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Long-time membrane experience at Torreele's water re-use facility in Belgium

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ABSTRACT

At the Torreele facility the Intermunicipal Water Company of Veurne-Ambacht (IWVA) treats secondary wastewater effluent for indirect potable re-use via groundwater recharge in the dune water catchment of St. André. The treatment combining ultrafiltration (UF), using the submerged ZeeWeed system, and reverse osmosis (RO), using brackish water low-energy membranes, enables to produce a high-quality infiltration water, and this leads to sustainable groundwater management of the dune water catchment of St. André. Since start-up, in July 2002, different measures have been taken to optimize the membrane performance. Intermittent use of air on the UF system and variable recovery on the RO system reduced energy consumption per cubic metre produced. The latter also resulted in lower chemical consumption as did the pauses in chloramination. The backwash water and RO concentrate are discharged into a brackish canal, together with the effluent that is not reused. Since 2003, IWVA performed tests using natural systems to further treat this water.

Keywords: Membranes; Water reuse; Managed aquifer recharge; Concentrate treatment

1. Introduction

The Intermunicipal Water Company of the Veurne region (IWVA) restored sustainable groundwater extraction by integration of wastewater reclamation in its existing drinking-water production process. This was possible because reverse osmosis (RO) membranes were used. RO gained worldwide acceptance in water treatment and can be considered as the best available technology when drinking water is at stake. Ultrafiltration (UF) is used prior to RO as it removes bacteria and suspended solids from the water. After RO, the water recharges an unconfined dune aquifer. The residence times of recharged water vary between 30 days and 5 years, whereby 50% of the water is recaptured after 55 days [7]. This managed aquifer recharge (MAR) scheme is operational since July 2002 and not only allowed sustainable groundwater management but proved successful in providing water with high-quality standards. This article will mainly focus on the long-time membrane experience.

2. The processes from sewage to the tap

The MAR scheme is based on the multi-barrier principle. It is composed of an activated sludge plant

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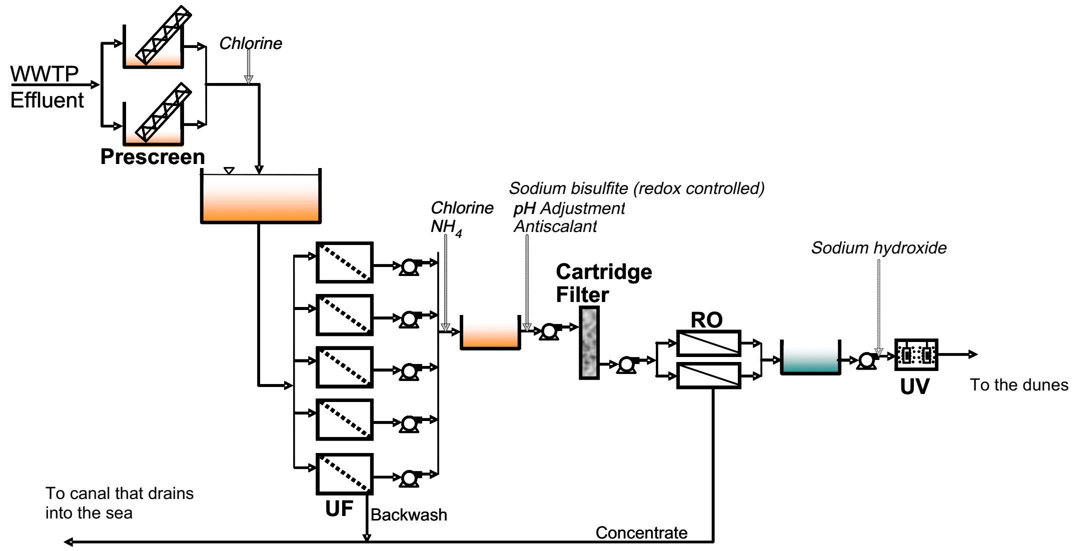

Fig. 1. Process scheme of the Torreele plant.

(WWTP Wulpen), an advanced water reclamation scheme (Torreele facility), a groundwater recharge unit and a groundwater treatment plant (St. André) (Fig. 1).

The *WWTP Wulpen*, built in 1987 for organic and suspended solids removal, was extended in 1994 to comply with nutrient removal. The sewerage network is of combined type. Mechanical treatment consists of 2-step screens, a sand trap and rectangular primary clarifiers. Biological treatment is conventional by a low-loaded pre-denitrification-activated sludge system. Phosphorus is removed by simultaneous chemical precipitation. Sludge-water separation is achieved by secondary settlement tanks. WWTP Wulpen, operated by Aquafin, meets all the EC Urban Waste Water Treatment Directive's limits for sensitive areas.

The effluent is conveyed to the *Torreele facility* by gravity. Before entering the effluent holding reservoir, it passes a mechanical pre-screen with 1 mm slots. Chlorine is added to control bio-growth. From the effluent reservoir, the water flows to five, parallel ultrafiltration (UF) trains. The UF units are ZeeWeed® modules by ZENON (ZW500C), working at a maximum design flux of 36 l/h m^2. The filtration time is 480 to 600 s, while backwash is 30 s. Every 30 to 35 backwashes chlorinated backwash is performed. UF filtrate enters a holding reservoir after being chloraminated. From there, it is pumped to the reverse osmosis (RO) system. Both scale inhibitor and sulfuric acid are injected to control scaling. A third pump can dose $NaHSO_3$ to neutralize free chlorine. Before the RO system, the water first passes through a cartridge filter (pore size of 15 μm). The RO permeate enters a reservoir (Table 1).

The RO is composed by low-energy membranes from DOW (BW30 LE-440) in 2/1 configuration with

Table 1
Summary of the Torreele facility

History of project	1997–1999, pilot testing using different MF/UF and RO systems on effluent of Wulpen WWTP
Status of project	Operating since July 2002
Capacity	2,500,000 m^3/year
Source water	WWTP secondary effluent
Pre-treatment	Pre-screen with 1 mm slots
Membranes	UF: Zenon (ZW500C), 15.600 m^2 surface area, maximum flux of 36 l/h m^2
	RO: Dow (BW30 LE-440), 15.744 m^2 surface area, maximum flux of 20 l/h m^2
Design flux	UF: max of 40 l/h m^2 recovery minimum 87%
	RO: max of 20 l/h m^2 recovery minimum 75%
Biofouling prevention	Chlorine (0.5–3 ppm) to effluent/monochloramine (0.5–1.5 ppm) to UF filtrate
	To prevent damage of the RO membranes, a redox controlled sodiumbisulfite
Scaling prevention	pH adjustment using sulfuric acid/antiscalant to UF filtrate
Concentrate disposal	Drained to canal together with part of effluent that is not treated

Table 2
Summary of groundwater recharge in St. André

History of project	Developed to achieve sustainable management of the dune aquifer
Status of project	Operating since July 2002
Infiltration capacity	2,500,000 m^3/year
Source water	WWTP secondary effluent treated using UF and RO
Method of recharge	Open infiltration pond of 18,200 m^2 excavated in the dune sands
	Direct contact with the unconfined aquifer
Extraction method	112 wells with filter elements between 8 and 12 m below surface area
Extraction capacity	3,500,000 m^3/year
	2,500,000 m^3 recaptured after recharge/1,000,000 m^3 natural groundwater
Treatment	Aeration and sand filtration
Disinfection	Possibility to dose NaOCl (prevention !) according to temperature;
	UV irradiation prior to distribution

an average recovery of 77% and a design flux of maximum 20 l/h m^2.

The RO filtrate, to which NaOH is dosed to increase the pH to about 6.5 (an extra treatment with UV disinfection system is possible as backup disinfection unit) is then transported by a pipeline over a distance of about 2.5 km to the recharge/extraction site of *St. André*, in the municipality of Koksijde (Table 2).

Since 2003, on average 2 Mm^3/year has been recharged in the unconfined sandy aquifer. The water is recaptured using 112-new wells with filter elements between 8 and 12 m depth [8] with a horizontal separation between the infiltration pond and the abstraction wells varying between 33 m and 153 m, with an average of 59 m. Since 2003, on average 2.7 Mm^3/year was recaptured. The underground passage ensured elimination of all pathogens.

The recovered water is conveyed to the potable water production facility at St. André. The facility consists of an aeration step, rapid sand filtration, a reservoir, and UV disinfection prior to distribution. Dosing of chlorine is possible as a preventive action to prevent re-growth and recontamination in the distribution network.

3. Membrane performance and optimization

More details of the membranes processes are summarized in Table 3.

Both online control and daily measurements by the operator are performed. The process parameters are varied according to the season, thus temperatures.

Submerged UF, using outside-in filtration, proved to be a good pre-treatment prior to RO. It was capable to cope with the expected variations in quality. Suspended solids and bacteria were removed. The turbidity of the UF filtrate is constantly below 0.1 NTU, most of the time below 0.05 NTU. Turbidity proved to be a good indicator when UF treatment fails and is used as a first quality control enabling shut down when threshold values are exceeded.

Since Torreele is operational, the UF-system was optimized in different ways, with both technical and economical advantages:

- The use of air was reduced from initially 50% of time to 25 or 30% of time: in 2003, 0.185 kWh/m^3 was used to produce a cubic meter UF filtrate compared with 0.138 in 2011;
- Citric acid cleanings were introduced to remove iron and manganese oxidation on the fibres; by implementing the RO CIP system these cleanings were made more effective (heating of the solution) resulting in a reduced chemical consumption;
- A membrane integrity test (MIT) was integrated by measuring the pressure decay of the UF skids after every maintenance cleaning.

The recovery of the UF increased to 89% on average.
The RO system was also optimized [10]:

- The recovery, initially 75%, was varied according to the conductivity of the UF filtrate; the recovery increases with decreasing conductivity as lower conductivity means less risk for scaling; it was called 'recovery control';
- In the chloramination process, initially continuous, no-dosing intervals were introduced.

As a result of these optimizations, the RO recovery increased to 77% on average and the energy consumption was lowered; in 2004, 0.630 kW h/m^3 was used to produce a cubic meter RO filtrate compared with 0.555 in 2011 for a comparable average flux and quality. The use of chemicals reduced substantially. Comparison between 2003–2004 and 2008–2009 learned that 47% less ammonium chloride and 38% less sodium hypochlorite was used. Sulfuric acid and sodium hypochlorite usage, respectively, dropped with 9% and 4% over this period.

The online measurements of pressures, flux and conductivity, the integrity of the RO membranes is

Table 3
Summary of the membrane processes at the Torreele facility

	Membranes/configuration	Production process	Cleaning process
Ultra-filtration (UF)	SUBMERGED 5 parallel trains	Trains fed by gravity pumps available if feed water level is too low	Backwash every 8–10 min using UF filtrate
	Each train contains 6 membrane cassettes (520 m^2 membrane surface area each) with ZeeWeed® 500c elements	Production by suction on the inside of fibres Air used intermittently to create turbulence along the membranes	Extended backwash using chlorinated UF filtrate after 25–35 backwash cycles Maintenance cleaning using chlorinated water and draindown every month
	OUTSIDE-IN FILTRATION	Backwash water is drained into tank and pumped to canal	Total disinfection twice a year
Reverse osmosis (RO)	2 skids with 36 pressure vessels (PV)	Production using variable HP pumps Recovery of minimum 75%	Cleaning-in-Place (CIP) using sodium hydroxide alternated with biocide or sodium hydroxide alternated with citric acid solution
	21 PV in 1st and 10 PV in 2nd stage contain 6 brackish water low-energy RO elements	Concentrate continuously drained to canal	CIP solution discharged at low-flow rates

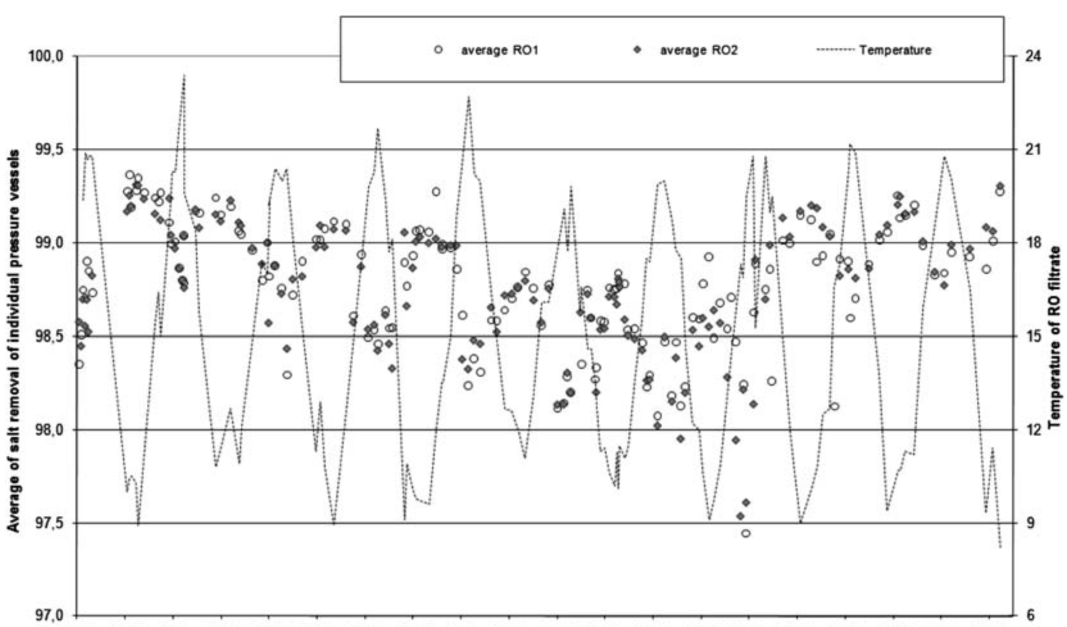

Fig. 2. Salt removal (average of results of every RO pressure vessel and based on conductivity) from start-up until March 2012.

monitored by regular control of the conductivity of the filtrate produced by every individual pressure vessel. Salt removal varies with temperature and decreases with the age of the membranes (Fig. 2).

Besides salt removal based on conductivity, which is monitored online, the removal based on analyses of TDS and specific elements (Na, Cl and SO_4) was monitored weekly. Boron proved to be a good parameter to follow up as it is not easily rejected by RO membranes. As the boron content in the recharged water is higher than in the natural groundwater, it was also used to monitor the extension of the recharged water in the aquifer [2].

4. Cleaning strategy and membrane replacement

The cleaning processes are shown in Table 3. For the RO, the normalized flow and the pressure drop coefficient of each stage, defined as the pressure drop measured from the inlet to outlet of each stage divided by the stage feed flow raised to the 1.5 power [4], were used to monitor the performance (Fig. 3) and the values are used as an indication to process cleaning in place (CIP). The cleaning strategy for biofouling prevention proved as efficient as the k_1 value was stable. The same is true for the scaling prevention. Whenever a sudden increase occurred, either of the k_1 or k_2 value, a preventive cleaning was performed. Up to the summer of 2008, the cleanings were able to restore the initial normalized flow or the k values.

A first set of membranes was replaced in December 2008 (stage 2 of RO1). The membranes of stage 2 of RO2 were replaced in June 2009. The elements used are DOW LE 440i. As the normalized flow could not be controlled anymore and salt removal was low, half July 2009, 7 years after start-up of Torreele, all membranes of the first stages were replaced. The elements used are DOW LE 440 and since then the decay of normalized flux is as it should be (Fig. 4), as is salt removal (Fig. 2).

Two autopsies of elements at the last position of the second stage, one in February 2008 (GE Ref. 2009-E028 RO2), and one in June 2009 (Genesys Report GA 090,637), showed no damage to the elements by use of chloramines as the Fujiwara test, which detects organically bound halogens, was negative. On the other hand, tests on the membranes showed that salt removal at this position reduced to 91.3% in 2008, whereas the first element of the second stage (GE Ref. 2009-E028 RO1) showed no loss of salt removal and was as high as 99%. In June 2009, the test revealed that salt removal was between 14.5% and 56.3% for the last element of stage 2 and the methylene blue test indicated that the salt rejection layer was irreversible damaged. This clearly proved the necessity of membrane replacement. Besides salt rejection also the flux

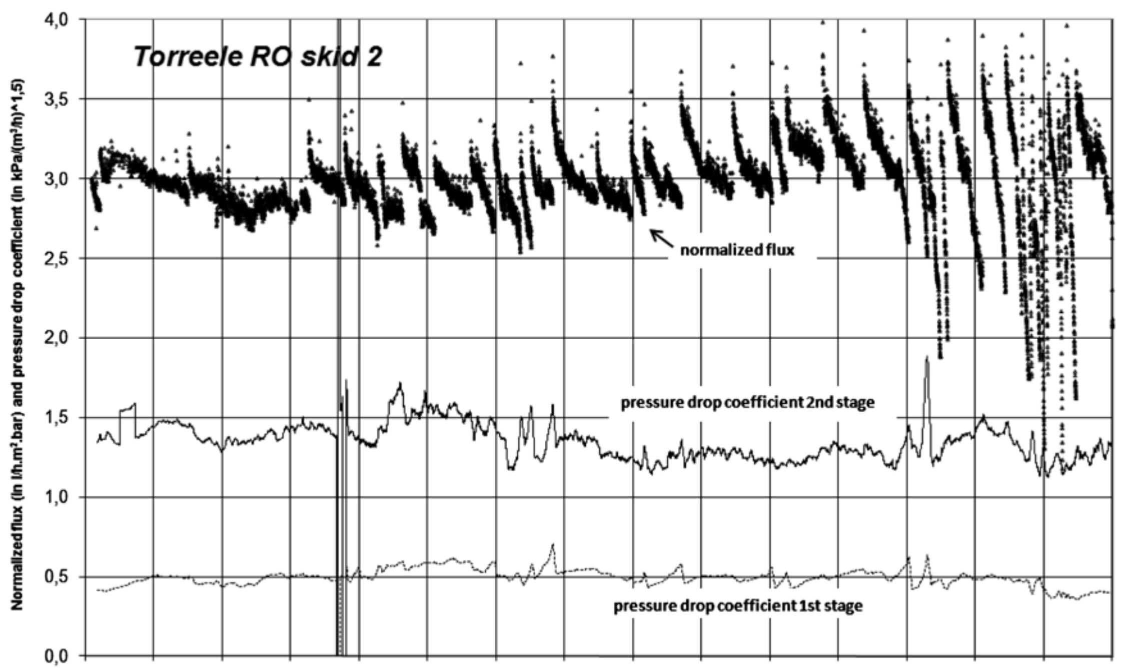

Fig. 3. Normalized performance of RO skid 2 from start-up until 31 March 2010.

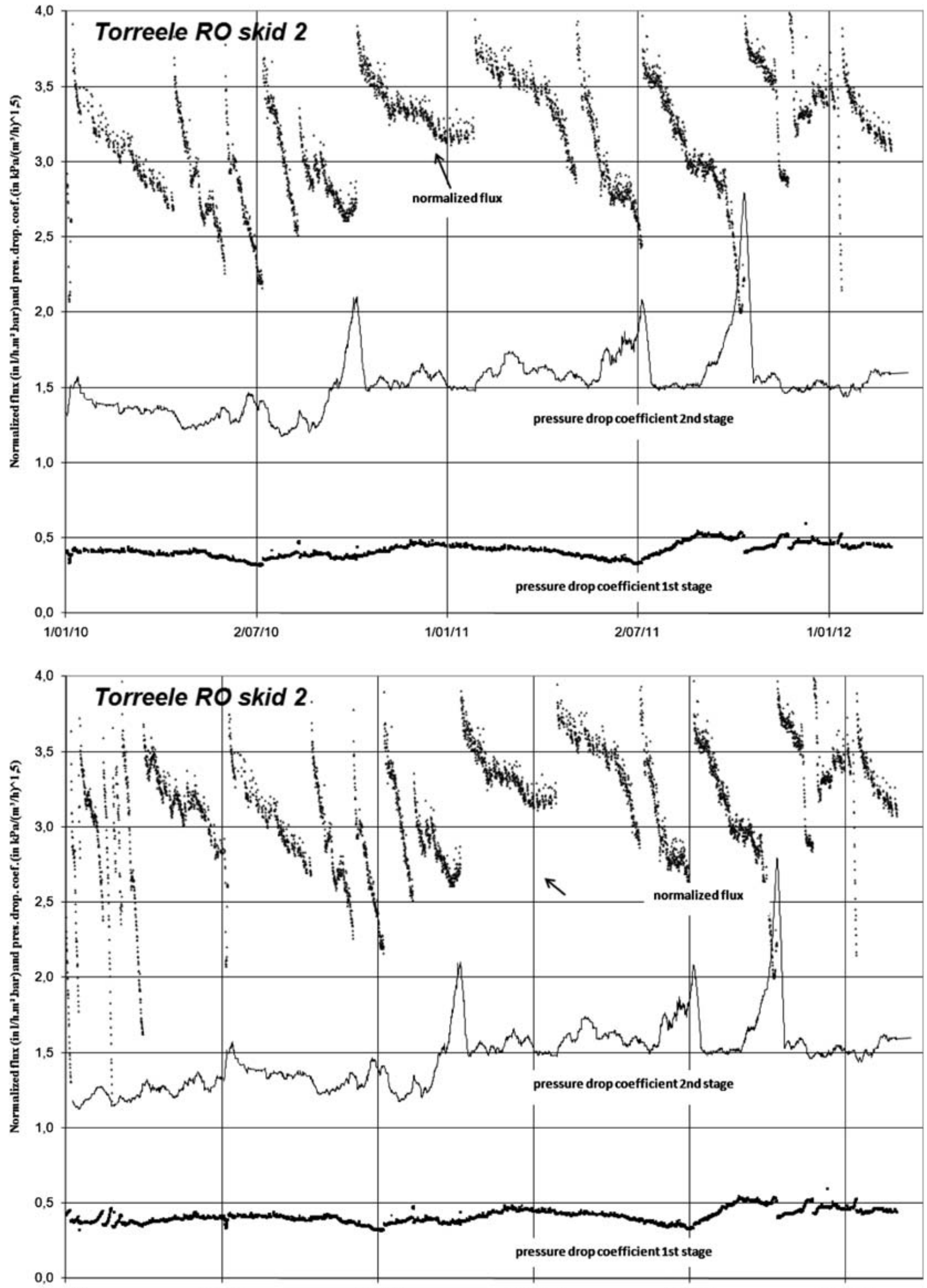

Fig. 4. Normalized performance of RO skid 2 from start-up from mid-2009 until March, 2012.

was far below the minimum value established by the manufacturer. The membrane surface was covered by a foulant mainly composed of aluminosilicates.

Based on these observations and on the trends of normalized flux and k values, the conclusion is that the membranes performed satisfactory until the summer of 2008, thus for a period of just over 6 years, but they should have been replaced shortly after.

UF fibres autopsy (GE Ref. 2009-E028, April 2009) indicated deposition on the fibres. The inorganic deposition mainly consisted of Mn, Fe and Ca, whereas the organic deposition consisted mainly of amides, likely as microbiological species. Replacement of UF membranes started in October 2009. A lot of light material, mainly plastic, was found at the top of the cassettes, between the fibres, and significant damage was observed to some fibres, although this did not seem to affect the number of coliforms in the filtrate. On the other hand, the heterotrophic plate counts (HPC) increased and the membranes had to be cleaned more often. The pre-screen was checked and adapted to prevent passage of lighter materials.

The last 'old' UF cassettes were replaced in January 2012.

5. Water quality

A general overview of water quality is shown in Table 4. Without intensive quality monitoring, water reuse intended for drinking-water production, both direct and indirect, is not possible. The quality of both UF and RO filtrate was as expected. UF was capable to produce water free of bacteria and suspended solids and hence proved to be a good pre-treatment for RO. Although values averaged for a certain period give an indication about the status of the different skids, SDI_{15} measurements which are commonly used on RO feed water, did not prove to be a good operational parameter. The air used in UF processes influence the SDI_{15} values as measurements just after the UF treatment typically are 0,4 higher than the same filtrate after the high-pressure pumps prior to RO.

In recent years, more attention goes to the presence of organic micropollutants in drinking water,

Table 4
Overview of quality in 2010

Parameter	UF filtrate	RO filtrate	Infiltration water
Conductivity (μS/cm)	1.211 (364 –1.735)	25 (5–54)	45 (<10–89)
pH	7.98 (6.94–8.33)	5.51 (4.96–6.00)	6.29 (5.28–6.86)
Total Organisch Carbon (mg/l)	10.4 (6.8–12.8)	0.3 (0.1–1.1)	0.4 (0.1–1.1)
Total hardness (mg/l als $CaCO_3$)	28 (11–40)	<0.5	<0.5
Chlorides (mg/l)	220 (53–360)	5.1 (1.2–18)	3.2 (1.0–4.7)
Fluorides (mg/l)	0.17 (0.08–0.53)	<0.2	<0.2
Sulfates (mg/l)	75 (31–109)	14 (0.1 - 5)	<1
Nitrate (mg NO_3/l)	19 (6–32)	2.2 (0.1–5)	2.5 (<1–6.3)
Ammonia (mg NH_4/l)	1.9 (0.07–4.2)	<0.1	0.13 (0.03–0.38)
Phosphate (mg PO_4/l)	19.4 (6.9–26)	0.4 (0.07–1.1)	<0.1
Silicium (mg SiO_2/l)			0.3 (0.1–0.4)
Total trihalomethanes (μg/l)			3.8 (1.2–6.7)
Aluminium (μg/l)	65 (19–128)	2.6 (0.6–21)	12 (2–59)
Chromium μg/l)	1.8 (0.5–5)	<10	<2.5
Copper (μg/l)	32 (15–52)	<20	<5
Iron (μg/l)	44 (16–91)	<20	<75
Lead (μg/l)	2.6 (1–10)	<20	<5
Manganese (μg/l)	155 (35–236)	<5	<10
Mercury (μg/l)	16 (7–32)	<20	<0.2
Nickel (μg/l)		3.7 (1.4–6.4)	<3
Sodium (mg/l)		<20	10.5 (4.5–17.7)
Zinc (μg/l)			<20
Total Coliform bacteria (counts/100 ml)	0–2	0	0
E. coli (counts/100 ml)	0	0	0
HPC 22°C (counts/ml)	22 (2–80)	2 (0–20)	<1 (0–10)

Table 5
Operating conditions during sampling

	Quality of UF-filtrate	Recovery	Salt removal based on online conductivity measurement
29/01/2007	1.265 μS/cm 10.9°C	75.8% (RO1) 76.2% (RO2)	97.5% (RO1) 97.2% (RO2)
23/07/2007	1.134 μS/cm 19.7°C	76.0% (RO1) 76.3% (RO2)	95.9% (RO1) 95.5% (RO2)
15/10/2007	1.267 μS/cm 16.6°C	75.6% (RO1) 76.0% (RO2)	96.2% (RO1) 95.9% (RO2)

for example pharmaceutical active compounds (PhACs) and endocrine disrupting compounds (EDCs). As the health effects related to the consumption of drinking water containing a cocktail of organic micropollutants is still unknown, the removal of these pollutants in the drinking-water treatment is desirable (Verliefde, 2008).

In Torreele, RO is the major and ultimate single barrier against both microbial and chemical contamination of drinking water and the aquifer alike. Observations show that RO offers complete removal of all pathogenic agents (Table 4) and can be considered as good practice for the removal of trace contaminants (e.g. pesticides). Three campaigns performed in 2007 (Table 5) to quantify the occurrence for PhACs and EDCs (analysis by German Federal Institute of Hydrology, BfG, in Koblenz) showed the absence of these compounds above detection limit (0.5 to 10 ng/l) after RO despite the presence of these compounds in the effluent and consequently the UF filtrate [1]. This investigation showed that a number of compounds are substantially lowered in concentration in the wastewater treatment plant itself, but most of the compounds are unaffected by the WWTP as for the UF treatment.

One control analysis for carbamazepine, an antiepilecticum, beginning of June 2009, prior to the membrane replacements, thus with old membranes, showed values below detection limit (10 ng/l) for RO filtrate of the separate skids, despite presence in the UF filtrate (465 ng/l). These analyses were performed by the laboratory of Antwerp waterworks and confirmed the 2007 results.

In May 2010 and April 2011 'Technologiezentrum Wasser' (TZW) in Karlsruhe screened 89 pharmaceutical residues in the RO filtrate, performing HPLC–MS–MS analysis [5] and [6], and EDCs, performing GC–MS analysis [5] and [6]. None could be detected.

Nitrosamines, often a concern with RO when chloramination is performed, tend to be very low in concentration. RO rejected about 50% of NDMA, while NMOR was rejected to a larger extent resulting in NMOR levels below DL [3]. The results from different campaigns showed that the probability of significant human exposure to nitrosamines from the reclaimed water was low and that low levels of NDMA, when present in the RO filtrate, are removed in the aquifer [3].

6. Concentrate disposal

As UF and RO both produce concentrate, an important volume of water is discharged. About 35% percent of the discharged volume is UF backwash water; 65% is RO concentrate.

The discharge of the mixed concentrates is into the adjacent canal, together with the part of effluent that has not been treated. The canal is brackish, so the salinity does not have a major negative effect on the quality.

From October 2003 until 2009 the IWVA performed a test using a 9 m^2 subsurface flow reed bed (constructed wetland) to look for mitigating the effect of concentrate disposal (mixed concentrates). The results of the monthly sampling in 2006, with a flow of 500 l/h, showed that suspended solids and nitrogen are removed substantially (Table 6). The organic content is removed to a minor extent and the phosphorous content remains as it was [9].

A short-test feeding the reed bed with RO concentrate showed that it had no salt tolerance [11].

In April 2007, a test started using willows (Salix) under the same conditions as reed. Besides reducing nitrogen and organic load, the phosphorous content was lowered.

Since the volume of effluent from the WWTP Wulpen reduced over the years, partly due to reduced consumption of drinking water, the IWVA decided no longer to focus on the treatment of the mixed concentrate but only on RO concentrate as the UF backwash water is planned to be reused after conventional treatment using sand filtration.

Tests with electrodialysis (ED) have been performed in 2009 and 2010 [13]. The purpose was to concentrate organics in one stream, which could be treated separately, and re-use the other stream (ED product). A decarbonation process was needed prior to ED as scaling prevented a continuous experiment.

Table 6
Comparison between the concentrate before and after treatment with an experimental reed bed at IWVA's Torreele facility in 2006 (Van Houtte and Verbauwhede, 2007)

Parameters	Concentrate before reed bed	Effluent of the reed bed
Total dissolved solids (mg/l)	2.449 (1.726–3.317)	2.472 (2.016–3.076)
Suspended solids (mg/l)	14 (7–37)	3.3 (0.8–14*)
Total nitrogen (mg N/l)	20.7 (6.8–32.0)	11.6 (3.8–18.5)
Total phosphorous (mg P/l)	2.1 (0.6–5.1)	2.3 (1.2–5.2)
Chemical oxygen demand (mg O_2/l)	89 (76–115)	73 (58–85)
Biological oxygen demand (mg O_2/l)	6 (<4–10)	<4

*One result was out of range—when this results is not considered the average SS content is 1.7 mg/l.

7. Treatment of RO concentrate using willows [11]

Based on the experiences with the pot tests, a test field with a surface area of 28.6 m^2 was constructed. The field, 70 cm deep, was filled with quartz sand (0.7–1.25 mm) from an old sand filter. The grains had iron oxides on the outside. The feed of concentrate was at surface level on one side (3 m wide) of the field and the effluent was gathered at the bottom of the sands at the other end of the test field, which was 9.5 m long [11].

As most of the cost for discharging the concentrates of Torreele is due to the volume itself and the content of COD, total nitrogen and total phosphate, the focus was mainly on these parameters. From May 2011 until December 2011, water samples were taken by IWVA and analysed by the laboratory of the Vlaamse Maatschappij voor Watervoorziening. The flow was set at 500 l/h beginning of June. In the beginning of November, it was reduced to 400 l/h.

The conclusion for the tests are as follows:

- It was observed that on one exception, COD content after the water passed the willows was lowered. On average, the reduction amounted 14.4%; the median being 12.8%;
- For total nitrogen, there were 3 exceptions, but generally, the content was lowered by the willows; on average, 4.6% with a median of 9.8% (if we do not consider the exceptions the nitrogen was reduced with 12% on average);
- The phosphate level lowered 43.4% on average with a median level of 49% and the removal reduced gradually, probably partly due to the presence of iron on the sand grains.

Based on visual inspection, weighing and evaluating biomass and growth, 4 of the 10 tested species were considered to perform the best. As these species were also the ones considered to perform best in pot tests, these tests could be considered a valuable and inexpensive way of evaluating plant performance. The test with the willows will be continued.

8. Conclusion

The long-time experience at Torreele showed that combining UF and RO enables to treat wastewater effluent in an effective and reliable way. RO is the major and ultimate barrier against both microbial and chemical contamination of drinking water and the produced filtrate is of excellent quality. As it was for artificial recharge, it enables sustainable groundwater management of the dunes of St. André.

The RO membranes performed very well for over 6 years and chloramination did not damage the membrane. UF membrane replacement started in the 8th year of operation and looking at the damage of the fibres was needed. These periods can be considered as very satisfactory.

Experiences using natural systems, first using reed beds and later willows, prove that this process has a potential to treat concentrates. This will not only mitigate the effects of discharging this water into the environment, but will by the production of biomass, contribute to the climate problem. The willows, by taking up the nutrient, organics and other elements from the concentrate, will harvest the energy out of this concentrate. This energy, in the form of biomass, that can be used for heating or power production in a carbon dioxide neutral way.

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