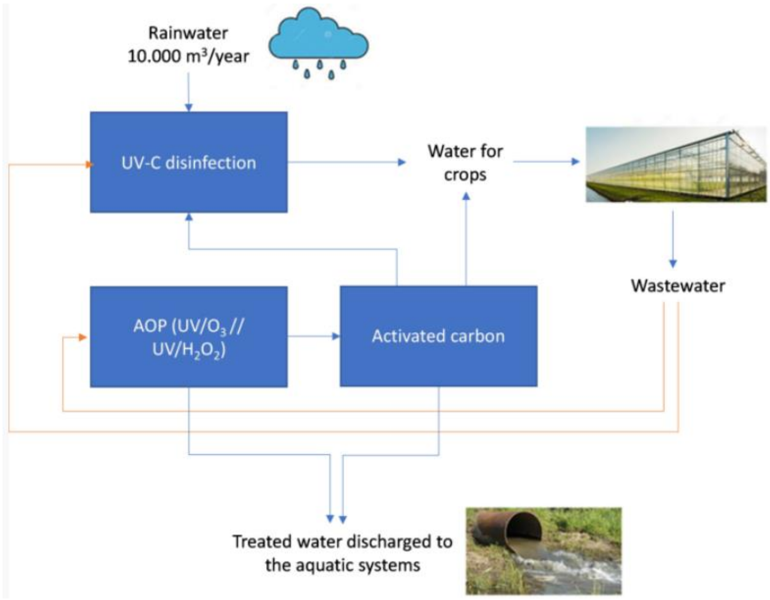

Figure 93. Simplified diagram of activated carbon process coupled to Acticated Oxidation Process (AOP).

Block diagram of the pre-existing treatment scheme in horticulture

In the current greenhouses water, gas, and power are utilised as shown in Figure 94.

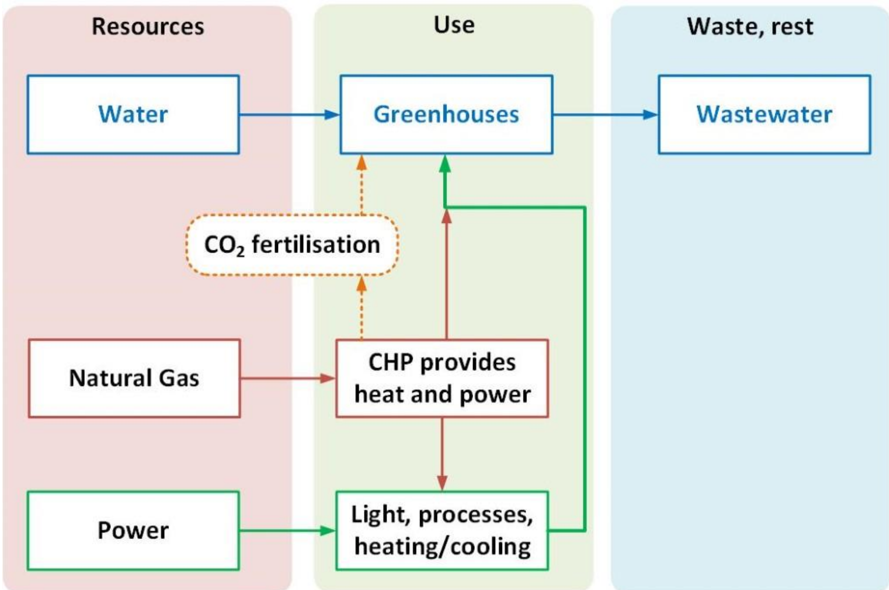

Figure 94. Diagram of the current system of Westland horticulture.

Current situation urban area Delfland region

All households in the cities of Rotterdam, The Hague, Delft and other areas are provided with good quality drinking water, are connected to the sewer, and all wastewater is treated in the municipal WWTPs.

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The urban areas are increasingly facing temporary flooding caused by heavy rainfall or water shortages due to longer drought periods. The conventional solutions aim to rapidly discharge the water and to supply water from external sources, but both approaches are unsustainable. Initiatives are taken to harvest and store rainwater in the underground, e.g. in aquifer storage & recovery systems. For example, at Spangen Rotterdam, the rainwater from the roof of the soccer stadium is stored and reused in an urban water buffer.

The municipalities and the water utility Evides additionally carry the additional responsibility of also addressing water scarcity. As such, fit-for-purpose water use, by replacing drinking water by rainwater or greywater within the urban planning programme of requirements, is being considered.

Municipal wastewater is treated at the 4 WWTPs, with advanced treatment systems including biogas production and nutrient recovery.
At the WWTP Groote Lucht, an additional wastewater treatment step of was investigated in a so-called freshwater factory. However, plans changed due to the problem of bromate formation during ozonation. Currently other techniques to enable the reuse of treated wastewater are under consideration.
At the WWTP Nieuwe Waterweg (Hoek van Holland), a fourth treatment step has been proposed to remove micropollutants from urban wastewater and plant productions products from the collective wastewater from Westland greenhouses. Like in Groote Lucht, plans here changed due to the problem of bromate formation during ozonation and other techniques to enable the reuse of treated wastewater are under consideration.
At the WWTP Harnaschpolder, the possibilities for treatment and use of effluent for the water system and horticulture have been investigated (Delft Blue Water).
At the WWTP Houtrust, biogas from sludge digestion is converted to natural gas quality (green gas), and CO_2 is liquefied, which can be used in horticulture and the food and beverage industry.

5.1.2. Motivation for implementing circular economy solutions in the water sector

The Province of South Holland aims to develop strategies towards wiser, more circular water management in the coming decades, in light of challenges such as a variable climate and changing population. Within the Westland Region, various projects, activities, and initiatives are already running that contribute to the objectives that have been set at national and provincial level, and by the Hoogheemraadschap Delfland and the municipality of Westland. The report 'Delfland Circular', written by Dijcker et al. (2017) on behalf of Hoogheemraadschap Delfland, states that there is still a lack of an integral and overarching strategy, with which an optimal mix of cost-effective measures can be realized together with improved environmental conditions . It is important to develop such a strategy because different objectives can sometimes be conflicting with each other when closing material, water, and energy cycles (for example, it takes energy to recover raw materials), and therefore considerations must be made with regard to these trade-offs.

The NextGen assessment addresses the following circular water technologies:

- Aquifer Storage & Recovery (ASR) / water banking systems and reuse of WWTP effluent for the horticulture sector
- circular urban water management solutions (rainwater harvesting, grey water recycling green roofs and domestic water saving)
- High Temperature - Aquifer Thermal Energy Storage system (HT-ATES) for the horticulture.

For the horticulture company in Westland (Figure 95), alternatives to improve the water and energy system in the horticulture sector are demonstrated by rainwater storage and effluent reuse (subtask 1.2.1, this report) and by High-Temperature Aquifer Thermal Energy Storage (HT-ATES) at the horticulture company Koppert Crest (subtask 1.3.5).

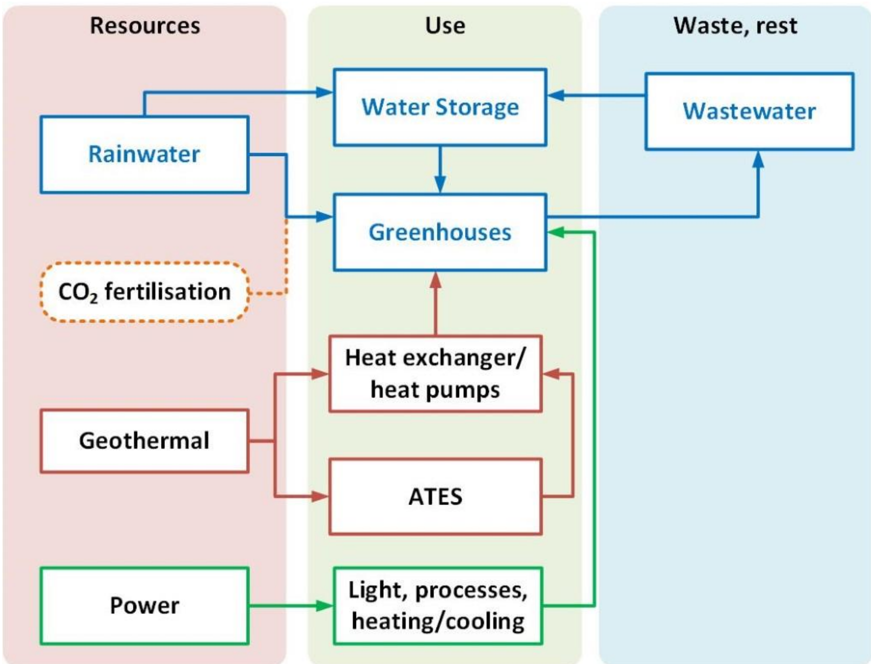

Figure 95. Diagram of the NextGen system for Westland horticulture.

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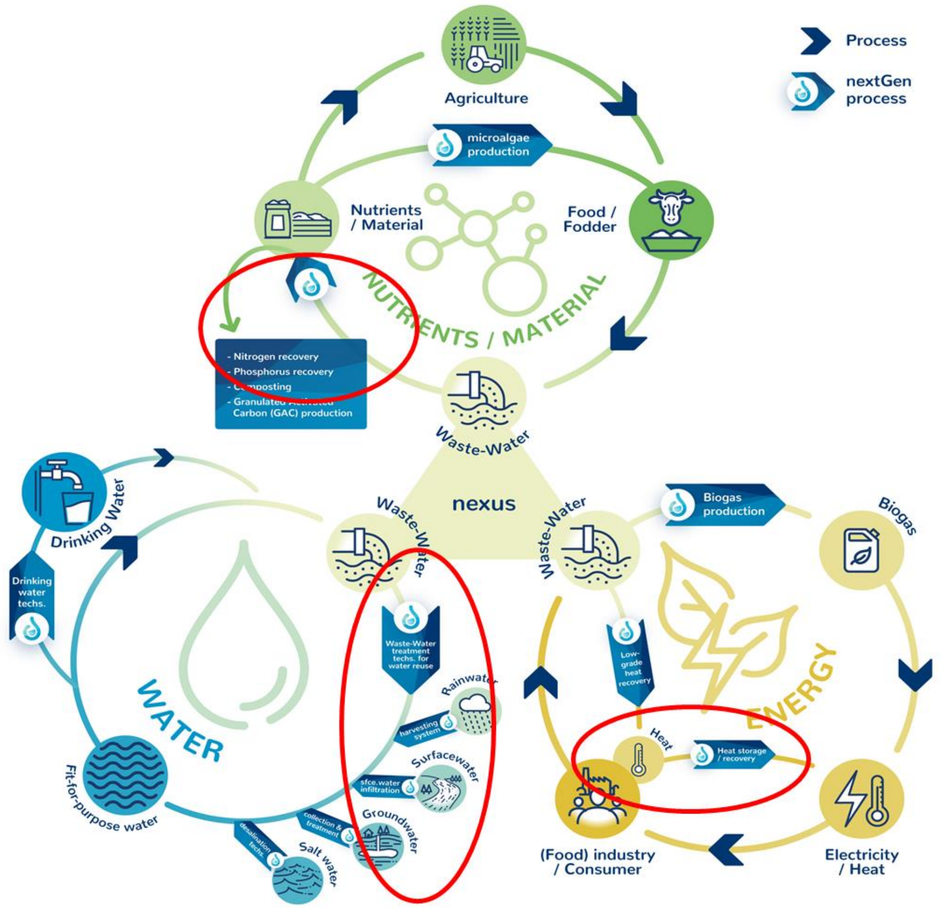

Figure 96. Westland Water in CE nexus

The key focus of the Westland demo case is not the demonstration of a particular technology at a specific location, but the demonstration of a circular water system at the Delfland region, building on existing circular initiatives spread over the region. NextGen provides an integrated assessment and scenario study of circular water systems.
In this WP1 report on technology demonstration, emphasis is put on the feasibility of ***ASR technology*** as a central concept in the integrated management of alternative water sources for the Westland Region.

5.1.3. Actions and CS objectives

The main objective of the Westland demo case is the demonstration of an integrated approach for a circular water system in the Delfland region.

The following actions have been undertaken:

1. Assessment of the feasibility and potential of the use of alternative water sources for the horticulture sector, through:
   - region-wide rainwater storage and reuse using large scale Aquifer Storage & Recovery / water banking systems
   - reuse of municipal WWTP effluent

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2. Modelling of circular scenarios for a more closed regional water system, including:
   - alternative water sources for horticulture: rainwater harvesting through ASR / water banking and the reuse of WWTP effluent
   - circular water measures for urban areas: rainwater harvesting, grey water recycling, green roofs and domestic water saving

Summary table

Table 67. Technical details for Westland demo case according to water components

Demo case	Subtasks	Technology baseline	NextGen intervention in CE for water sector	TRL	Capacity	Quantifiable target
#3 Westland region	1.2.1 Integrated management of alternative water sources	Pilot set-up	Aquifer Storage systems: ASR / water banking	For ASR: TRL 7/8 → 9 For water banking: TRL 7	8500 m^3/ha/year of rainwater stored	Irrigation water produced from rainwater (ASR / water banking) (Mm3/j)

5.1.4. Unique selling points

Aquifer Storage & Recovery (ASR) systems harvest and collect rainwater to later inject it to the aquifers aiming to replenish them, to store freshwater in aquifers, and to reuse it for beneficial purposes (e.g. irrigation). These systems aim to avoid aquifer salinization as well as to improve the quantity of available water used for different applications.

Unique selling points of ASR

- Ecosystem services - ASR makes use of the natural conditions of the subsurface to store water of good quality.
- Limited use of aboveground space and applicable in built areas.
- The subsurface provides space and time to store large quantities of water, to balance water supply and demand over time.
- Relatively simple technique and low (energy) costs.
- Water banking is an economic mechanism that makes it possible to pass on mitigation costs to those who actually contribute to adverse environmental impacts. Through pricing, it should promote rainwater infiltration and discourage brackish water extraction. If implemented correctly, brackish water extraction is limited by actual mitigation activities.

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5.1.5. Principal characteristics of the technology

Description of the technology

Aquifer Storage & Recovery (ASR) systems are human-made or human-enhanced natural systems that harvest (e.g. from roof) and collect (e.g. in basins) rainwater to later inject it to the aquifers to replenish them, so that freshwater can be temporarily stored in aquifers and reused for beneficial purpose (e.g. agriculture irrigation). These systems aim to improve the quantity of available water used for different applications (irrigation, drinking water, etc.). They are linked to ecosystem restoration projects. Moreover, they are cost-effective systems because of optimal use of the natural conditions (Zuurbier, 2016).

The recovery efficiency of ASR systems in saline and brackish groundwater environments could be relatively low because of mixing of the injected rainwater with the ambient brackish groundwater. From an environmental perspective it could still be beneficial to infiltrate excess rainwater, as it may help to reduce overexploitation of the aquifer, counteracting local and regional salinization. In NextGen, this water banking concept (see Figure 97), or balancing groundwater extraction with rainwater infiltration, was evaluated as a regional strategy for the Westland area.

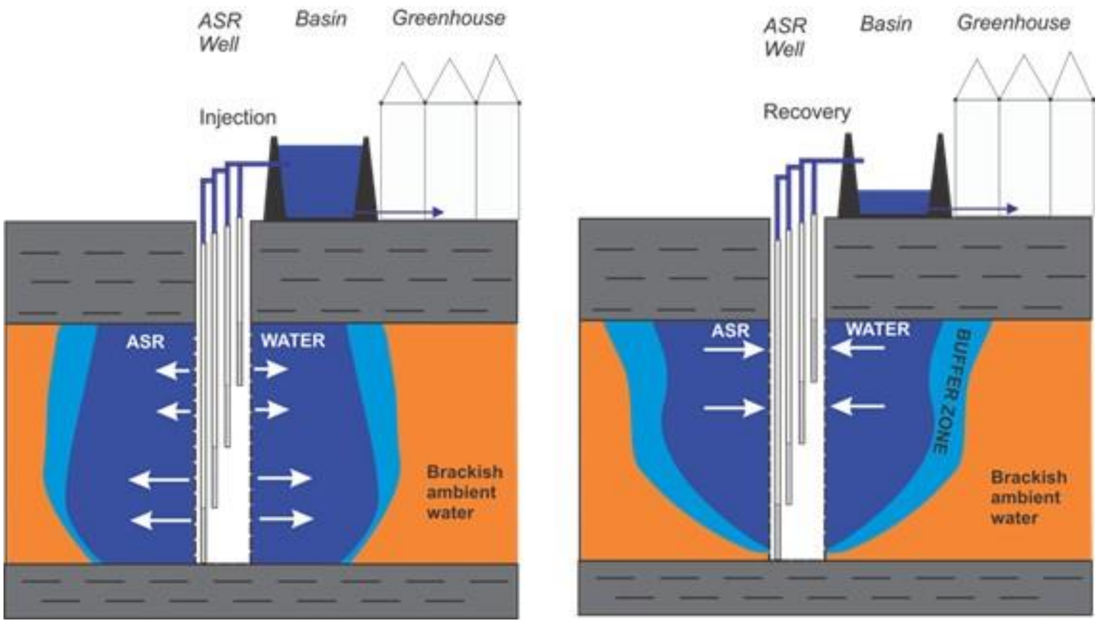

Figure 97. ASR-system.

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Synergetic effects and motivation for the implementation of the technology

Reduction of aquifer salinization and ecosystem restoration
ASR systems allows aquifers to be replenished with rainwater, which has a low electrical conductivity. Storage of rainwater in aquifers contributes to reducing the exploitation of groundwater, avoids/minimizes the saline water intrusion into freshwater aquifers, and may have a positive effect on reducing land subsidence, thus contributing to ecosystem restoration.
Reduction of the groundwater abstraction
In the proposed scheme, the recovery of the stored rainwater in summer is an effective alternative for desalination of brackish groundwater. The recovered water can later be used for several applications, including irrigation.
Balance extraction with infiltration
Water banking uses the technique of ASR to attain a net balance between groundwater extraction and rainwater infiltration on a regional scale. Groundwater extraction becomes conditional to rainwater infiltration. Overexploitation of groundwater is reduced, and salinization is reduced at a regional scale.

5.1.6. Technology implementation requirements

ASR systems can temporarily store excess rainwater (winter) in an aquifer so that it can be recovered in the summer period as e.g. irrigation water.

Most important requirements:

- Presence of a suitable aquifer for storage: good permeability, limited groundwater flow, fresh to brackish ambient groundwater, limited geochemical interactions with reactive sediments.
- The (seasonal) availability of good quality water for infiltration. Depending on the source of water (rainwater, surface water, reuse water), more advanced treatment may be required before infiltration.
- Knowledge of (intentional and unintentional) environmental effects.
- Water banking requires (besides technical/environmental conditions) a legislative system that makes it possible to set and enforce conditions for groundwater extraction. This requires:
    - Acknowledging the need for a water banking system
    - Framework of regulations, accounting of extracted and injected water, enforcement of regulations
    - Confidence in sufficient availability for future water demand
    - Financing options
    - Institutional system that links policy and investments

The specifications for ASR in Westland are presented at the beginning of the following section.

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5.1.7. Results obtained

This section presents the results obtained in *sub-task 1.2.1 Demonstration of integrated management of alternative water sources* for the demo case (#3) Westland Region. It consists of three parts:

- rainwater harvesting through aquifer storage (Aquifer Storage Recovery or water banking)
- the reuse of municipal WWTP effluent for horticulture
- circular scenarios including rural and urban water management systems.

ASR / water banking

ASR systems

Due to their intensive demands, horticulture companies in Westland currently rely on rainwater harvesting through (shallow) water basins for coverage. With an average volume capacity of 800 m^3/ha, this system is widely used but cannot cover demand peaks (particularly in the summer) and cannot store all precipitation (particularly in winter), as the storage capacity is low due to space limitations and high property prices per m^3. This results in a mean annual irrigation water demand deficit that needs to be covered using other sources. Additional freshwater for irrigation is provided from brackish groundwater extraction and desalination by reverse osmosis. This currently used practice is unsustainable, as it leads to net withdrawals from the aquifer that are associated with further salinization and, in part of the area, with subsidence. Moreover, desalination produces a residual flow of saltier concentrate (also referred to as brine) that has detrimental effects on the environment and is currently discharged via infiltration into the deeper subsurface. Infiltration of excess rainwater in Aquifer Storage Recovery (ASR) systems is an interesting sustainable alternative.

With ASR systems the excess of rainwater (winter) is temporarily stored in an aquifer (app. 20m to 40 m below surface) so that it can be recovered in the summer period as irrigation water. The rainwater is collected from the roofs and partly stored in aboveground basins. By combining aboveground basins with ASR, many companies could harvest almost all the annual rainfall (average about 8500 m3/ha/year). However, recovery of the freshwater that is stored in the subsurface is only possible when it is applied at a small scale (roof area that is used for rainfall harvesting) and in areas suitable for ASR: the aquifer in which the water is stored must meet several requirements regarding thickness, hydraulic conductivity and salinity.

The aquifers in the Westland area generally do not meet the requirements for ASR at the scale of several tens of hectares of greenhouse roofs, as groundwater salinity is too high. As freshwater has a lower density than brackish or saline water, any freshwater stored in the aquifer tends to move upwards, leading it to spread horizontally and mix with the brackish water, which makes it unsuitable for recovery.

In a pilot study at Prominent horticulture in Westland (DESSIN, Zuurbier et al. 2017), the performance of an ASR system was improved by combining it with multiple partially penetrating wells and an RO system (Figure 98). The combined technology was named 'ASR/RO'.

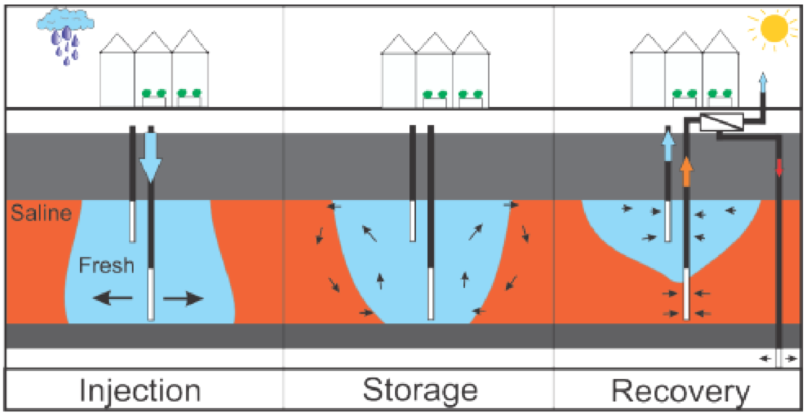

Figure 98. Scheme of the ASR/RO system at Prominent in Westland.

The multiple partially penetrating wells makes it possible to extract water from deeper and shallower layers separately. Extraction from deeper layers of the aquifer can help to prevent salinization of the upper well, as 'upconing' (upward flow of brackish water) can be counteracted. The upper well is used to maximize the direct extraction of fresh water, without the use of RO, which is possible if salinity remains below 20 mg/l. When salinity levels exceed this threshold, the extracted water is desalinized by the RO system and the remaining concentrate is injected into the secondary (deeper) aquifer.

The system was implemented for a group of horticulture companies (4 companies, with a combined roof area of 27 hectares). The results of the pilot project (Zuurbier, 2017) showed that direct recovery of the injected fresh water (without the use of RO) was limited, but that the technology could help to mitigate some of the negative impacts of traditional groundwater use. The potential environmental, societal, governmental and economic impacts were evaluated as well (Stofberg & et al., 2017). The evaluation showed that positive effects can be expected for groundwater salinity, stormwater retention and WFD compliance, but that the technology requires higher energy use and comes with the risk of introducing chemicals from the rainwater (such as zinc or pesticides) into the aquifer. The technology is more expensive (CAPEX and OPEX) than traditional irrigation water production. However, when the other impacts were considered in the economic analysis, ASR/RO was shown to be more favourable than traditional irrigation water production.

Conclusion on ASR

Considering the water related challenges in the Westland area (irrigation water demand, groundwater salinization and flood risk), ASR was considered a potential NextGen solution. However, the Prominent pilot showed that the potential recovery efficiency in this region is relatively low for ASR at the scale of several tens of hectares of greenhouse roofs (although much larger systems could have better recovery efficiencies). Conventional ASR renders

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relatively low recovery efficiencies in the Westland area (about 30%, whereas the recovery can increase to >90% for the fresh groundwater environment) because of mixing of the injected rainwater with the ambient brackish groundwater. For horticulturalists, there would be no incentive to invest in this technology, as ASR cannot replace the need for RO systems. However, from an environmental perspective it could be very useful to infiltrate excess rainwater, as it could counteract local and regional salinization and reduce flood risk during peak rainfall events.

Water banking: aquifer storage of excess rainwater

As a more sustainable alternative, infiltration of excess rainwater from greenhouses that have relatively large potential (seasonal) excess availability to the subsurface (and, secondarily, reuse via pumping and treatment during dry months) is proposed, through a system of infiltration wells that are used to create a balance between infiltration into and extraction from a groundwater system. This system has been studied in detail and is known as water banking (Stofberg et al., 2021), as it works in a similar manner to the more common practice of waterbanking in regions that risk groundwater depletion. The main difference with ASR systems is that the infiltration and extraction points need not be in close proximity or in the same aquifer zone: what matters is that the net regional balance to the aquifer is restored. Using this alternative, infiltration does not necessarily take place at the same location as the extraction (although some proximity is desired).

Water banking to counteract salinization and flooding

Storing collected rainwater in the subsurface may help to counteract groundwater salinization and provide space in the basins in which peak rainfall can be collected. However, recovery of stored water from brackish aquifers is difficult, so incentive is lacking. This incentive could be created through water banking: groundwater extraction becomes conditional upon rainwater infiltration (e.g., equal to the amount that is net extracted, which is the total extraction minus the concentrate discharge, resulting in a water balance of zero for the combined aquifers). As a result of temporal variability of water demand and rainfall, net infiltration will mainly occur in winters and relatively wet years, while net extraction occurs during summers and relatively dry years. Due to spatial variability in water demand and storage (some companies require more water than others, some companies have larger basins than others), infiltration will not necessarily take place at the same location as groundwater extraction. If companies can compensate their own net groundwater extraction with infiltration at other companies, some sort of economic system for trading 'groundwater credits' (the right to extract groundwater) is required, which is found in the practice of water banking (see Figure 99).

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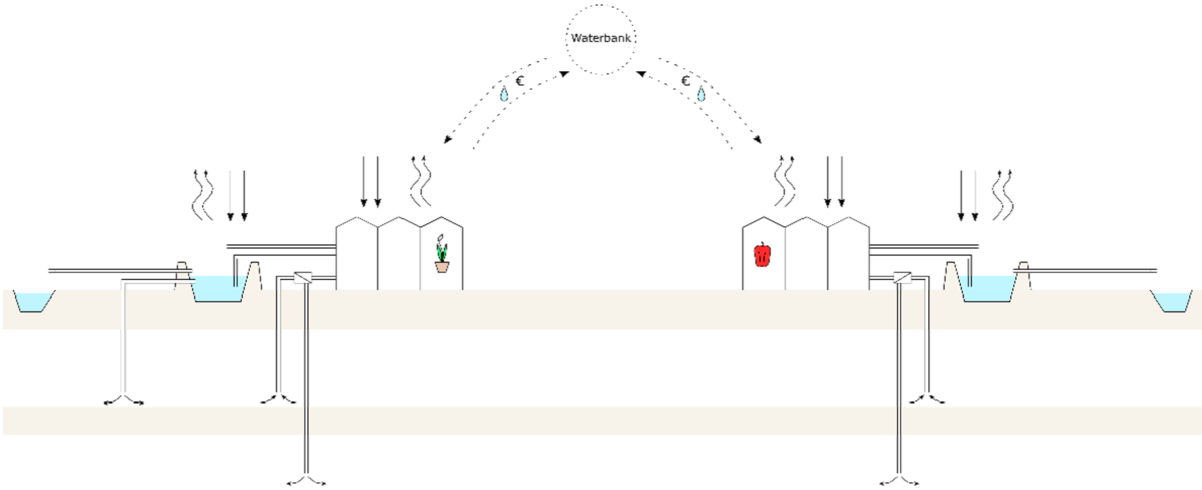

Figure 99. Water banking system for horticulture companies.

The water banking concept is further investigated as part of the COASTAR research program (https://www.coastar.nl/kennisprogramma/) and reported on by Stofberg et al. (2021). In that research, several types of water banking systems are explored. In practice, a mix of these types would be expected:

- Individual horticulture companies: individual horticulture companies which collect sufficient excess rainwater inject this water into the subsurface to compensate for companies which only extract (or extract more than they can inject).
- Clustered horticulture companies: groups of horticulture companies (clusters) work together by connecting their rainwater basins and constructing collective infiltration systems.
- Also, other companies: besides horticulture companies, other companies with large roofs can participate in the water bank, allowing them to collect and inject rainwater as well.

For these types of water banking systems, several topics were investigated:

- Water balances, including system efficiency (number of injection locations) and overflow into the surface water system during rainfall events (flood risk)
- Effects on regional groundwater flow and salinity
- Requirements and effects at local scale
- Economics and governance

Assessment results

The results of this research are summarized in this paragraph. For methods and detailed results, we refer to the COASTAR report (Stofberg et al., 2021).

The water balances of the reference situation and three main types of water bank systems are shown in Table 68. It is possible to ‘compensate’ all net extractions with infiltrations if about half of the individual horticultural companies (600) would infiltrate excess rainwater (5.0 Mm^3/j irrigation water produced from groundwater ≈ 5.0 Mm^3/j injected rainwater). If companies work together or if other roofs (large industry) are also used, the number of

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infiltration locations can be greatly reduced (up to <150 locations of the total 1291 companies).

Sensitivity analyses showed that the system is very sensitive to an increase in irrigation water demand. A 10% increase of demand would make it impossible to reach a balance between net extraction and infiltration without the use of non-horticultural roofs. It is, however, not clear if such an increase is expected as opposite trends are observed: on one hand, the horticulture companies aim to increase water use efficiency (recirculation and reclamation of irrigation water), but on the other hand they also aim to improve spatial efficiency by increasing the yield per greenhouse roof area (more than one crop layer, lighting, etc).

Overflow to surface water is strongly reduced in all water bank cases, even for large precipitation events, which can be improved if weather forecasts are used, and a water bank system is combined with the RainlevelR system (Hoogheemraadschap van Delfland). Extra tweaking (such as including weather forecast and combination with other measures) can result in greater efficiency.

Table 68. Water balances of the reference situation and three types of water bank systems for the Westland horticultural area, based on 30 years of meteorological data. No data is entered if values do not differ from the reference situation.

	Reference	Waterbank, individual companies	Waterbank, with other companies	Waterbank, with clusters
Area of horticultural companies (ha)	2431		2807	
Precipitation on roofs (million m^3/y)	21.6		25.0	
Retention /roof evaporation (million m^3/y)	2.7		3.1	
Net collected precipitation (million m^3/y)	18.9		21.8	
Irrigation water demand (million m^3/y)	17.7		17.7	
Irrigation water produced from groundwater (RO) (Mm^3/j)	3.7	5.0	4.3	4.2
Number of horticulture companies	1291		1291	
Number of other companies	118		118	
Number of horticulture groundwater injection locations	0	600	122	141 of which 77 clusters
Number of other groundwater injection locations	0		44	
Injected rainwater (million m^3/y)	0.0	5.0	4.3	4.2
Basin evaporation (million m^3/y)	0.2			
Overflow to surface water (million m^3/y)	4.7	1.0	3.1	1.0
Discharge from roofs other companies (million m^3/y)	2.9		0.8	-

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Simulations of regional groundwater flow and salt transport show that water bank scenarios lead to reduction of overall (regional) salinization, but that effects vary locally, with zones of increased and decreased salinity.

Collected data of water demand of two horticultural clusters showed that the local water balances may differ from the regional water balance, as in some regions more vegetables are grown (demanding a relatively large amount of water), while other regions have more cultivation of flowers. This means that a local balance between net groundwater extraction and injection is not possible without additional measures (such as collecting rainwater from roofs of other companies).

For a cluster of 10 companies in Westland, detailed groundwater simulations were done to assess effects on local groundwater salinity for three scenarios (Figure 100) and potential recovery of injected fresh water without the use of RO in the water bank scenario with collective injection and extraction facilities. The results showed that also at this scale, a water bank system can counteract salinization. As the cluster is located in an area with a lot of background flow, only 20% of injected rainwater could be recovered without the use of RO (a threshold of 20 mg/l was used).

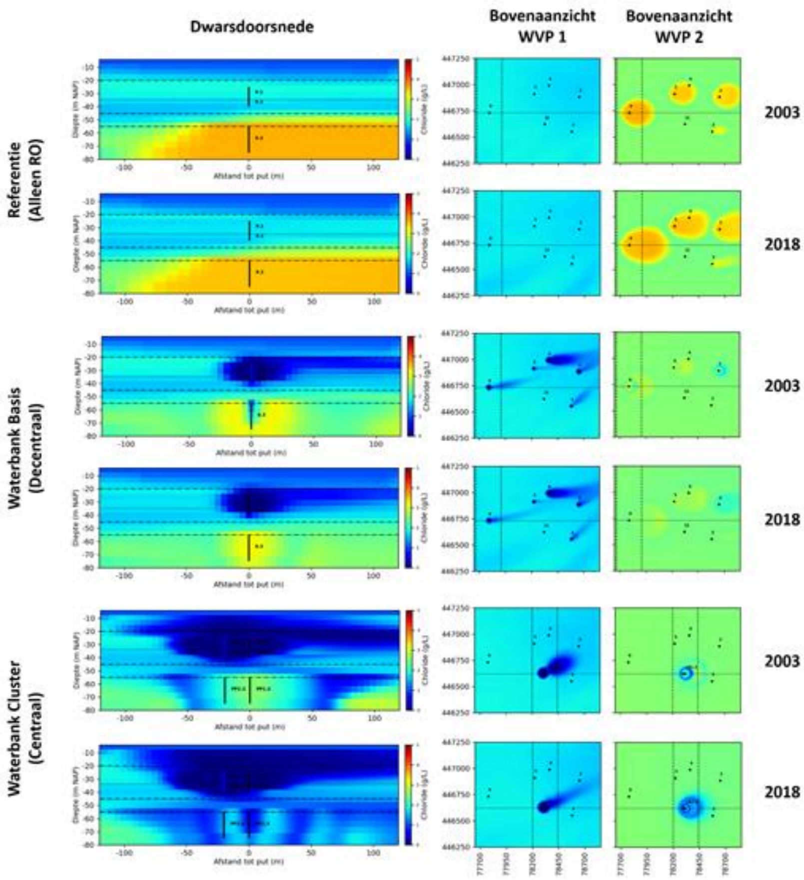

Figure 100. Cross sections and top views of groundwater salt concentrations for the first aquifer (WVP1, where groundwater extraction and rainwater injection occurs) and the second aquifer (WVP2, where concentrate is discharged) after 15 (2003) and 30 (2018) years of simulation for three scenarios: reference (upper), water bank with individual companies (middle) and water bank with clusters (lower, with collective injection and extraction facilities).

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Economics and governance

An economic analysis of the proposed water banking system showed that the costs would be relatively high, depending on the type of system and the possibility to convert extraction wells into wells that are suitable for both injection and extraction (€ 0,97 - € 1,26 extra costs for each cubic metre of extracted groundwater, with an estimated uncertainty of 40%). In case of contamination of the collected rainwater, additional expenses for water treatment would be incurred. However, implementation of a water banking system can lead to environmental and societal benefits (that have not been quantified), including reduction of salinization and flood risks.

Governance and legal possibilities were assessed together with a group of experts from various local government levels(province, water authority and municipality) and a representative of the horticultural sector. Several legal issues regarding groundwater extraction and concentrate discharges into the subsurface were found to be subject to differences of interpretation, and in some cases seem to be incongruent with environmental issues. For these issues, coordination and possible streamlining of legislation, regulations and policy between different government layers appears to be desirable. However, the national policy framework could probably, with a few small changes, accommodate the type of water banking system that was proposed.

There are many possible ways to organise a water banking system. Based on various considerations, as well as discussions with local stakeholders, a system in which governmental bodies define the framework of conditions (groundwater extraction is conditional to infiltration within certain spatial and temporal limits) is proposed. The horticultural companies could organize themselves into water banking units, that would be able to choose their own preferred way of realizing those conditions. Exchange of tradeable 'extraction rights' between the water banking units would be optional, and the spatial and temporal limits would have to be observed.

Conclusion on water banking

Considering the need for an alternative source of irrigation water in the Westland region, water banking was considered as a potential NextGen solution. In a water banking system groundwater extraction is only allowed if freshwater is injected in exchange. The assessment of the water balances of the water bank systems show that it is possible to compensate all net extraction with infiltration if about half of the individual horticultural companies will infiltrate excess rainwater. If companies work together or if other roofs (large industry) are used as well, the number of infiltration locations can be greatly reduced. Simulations of regional groundwater flow and salt transport show that water bank scenarios can counteract salinization. By employing a water banking system, the cost related to rainwater infiltration is shared between the parties that mainly benefit from groundwater withdrawals, i.e. the users that have the highest demands due to their more intensive crop types.

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In the coming years it will likely become clearer whether water banking will prove to be a useful option in the Westland area. This will depend on the following:

- Further development and testing of the concept, which could take place at a demo site
- Progress of legal discussions regarding possible prohibition of the current practice of concentrate discharge and legal perspective on the alternatives
- (Local differences of the) costs and benefits of the alternative solutions, such as the reuse of WWTP effluent.

Regarding testing of the concept, in 2022 a water banking pilot started at De Hooghe Beer (40 ha, Westland Region) with the involvement of 10 horticulture companies, Glastuinbouw Nederland, Deltares and KWR.

Reuse of WWTP effluent

WWTP effluent is a relatively constant potential source of water, available in relatively large quantities in densely populated areas. For the Delfland region, the potential for reuse of effluent from a water quantity perspective was explored by Krajenbrink et al. (2021).

In this study, the regional water balance was first analysed for separate months and for a whole year for an average year (Figure 101) and a dry year (see Figure 102) based on data that was provided by the Hoogheemraadschap van Delfland and the water banking study. The results clearly show that the lack of storage results in a dependency on external water sources, despite excess precipitation. About 130 million m^3/y of effluent is discharged into the external water system by four WWTPs (even though one plant is located in the middle of the area, but the effluent is transported to the sea). An even larger volume of 172 million m^3/y of excess surface water is discharged as well. However, more than 100 million m^3/y of water are supplied from external sources (river water, groundwater) for drinking water, surface water management, and irrigation. During dry years, less water is discharged and more water is supplied to the region, but, still, a net outflow is observed. During dry summer months the balance is reversed, and more water is supplied than is discharged.

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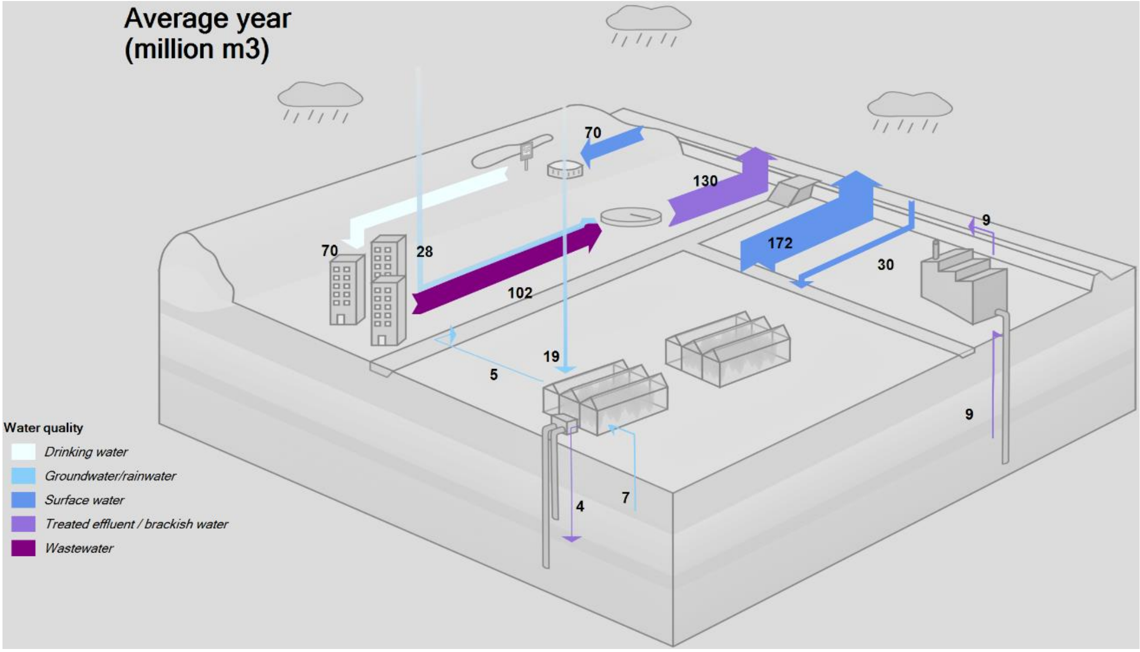

Figure 101. Water balance of the Delfland region during an average year

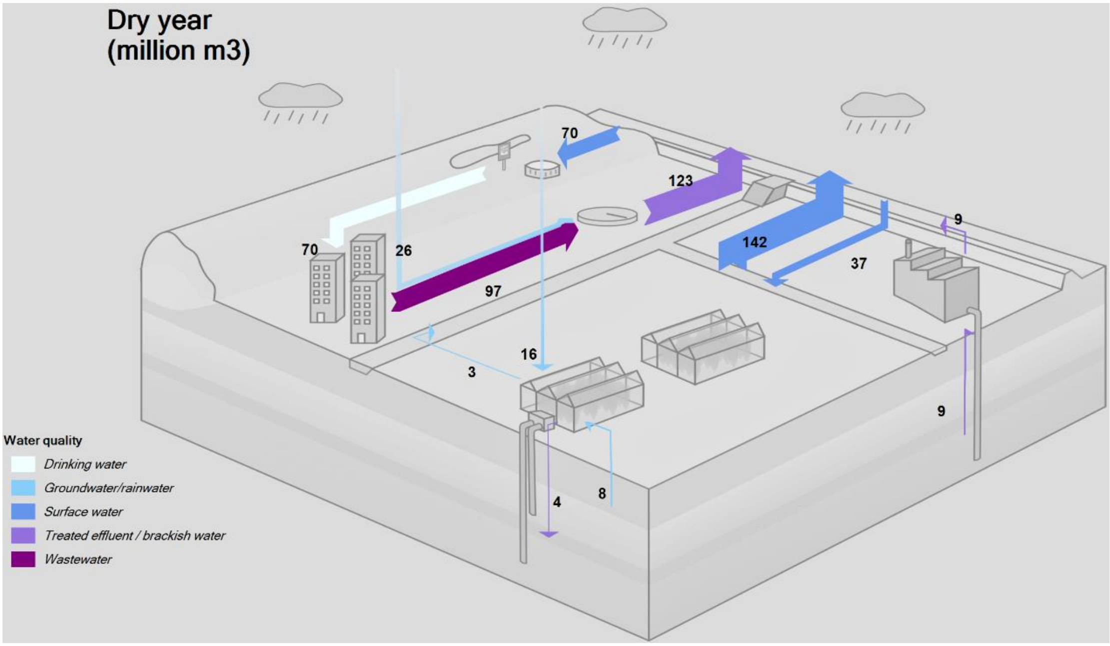

Figure 102. Water balance of the Delfland region during a dry year.

The system was assessed for its self-sufficiency, which was defined as the quotient of the sum of all discharges by the net discharge over a period of time. If this number is larger than 1, more water is discharged than would be desirable in a perfect self-sufficient situation, and supply of water from external sources is needed. Higher numbers represent less self-sufficiency.

Together with representatives of the regional water authorities (Hoogheemraadschap van Delfland), three scenarios for effluent reuse were formulated:

1. Reuse for horticulture, with
    a. Effluent replacing extracted groundwater

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   b. Effluent being used for all irrigation water (replacing rain water as well)
2. Reuse of effluent for surface water management
3. Reuse of effluent for drinking water

These scenarios were implemented in the water balance model, and potential consequences for the water system were analysed.

For the first scenario, the Nieuwe Waterweg and Harnaschpolder WWTPs were found to be close enough to the horticulture area to provide it with irrigation water. There would be enough water available to replace groundwater as irrigation water (scenario 1a, Figure 103) and even to replace precipitation as well (scenario 1b, Figure 104). Replacing the groundwater would improve self-sufficiency (slightly) and would not affect rainwater basin overflow into the surface water (assuming that basin size etc would remain the same). As the irrigation water demand reaches its peak in summer, the transport and distribution pipelines would need to be relatively large (expensive) or, alternatively, local storage solutions would be needed. If horticultural companies would rely more on effluent as a source of water (scenario 1b), perhaps replacing their basins with greenhouses, more rainwater would flow (indirectly) into the surface water, potentially leading to increased flood risk.

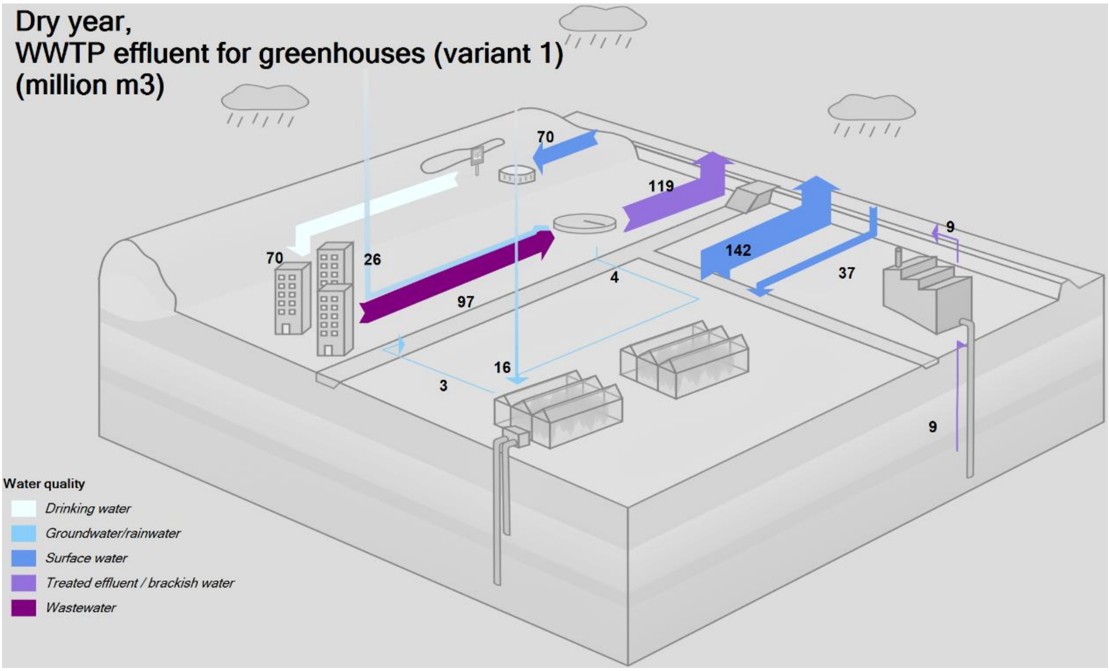

Figure 103. Scenario 1a Effluent to horticulture, replacing groundwater (for a dry year).

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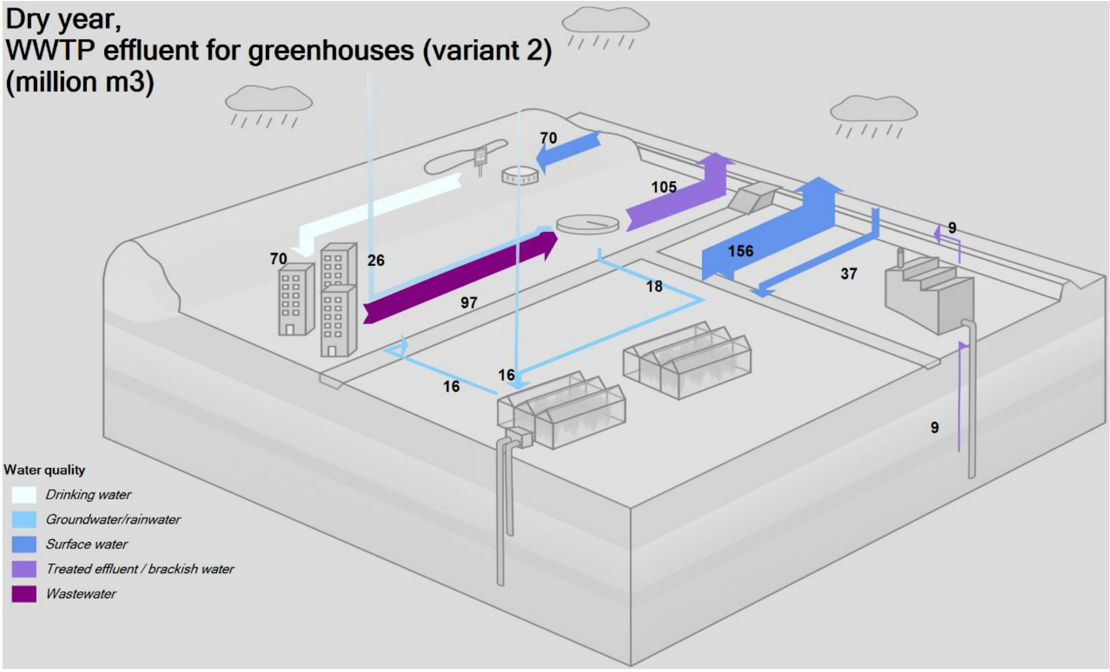

Figure 104. Scenario 1b Effluent to horticulture, replacing groundwater and rainwater (for a dry year).

In scenario 2, whether WWTP effluent can be used for surface water management was explored, which means that it would mainly be used to keep surface water levels constant. The yearly demand of water for surface water management is much smaller than the total effluent, but that does not mean that the total demand can be covered by effluent, as peak demands in summer exceed effluent supply (Figure 105). Using effluent for surface water management might mean that additional treatment is necessary to comply with WFD standards.

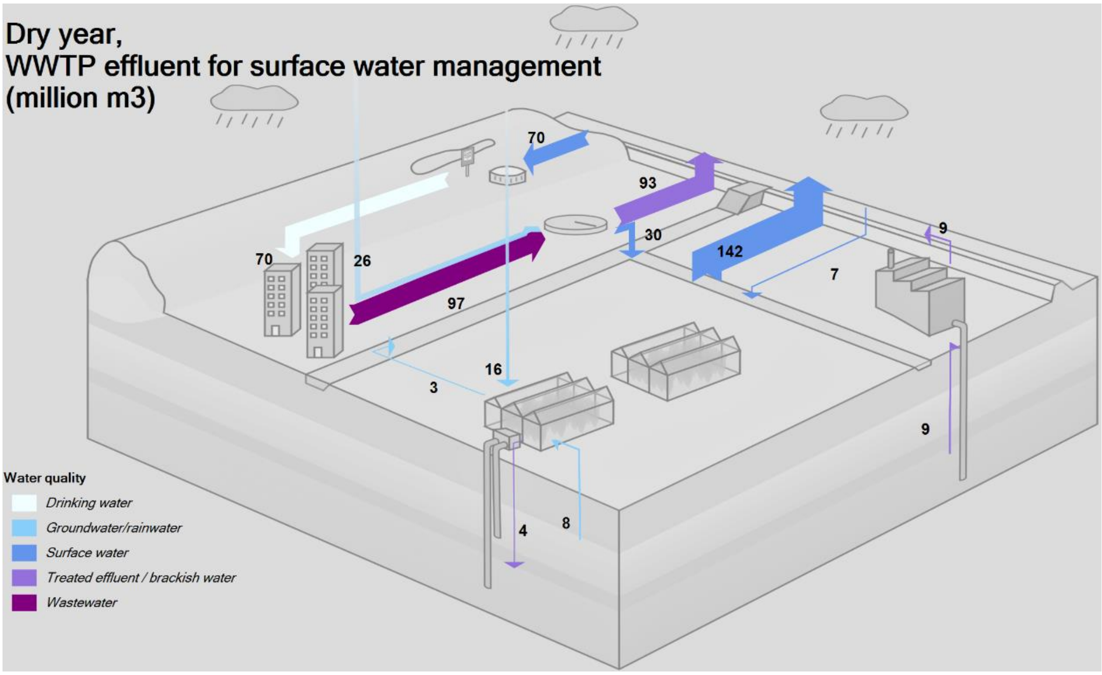

Figure 105. Scenario 2 Effluent for surface water management (for a dry year).

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In scenario 3, whether the drinking water of Dunea (one of the two drinking water companies in the region) could be produced using WWTP effluent was explored. Two relatively nearby WWTPs were selected as potential sources. During all months, enough effluent would be available. The resulting water balance is shown in Figure 106. This scenario would have implications for the level of treatment, as very robust treatment is necessary in order to use it as a source for drinking water production. Furthermore, additional attention would be needed for societal perception and the (legal) consequences for the drinking water company and the water authority responsible for the WWTP.

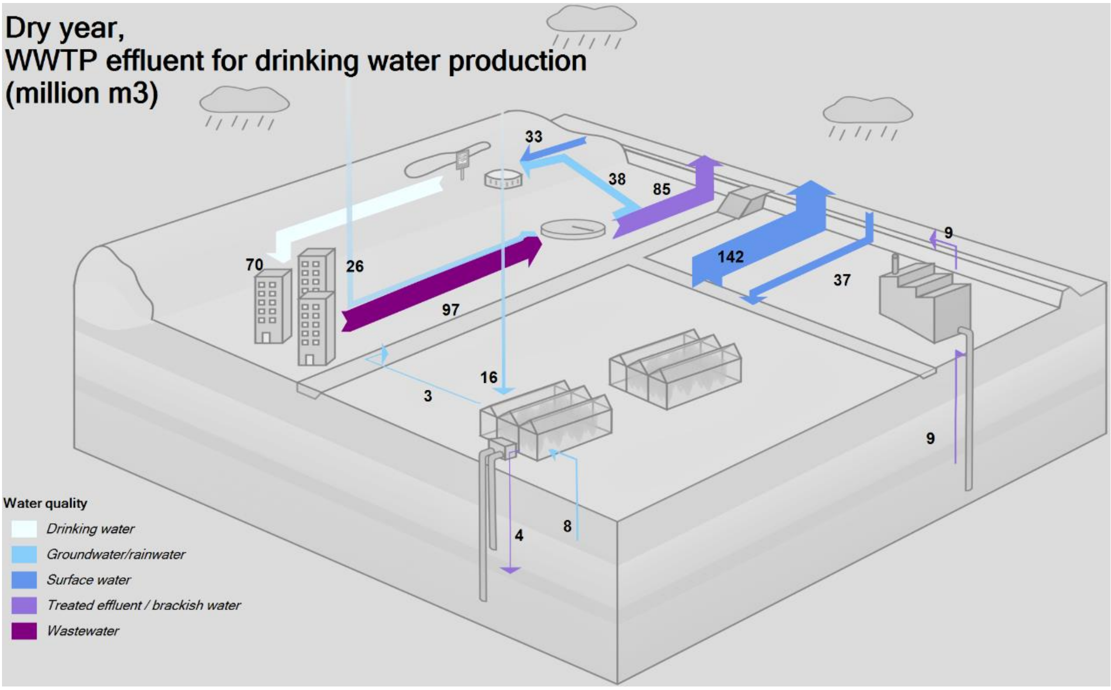

Figure 106. Scenario 3 Effluent for drinking water (for a dry year).

For the three scenarios, the discussed results are summarized briefly in Table 69. Comparison shows that using effluent for drinking water production has the largest effect on the system's self-sufficiency. Even though the reuse scenarios are treated separately, combinations of scenarios could be possible. If one or more scenarios are considered for further development, many aspects should be further investigated, including:

- Desired water quality, necessary treatment steps and residual flows
- Transport and storage
- Societal and environmental costs and benefits
- Legal issues and governance
- Future developments
- Considering the whole water system and the best sources for each water demanding sector (as opposed to this analysis, where the best purpose for one source was investigated).

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Table 69. Overview of results and possible implications of the three effluent reuse scenarios.

	Reference, dry year	Scenario 1. Horticulture	Scenario 2. Surface water management	Scenario 3. Drinking water
Water supply – per year (mln m³)	111	107 -4%	81 -27%	74 -33%
Water supply – summer month (mln m³)	22,5	20,6 -9%	16 -29%	18,6 -17%
Self-sufficiency index	1,81	1,75	1,61	1,56
Effects on water system and nature (water quantity)		1a: limited effect. May decrease risk of soil subsidence. 1b: more basin overflow, increased flood risk	Limited effect. If helophyte filters are used for water treatment, combination with nature goals possible.	Limited effect.
Quality		Advanced treatment focused on pathogens and micropollutants	Treatment probably necessary to allow discharge on local surface water (WFD)	Additional robust treatment and soil passage necessary
Storage		Needed storage depends on peak demand related to supply pipeline size. If constant transport is desired, local storage might be necessary (subsurface, ASR)	Increased storage might allow for supply/demand mismatch in dry summer months but is probably not available	Some storage needed as buffer for quality fluctuations
Transport, spatial integration		Implementation of a distribution network is complex and expensive.	Opportunity to implement nature-based solutions (helophyte filter)	Mostly using existing infrastructure, some local modifications needed
Costs		Expenses of treatment can be competitive with other sources, but additional costs for distribution not clear (possibly high costs)	Expenses would consist mostly of additional treatment steps (depend on what is needed)	Expenses for additional treatment steps and monitoring
Policy and legal implications		No separate law for irrigation water. In case of subsurface storage additional quality demands exist	WFD standards for discharge in local surface water	Quality standards for drinking water would have to be met. Collaboration required - the drinking water company will depend on the WWTP.
Society and perception		Possible negative perception if effluent is used for food. Communication may become important.	-	Possible negative perception if effluent is used for drinking

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				water. Communication will be important.

Conclusion on reuse of WWTP effluent

The current water balance of the Delfland region shows that the lack of storage results in a dependency on external water sources, despite excess precipitation. The options to use WWTP effluent to improve the systems' self-sufficiency has been assessed. One option is the reuse of effluent as an alternative water source for the horticulture companies. It appeared that there would be enough water available from two WWTPs (Nieuwe Waterweg and Harnaschpolder, which are close enough to the horticulture area) to replace groundwater as irrigation water and even to replace precipitation. Options to reuse WWTP effluent for surface water management and drinking water production resulted in further improvement to the system's self-sufficiency.

Water quality considerations of WWTP effluent reuse

Next to the availability of WWTP effluent as a source for horticulture irrigation, the water quality of the effluent needs to be considered. Although the NextGen Westland demo cases focuses on quantity of the regional water system, considering the relevance of water quality for reuse purposes, a limited assessment was conducted. The average effluent quality of Dutch WWTPs is 4 mg/l BOD and 8 mg/l TSS, which are below the EU Regulation 2020/741 standards for irrigation (i.e., both <10 mg/l). However, the average *E. coli* number in Dutch WWTP effluent is 2.7 x 10^4/100 ml, which is above the EU standard of < 10/100 ml (for class A products), thus further disinfection would be required.

For the Westland horticulture companies the physical-chemical quality and the possible presence of phytopathogens in the treated effluent is also of importance. For that reason, over a period of six months (December 2021 to June 2022), a number of samples of effluent from both the Harnaschpolder and Nieuwe Waterweg WWTPs were taken. These results are presented below:

- The pH of the effluent was on average 7.4, which is slightly higher than the desired value of irrigation water for horticulture (pH 6.5).
- The electrical conductivity of the effluent is on average 1.3 mS/cm, which is higher than the desired value for irrigation water (<0.2 mS/cm).
- The mean concentrations of NH4, Si, SO4, Fe, Mn, Zn, Cu, B and Mo are lower than the target value.
- However, the average concentrations of Cl, Na, Ca and Mg are (much) higher than the target value, and will therefore have to be removed before the effluent can be used as irrigation water.
- In 4 out of 5 samples (at both effluents), potassium was below the target value of 1.2 mmol/l, whereas it was above the target level in one sample.

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Of the phytopathogens, 3 types of bacteria, 2 viruses, 1 mould and 1 water fungus (oomycete) were measured in the WWTPs (i.e. through plating, bio-PCR, Rt-PCR or ELISA), see Table 70.

- *Fusarium spp*. (mould) was found in almost all samples. Concentrations ranged from <2 to 60 CFU. There does not appear to be a seasonal trend visible in the increase or decrease in concentrations.
- *Pythium* (oomycete) was found in 5 of the 7 samples at Harnaschpolder but was not found at Nieuwe Waterweg.
- *Erwinia spp*. (bacteria) was found in all samples from Harnaschpolder, and in 4 samples from Nieuwe Waterweg.
- It is striking that CGMMV (virus) was observed in both effluent in the week 11 sample, and not at the other times.
- *Agrobacterium rhizogenes, Agrobacterium tumefaciens*, and *PMMoV* (virus) were not found in any effluents.

Table 70. Measurement results samples of phytopathogens in WWTP effluent.

Pathogen	Group	wk 51 test	wk 11	wk 13	wk 16	wk 19	wk 22	wk 24
Harnaschpolder								
Fusarium spp (cfu/l)	Mould	16	6	14	40	60	24	10
Pythium spp	Oomycete	+	-	+	+	+	+	-
Erwinia spp	Bacterium	+	+	+	+	+	+	+
Agrobacterium rhizogenes	Bacterium	-	-	-	-	-	-	-
Agrobacterium tumefaciens	Bacterium	-	-	-	-	-	-	-
CGMMV	Virus	-	+	-	-	-	-	-
PMMoV	Virus	n.a.	-	-	-	-	-	-
Nieuwe Waterweg								
Fusarium spp (cfu/l)	Mould	48	12	6	<2	34	18	20
Pythium spp	Oomycete	-	-	-	-	-	-	-
Erwinia spp	Bacterium	-	+	-	+	+	+	+
Agrobacterium rhizogenes	Bacterium	-	-	-	-	-	-	-
Agrobacterium tumefaciens	Bacterium	-	-	-	-	-	-	-
CGMMV	Virus	-	+	-	-	-	-	-
PMMoV	Virus	n.a.	-	-	-	-	-	-

Although the influent of the Nieuwe Waterweg WWTP receives a much larger share of discharge water from greenhouse horticulture companies than the Harnaschpolder WWTP, a significantly greater amount of phytopathogens were not found in the effluent of the Nieuwe Waterweg WWTP. No influent samples were taken, so the degree of removal per species cannot be determined. In both WWTP purifications, biological nitrogen (N) and phosphorous

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(P) removal takes place. Subsequently, a chemical P removal takes place at Harnaschpolder, while at Nieuwe Waterweg this is a biological anaerobic P removal.

Both treatment plants do not yet contain any additional purification steps aimed at the removal of microorganisms from the effluent. However, microorganisms are already (partially) removed in the system. They attach to the sludge and settle with it, or are consumed by other organisms in the sludge. In addition, some microorganisms are rather unstable in the water and die. Because the Nieuwe Waterweg WWTP has an extra biological step, this could be an explanation for the lower presence of *Pythium* and *Erwinia*. This was not investigated per purification step, however it can be established that additional treatment should at least focus on the removal of fungi and bacteria (*Erwinia spp.*).

Currently, at the Harnaschpolder WWTP, the possibilities for treatment and use of effluent for the water system and horticulture are under investigation. Also, at the Nieuwe Waterweg WWTP, a fourth treatment step is proposed to remove micropollutants from urban wastewater and to remove plant production products from the collective wastewater from the Westland greenhouses. Such advanced treatment would possibly make the effluent suitable for reuse in horticulture, but an additional step for reduction of salt concentration would still be needed.

Circular scenarios

Circular urban water management solutions

Cities such as Rotterdam are becoming increasingly aware that there is a need to reconsider traditional water management models. The municipality has the ambition to reduce urban heat islands and address water scarcity through improved climate-adaptive urban design. A striking example is the Urban Water Buffer (UWB) project in Rotterdam, where the rainwater collected from the Sparta soccer stadium is stored in the subsurface and reused for irrigation of the green areas and sport fields. In general, a more circular approach which supplements large central infrastructure with an array of decentralized water options applied at household level and neighbourhood-scale (Bouziotas et al., 2019) is envisioned. In the urban areas of the Westland Region, initiatives are already being undertaken to implement several circular urban water management solutions, such as:

- rainwater harvesting: rainwater harvesting schemes at the neighbourhood scale that collect water from household roofs and public (impervious) areas, purify it and use it for urban water needs or locally infiltrate it (e.g. through a sustainable urban drainage system.
- grey water recycling: greywater recycling schemes at the neighbourhood scale that collect wastewater from selected uses such as the shower and handbasin, purify it through a nature-based helophyte filter, and redirect it in the urban water cycle.
- green roofs: green roofs (vegetation planted over a waterproofing system installed on roof tops) present a relatively high potential for cooling (urban heat islands) and storm water runoff mitigation.

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- water-saving household devices: vacuum toilets, water-saving showers and recirculation showers which have a reduced water footprint and lead to lower demands at a tap (household) level.

The previous sections showed the potential of a number of circular water technology options. In this section, the contribution of these options to further close the water system at the Delfland region is modelled. The modelled circular scenarios include large scale rainwater harvesting through water banking, the reuse of WWTP effluent for horticulture, and urban circular water management systems. Modelling is done with the Urban Water Optioneering Tool (UWOT). Details on the model and results are presented in the *NextGen Deliverable D2.3:* in this report the main results are summarised.

UWOT is a simulation-based Decision Support System, of the metabolism modelling type, able to simulate the complete urban water cycle. It models individual water uses and technologies/options for managing them and for assessing their combined effects at multiple scales, starting from the household level and progressing up until the neighbourhood, regional and entire city level (Bouziotas et al., 2019; Makropoulos, 2017; Rozos & Makropoulos, 2013).

To prepare the data inputs for UWOT, raw data from different sources are first collected, evaluated, and inserted into one common database that includes spatial (GIS) files, as well as tabular (MS Excel) data. As an integrated urban-rural water system model, the data requirements include urban system data (urban coverage and uses, household occupancy and consumption, rainfall data, past recorded demands and WWTP effluent timeseries) as well as rural system data (rainfall and evaporation data, greenhouse units, greenhouse demand consumptions, technical characteristics of the horticulture roofs and basins). The data is obtained from multiple (open) sources to form baseline conditions. Baseline conditions for Westland reflect the present-day state of the regional water system, including both urban and rural (horticulture) uses. Table 71 presents the validated model data used.

Table 71. Baseline water system values in UWOT.

Water system	Value in UWOT
Urban system	
Total drinking water demand	77.4 hm^3/year
Residential drinking water demand	54.0 hm^3/year
Municipal wastewater	126.2 hm^3/year
Horticulture system	
Number of greenhouses	1291
Rainfall on greenhouses roofs	21.2 hm^3/year
Greenhouses demand deficit, covered by RO	3.8 hm^3/year
Overflow to surface water	4.7 hm^3/year

For the combined urban-rural water system of Delfland, the UWOT baseline model setup has been prepared, consisting of the horticulture system (see Figure 107 as example representation), and urban components (households water management, urban runoff, wastewater treatment).

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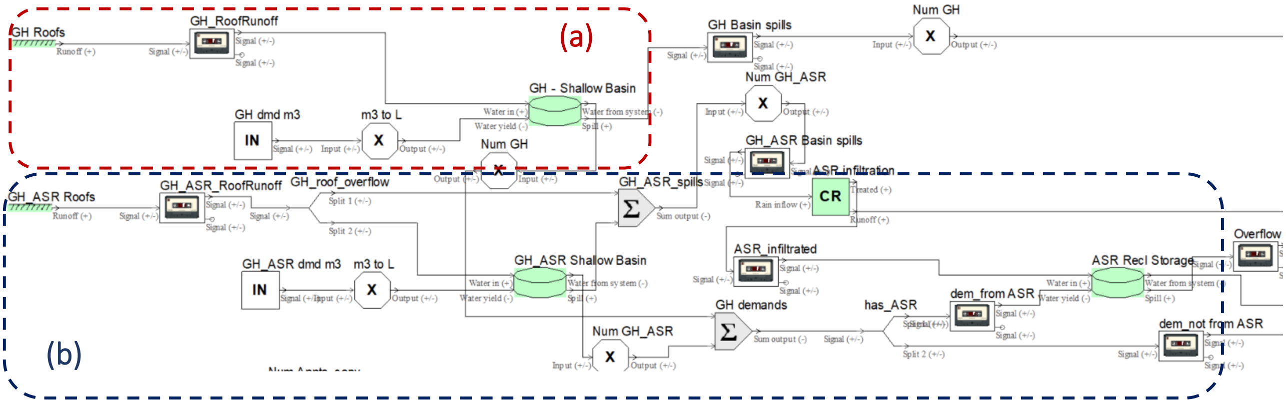

Figure 107. Schematic of the horticulture system components in UWOT.

Preparation of the circular redesign scenarios

In the Westland region, redesigning the system means proposing an alternative setup of decentralised or centralised water management (WM) interventions at any or many of the included model domains (drinking water, runoff management, wastewater, and horticulture water management), in order to change the currently predominantly linear water management model to a more circular one. Such alternative setups are envisioned to be the product of:

- consistent policy changes that translate to WM interventions at the household, neighbourhood, or regional scale. Such a policy change is, for instance, to actively support the uptake of rainwater harvesting (RWH) systems at neighbourhoods or in urban parks.
- behavioural or cultural shifts, for instance resulting from an increased level of customer awareness. An example of such a shift is the introduction of water-saving devices in houses, for instance due to a larger portion of customers being water-aware.
- upscaling a promising WM technology, such as Aquifer Storage and Recovery (ASR) or water banking, to a regional level. Multiple pilots exist for promising technologies in Delfland, such as small water banking clusters in Westland, and wastewater reuse units for greenhouse horticulture in Nieuwe Waterweg. It would be thus worthwhile to explore upscaled scenarios where these pilots become regionally important.
- materialising a regional vision, i.e. a cross-sectoral master plan for the region linked to an integrated water management theme, such as climate change proofing, achieving circularity, or becoming water-smart. Regional visions exist for Delfland (Dijcker et al., 2017) and have been used as building blocks for elements of the proposed redesign scenarios.

As a preliminary step, five redesign scenarios were created, see Figure 108. These redesign scenarios have varying complexity, starting from simpler interventions at specific parts of the regional water cycle, and expanding to more complex changes across multiple water cycle domains. The scenarios are:

1. The baseline (abbr. BAU) scenario, where households (hhs) follow linear water management (WM), greenhouses (GH) rely on rainwater (RW) basins, and urban areas have conventional (combined) sewer and wastewater systems.
2. The Rainproof (abbr. RAINP) scenario, where Rainwater Harvesting (RWH) is introduced to households in Delfland, for instance through a supporting, enabling policy. The harvested

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rainwater is then used to cover part of the household demands, reusing water at a local scale. As a result, the goal that *x*% of households have a RWH system installed by 2023 could be achieved. The RWH system would share a storage unit at neighbourhood level.

3. The Green roof (abbr. GREEN) scenario, where RWH is extended beyond the household level and which includes regional-scale interventions as well, such as green roofs in some (*y*%) office spaces and certain public impervious areas (*z*%), as well as a water banking system for greenhouses in Westland, where *c* greenhouse units infiltrate rainwater to deeper groundwater layers.
4. The Circular (abbr. CIRC) scenario, where circular technologies are introduced to a percentage of households in Delfland. Circularity lies in the reuse of household effluent (greywater, GWR), as well as the capturing of rainwater (RWH), in a hybrid RWH-GWR system installed at neighbourhood level. As a result, *x*% of households have a hybrid RWH/GWR system installed.
5. The Water-wise (abbr. WATWISE) scenario, where these circular household technologies are complemented by active demand reduction measures (DRMs) at the household level, with the introduction of water-saving devices. Moreover, water banking is also employed as a circular intervention for greenhouse units in the rural domain.
6. The Black to Green (abbr. WW2G) scenario, where urban circularity technologies (including demand reduction options) are paired with the (re)use of urban wastewater effluent as a resource for horticulture in the region. This means that, by 2030, *a*% of the water treated from one of the regional WWTPs will be reused to cover the greenhouse demands and increase the sustainability of the greenhouses.

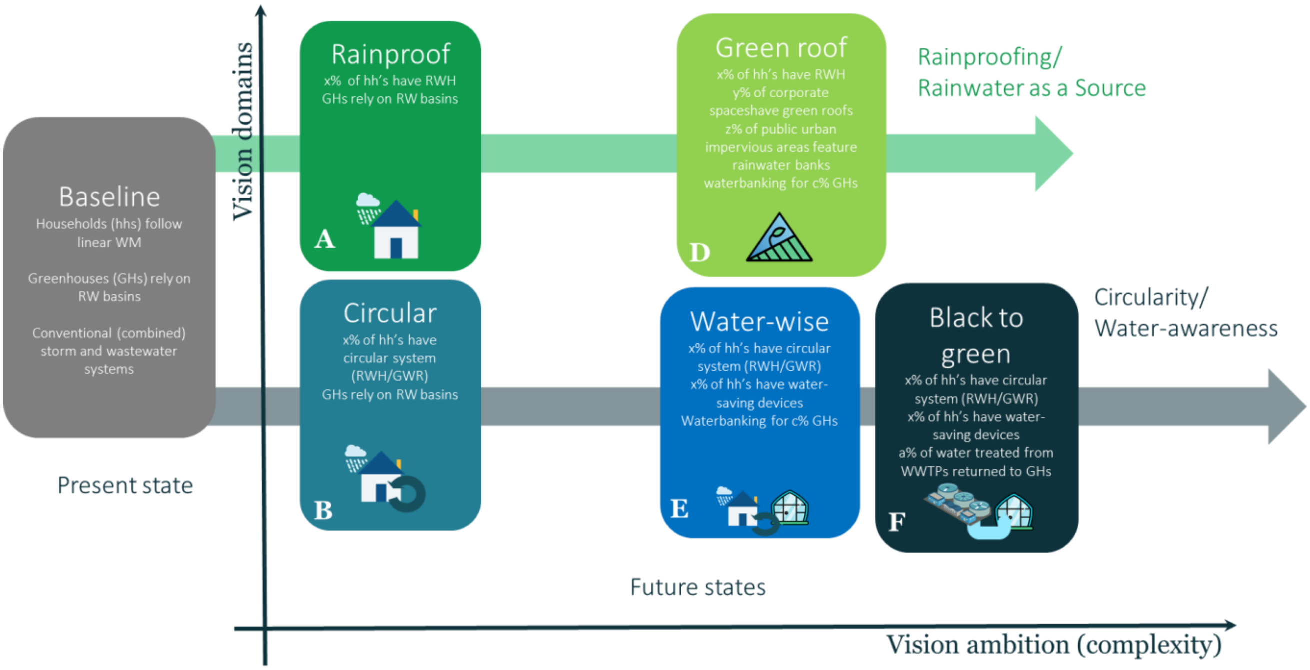

Figure 108. Mapping of the five initial redesign scenarios for Delfland.

An overview of these five redesign scenarios is given in Figure 108, scaled against the vision ambition and complexity for each redesign. As part of the 2nd NextGen Westland CoP (held in 2021), these scenarios have been evaluated by the participating regional stakeholders in terms of practicality and interest. The stakeholders find more complex redesign visions more

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compelling, with greatest interest in the Green Roof and Black to Green redesigns, followed by the Water-wise redesign. As a result, it was decided to progress with the three of the most complex redesign scenarios (GREEN, WATWISE, WW2G). The CIRC scenario was also included as a first step to model scenarios of higher complexity, since no other modelling study for Delfland currently covers urban circular intervention scenarios. The least interesting option (RAINP) was excluded from the further modelling process.

Finally, the parameterisation of the scenarios has been discussed. The aforementioned quantities that can be reached by 2030 (e.g., *x*% of households with RWH systems installed) have to reflect the ambition of regional stakeholders and governance, but are also limited by practical factors such as the available capital for investment, legislation, water quality restrictions, etc. The discussion of parameters with the stakeholders led to the conclusion that a range of 15%-30% for these parameters is a good trade-off between high ambition and applicability.

The knowledge obtained from the studies presented in the previous sections was used as well. For instance, for each scenario that includes water banking for horticulture, the guidelines and scenarios presented in *ASR/water banking* section are employed, which estimate that 600 horticulture units (HUs) for infiltration are needed to reach a balance. For the scenario that includes wastewater reuse for horticulture, the findings presented in *Reuse of WWTP effluent* section are used, which indicate that 5% of the annual wastewater effluent from selected large WWTPs in the area (Nieuwe Waterweg and Harnaschpolder, whose effluent totals 78 hm^3) would be needed for an upscaled reuse system.

The parameters in Table 72 were thus selected as quantitative targets of each redesign vision.

Table 72. Overview of the redesign scenario parameterizations.

Redesign scenario	Parameter	Unit	Value
CIRC	x_1% of houses that are circular	%	20.0%
	x_2% of apartments that are circular	%	25.0%
WATWISE	x_1% of houses that are circular	%	20.0%
	x_2% of apartments that are circular	%	25.0%
	x_3% of houses that have demand reduction measures	%	20.0%
	x_4% of apartments that have demand reduction measures	%	25.0%
	x_5% demand reduction for office spaces	%	20.0%
	Number of greenhouses (GHs) with infiltration *c*	-	600
	Number of conventional GHs	-	691
GREEN	x_1% of houses that are circular	%	20.0%
	x_2% of apartments that are circular	%	25.0%
	y% of the commercial/industrial surface converted to green roofs	%	30.0%
	z% of public impervious spaces converted to green spaces	%	30.0%
	Number of GHs with infiltration *c*	-	600

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	Number of conventional GHs	-	691
WW2G	x_1% of houses that are circular	%	20.0%
	x_2% of apartments that are circular	%	25.0%
	x_3% of houses that have demand reduction measures	%	20.0%
	x_4% of apartments that have demand reduction measures	%	25.0%
	x_5% demand reduction for office spaces	%	20.0%
	α% of WW effluent gets reused	%	5.0%

Redesign results at the coarse scale

Following the completion of different UWOT schematisations – both for the present-day, Business as Usual (BAU) case, and the alternative proposed redesign scenarios – the simulation was executed to obtain results at the fine (i.e. daily) time scale. As the UWOT model provides output at a daily timestep, the results can be analysed at coarse or fine scale. At a coarse scale, one may aggregate to a monthly, seasonal or annual scale and obtain flows at different parts of the Urban Rural Water System (URWS), for instance in hm^3/year (or Mm^3/y). Since the model is integrated and includes multiple facets of the water cycle at both urban and rural domains, these flows can be collected at multiple points to form an extensive output dataset from tap to source, and from the initial runoff surface to the outlet.

One of the most efficient ways to visualize the model outcome at the coarse scale and at the system level is through the use of Sankey diagrams, which were originally developed to visualize flows in energy systems but have been adapted for use in water systems (Pronk et al., 2021). To represent system results at coarse scale, Sankey diagrams are developed to summarize the average annual water flows at multiple locations of the URWS in Delfland. The relative quantity of the water flows is expressed by the size of the arrows, while the different domains (stormwater (SW), drinking and clean water (DW) and wastewater (WW) are visualized as different hues (green, blue and brown correspondingly). Some key limitations to consider for the Sankey graphs are: (a.) the surface water system and some groundwater processes (e.g. percolation) are not explicitly modelled, so the relevant quantities are not depicted in detail, especially in the rural system; (b.) the supply network and wastewater treatment losses are not included in the calculations; (c.) the deficit (clean, processed water) needs for the horticulture system are depicted, but real raw water needs will be increased due to the limited extraction and RO efficiency. Moreover, brine output is not modelled or shown.

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BAU results

The results for the BAU present-day, conventional water management can be seen in Figure 109. Sankey diagram of the UWOT baseline *(*BAU) case. One may observe a predominantly linear management that propagates from source to tap or outlet in three main flow lines along two domains (urban and rural):

a) drinking water treatment (77.4 hm^3/year) that covers urban demands and is then converted to wastewater, disposed of as sewage, and processed in WWTPs
b) rainfall in urban areas (equal to 194.3 hm^3/year on average) that falls on built (impervious) and open (pervious) spaces, of which 49.3 hm^3/year ends up in the (partly combined) sewer system and thus the WWTPs, while the rest is split between urban drainage (stormwater sewers) and water going in the surface (canal) system or infiltrating in deeper layers,
c) rainfall in rural areas (equal to 163.7 hm^3/year on average) that falls on open (pervious) spaces and on horticulture roofs, where it is directed to the shallow basin system and used to cover horticulture demands (17.6 hm^3/year). An annual deficit of (on average) 3.8 hm^3/year is obtained through brackish pumping and desalination with RO. The treated wastewater, stormwater overflows and seepage from rural areas all flow to the regional outlet recipients of Het Scheur and Noordzee.

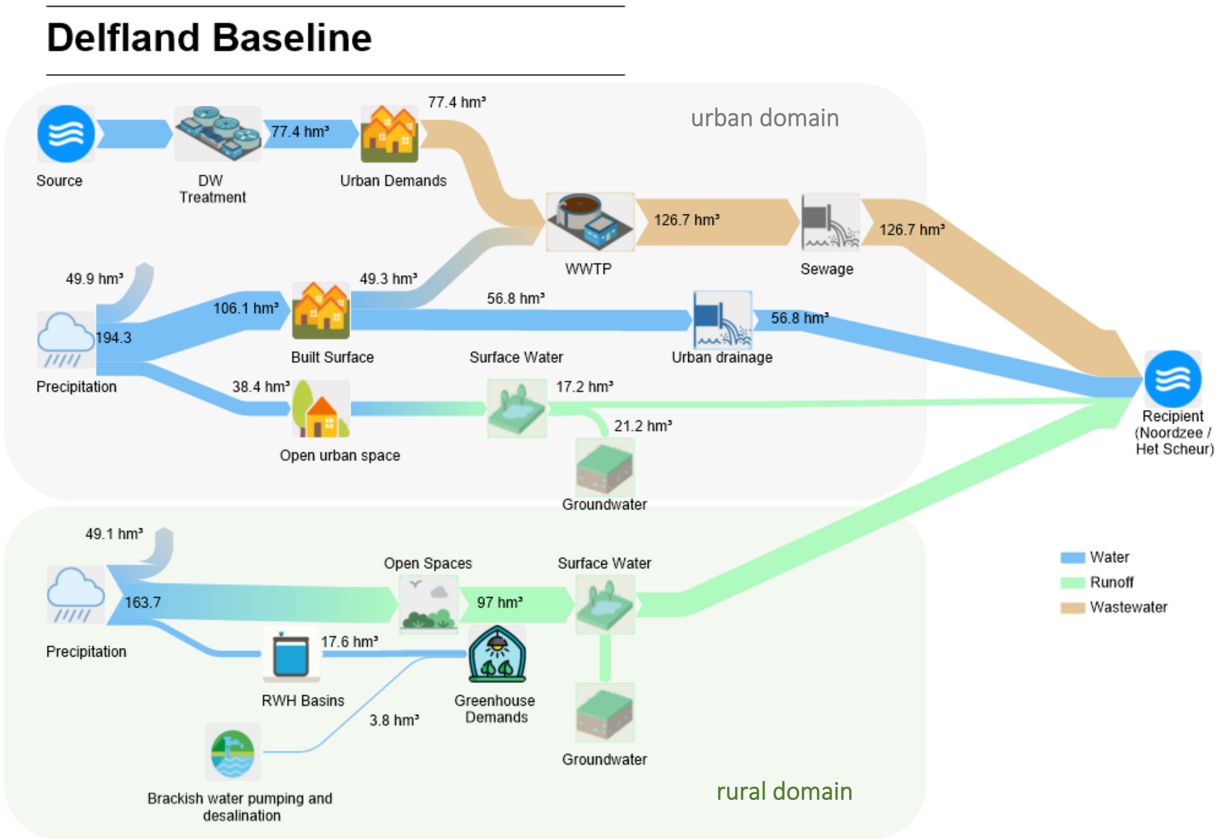

Figure 109. Sankey diagram of the UWOT baseline (BAU) case.

CIRC results

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This largely linear water management scheme is changed to a more circular one when urban circular measures are introduced in the CIRC scenario (Figure 110), with loops of water recycling and reuse being introduced to the urban domain.

a) The drinking water demands from the central utility become reduced by 10.7% to 69.1 hm^3/year as a portion of households has now become circular, featuring RWH systems that manage to capture 4.3 hm^3/year annually and GWR systems that recycle 3.0 hm^3/year. This results in less water entering the urban drainage systems and, along with the reduction in central water, results in 8.8 hm^3/y (= 6.9%) less wastewater at the entry point of WWTPs.
b) The horticulture system remains unchanged in this scenario, with all HUs using shallow basin units and thus having identical demands as the baseline scenario.

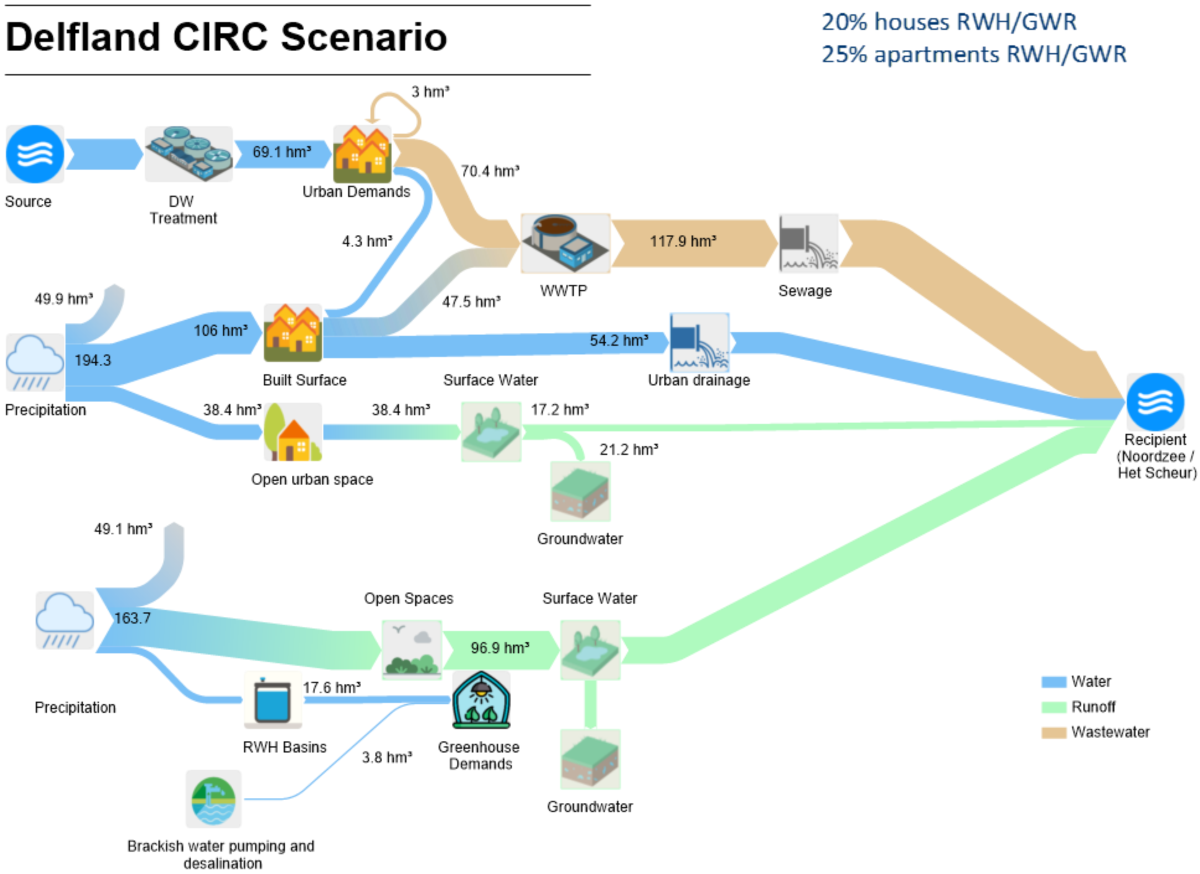

Figure 110. Sankey diagram of the CIRC redesign scenario.

WATWISE results

Circularity is further reinforced in the WATWISE scenario (Figure 111), which combines - besides residential interventions in the form of a hybrid RWH/GWR system – demand reduction measures in the form of water-saving appliances and the introduction of a water banking system for horticulture. One may now observe all circularity measures:

a) reduction, as the demand management measures further reduce the reliance of central drinking water to 62.6 hm^3/year, in a more drastic reduction by 19.1% compared to BAU,

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b) reusing, both in the urban and rural domains, as rainwater is efficiently captured and used, both directly in households (4.3 hm^3/year) and through the water banking system (15.9 hm^3/year in the shallow basins and 4.8 hm^3/year infiltrating in deeper layers),
c) recycling, with the internal household loop from the GWR system. Interestingly, due to the demand reduction at the appliance scale, the yields of this loop are lower than the CIRC scenario to 2.4 hm^3/year.
d) The introduction of water banking in the horticulture domain is also important, as it negates, for the most part, the deficits to 0.7 hm^3/year, with 4.8 hm^3/year being sustainably covered by the infiltration system from the greenhouses that feature infiltration wells as well as a shallow basin. The yield rate from the shallow basin system is now reduced to 15.9 hm^3/year, due to the different operating rules of shallow basins that now need to account for infiltration and reserve some space for flood protection.

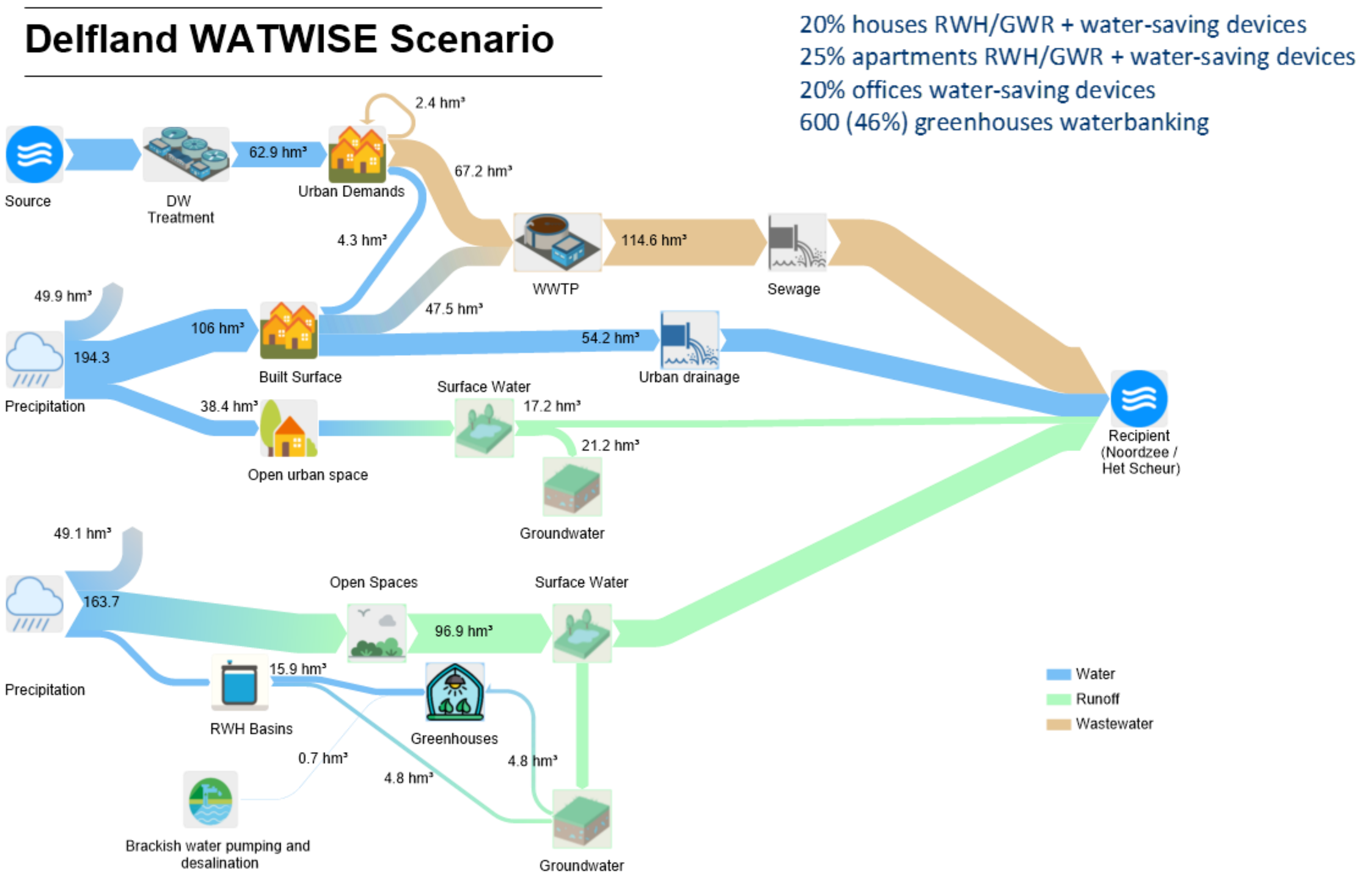

Figure 111. Sankey diagram of the WATWISE redesign scenario.

GREEN results
A different vision of circularity can be seen in the GREEN scenario (Figure 112), which combines more substantial RWH for households in combination with green roofs for a percentage of urban spaces.

a) Urban demands are reduced by 11.3% to 66.8 hm^3/year, a reduction caused by the introduction of RWH in circular households and apartments. As the GREEN scenario emphasises RWH more than previous circular scenarios with a larger design, the reuse of

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rainwater is more efficient, with 6.3 hm^3 being able to be captured and used to cover household demands annually.

b) A more notable difference is the change in the urban runoff stream, with effects being introduced by the use of green roof spaces instead of the conventional impervious built surface. A larger quantity of water is returned to the atmosphere, through interception and direct evaporation and through plant transpiration from the green roofs. Moreover, the distribution of runoff between impervious and pervious surfaces changes, as green roofs are considered pervious and direct their infiltration and overflow to pervious areas.
c) Finally, a notable difference is that sustaining green roofs also leads to higher water demands in dry seasons, with a demand deficit of 1.9 hm^3/year on average that needs to be covered by other sources besides rainfall (i.e., the drinking water system).
d) The horticulture system is the same as the WATWISE case, with most of the water being covered sustainably.

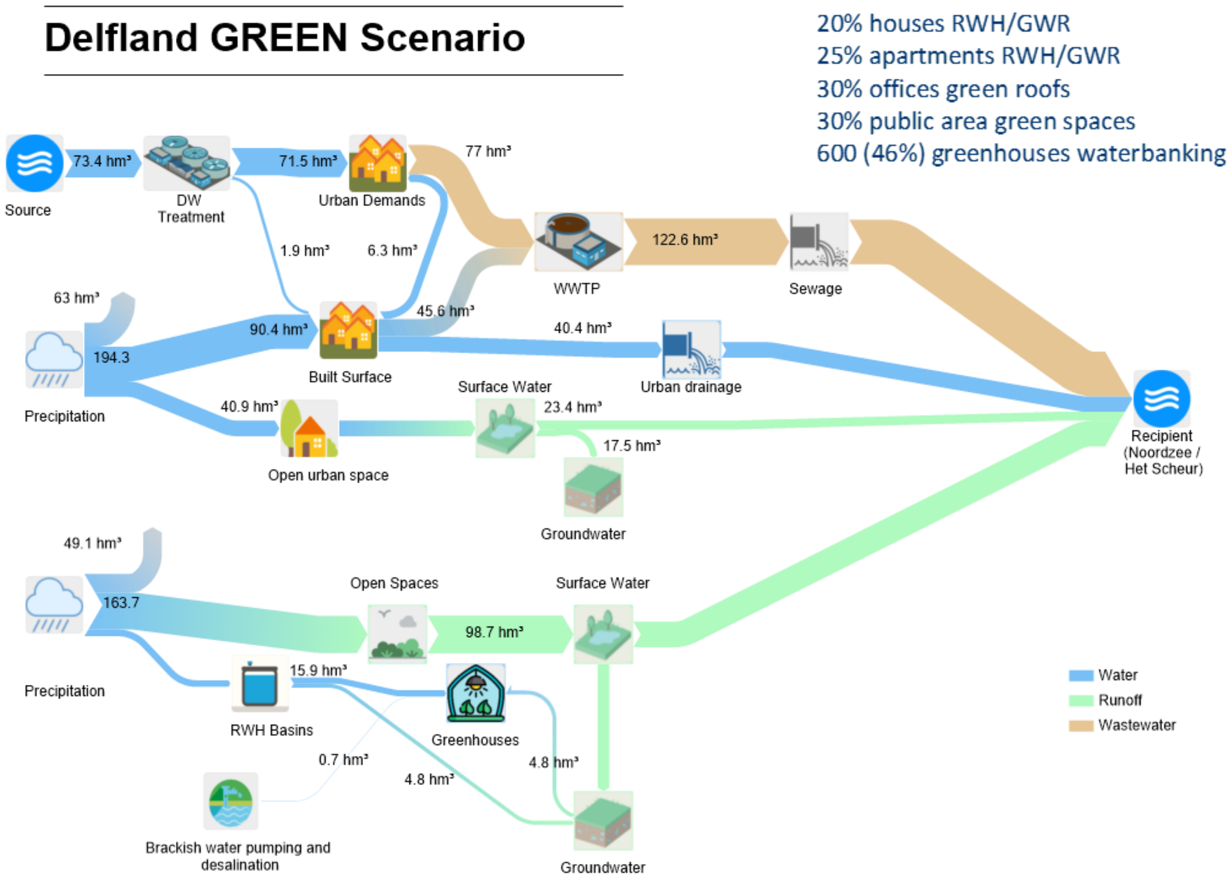

Figure 112. Sankey diagram of the GREEN redesign scenario.

WW2G results

Finally, the WW2G scenario results at the coarse scale, seen in Figure 113, are comparable to the WATWISE scenario, with the notable difference that coverage of the greenhouse demands is now mainly through reusing part of the wastewater effluent.

a) The greenhouse demand is mainly covered through wastewater effluent reuse, equal to 5.0 hm^3/year. This, in combination with the shallow basin system, practically negates any

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deficits and unsustainable groundwater abstractions to 0.07 hm^3/hear, with only one year out of the ten simulated ones indicating such abstractions.

b) The rest of the displayed loops feature the same quantities as the WATWISE scenario, as the intervention options are the same.

c) It is noted that, in the WW2G redesign scenario, the underlying assumption is that treated wastewater is directed through infiltration to the subsurface in a similar manner to the water banking system, even though there are other possible uses of the WW reuse technology for horticulture, such as direct transport to the basins of horticulture units. This assumption is selected because of the higher cost the pipelines would have, especially considering the coverage of peak demands. There are also secondary effects stemming from this assumption, such as mixing issues of WW with brackish water, which may require additional treatment of the infiltrating water, such as the use of RO.

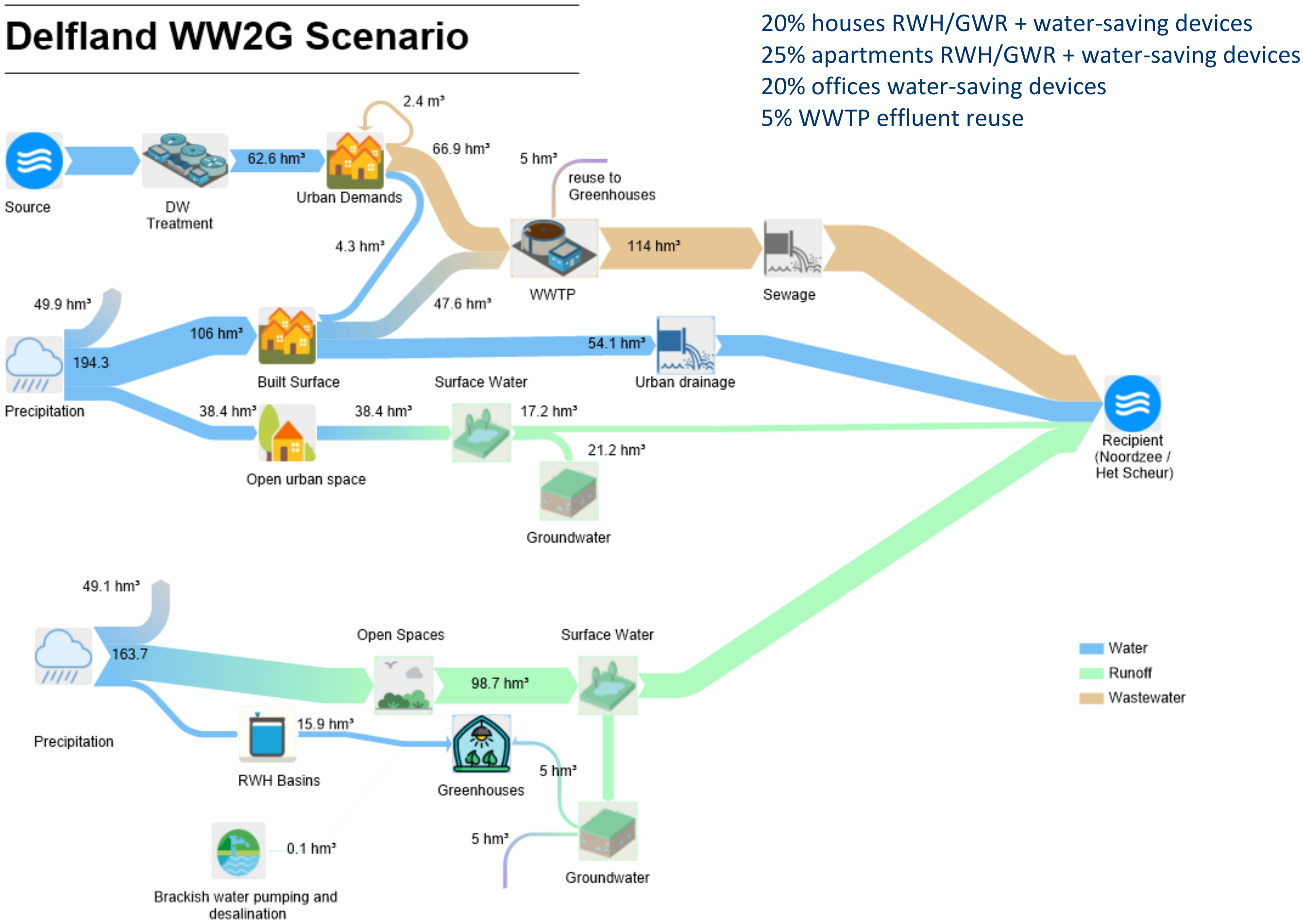

Figure 113. Sankey diagram of the WW2G redesign scenario.

Redesign results at the fine scale

Besides results at aggregate scales (annual or monthly), one may consult the simulation outcome at its native (daily) scale. The situation concerning the GH system demand deficits changes substantially once more sustainable redesigns, such as water banking (WATWISE, GREEN) or WW reuse (WW2G) are considered. On the first case with water banking, variable

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runoff volumes are infiltrated into the ground, leading to a positive cumulative infiltration storage that covers the summer deficits to a very large extent. Some deficits are still observed in dry summers, leading to a small average deficit of 0.7 hm^3/year, as presented before, but the system is more sustainable and doesn't rely on water imports every simulated summer. On the second case, where WW is reused, a smaller but much more constant stream of treated water is infiltrated in the subsurface, leading to a more robust cumulative infiltration storage that has a net benefit across the 10 years of simulation. The demands are largely covered, with only one simulated event of demand deficit, thus bringing the average annual deficit to 0.1 hm^3/year. The cumulative infiltration storage also shows the infiltration and extraction rates of the GH system, that builds up stored water slowly in the subsurface but uses it, with a more rapid rate, when needed.

Stress-testing of the circular scenarios

The four circular water redesigns (CIRC, WATWISE, WW2G, GREEN), as well as the present-day condition of the region (BAU), are tested against a range of possible futures, driven by stress-testing scenarios in terms of climate, occupancy and horticulture demand. For this array of possible futures, the resilience of the urban and rural water systems is quantitatively evaluated using two proposed metrics that are based on both event-based (i.e. time-based) and volumetric reliability.

- The results demonstrate that any circular intervention will mitigate the loss of system resilience that occurs for more extreme futures in the BAU case. The options with the highest overall resilience across different futures are WATWISE and WW2G, followed by the GREEN scenario, which also comes with the compromise of higher water demands due to maintaining green roof spaces in warmer futures.
- The CIRC intervention also significantly improves system resilience, despite being the most simple circular water system option.

More information can be found in the NextGen deliverable D2.3.

Conclusions on circular scenarios

In this chapter, four circular redesigns based on corresponding circular water management strategies have been proposed (CIRC, WATWISE, WW2G, GREEN) for the Westland region and have been compared to the present-day (BAU) scenario. These redesigns are of varying complexity and propose alternative setups for water management that combine centralised and decentralised water management interventions at any or multiple of the urban-regional water system (URWS) water cycle streams (drinking water, runoff, wastewater and horticulture water demands). The redesigns have been modelled using different UWOT topologies and their results are demonstrated, both at the coarse and at the fine scale.

The results quantify the beneficial effects of circular water interventions:

- there is a potential reduction of urban drinking water demands by 10.7%-19.1%,
- a potential of rainwater reuse at the household scale at around 4.3-6.3 hm^3/year,
- a potential of greywater reuse at the household scale at around 2.4-3.0 hm^3/year,
- and a drastic reduction in unsustainable abstractions for horticulture, from 3.8 hm^3/year to 0.1-0.7 hm^3/year (through WWTP effluent reuse or waterbanking respectively).

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To conclude:

- Among the compared redesigns, the more ambitious redesign strategies that include sustainable options for horticulture and combine demand reduction measures with decentralized RWH and GWR for the urban area were found to be the most efficient in reducing demands, reusing and recycling water locally and securing the system against future uncertainty.
- Among them, WW2G was found to increase reliability the most in the water cycle, followed by the WATWISE and GREEN options. Even simpler strategies that target one domain (such as CIRC) are significantly beneficial to the region and lead to a more resilient future.
- In any case, the cost of inaction for Westland region will be high, as the conventional, linear water management system will not be able to secure urban and horticulture demands reliably without significant investment in increasing central supply.

Conclusions for the Westland Region water demo case

Considering the need for an alternative source of irrigation water for the horticulture greenhouses in the Westland region, Aquifer Storage Recovery (ASR) systems, that temporarily store the excess of rainwater in winter in an aquifer so that it can be recovered in summer, are considered as a potential NextGen solution. However, conventional ASR renders relatively low recovery efficiencies in the Westland area (about 30%, whereas the recovery can increase to >90% for the fresh groundwater environment) because of mixing of the injected rainwater with the ambient brackish groundwater. From an environmental perspective it could still be useful to infiltrate excess rainwater, as it could help to balance the aquifer, counteracting local and regional salinization and reduce flood risk during peak rainfall events. In NextGen, this water banking concept, where groundwater extraction becomes conditional to rainwater infiltration, was evaluated as a regional strategy in the Westland area. The assessment of the water balances of the water bank systems for Westland show that it is possible to 'compensate' all net extraction with infiltration if about half (600) of the individual horticultural companies will infiltrate excess rain water (i.e. zero net groundwater extraction). Simulations of regional groundwater flow and salt transport show that water bank scenarios can counteract salinization.

As another alternative water source for the horticulture companies, the reuse of WWTP effluent has been assessed. The assessment of the regional water balance shows that there would be more than enough water available from two WWTPs to replace groundwater as irrigation water for horticulture (5% of 78 Mm^3/y would be sufficient to deliver 4 Mm^3/y) and even to replace precipitation as well. This does require large investments in infrastructure for transport and/or storage, in particular to cover peak demands. Options to reuse WWTP effluent for surface water management and drinking water production showed a further improved water systems' self-sufficiency in the region.

Next, the contribution of rainwater harvesting through water banking and the reuse of WWTP effluent for horticulture to further close the water system at the Delfland region was

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modelled. Four redesign scenarios have been modelled, including urban circular water management systems. The modelling results show the beneficial effects of circular water interventions, such as a potential reduction of urban drinking water demands by 10-20% and an almost complete reduction in unsustainable groundwater abstractions from horticulture. The introduction of water banking at 600 horticulture companies substantially reduces the deficits to 0.7 Mm3/year. The greenhouse demand is mainly covered through reuse of 5% of the WWTP effluent, and in combination with the shallow basin system, practically negates any deficits and unsustainable groundwater abstractions.

To summarise, an ambitious regional strategy that combines options for alternative water sources for the horticulture (rainwater through water banking and/or WWTP effluent) with circular water options in the urban area (demand reduction measures with decentralized RWH and GWR) will lead to a more circular, resilient water system.

5.1.8. Comparison of baseline situation and NextGen KPIs

Table 73 presents the current and potential KPI values for Westland Region.
Conventional ASR renders relatively low recovery efficiencies in the Westland area (about 30%, whereas the recovery can increase to >90% for a fresh groundwater environment) because of mixing of the injected rainwater with the brackish groundwater. From an environmental perspective it is still useful to infiltrate excess rainwater through water banking (balancing extraction with infiltration), as it counteracts salinization and reduces flood risk.

Implementing water banking at about half of the horticulture companies in Westland can result in an almost zero net groundwater extraction (defined as the total amount of groundwater extraction minus rainwater infiltration). The unsustainable groundwater abstraction would be reduced from 3.75 to 0.7 Mm^3/y (>80%).

About 5% of the effluent from two nearby WWTPs would provide sufficient irrigation water for the horticulture greenhouses as an alternative water source.

Introducing demand reduction measures and rainwater and greywater reuse at households show substantial reductions in drinking water consumption and wastewater discharged: the reached values depend on the number of households that will introduce these interventions (an ambitious but applicable 20% was used in the assessment).

Table 73. KPI values for the Westland demo case.

Objectives	Specific Key Performance Indicator (KPI)	Current value	Potential value *
ASR / water banking	Percentage of rainwater stored and amount harvested for horticulture	<1% 14 Mm^3/y	22-26% 17.9 Mm^3/y

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Water banking	Net groundwater extraction	3.75 Mm^3/y	0.7 Mm^3/y (if applied at 50% horticulture)
WWTP effluent reuse	Amount of effluent reuse for horticulture irrigation	0 Mm^3/y (0%)	4 Mm^3/y (5% of 78 Mm^3/y sufficient)
Circular urban water measures	Percentage of demand reduction and amount of rainwater / greywater reuse	minimal	10-20% demand reduction ca. 8 Mm^3/y reused (if applied at 20% households)

** The objective of NextGen Westland Region case study was to conduct an assessment of integrated management of alternative water sources, i.e. to assess the feasibility and potential but not to implement regional ASR / water banking, WWTP effluent reuse or circular urban water measures. Therefore, the potential values are presented.*

5.1.9. Lessons learned

Required competence | LOW  HIGH

Which knowledge is required to operate the plant?

Good design is key for success of ASR system. Operation can be largely automated, when operational parameters (water pressures, water flows, electrical conductivity,) are monitored online and reported back. Operation should include regular backwashing to prevent well clogging

What kind of training is necessary?

Basic knowledge of groundwater and aquifers, pumps, water wells.

Maintenance | LOW  HIGH

Frequency of plant maintenance per month or per year:

Yearly check of the system. Especially clogging of injection wells may cause operational problems. Wells need to be cleaned, mostly once every 1 – 3 years. The pretreatment system (rapid and slow sand filter) needs a yearly check.

Duration of a normal maintenance procedure.

1 – 2 days per year

Duration of active process control per day (manual process control, unforeseen events).

Operation can be largely automated, when operational parameters (water pressures, electrical conductivity) are monitored online and reported back.

Are external experts required to conduct the maintenance procedure?

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<table>
<tr><td colspan="3">Various companies provided services for well maintenance (inspection, cleaning). Technology providers can help check and maintain other infrastructure (pumps, pretreatment, pipes).</td></tr>
<tr><td>Technological risks</td><td>LOW</td><td>HIGH</td></tr>
<tr><td colspan="3">Reasons for downtimes or technical risks:

The most important operational risk is clogging of the infiltration wells. An appropriate design and operation, and proper pretreatment of the infiltration water can minimize these risks. Infiltration water should be low in fines and low in nutrients (N, P) to limit microbial growth and biomass production that may clog well screens. In brackish groundwater environments, monitoring the salinity of the recovered water is crucial. Groundwater modelling can help to keep track of freshwater still available for recovery

Frequency of plant downtimes per year.

This depends on scale, natural condition, et cetera, but generally only a few times per year

Duration of plant downtimes.

Similar, but generally not much longer than a few hours. Key is to properly monitor injection wells, receive alarms for urgent matters, and have proper maintenance.

Are external experts required to restart the plant?

This depends on the nature of the problem. Most occurring problems are related to clogging of infiltration wells.

Which measures can avoid such downtimes?

Good design, especially pretreatment, automated monitoring of water pressures and well performance, regular (yearly) maintenance.</td></tr>
</table>

5.1.10. Best practice guidelines for operating the technology

Important for the realization of an ASR system is to have knowledge of the local hydrogeology and the natural water balance. The former includes for example the parametrization of the target aquifer and of confining clay layers, whereas the latter includes insight in the seasonal variation of all available water sources and the requirements of the water demand.

Water quality is crucial for the optimization of ASR. Once in place, the infiltration wells should be protected from clogging by only infiltrating water with a suitable chemical composition and having a low content of fines and nutrients. Moreover, the well screens that are used for recovery of the stored water should be prevented from salinization and from frequent changes in geochemistry (e.g. redox conditions). Pretreatment of infiltration water and a proper operation of wells are thus important parameters that directly affect the water quality.

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To prevent the risk of well clogging, operational guidelines have to be followed regarding the quality of infiltration water. This includes for example maximum concentrations for fines and nutrients. Moreover, the infiltration water may not pollute the aquifer. Hence, legal requirements for the quality of the infiltration water have to be complied as well. In addition, water quality requirements upon recovery should be known and the expected changes in water quality upon aquifer storage should be anticipated. Lastly, the salinity of the recovered water should be monitored to prevent well salinization.

Upscaling

The future implementation and upscaling of the technology very much depends on the regulatory framework in Westland. The EU Water Framework Directive and the Groundwater Directive have the prevent & limit principal, i.e. deterioration of groundwater quality is to be prevented. However, regarding ASR, the national policy framework can potentially accommodate this type of system. Several legal issues regarding groundwater extraction and concentrate discharges into the subsurface seem subject to differences of interpretation, and in some cases seem to be incongruent with environmental issues. The national Water Law and Spatial Law (Omgevingswet in preparation) prohibit the discharge of brine from production of irrigation water. In order to be allowed to discharge concentrate, an exemption from the prohibition on this is required, via a tailor-made regulation. In the case of brine discharges, the competent authority is the municipality (Westland, Haaglanden Omgevingsdienst). In connection with a transitional arrangement, with the aim of ending the discharge of brine into the subsoil, the tailor-made regulations apply to the discharge of brine by horticulture industry in Westland until July 2022. In order to implement the regional water programme, the Province of South Holland is consulting with provinces, municipalities, water boards, the central government and the sector to establish a joint policy framework with regard to the discharge of brine after July 2022 (e.g. keeping in line with the EU Water Framework Directive).

Our assessment for the transition to water circularity in the Westland demo case (WP4, see Afghani et al., (2022)) pointed out the economic, legal, and regulatory barriers that might slow down the change. First, there is a lack of a suitable legal framework for water reuse in terms of the legal-regulatory obstacles. Yet, the Dutch institutional setting is organized to positively react to the EU review of the water directives, including the new guidelines and regulations for water reuse. Secondly, in terms of economic barriers, the lifespan of the existing groundwater desalination and the large investments by the horticulture companies can reduce the legitimacy for new water solutions. At the same time, the analysis of the ongoing actions to increase the legitimacy of new water solutions, revealed that the main actors in the horticulture water regime were found to coordinate, collaborate, theorize, and advocate for finding solutions to the groundwater salinization problem. However, more efforts are necessary to focus on the negative impacts of brine emissions on the environment. In addition, the effects of groundwater salinization on the horticulture companies' business revenues and the economic feasibility of the new suggested technologies need to be evaluated. Such theorizing efforts are necessary to change the horticulture companies' perceptions of existing practices and legitimize the policy's intention to impose strict brine emissions regulations.

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For Aquifer Storage and Recovery / water banking systems, a transition pathway is envisioned, with actions that aim to increase the economic, social, and environmental incentives for ASR by (a) advocating its role in combating climate change, (b) evaluating its performance from an economic point of view, (c) assessing its performance to reduce groundwater salinization (d) maximize collaborating efforts to ensure optimal tasks distribution.

Finally, our assessment showed the benefits of circular interventions for horticulture and urban areas that reduce water demand and locally reuse water. A regional strategy aimed at a further uptake of these interventions combined will result in a more closed, self-sufficient, and resilient water system in Westland and the Delfland region.

5.2 Real time measurements of the water balance in Gotland (SE)

Authors: Staffan Filipsson and Fredrik Hedman (ivl)

5.2.1. Description of the demo site

The demo site is described in chapter 3.5.1.

5.2.2. Motivation for implementing circular economy solutions in the water sector

Please view chapter 3.5.2.

5.2.3. Actions and CS objectives

Please view chapter 3.5.3.

5.2.4. Unique selling points

- **Mapping of potential for local and sustainable and secure water supply via** a unique measurement system based on real-time sensors for precipitation, waterflow in ditches and ground- and surface water levels.
- **Enhanced natural storage volume** via an innovative automatic floodgate.
- **Direct membrane filtration of municipal sewage** for a decentralized reclamation system for producing drinking water quality.
- **Increased potential for energy and nutrient recovery** optimisation which includes all the relevant actors (government as potential resource managers and citizens as producers and receptors)

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5.2.5. Principal characteristics of the technology

The core of the testbed Storsudret is the real-time online sensors that have been installed and calibrated (see Figure 114). The location of these meters that send signals online via the cellular network is shown in Figure 115.

Figure 114. Installations of measurements stations for flow in ditches.

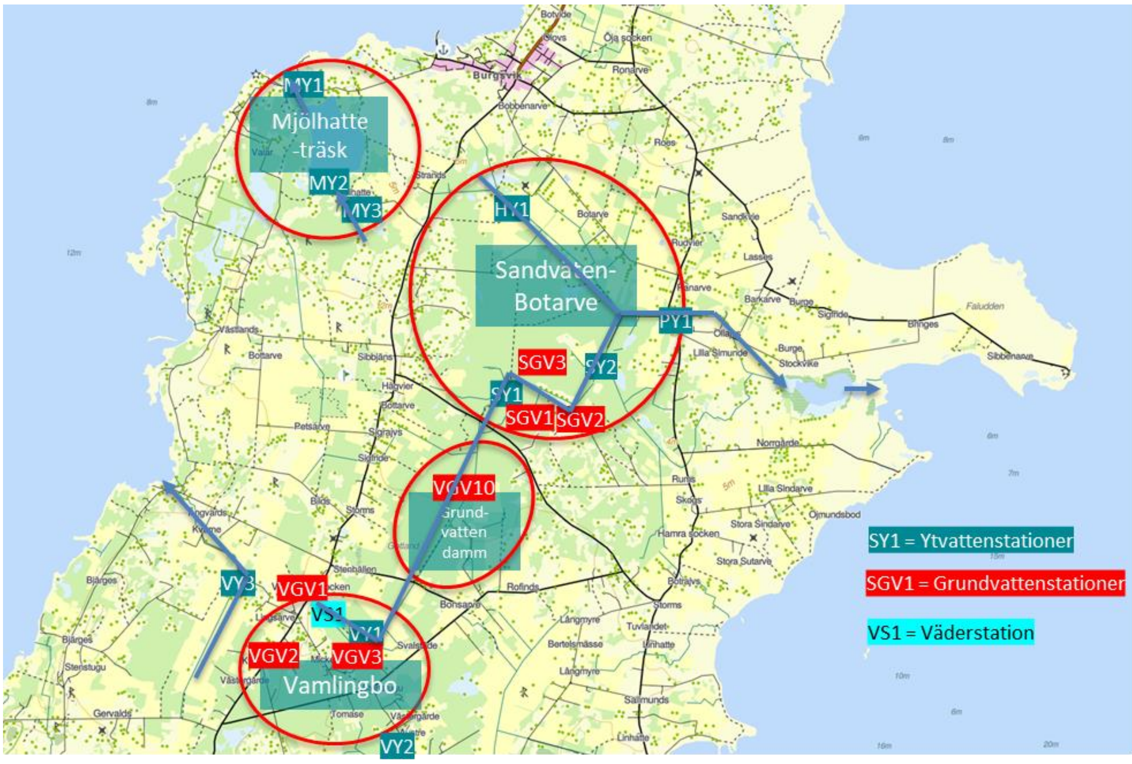

Figure 115. The main larger ditches at the case study area (left) and the calibrated infrastructure (right) for real-time measurements of precipitation (blue), surface water flows and levels (green) and ground water levels reflecting the water balance within three parts of Storsudret: Mjölhatteträsk, Sandväten/Halshageträsk and Vamlingbo.

5.2.6. Technology implementation requirements

As the stations might hinder fish migration, each station needed a permit from the county administration. The installed sensors for real time measures of flow in ditches, surface- and groundwater levels and precipitation were calibrated several times (Figure 116). The calibration was an extensive job but was critical to ensure results of the water balance were correct.

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Another important area for the establishment of the water balance was also discovered after the installation and calibration of the origin set up of sensors. Therefore, two more sensors for groundwater level measurements and 6 observation holes were drilled. In addition, at the same area where the new sensors were installed, a larger borehole was made in the soil layer and two capacity tests were performed to roughly estimate the capacity of the sand and clay formation (see Figure 117). To visualize the ground water flocculation, an additional larger hole was drilled close to the large borehole (Figure 118).

Figure 116. Calibration of the real time, online measurement system for water flows and levels.

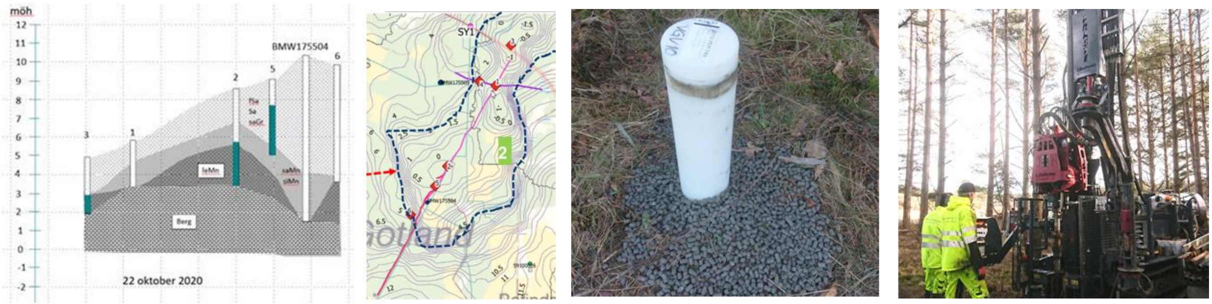

Figure 117. The soil layer profile was established by drilling of several boreholes in area of particular interest for water balance research. In addition, a larger bore hole for making capacity tests was drilled.

Figure 118. With the aim to visualize the ground water flocculation, a larger hole was dug in the same area where the larger borehole and its surrounding observation holes were drilled.

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5.2.7. Results obtained

Based on the precipitation measurements, an estimated volume of 70 million cubic meters (Mm^3) rainwater is hitting the Gotland case area, Storsudret, during a normal year. Of this volume, 20 Mm^3 remains after evaporation. The large ditches in combination with the very thin soil depths contribute to the stressed water situation at Storsudret. Shortly after a rainfall, the soils and natural reservoirs are drained, including the areas that were once wetlands and contributed to water storage. By studying the figures below, the seasonal interference between the precipitation, the flow in the ditches, and the surface- and groundwater levels were visually discerned and could be calculated to establish the water balance.

From the observed data for the flow in the largest ditch, Petesdiket, 1,3 Mm^3 of rainwater per year was calculated to travel from the land to the Baltic Sea (Figure 119).
At another part of the case study area, the annual outflow from Mjölhatteträsk to the Baltic Sea rose each year between 2019 to 2021, see Table 74 and Figure 120. However, when the data were arranged summer to summer (column B) instead of winter to winter (column A), the difference between the years was much smaller. A reason for this could be a shift from relatively even precipitation distribution of over the seasons to a more uneven distribution, where much more occurs during the winter season. If this is the case, it demonstrates that future climate models should account for more precipitation during winter and less during summer. Such scenario is highly challenging and would require measures to avoid increased water shortages during the summer.

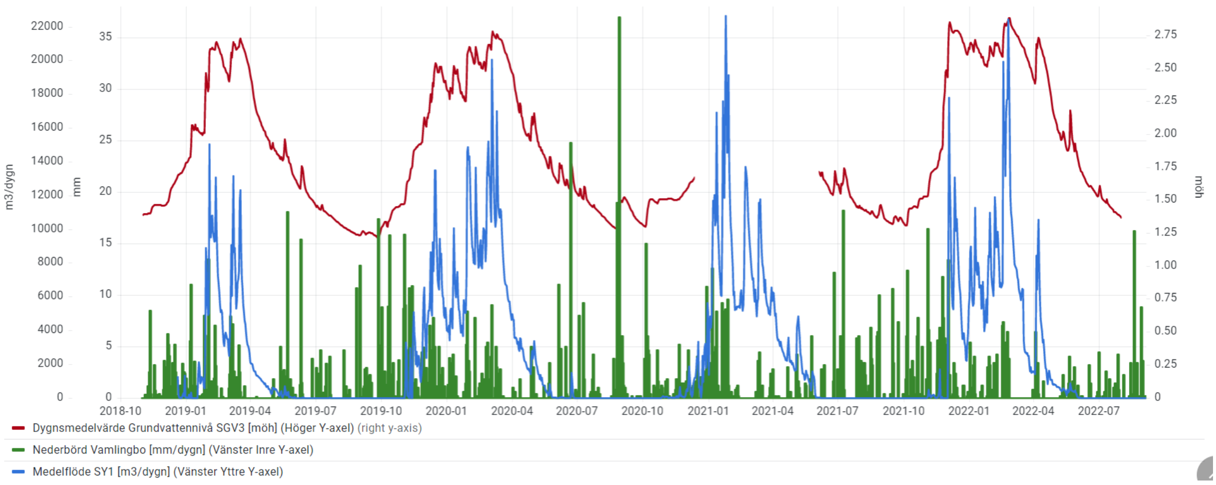

Figure 119. Real time data for precipitation (green), flowrate in the ditch (blue) and groundwater level (red) from the area Sandväten.

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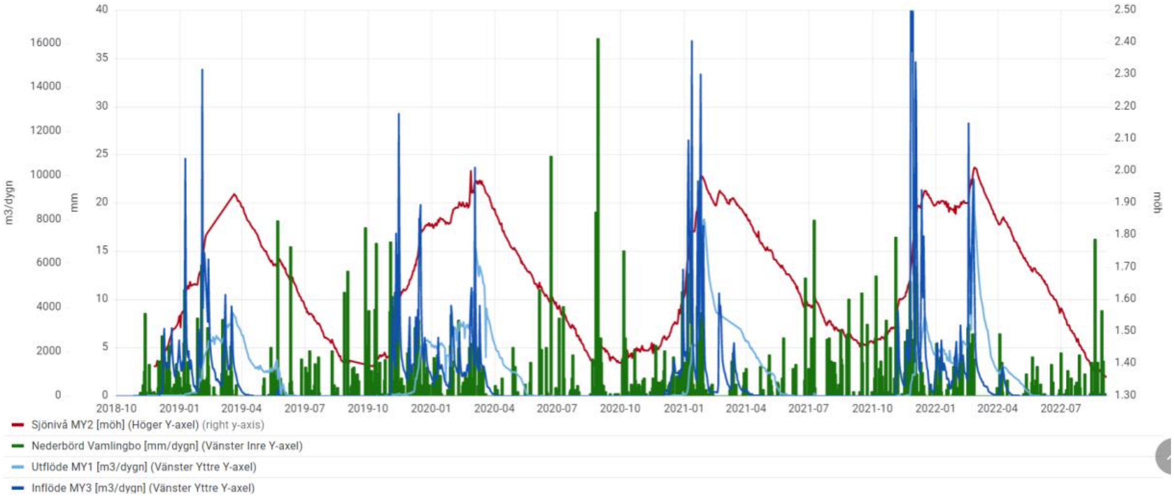

Figure 120. Real time data for precipitation (green), flowrate in in-flowing ditch (dark blue), flowrate in the out-flowing ditch to the sea (light blue), and the surface water level (red) for the lake Mjölhatteträsk.

Table 74. The annual flow of rainwater from lake Mjölhatteträsk to the Baltic Sea. Column A shows the flow from January to December and column B the flow from July to June.

Period (summer-summer in parentheses):	A/ Total outflow winter -winter (m^3/year)	B/ Total outflow summer – summer (m^3/year)
2019 (2019-2020)	301 587	405 170
2020 (2020-2021)	355 243	386 068
2021 (2021-2022)	466 158	369 686
Average:	**374 330**	**386 980**

The flow in the south-eastern ditch, represented by VY3 in Table 75, shows that more than 800 000 m^3 is water flowed from the central area of the case study to the Baltic Sea.

Table 75. The flow in the eastern ditch at the central case study area as measured in the real-time sensor station VY3.

	October 2018	November 2018	January 2019	Februariy 2019	March 2019	April 2019	May 2019	Jun 2019	Total:
VY1	100*	59*	1 085*	9 728*	16 192*	13 629*	2 729*	1 539*	46 184*
VY2	175	104	1 903	17 062	28 400	23 903	4 787	2 699	81 001
VY3	2092	7 272	21 067*	188 902*	319 908	253 979	34 066	13 058	842 154*

Regarding the water quality (Table 76), some parameters differ notably between different water bodies. The groundwater at Sandväten, SGV3, has particularly high salt (NaCl) concentrations and high concentration of lead (Pb) when compared with other water bodies.

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Table 76. The water quality of different water bodies samples in the case study area.

Parameter		Mjölhatteträsk MY2 (surface water) 20180702	Mjölhatteträsk MY2 (surface water) 20180905	Sandväten SGV3 (ground water) 20180702	Vamlingbo VGV3 (ground water) 20180702
Cl	mg/l (mg/g)	36	44	420	6.2
Ca	mg/l	25	53	350	95
pH	upH	8.9	x	7.8	8.1
CE	mS/m	35	x	160	39
TOC (unfiltered)	mg/l	33	34	19	4.6
DOC 0.45 µm	ug/l	32		18	5.4
TN (unfiltered)	mg N/l (mg N/g)	2	2.6	0.8	1.5
Ammonium NH_4	mg N/l	0.16	0.62	0.089	<0.03
Total phosphorus (TP)	mg P/l (mg P/g)	0.015	0.055	x	x
NO_2	mg N/l	<0.01	<0.01	<0.10	<0.01
NO_3	mg N/l	0.007	<0.005	0.089	1.4
SO_4	mg S/l	9.1	12	92	1.9
PO_4	mg N/l	<0.01	<0.01	<0.01	<0.01
P	mg/l	0.015	0.055	0.7	0.019
Mn	mg/l	<0.05	0.017	0.68	0.028
Fe	mg/l	0.008	0.044	15	0.43
Al	mg/l	0.013	0.03	15	0.33
Si	mg/l	7.8	7.4	69	4.9
Na	mg/l	21	25	350	2.9
Mg	mg/l	17	23	85	2.1
K	mg/l	4.2	6	25	0.87
S	ug/l	11000	16000	130000	3100
V	ug/l	0.76	1.4	28	1.3
Cr	ug/l	0.12	0.27	15	0.59
Co	ug/l	0.11	0.12	6.5	0.31
Ni	ug/l	1	1.3	11	1.2
Cu	ug/l	1	0.69	17	1.5
Zn	ug/l	1.3	2.1	37	8.1
As	ug/l	1.6	2.9	8.8	0.65
Sr	ug/l	160	210	1200	170
Mo	ug/l	0.51	1.1	0.83	0.16
Cd	ug/l	0.012	0.006	0.26	0.018
Ba	ug/l	9.3	19	69	9.5
Pb	ug/l	0.43	0.8	22	0.84

5.2.8. Comparison of baseline situation and NextGen KPIs

Before the installation of the real-time sensors for precipitation, flowrate in ditches and surface- and groundwater levels, there was no information on the water balance at the case study area Storsudret. The establishment of the water balance (precipitation, flowrate in ditches, surface water levels and groundwater levels) has shown that even areas with very

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limited opportunities for groundwater formation can develop into net producers of fresh water. The measurement results from only three ditches in the case study area, in total almost 1,9 million cubic meters of rainwater, strongly indicates that there is enough water not only for the case study area Storsudret, but also for supplying to other areas in Gotland. The challenge is to store the water from the winter season to summer. Figure 121 summarises the water flow for some of the ditches at Storsudret.

Figure 121. Based on the real time meassurements of the flow in the main ditches, the potential of for rainwater harvesting is calculated.

Based on the findings from the setup of the water balance and the planning and implementation of the testbed at pilot-scale, a conceptual design of a full-scale system capable to provide 500,000 m^3/year of fresh water for supply of tap water and for irrigation of crops was developed for comparison of the baseline and the NextGen KPIs. This comparison provided a valuable basis for future planning in areas with relatively poor conditions for water supply, starting at regional level in Gotland, going up to national level Sweden and all the way to the European level.
Based on the established water balances, it is very likely that significantly larger volumes of water than are needed locally at Storsudret can be provided by combining the information from the real time measurement system with the other infrastructure of the case study, a full-scale system for water supply could be designed. The other parts of the system that supplies water to the system are the following (see figure :

- Storage of rainwater from the winter to the dry summer period through automatic and active regulation of the lake Mjölhatteträsk (see 3.5).
- Energy efficient membrane filtration for purification of the stored surface water in Mjölhatteträsk for drinking water production (by using the stored water in the lake)
- Recycling of raw sewage wastewater by use of ultrafiltration and reverse osmosis (see 4.1).
- Subsurface pond for cost- and energy efficient local water supply

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Figure 131: Besides the infrastructure for real-time measurement of the water balance, the following four parts will be included in the pilot system: 1/ Automatic floodgate for storage of water from winter to summer 2/ Treatment of surface water for drinking water supply. 3/ Sewage water reuse in Burgsvik by UF+RO 4/ Groundwater pond for secure, local water supply

Based on the results of the water balance measurements for Storsudret and the use of the systems mentioned above, Figure 122 shows a system which could produce 450,000 m^3 of drinking water and 100,000 m^3 of irrigation water annually. Half of the annual drinking water supply would take place during the critical supply period from May to October. Irrigation water could be produced through collecting and storing rainwater to ensure the continued local commitment to the case study area Storsudret, which so far has been very large.

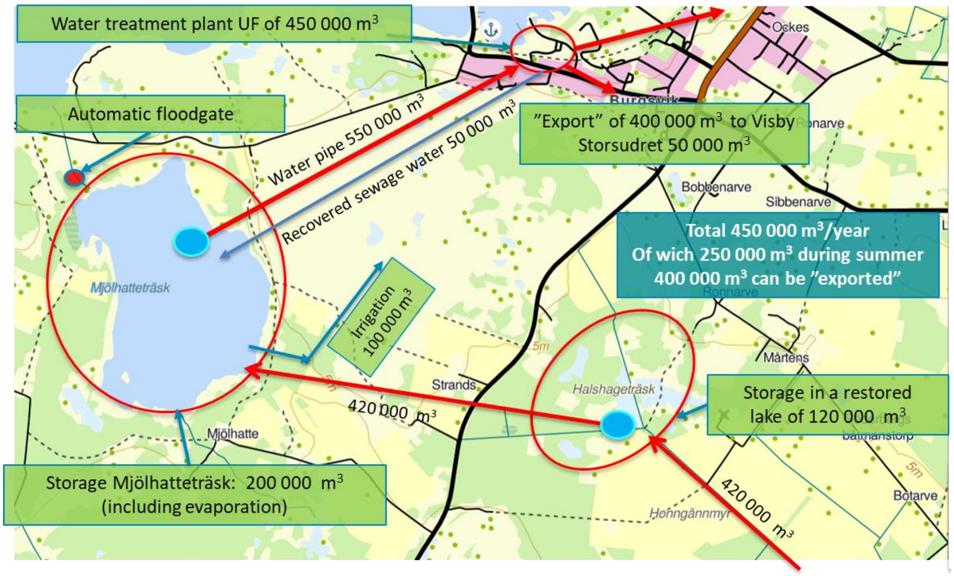

Figure 122. A system design, based on the results from the water balance measurements,which could provide/store 450,000 m3 of drinking water and 100,000 m3 of irrigation water. 250 000 m3 of the drinking water volume is available during summer. If use for drinking water production is not relevant, half of the stored volume could be used for irrigation purposes. 50 000 m3 of drinking water could be provided to the local drinking water distribution network, while 400 000 m3 could be exported outside of the area.

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Table 77. Specific Key Performance Indicators (KPI) for the potential of local water supply by collection and storage of rainwater.

Topic	Objectives	Specific Key Performance Indicator (KPI)	Current value	NextGen values
Rainwater harvesting and storage	To collect and store rainwater for irrigation and the municipal drinking water system.	Water yield of the system [% of collected and stored water for irrigation]	<0.1 %	1 %
Energy	To reduce electricity consumption of the NextGen system compared with today´s situation	Electricity consumption for drinking water treatment and pumping [kWh/m^3 reclaimed water]	4.75 kWh/m^3	< 2 kWh/m^3
Costs	To reduce the cost for energy (electricity)	Cost for Electricity related to water treatment and pumping of drinking water [kWh/m^3 reclaimed water]	0.8 Euro/ m^3	<0.33 Euro/ m^3

Regarding the water quality (Table 78), some parameters differ to a high extent between different water bodies, such as the higher salts and metals concentrations in Sandväten (SGV3). KPIs for the water quality come from the Swedish regulation for drinking water (SLVFS 2001:30), and the comparison between the different water bodies and the KPIs is shown in Table 78. All water bodies except Vamlingbo (VGV3) have arsenic (As) concentrations which exceed the limit. Sandväten groundwater has several parameters (e.g., lead (Pb)) over the limits for drinking water, as well as several parameters at concentrations greater than the classification “Drinkable with remark”. The most usable water for producing drinking water is the Vamlingbo groundwater, where only for iron and aluminum concentrations are slightly higher than the classification “Drinkable with remark”. Except for arsenic, lake Mjölhatteträsk (MY2) also shows good values and could serve as a drinking water reservoir.

Table 78. Comparison of analysis of samples taken in three different water bodies at the case study area with the KPI figures represented by the Swedish limits for drinking water. Yellow cells represent values over the classification “Drinkable with remark” and red cells represents values over the limits. Several of the parameters is above the limits for drinking water, especially for Sandväten SGV3 and Vamlingbo VGV3. If those water sources should serve for water supply, those would need some kind of treatment.

Parameter		Mjölhatteträsk MY2 (surface water) 20180702	Mjölhatteträsk MY2 (surface water) 20180905	Sandväten SGV3 (ground water) 20180702	Vamlingbo VGV3 (ground water) 20180702	Limits for drinking water (SLVFS 2001:30)
Cl	mg/l (mg/g)	36	44	420	6.2	100*
Ca	mg/l	25	53	350	95	100*
pH	upH	8.9	x	7.8	8.1	10,5
CE	mS/m	35	x	160	39	250
TOC (unfiltered)	mg/l	33	34	19	4.6	
DOC 0.45 µm	ug/l	32		18	5.4	

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TN (unfiltered)	mg N/l (mg N/g)	2	2.6	0.8	1.5	
Ammonium NH4	mg N/l	0.16	0.62	0.089	<0.03	0,5
Total phosphorus (TP)	mg P /l (mg P/g)	0.015	0.055	x	x	
NO2	mg N/L	<0.01	<0.01	<0.10	<0.01	0,1
NO3	mg N/L	0.007	<0.005	0.089	1.4	20
SO4	mg S/l	9.1	12	92	1.9	100*
PO4	mg N/l	<0.01	<0.01	<0.01	<0.01	
P	mg/l	0.015	0.055	0.7	0.019	
Mn	mg/l	<0.05	0.017	0.68	0.028	0,05*
Fe	mg/l	0.008	0.044	15	0.43	0,1*
Al	mg/l	0.013	0.03	15	0.33	0,1*
Si	mg/l	7.8	7.4	69	4.9	
Na	mg/l	21	25	350	2.9	100*
Mg	mg/l	17	23	85	2.1	30*
K	mg/l	4.2	6	25	0.87	
S	ug/l	11000	16000	130000	3100	
V	ug/l	0.76	1.4	28	1.3	
Cr	ug/l	0.12	0.27	15	0.59	50
Co	ug/l	0.11	0.12	6.5	0.31	
Ni	ug/l	1	1.3	11	1.2	20
Cu	ug/l	1	0.69	17	1.5	2
Zn	ug/l	1.3	2.1	37	8.1	
As	ug/l	1.6	2.9	8.8	0.65	1
Sr	ug/l	160	210	1200	170	
Mo	ug/l	0.51	1.1	0.83	0.16	
Cd	ug/l	0.012	0.006	0.26	0.018	5
Ba	ug/l	9.3	19	69	9.5	
Pb	ug/l	0.43	0.8	22	0.84	10

5.2.9. Lessons learned

Required competence	LOW ▲ HIGH

- The real-time measurement system for the water balance is up and running but there is a need for competence to maintain and recalibrate the system.
- The data collected is available on different aggregation levels. Each level has it´s own requirement for competence, so it varies. For some of the sensors, the result is displayed on the website of the case study area for the public to see, which does not require

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specific knowledge for comprehension. On the other hand, to be able to use the database for research on, e.g. groundwater hydrology, there is a need to understand how to extract the data. • The need for training is also varying for different purposes.	
Maintenance	LOW  HIGH
▪ The sensor stations are powered by rechargeable batteries requiring replacement ever 4 months. ▪ A recalibration of the sensor station should be performed every second year. ▪ The competence for running and maintaining the system is available in-house.	
Technological risks	LOW  HIGH
▪ The main risk for downtimes are the unexpected need for battery recharge and physical damage of cables. ▪ The overall system has not had any downtimes, but downtimes for individual sensors are relatively frequent, approx. once every second month. When a downtime occurs, there is a need to replace batteries, cables, or other material, which normally takes a week to organize. Restarting a sensor station seldom requires external personnel. ▪ The knowledge regarding maintenance and sensitive hardware is increasing and results in fewer downtime events.	

5.2.10. Best practice guidelines for operating the technology

The establishment of the water balance (precipitation, flowrate in ditches, surface water levels and groundwater levels), showed that even areas with very limited opportunities for groundwater formation can develop into net producers of fresh water. A design of a full-scale system for water supply has shown that case study area of could store/provide 500,000 m^3/year.

The need for manpower during installation of the measurement system for the water balance was extensive and much higher than expected. This resulted in higher investment costs than expected. Especially the calibration of the installed sensors required many manhours and many field trips. Additionally, several sensors did not perform well from start and had to be replaced and recalibrated. There were also some initial issues with downloading the real time data smoothly which also required more resources than expected.

Apart from the issues with the sensors and data collection, some of the groundwater pipes which were in contact with the sensors also faced geological/hydrological challenges in some areas with fine sand particles.

Due to the quite extensive need for service and maintenance of the measurement stations, one of the stations was put on standby and for the moment does not collect data.

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6. Conclusions

This section groups the main outcomes obtained during the NextGen project regarding the technologies demonstrated and the feasibility studies realised specifically for closing the water cycle. These outcomes are presented in terms of the benefits and challenges of the technologies, and best applications in order to promote their replicability, transferability and other future implementations.

6.1. Benefits and challenges of the technologies

The main benefits and challenges concluded after the technology demonstration and the feasibility studies are presented in this section, grouped into membrane-based wastewater treatment technologies for water reuse, feasibility study on reclaimed water production at a local and regional level, rainwater harvesting studies, and groundwater storage studies.

Feasibility study on reclaimed water production at a local and regional level

In addition to the current EU regulation 2020/741, which sets clear rules for wastewater reuse for irrigation, other new technologies are also available for wastewater treatment and for producing reclaimed water. The sector is growing, and there are many ongoing field projects which promote circular economy and climate change mitigation.

The feasibility study conducted in Timişoara demonstrated that it is technically possible to implement a circular economy solution for reclaimed water production. Financial investments or other funding options are already available on the Timis region. However, when comparing the costs related to usage of raw water and wastewater reuse, it remains a critical challenge to make the water reuse technologies' implementation more financially attractive. Also, a lack of communication and dissemination activities on water reuse and circular economy were identified, both at the citizen and administration level, which leads to low social acceptance, and weak institutional cooperation at local level for the implementation of treatment systems producing reclaimed water.

Advanced wastewater treatment technologies for water reuse

During the NextGen project, it has been demonstrated that the membrane-based systems tested produce high quality water suitable for different purposes, transforming a waste into a source. For example, the reclaimed water could be used for farming, industrial uses, urban and private irrigation, indirect potable reuse, and other non-potable uses. For these uses, the required quality is not as high as for drinking water and therefore the reclaimed water can be a feasible alternative. In addition, the high quality water produced can be used for many non-potable purposes, therefore the drinking water demand can be reduced. In areas which are experiencing long drought periods, reclaimed water can help prevent water scarcity.

The different case studies agree that one of the main benefits of the membrane-based technologies is that they are compact with a small footprint. Also, this type of system can be

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used either as an alternative or complementary treatment to improve the effluent quality of a WWTP, as in Spernal or Costa Brava, or as a decentralized system to produce high quality water locally, like in Athens, Gotland, or La Trappe. The challenge is the complexity of their operation, which requires qualified personnel. However, they can be easily controlled remotely to optimise the maintenance visits in case of a decentralized application. Despite the potential for their replication, their full-scale implementation still remains a challenge, since they have not yet been tested at full-scale in the case studies, and knowledge dissemination needs to be done to improve the social acceptance.

In addition, the investment costs, i.e. CAPEX, are high and vary according to each market, since they are directly associated with the energy and personnel costs for the system's fabrication. The operation costs, i.e. OPEX, may vary depending on the scale of the system. For example, for a small pilot, the ratio between the operating costs and the volume of the reclaimed water produced is higher than for a bigger treatment plant.

Rainwater harvesting systems

Rainwater harvesting studies realized during the NextGen project in Gotland and in Filton Airfield demonstrated that rainwater is a suitable alternative source to drinking water for non-potable uses like urban uses, agricultural irrigation and toilet flushing. The main interest in implementing such a system is to reduce the potable water demand while preventing water scarcity on the freshwater bodies.

In Gotland, the natural area of the study allows collection of large rainwater volumes during the year using simple and low-cost automatic floodgates for rainwater storage. However, an assessment on the status of the environment and the impact of the floodgate installation for rainwater storage in the area must be performed prior to the installation of the system. The main challenge observed was that the public and private landowners need to agree on the installation, and this must be approved by the land and environmental court.

For the Filton Airfield case study, different urban water resources harvesting options exist in the area. Additionally, rainwater, which meets the quality standard for irrigation, can be directly used. However, water treatment technologies must be implemented before the use of the rainwater for other uses. Other key points to consider when implementing a rainwater harvesting system are the seasonal variation, the urban/population density, the economic impact, and the potential impact on the WWTP.

Aquifer storage systems

Groundwater storage may prevent water evaporation and therefore losses of the resource. Nevertheless, system implementation comes with costs, for example the construction of additional wells, and compliance with legal requirements.

In Westland, the storage of rainwater in an aquifer can replace unsustainable RO treatment of brackish groundwater. Also, storage reduces the saline water intrusion and flood risks. However, storage must be organized together with the local water banking system so that the aquifer is suitable for the ASR system in terms of thickness, hydraulic conductivity and salinity.

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In case the collected rainwater is contaminated, additional treatment (depending on the final use) will be required.

6.2. Best applications of the technologies

During the NextGen project, ten different technologies and studies have been evaluated for closing the water cycle from different aspects. The common point linking all of them was the use of alternative water sources to reduce the drinking water demand and prevent water scarcity. Six of the demonstrations were focused on recovering a waste and transforming it into a resource. The other four demonstrations were mainly focused on the harvesting and storage of rainwater as an alternative water source.

Feasibility study on reclaimed water production at a local and regional level

The first step in a feasibility study is to elaborate an initial market approach to evaluate the economic activity of the area of interest. This first evaluation includes the potential industrial clients which would use reclaimed water produced at the municipal wastewater treatment plant (up to the current flow of the WWTP of 10 800 m^3/h). The stakeholder selection process must consider several factors which could hinder their participation and engagement in reuse, like the cost of fresh and potable water, the bureaucracy for obtaining various permits, the current status of the local wastewater balance, the climate change impact on water availability for all users, the finite character of the potable water resource, or the water legislation.

To establish the content of the reclaimed water use study, the model used came from the AQUAREC project, which allowed estimation of the economical investments for the implementation of the installation, as well as the impact of it on different sectors such as on the wastewater infrastructure, industry, the public health, the environment, or the education.

Advanced wastewater treatment technologies for water reuse

The technologies tested for reclaimed water production have a technology readiness level (TRL) between 7 and 8. In other words, they have been implemented and tested at a pilot-scale, and further investigations and testing under other conditions are recommended before their implementation and application at full-scale. The key parameters for operating the NextGen pilot plants are presented in Table 79.

A membrane system needs to be preceded by another treatment to minimize membrane fouling while increasing filtration cycles and reducing frequency of cleaning sequences. In case of the AnMBR and the MBR systems, the membrane filtration step follows the bioreactor. In case of RO systems, there is a need to install another filtration step, such as microfiltration or ultrafiltration membranes, eliminate solids and nutrients.

Furthermore, membrane-based systems require cleaning sequences to control membrane fouling, which requires chemicals and/or air for regular cleaning and cleaning-in-place activities. The optimal frequency has to be adjusted according to the characteristics of the

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wastewater being treated. To optimize the sequences, a control system monitoring key parameters such as the transmembrane pressure, the flux or the turbidity can be utilised. Such a control system is also crucial for remote operation, as was demonstrated in Athens, to implement the MBR as a decentralized system to treat sewer water locally.

The MBR as a sewer mining unit, the MNR coupled to a MELiSSA MF/RO system, and the decentralized RO unit have all shown that they can be implemented as decentralized systems and can be monitored and controlled remotely. The main benefit observed was the availability to treat wastewater locally, optimizing the costs of the collection and distribution networks.

Table 79. Relevant parameters for operating and implementing NextGen pilot plants for reclaimed water production.

Parameters	AnMBR	MBR (SM unit)	MNR + MELiSSA MF/RO	UF + regenerated RO	Decentralized RO
TRL	**7**	**8**	**7**	**7**	**7**
Flow rate	500 m^3/d	25 m3/d	100 L/h	2 m^3/h	1.6 m^3/h
Recovery rate	99 %	99 %	MNR: 99 %, MF/RO: 20 - 30 %	70 – 75%	75 %
Chemicals	No chemicals used.	Sodium hypochlorite 12-14 % Citric acid 50%	Data not provided.	Sodium bisulfite, sodium hypochloride	HCl, NaOH, surfactants
Energy demand	0.43 kWh/m3	SM system: 50 – 55 KWh/day	MNR: 3.5 kWh/m^3	0.9 – 1 kWh/m^3	8.5 kWh/m^3
CAPEX	Data not provided. Full scale costs estimation presented at D2.2	1.74 €/m3. . Full scale costs estimation presented at D2.2	Data not provided. Full scale costs estimation presented at D2.2	70 k€	Data not provided. Full scale costs estimation presented at D2.2
OPEX	Data not provided. Full scale costs estimation presented at D2.2	0.50 €/m3. Full scale costs estimation presented at D2.2	Data not provided. Full scale costs estimation presented at D2.2	Data not provided. Full scale costs estimation presented at D2.2	Data not provided. Full scale costs estimation presented at D2.2
Water Quality Standards	No water reuse guidelines in the UK	Greek legislation 354/8-3-2011	Data not provided.	Spanish regulation RD 1620/2007	Swedish regulation SLVFS 2001:30
Uses	Farming, industrial uses	Urban irrigation, other non-potable uses	Bottles washing, aeroponics and aquaculture	Private uses	Indirect drinking water supply

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Rainwater harvesting systems

The studies carried out demonstrate that it is possible to obtain significant drinking water savings while implementing rainwater harvesting systems and strategies. A comparison of the obtained results is presented in Table 80.

Table 80. Relevant parameters for rainwater harvesting system implementation.

Parameters	Innovative floodgate	Alternative water sources
Annual rain	Data not provided	811 mm
Rainwater volume collected	100000 m^3/y	Data not provided
Water savings	25 %	10 – 75%
Catchment surface	110 km^2	13000 – 30000 m^2
Energy demand	< 2 kWh/m^3	Data not provided
CAPEX	Data not provided. Full scale costs estimation presented at D2.2	Data not provided. Full scale costs estimation presented at D2.2
OPEX	<0,33 Euro/ m^3. Full scale costs estimation presented at D2.2	Data not provided. Full scale costs estimation presented at D2.2
Water Quality Standards	Swedish regulation SLVFS 2001:30	Adhikary et al. (2010); Salman et al. (2015); 98/93/EU directive; Steenvoorden (2007); WHO (2017)
Uses	Urban and agricultural uses	Toilet flushing and public irrigation

For an appropriate implementation of rainwater harvesting systems, it is necessary to select an appropriate location to collect and store the rainwater considering the available surface area, the materials available, the location characteristics, while also considering the legislation limits, and the unpredictable and non-uniform rainfall throughout the year. Another key factor for implementation is the commitment of the landlords, house owners, and local and regional administrations. On some occasions, the agreement of the landlords and an approval from the land and environment court are required.

Aquifer storage systems

Groundwater storage systems allow the saving of a significant quantity of annual drinking water consumption. As an alternative source of water for non-potable uses, the most relevant characteristics determined during the project are presented in Table 81.

Like for rainwater harvesting systems, prior to the implementation of the groundwater storage treatment, it is necessary to determine whether the area has a suitable aquifer for ASR and a water banking system. The main characteristics of the soil which should be evaluated are thickness, hydraulic conductivity, mineral composition, and the material. Obviously, the implementation needs to meet the legal requirements, and collaboration and approval from the administration is also necessary.

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Table 81. Relevant paramters for groundwater storage systems for their implementation.

Parameters	ASR	Real time measurements
Annual rain	845 mm	Data not provided
Rainwater volume collected	17.9 Mm^3/y	100000 m^3/y
Water savings	30 %	25 %
Catchment surface	410 km^2	110 km^2
Energy demand	Limited	3 kWh/m^3
CAPEX	44 – 55 M€ (for the water bank)	Data not provided. Full scale costs estimation presented at D2.2
OPEX	71 M€ (for the water bank)	<0,33 Euro/ m^3. Full scale costs estimation presented at D2.2
Water Quality Standards	Groundwater quality related regulations	Swedish regulation SLVFS 2001:30
Uses	Horticulture irrigation	Urban and agricultural uses

6.3. Transferability: application at other sites

For the transferability of NextGen's technologies and studies and implementation at other sites, some key points were identified and are presented in this section.

Feasibility study on reclaimed water production at a local and regional level

The feasibility study has shown that the production and reuse of reclaimed water allows reduced the drinking water demands for non-potable uses such as industrial purposes. However, the current WWTP needs to be updated to meet the water quality standards for the different uses. The implementation of a system for reclaimed water production requires communication and dissemination activities, actions to combat the lack of knowledge of the citizens, and promotion of social acceptance. Apart from the social acceptance, the cooperation with the administration at local and regional level is also a key factor for success.

Advanced wastewater treatment technologies for water reuse

For future implementation of the AnMBR, the unit showed that it was possible to quickly start it up with fresh influent and that it was resilient to varying temperatures. Membrane fouling was low and could be reversed, although more work should be done on optimising the cleaning sequences using biogas. High quality effluent is expected once the unit is operating steadily after its optimization.

The sewer mining unit containing an MBR was implemented and tested for the first time in Greece and in a real-world application. It can serve as a blueprint for broader expansion of MBR usage for producing reclaimed water locally, especially as a decentralized system. The tested configuration demonstrates modularity, flexibility, scalability, and replicability, which are important characteristics for innovation uptake within the emerging circular economy context. Finally, the technology provides "climate-proofed" non-potable water for green space irrigation in dense and arid urban environments, such as cities in the Mediterranean region.

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The MNR system coupled to a MELiSSA MF/RO was a modular technology generating high quality permeate that can be changed depending on usage (fit-for-use). The MF/RO permeate quality is affected by the MNR effluent characteristics, thus the fluctuating influent (mainly in terms of suspended solids and nitrogen concentrations) made testing under representative conditions difficult. Further testing is needed to optimize the operation of the MELiSSA unit.

The end-of-life RO membranes can be regenerated to obtain different molecular cut-offs, thus different quality levels can be obtained. This was also a modular technology, providing flexibility and scalability and transferability. However, it requires low particle and organic matter concentration influent to minimize membrane clogging and cleaning activities. Seasonal temperature variations affect the performance of the system, which requires the operating conditions to be adapted. The demonstrated system also ensured partial removal of emerging compounds, although that may vary depending on the influent wastewater characteristics.

Finally, the replication potential of the decentralized RO system is high, but also requires integrated management for energy and nutrient recovery. The system offers a high product quality, but the seasonal temperature and influent concentrations may affect the operating conditions required to maintain the product quality, and the system has to be optimised using a trial-and-error approach with the help of a control system. There is a need for further investigations on energy and nutrient recovery from the concentrate.

Rainwater harvesting systems

The innovative floodgate system allows storage of large volumes of water by implementing a simple system with low energy consumption and low cost of implementation. But previous studies are required to elaborate an inventory of the area that the rainwater catchment and storage to evaluate the environmental risks and the impact that it will generate. Similar to other studies, some communication and dissemination activities are required before the installation of the technology since it is necessary to have the approval from the landowners and from the administration.

The study about using rainwater as an alternative water source carried out during the NextGen project options for selecting sustainable urban water management strategies in a new residential development area. The study as what was undertaken in this project also permitted the evaluation of different urban water management strategies based on water-energy cycle aspects. For further implementation of this study or strategies, it is necessary to consider the seasonal precipitation variation and the possible effect on the performance of the water cycle. Thus, weather conditions and climate change scenarios must be assessed. A physical implementation of the presented solution needs to consider the implementation of decentralized water solution schemes.

Aquifer storage systems

The implementation of an ASR system depends on the local regulations. The EU Water Framework Directive and the Groundwater Directive are focused on the prevention of the deterioration of groundwater quality. However, ASR systems could already be specifically included in local or national regulatory frameworks. The system also requires the installation of extra wells for the extraction or specific water discharges. Depending on the quality of the collected rainwater, additional treatment prior to use may be required to meet the legislation related to the use.

Like the innovative floodgate, the real time implementation for water balance can allow storage of large water volumes at a low energy demand. However, a preliminary study to identify the appropriate area and media (sand) to implement this type of system is needed. Additionally, this study's results should be replicated at other locations, so the risk of not achieving desired capacity is reduced.

6.4. Recommendations for future implementations

As presented in this chapter, the demonstrated technologies and the feasibility studies still require further preliminary studies. In terms of the implementation of wastewater treatment technologies for reclaimed water production, there is a need to characterize the influent water to be treated and define the further uses the reclaimed water will be used for. Despite the fact that the demonstrated technologies are modular, which promotes their scalability and replicability, testing the treatment unit with the specific influent is recommended to optimize the process operation, control and energy consumption.

Regarding the studies carried out on the implementation of rainwater harvesting and groundwater storage systems, further inventories of the regions is required to determine the most appropriate area to install the groundwater storage system or to harvest rainwater.

All demonstrations revealed that the current EU legislation allows the installation of these types of solutions. The current regulatory framework is mainly focused on the reclaimed water quality for usage and storage, to prevent environmental deterioration and reduced possible toxicity for both environmental and human health. But at some locations, some legal or regulatory obstacles at local or regional levels limit their implementation. There is still a lack of regulations regarding reduction of drinking water usage, the water savings, and the benefits on scarcity prevention, which would help support the installation of circular economy solutions.

Compared to drinking water production, reclaimed water production can face an economic barrier, since some treatment technologies are more costly in terms of investments and operation. An environmental assessment should also accompany economic studies to consider the ecological benefits and impacts of the installation of circular economy solutions.

The studies of the different technologies showed that social acceptance is essential to promote reclaimed water usage at public, private or industrial levels, and for the installation of water harvesting and storage systems. A key point seems to be dissemination and communication activities to increase the citizen awareness and to improve the collaboration with the local and regional administrations.

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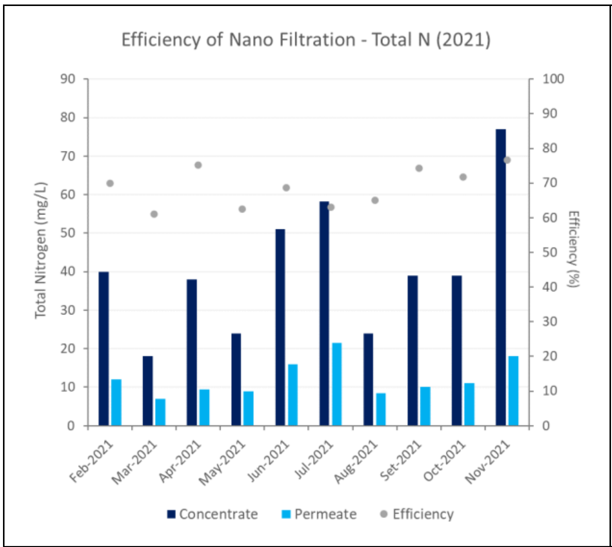
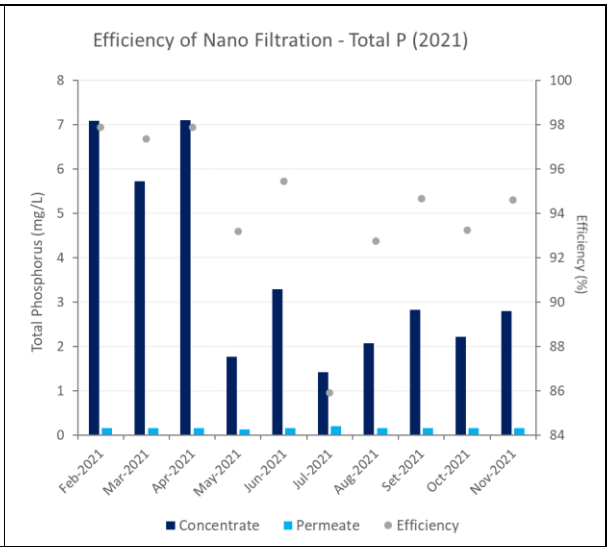
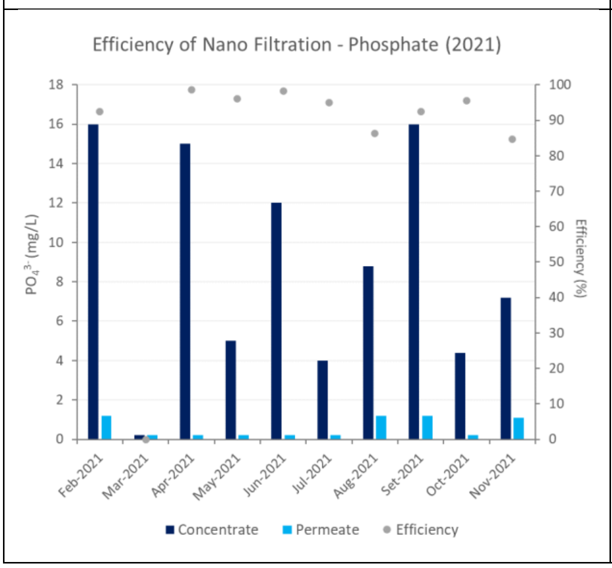
Annex 1: Results of Ultrafiltration (UF) and nanofiltration (NF) system with reverse osmosis regenerated membranes in Costa Brava

A.1 Nanofiltration efficiency: Water quality parameters







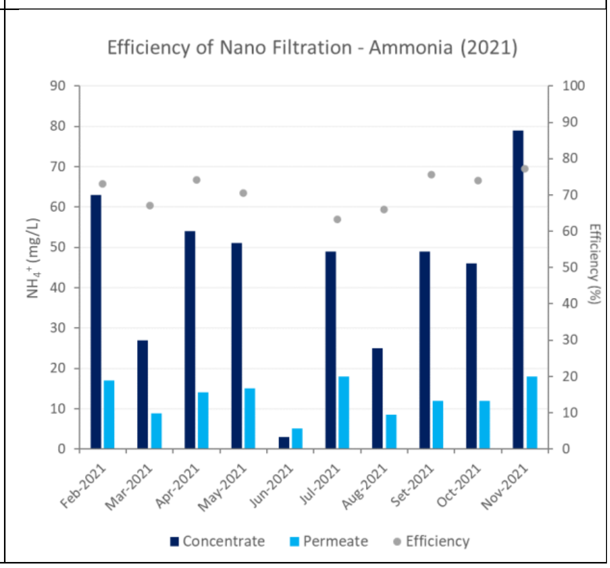


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Figure 123. Concentration at inlet and outlet of the NextGen pilot plant and removal efficiencies of the water quality parameters. From the left to the right, and from the top to the bottom: (a) total nitrogen; (b) total phosphorous; (c) phosphate; (d) ammonia; (e) nitrates; (f) nitrites; (g) calcium ion; (h) magnesium ion; (i) potassium ion; (j) sodium ion.

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A.2 Nanofiltration efficiency: Endocrine disruptors

A.

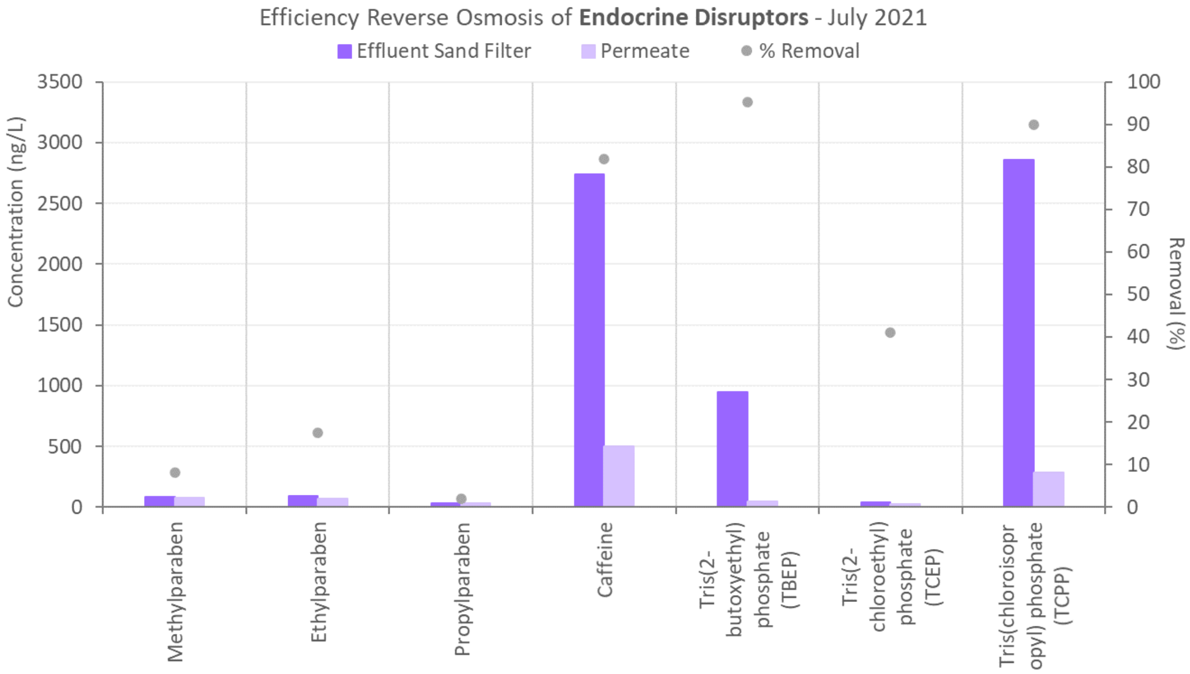

Figure 124. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the endocrine disruptors detected in July 2021.

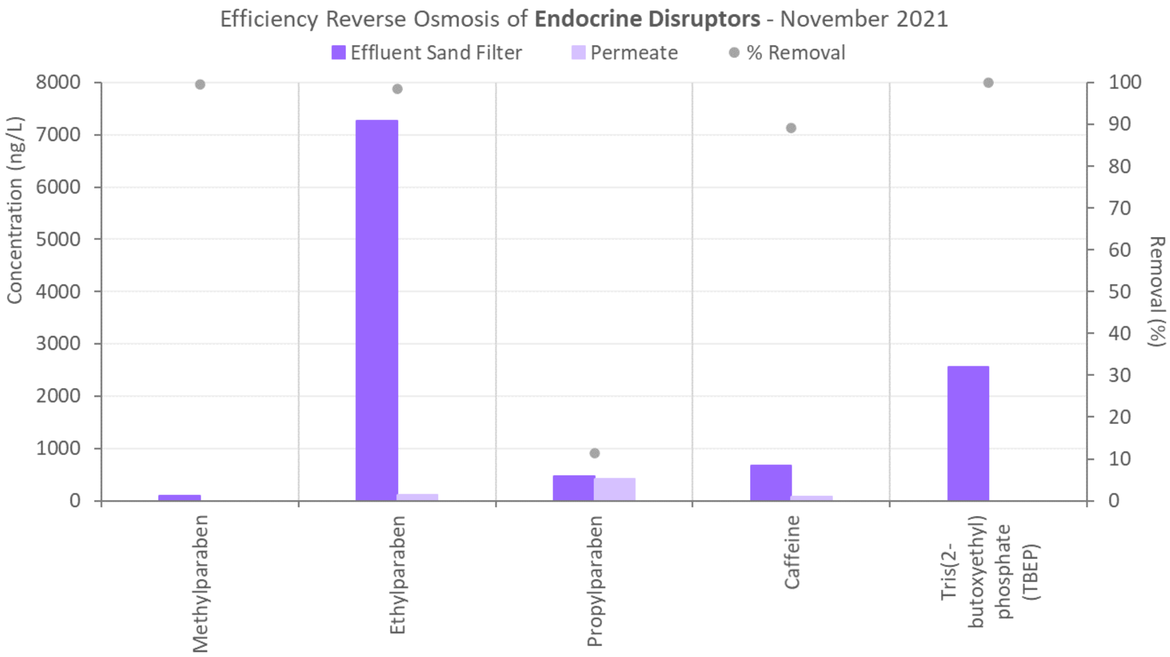

Figure 125. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the endocrine disruptors detected in November 2021.

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A.3 Nanofiltration efficiency: Pharmaceutical compounds

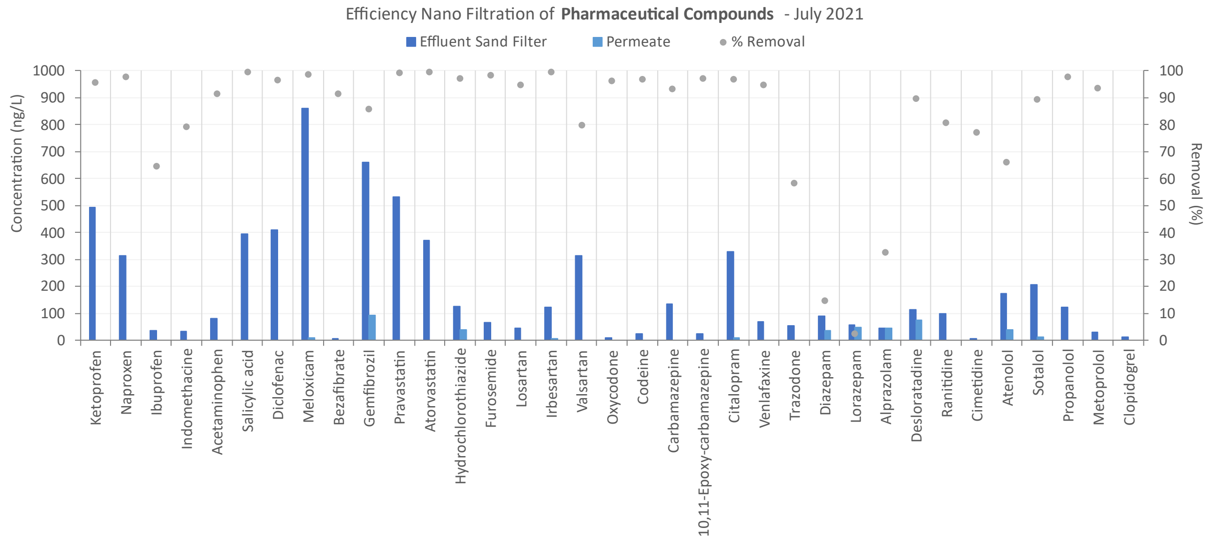

Figure 126. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the pharmaceutical compounds detected in July 2021.

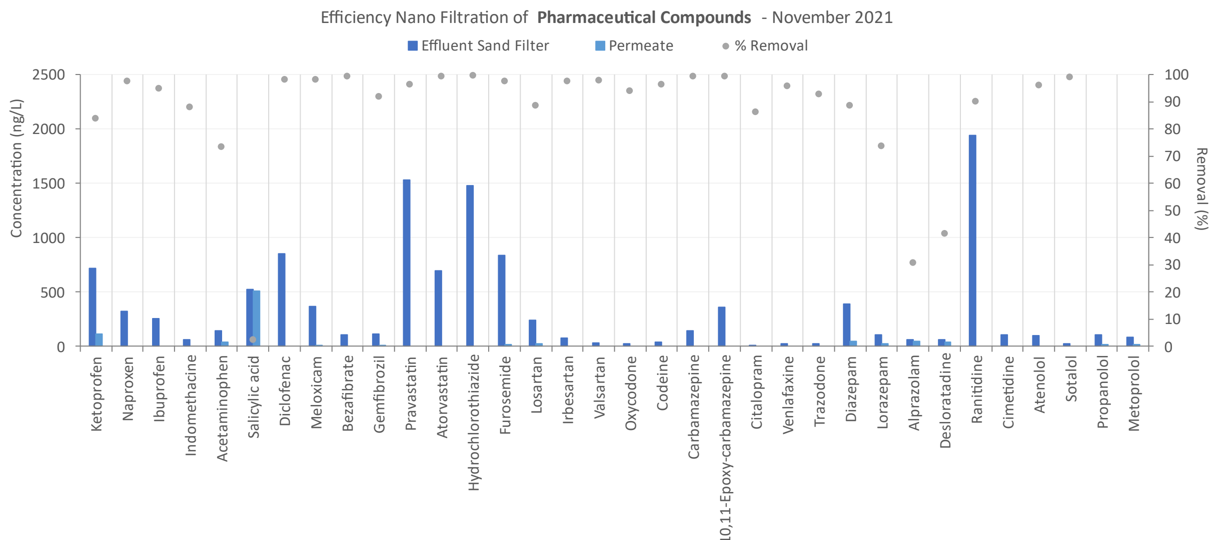

Figure 127. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the pharmaceutical compounds detected in November 2021.

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A.4 Nanofiltration efficiency: New pharmaceuticals

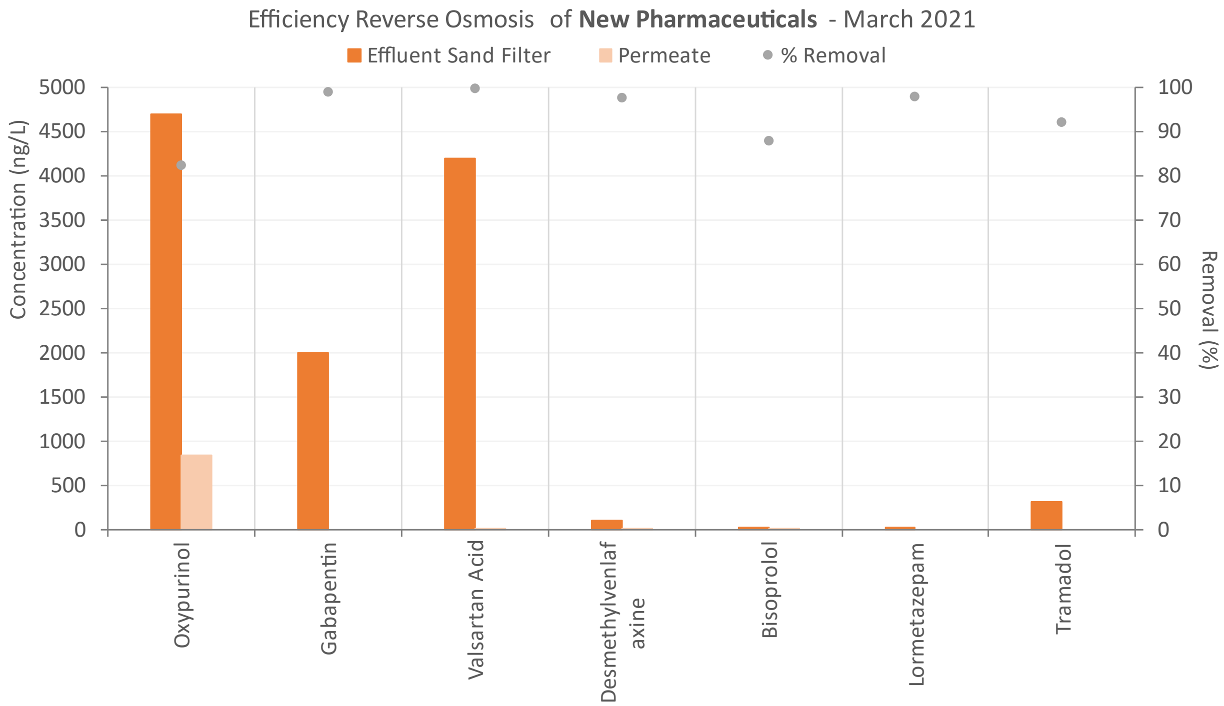

Figure 128. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the new pharmaceuticals detected in March 2021.

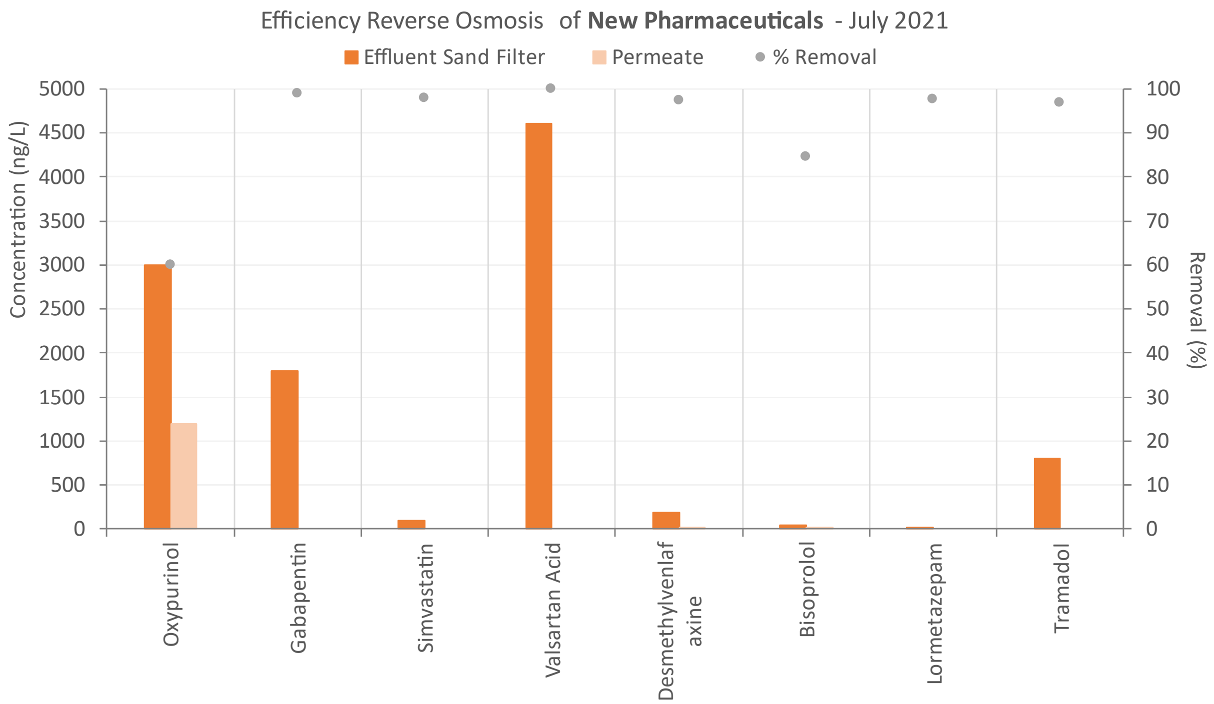

Figure 129. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of the new pharmaceuticals detected in November 2021.

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A.5 Nanofiltration efficiency: Pesticides and herbicides

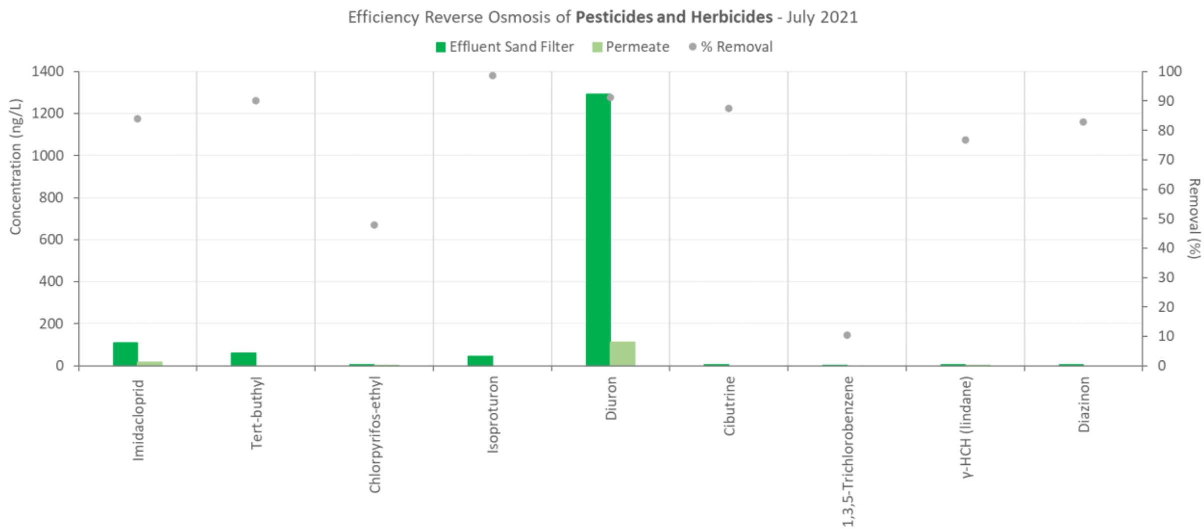

Figure 130. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of pesticides and herbicides detected in July 2021.

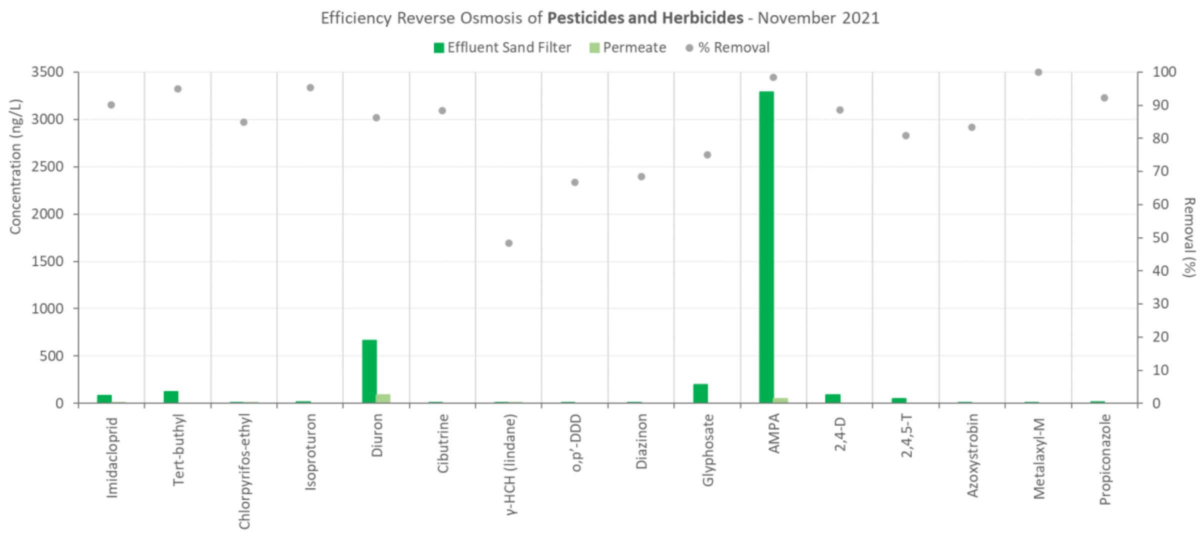

Figure 131. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of pesticides and herbicides detected in November 2021.

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A.6 Nanofiltration efficiency: Household products

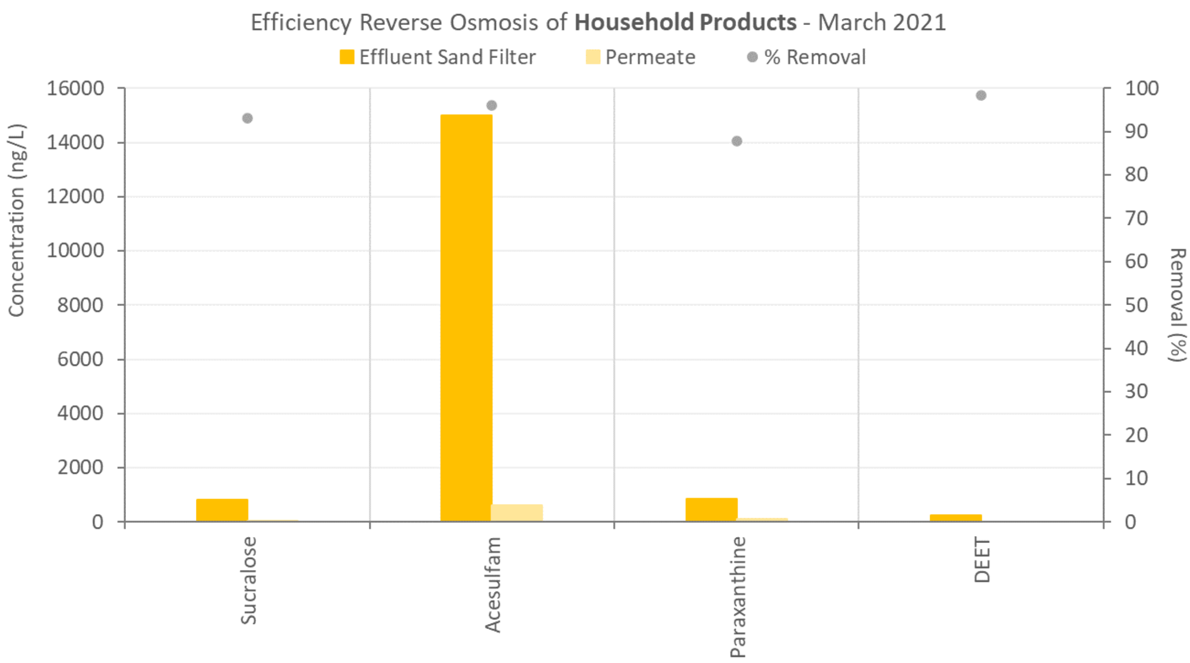

Figure 132. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of household products detected in July 2021.

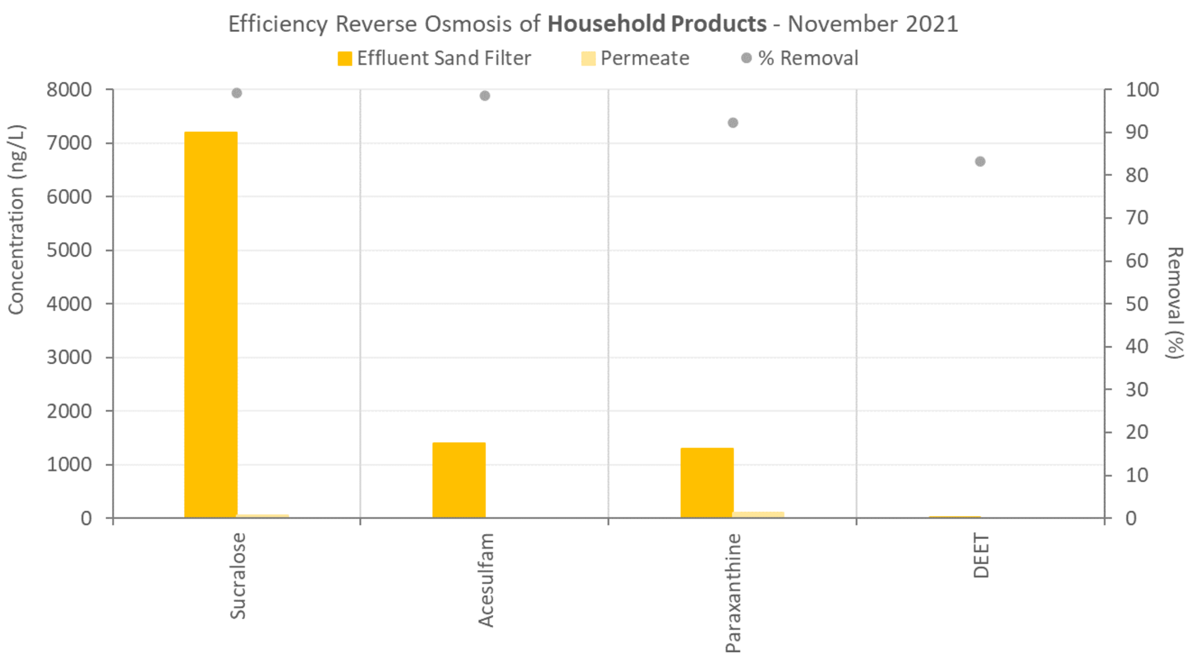

Figure 133. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of household products detected in November 2021.

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A.7 Nanofiltration efficiency: Benzotriazole compounds

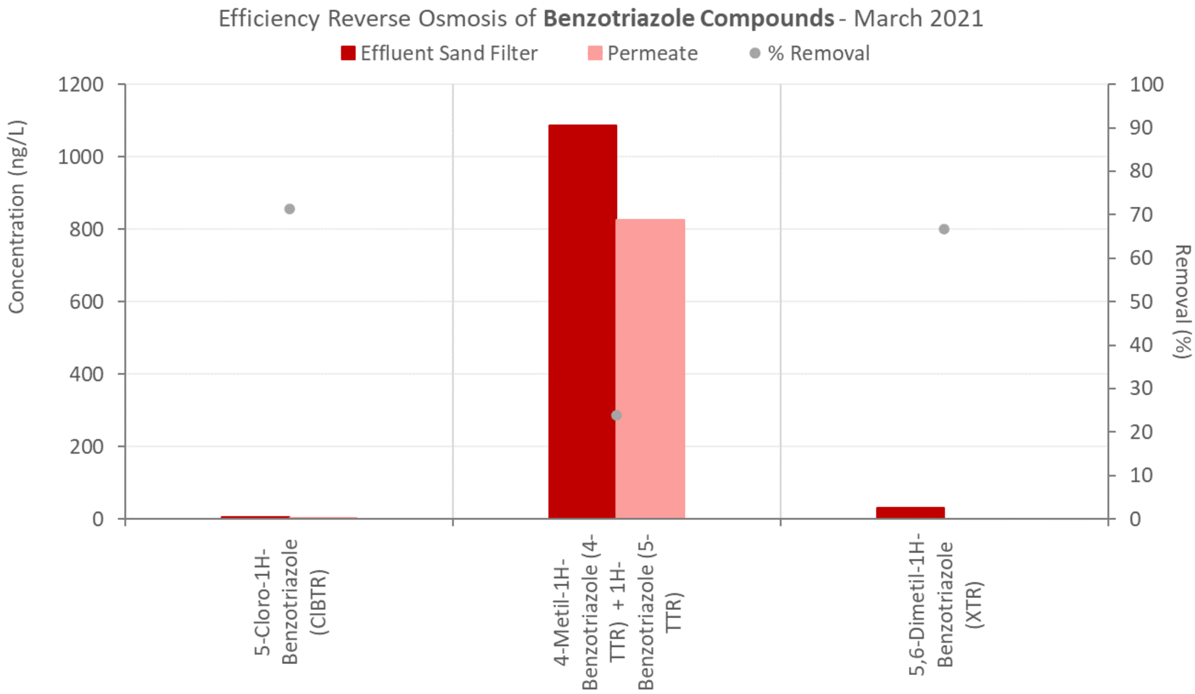

Figure 134. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of benzotriazole compounds detected in March 2021.

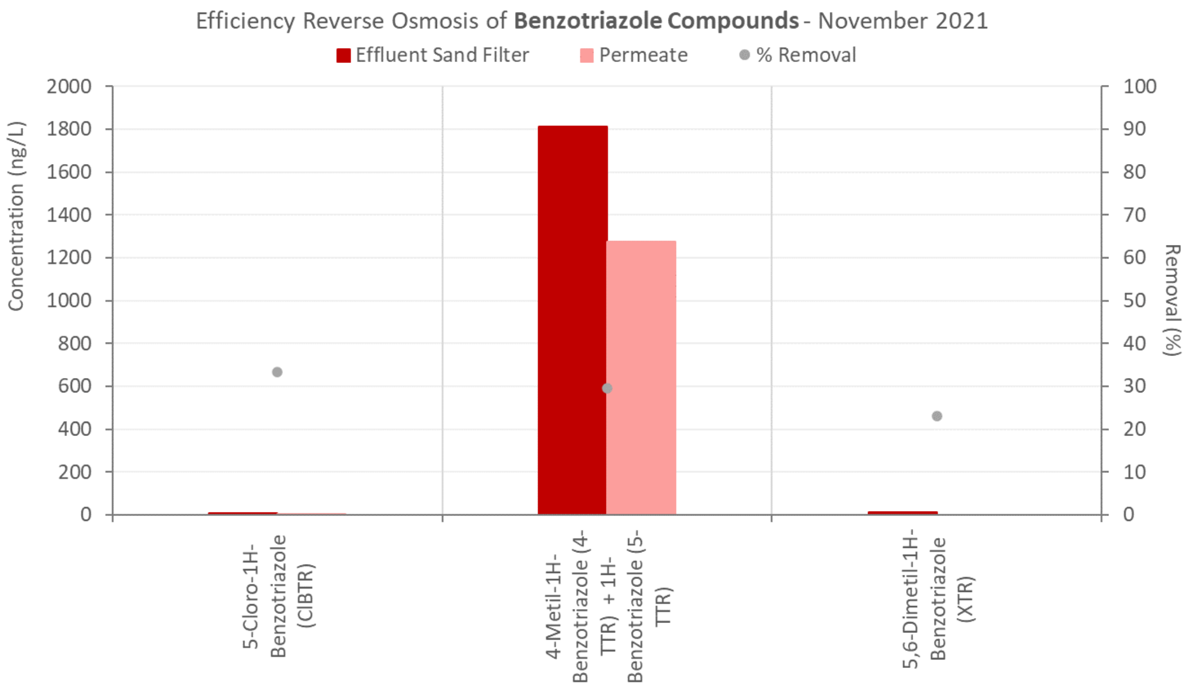

Figure 135. Concentrations at the inlet and outlet of the NextGen pilot plant and removal efficiencies of benzotriazole compounds detected in November 2021

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Annex 2: Results from the rainwater harvesting in Filton Airfield

Table 82 Physiochemical and microbiological analysis methods (UKAS, 2020).

Parameter	Method No.	Techniques used
Physiochemical parameters		
pH	-	pH/EC/TDS meter Hanna Instruments™ HI9812-5
Conductivity at 25 °C	-	pH/EC/TDS meter Hanna Instruments™ HI9812-5
Turbidity	3:404	Turbidity meter; **nephelometric method (Hach 2100N Turbidimeter)**
Alkalinity ($CaCO_3$)	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Total dissolved solids, TDS	-	pH/EC/TDS meter Hanna Instruments™ HI9812-5
Biochemical oxygen demand	2:702	Incubation at 20 °C
Chemical oxygen demand	2:703	Acid Dichromate - Colorimetric
Total hardness ($CaCO_3$)	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Ca. Hardness	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Mg. Hardness	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Nutrients, major ions and metals		
Chloride, Cl	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Nitrite, NO_2	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Nitrate, NO_3	-	Calculation
Ammonium, NH_4	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Sulphate, SO_4	2:550	Automated - Colorimetry by Discrete Autoanalyzer
Fluoride, F	3:408	Ion Selective Electrode
Calcium, Ca	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Potassium, K	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Magnesium, Mg	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Sodium, Na	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Iron, Fe	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Manganese, Mn	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Copper, Cu	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Chromium, Cr	2:302	Inductively Coupled Plasma - Mass Spectroscopy
Cadmium, Cd	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Nickel, Ni	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Zinc, Zn	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Lead, Pb	2:301	Inductively Coupled Plasma - Mass Spectroscopy
Microbiological parameters		
E.Coli	3:301	Membrane filtration

Table 83 Equations used to calculate water demand for toilet flushing and irrigation applications (Matos et al., 2013).

Water demand for toilet flushing

$$D_{WC} = V_{WC} \times F_{WC} \times N$$

where D_{WC} is the total demand for toilet flushing (m^3), V_{WC} is the volume of water used per flush (m^3), F_{WC} is the frequency of toilet use/flush (-) and N is the number of people using the toilet (-).

Water demand for irrigation

$$D_{IR} = V_{IR} * F_{IR} * IA$$

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where D_{IR} is the total demand for irrigation (m^3/day), V_{IR} is the consumption unit per irrigation area (m^3/m^2), F_{IR} is the frequency of irrigation (day^{-1}) and IA is the irrigation area (m^2).

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Table 84. Physio-chemical and microbial characteristics of raw rainwater.

Parameters	Units	Range (Min-Max)	Mean	SD	Irrigation water quality standards	Drinking water quality standards
Physiochemical parameters						
pH	-	7.0-8.4	7.57	0.36	6.5-8.4[a]	6.5-8.5[b]
Conductivity at 25 °C	µm/cm	8-62	25.20	16.02	700[a,c]	400[b]
Turbidity	NTU	0.11-0.6	0.25	0.11	5[b]	5[b]
Alkalinity ($CaCO_3$)	mg/L	<20	-	-	100[b]	100[b]
Total dissolved solids, TDS	mg/L	2.9-60	20.69	17.35	500[a,c]	500[d]
BOD	mg/L	<4	-	-	NS	NS
COD	mg/L	<50	-	-	NS	NS
Total hardness ($CaCO_3$)	mg/L	1.0-8.32	3.86	2.15	0-460[a]	500[e]
Ca. Hardness	mg/L	1.0-7.5	3.06	2.06	NS	NS
Mg. Hardness	mg/L	0.4-1.6	0.88	0.28	NS	NS
Microbiological parameters						
Chloride, Cl	mg/L	<3			250[c]	250[b]
Nitrite, NO_2	mg/L	<0.04	-	-	NS	3[b,d]
Nitrate, NO_3	mg/L	<0.2	-	-	5	50[b,d]
Ammonium, NH_4	mg/L	<0.4	-	-	0.5[c]	0.2[b]
Sulphate, SO_4	mg/L	<10	-	-	2-170	250[b]
Fluoride, F	mg/L	<0.04	-	-	1.5[c]	1.5[d]
Calcium, Ca	mg/L	0.3-3.0	1.19	0.84	NS	100[b]
Potassium, K	mg/L	0.1-1.0	0.22	0.25	12[c]	20[e]
Magnesium, Mg	mg/L	0.1-0.4	0.22	0.07	140	50[e]
Sodium, Na	mg/L	0.6-2.9	1.56	0.60	70[b,c]	50[d]
Iron, Fe	mg/L	<0.01	-	-	5.0[c]	0.3[b]
Manganese, Mn	mg/L	<0.001	-	-	0.2[c]	0.5[e]
Copper, Cu	mg/L	<0.01	-	-	NS	2.00[d]
Chromium, Cr	mg/L	<0.001	-	-	0.10[c]	0.05[b,d]
Cadmium, Cd	mg/L	<0.0001	-	-	0.01[c]	0.003[d]
Nickel, Ni	mg/L	<0.002	-	-	0.20[c]	0.07[d]
Zinc, Zn	mg/L	<0.01	-	-	2.0[c]	3.0[e]
Lead, Pb	mg/L	<0.0001	-	-	5.0[c]	0.01[b,d]
Microbiological parameters						

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E.Coli	no/100 ml	30-500	109.6	130.02	1000[c]	0[d]

NS: Not Specified
SD: Standard deviation
[a] Abdollahi et al. (2017), Food and Agriculture Organization (FAO)
[b] Adhikary et al. (2010) and Salman et al. (2015)
[c] 98/93/EU directive, Steenvoorden (2007)
[d] WHO (2017)
[e] Al-Khashman et al. (2017)

Table 85. The quality of air in Central Bristol from 2007 to 2020.

Annual Mean, µg/m³	NO_2	SO_2	PM_{10}
2007	31	2	20
2008	32	2	20
2009	30	2	19
2010	32	2	20
2011	27	2	N/A
2012	32	2	18
2013	28	N/A	18
2014	28	N/A	17
2015	26	N/A	15
2016	27	N/A	15
2017	24	N/A	15
2018	24	N/A	15
2019	23	N/A	16

Data is only available from 2007. N/A: not available
NO_2: Annual mean < 40 µg/m³
SO_2: Annual mean < 20 µg/m³
PM_{10} particulate matter (hourly measured): Annual mean < 40 µg/m³
https://www.airqualityengland.co.uk/site/statistics?site_id=BRS8

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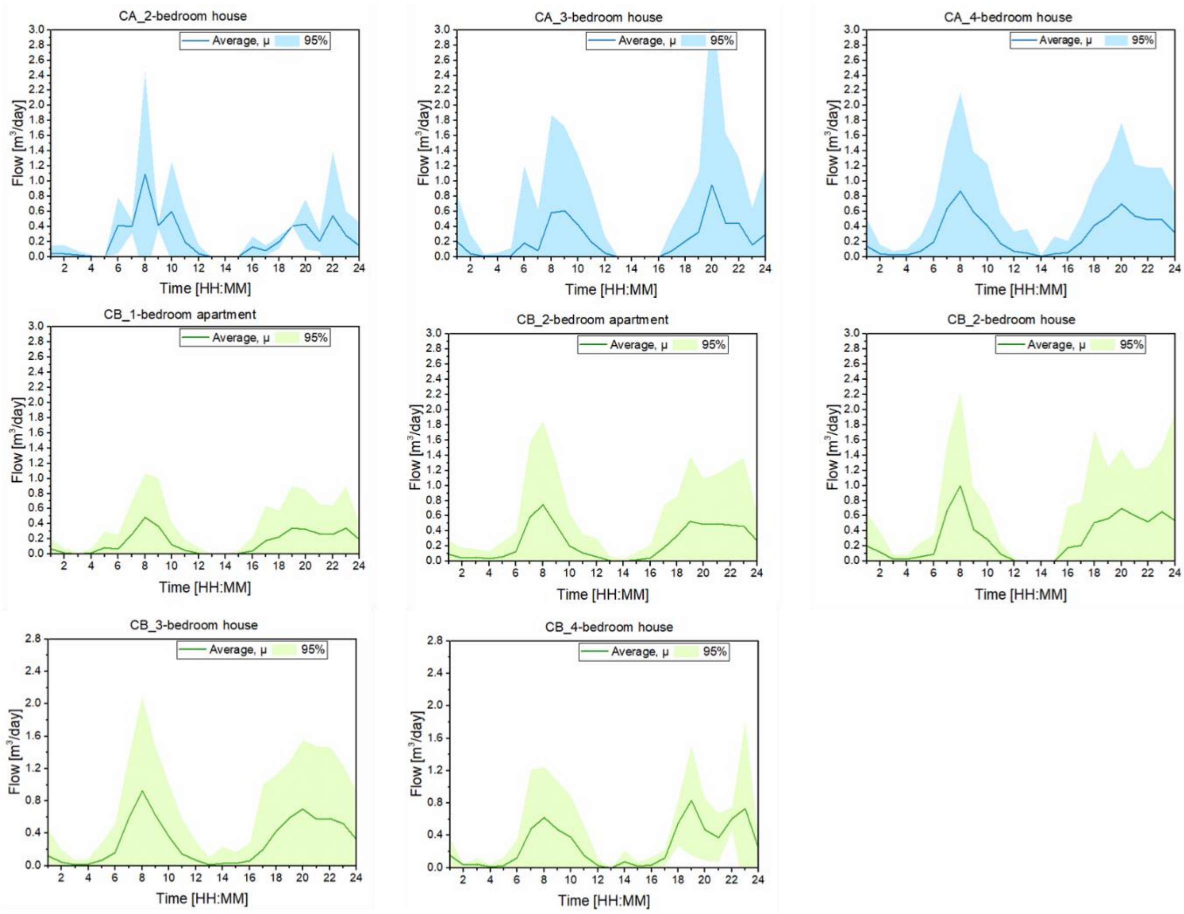

Figure 136. SIMDEUM simulations for each household types in catchments A and B.

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Table 86. Rainfall data collected from the Filton site and weather stations close to the site.

Rainfall Quantity		Rainy days [days]				Rainfall volume [mm]			
		Filton (UOB)	Gloucestershire	Little Stoke	Horfield	Filton (UOB)	Gloucestershire	Little Stoke	Horfield
2019	September	9	10	9	9	103.8	52.0	65.9	123.6
	October	21	19	18	20	173.8	81.2	156.6	175.0
	November	17	21	15	17	107.3	124.9	83.4	119.6
	December	16	16	14	16	98.8	72.3	77.4	117.0
	Total	63	66	56	62	483.7	330.4	383.3	535.3
	Max	21	21	18	20	173.8	124.9	156.6	175.0
	Min	9	10	9	9	98.8	52.0	65.9	117.0
	Average	16	17	14	16	120.9	82.6	95.8	133.8
2020	January	16	12	13	16	72.9	43.3	66.2	90.8
	February	20	17	20	20	140.5	99.8	121.8	167.0
	March	13	10	12	15	57.9	34.3	55.0	83.5
	April	6	7	6	6	39.0	24.6	33.2	39.0
	May	1	3	1	1	4.6	11.9	4.0	2.1
	June	10	19	11	11	84.5	91.5	92.8	116.0
	July	12	12	12	12	47.2	42.5	40.4	61.6
	August	13	15	10	13	116.4	74.4	100.4	133.7
	September	6	5	6	4	23.1	32.3	23.8	23.0
	October	19	20	20	20	101.5	96.6	118.5	141.0
	November	16	11	6	17	65.8	48.7	25.0	86.2
	December	19	21	16	19	111.6	105.2	101.8	154.0
	Total	151	152	133	154	864.9	705.1	782.8	943.9
	Max	20	21	20	20	140.5	105.2	121.8	167.0
	Min	1	3	1	1	4.6	11.9	4.0	2.1
	Average	13	13	11	13	72.1	58.8	65.2	85.8
2021	January	13	14	12	14	80.4	79.0	67.6	105.4
	February	10	16	10	10	48.2	66.1	49.4	43.8
	March	5	6	6	6	32.8	24.9	38.0	39.2
	April	4	2	3	4	23.1	9.9	19.6	31.6
	May	18	21	18	19	119.5	75.7	98.5	135.1
	June	5	8	6	6	23.1	57.8	19.4	30.4
	July	11	18	6	10	72.0	72.6	42.6	86.6

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	August	9	9	4	9	72.8	32.0	26.5	93.6
	September	7	4	6	7	59.0	20.0	40.6	77.4
	October	12	11	11	12	115.3	122.7	82.5	151.2
	November	5	4	4	5	17.0	13.2	14.6	18.9
	December	13	9	11	14	88.6	44.4	59.4	78.6
	Total	112	122	97	116	751.8	618.3	558.6	891.7
	Max	18	21	18	19	119.5	122.7	98.5	151.2
	Min	4	2	3	4	17.0	9.9	14.6	18.9
	Average	9	10	8	10	62.7	51.5	46.5	74.3
2022	January	7	7	6	7	42.6	20.0	23.2	29.2
	February	11	13	11	11	70.9	42.0	63.3	79.2
	March	9	10	8	9	37.5	71.7	29.9	41.0
	April	4	9	4	4	19.7	25.9	19.4	21.2
	May	10	7	10	9	51.8	34.8	57.1	61.8
	June	7	7	5	9	59.4	40.2	33.2	77.6
	July	4	4	3	4	16.7	20.6	14.6	24.8
	August	5	6	6	3	21.3	25.9	19.9	18.8
	Total	57	63	53	56	319.9	281.1	260.8	353.7
	Max	11	13	11	11	70.9	71.7	63.3	79.2
	Min	4	4	3	3	16.7	20	14.6	18.8
	Average	7	8	7	7	40.0	35.1	32.6	44.2

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