

Alma Mater Studiorum Università di Bologna
Archivio istituzionale della ricerca

Concentrate reduction in NF and RO desalination systems by membrane-in-series configurations-evaluation of product water for reuse in irrigation

This is the final peer-reviewed author's accepted manuscript (postprint) of the following publication:

Published Version:

Hacifazlioglu M.C., Tomasini H.R., Bertin L., Pek T.O., Kabay N. (2019). Concentrate reduction in NF and RO desalination systems by membrane-in-series configurations-evaluation of product water for reuse in irrigation. DESALINATION, 466, 89-96 [10.1016/j.desal.2019.05.011].

Availability:

This version is available at: <https://hdl.handle.net/11585/698188> since: 2019-09-07

Published:

DOI: <http://doi.org/10.1016/j.desal.2019.05.011>

Terms of use:

Some rights reserved. The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>).
When citing, please refer to the published version.

(Article begins on next page)

This is the final peer-reviewed accepted manuscript of:

Hacıfazlıoğlu, M.C., H.R. Tomasini, L. Bertin, T.Ö. Pek, and N. Kabay. 2019. "Concentrate Reduction in NF and RO Desalination Systems by Membrane-in-Series Configurations-Evaluation of Product Water for Reuse in Irrigation." *Desalination* 466 (September): 89–96.

The final published version is available online at:

<https://doi.org/10.1016/j.desal.2019.05.011>

Rights / License:

The terms and conditions for the reuse of this version of the manuscript are specified in the publishing policy. For all terms of use and more information see the publisher's website.

This item was downloaded from IRIS Università di Bologna (<https://cris.unibo.it/>)

When citing, please refer to the published version.

CONCENTRATE REDUCTION IN NF AND RO DESALINATION SYSTEMS BY MEMBRANE-IN-SERIES CONFIGURATIONS- EVALUATION OF PRODUCT WATER FOR REUSE IN IRRIGATION

M.C. Hacifazlıoğlu^{1,4}, H.R. Tomasini^{1,3}, L. Bertin³, T.Ö. Pek², N. Kabay^{1*}

¹Ege University, Faculty of Engineering, Chemical Engineering Department, Izmir, Turkey

²ITOB Organized Industrial Zone, Tekeli-Menderes, Izmir, Turkey

³Alma Mater Studiorum, University of Bologna, School of Engineering and Architecture,
Bologna, Italy

⁴Istanbul Technical University, Faculty of Chemical and Metallurgical Engineering,
Chemical Engineering Department, Istanbul, Turkey

Abstract

Wastewater reclamation and reuse became essential to meet the more restrictive discharge limits and to overcome the water scarcity issue. Industrial wastewaters treated by membrane bioreactor (MBR) systems generally include high amounts of salinity, nutrients as nitrogen and phosphorus, heavy metals, hardness, etc. which in most cases, do not fit with discharge and reuse limits. Membrane processes like nanofiltration (NF) and reverse osmosis (RO) are widely adopted for secondary effluent treatment producing high-quality water. Since untreated brine can damage the environment, this work focused on reduction of amount of concentrate by working in membrane-in-series configuration. Tests with two membrane-in-series (NF90+NF90, BW30+BW30, BW30+NF270 combinations) were performed as the concentrate stream of the first one was fed to the second one. Water recoveries were over 80% in each experiment. Water fluxes of 44.0, 41.4 and 73.4 L/m².h were obtained with NF90+NF90, BW30+BW30, BW30+NF270 combinations, respectively. Also, salinity rejections represented by electrical conductivity were 93.0%, 97.4% and 42.4% for NF90+NF90, BW30+BW30, BW30+NF270 configurations, respectively. Permeates of BW30+BW30 and NF90+NF90 combinations seem to be useable for agricultural irrigation although soil permeability is an important issue, not only ion concentrations and salinity of water used.

Keywords: Desalination, concentrate reduction, membrane processes, nanofiltration (NF), reverse osmosis (RO), water reuse.

***Corresponding author:** Nalan Kabay

(Phone: +90-232-3112290, Fax: +90-232-3887776, e-mail: nalan.kabay@ege.edu.tr)

1.0 INTRODUCTION

Urbanization, agricultural practices and industrialization increases both the water demand and the volume of wastewater produced. Also, researchers draws attention to increasing restriction on discharge limits due to environmental issues and the need to reclaim and reuse wastewaters^[1-2]. Membrane bioreactor (MBR) process is replacing conventional activated sludge process as a secondary treatment unit, especially for domestic wastewater treatment, nowadays. Stability of MBR effluent quality represents a favorable approach for water reuse^[3]. However, high amounts of salinity, nutrients and hardness make industrial secondary effluents from MBR process not reusable and sometimes not even dischargeable^[4]. MBR effluent should be demineralized via one of the desalination methods such as nanofiltration (NF) and reverse osmosis (RO) when the salinity is high prior to reuse of MBR effluent for various purposes. On the other hand, concentrate streams generated from NF and RO processes are of important concern. Indeed, untreated or improperly managed brine can lead to serious negative effects on the environment^[5]. Both the need to reclaim water from industrial or domestic effluents and to decrease discharge amount let researchers use membranes for tertiary treatment.

Several flow configurations of NF and RO systems are used to reduce brine generation (Figure 1). Among them, membrane modules can be connected in series, in which the concentrate stream of the first membrane is fed to the second one ^[6].

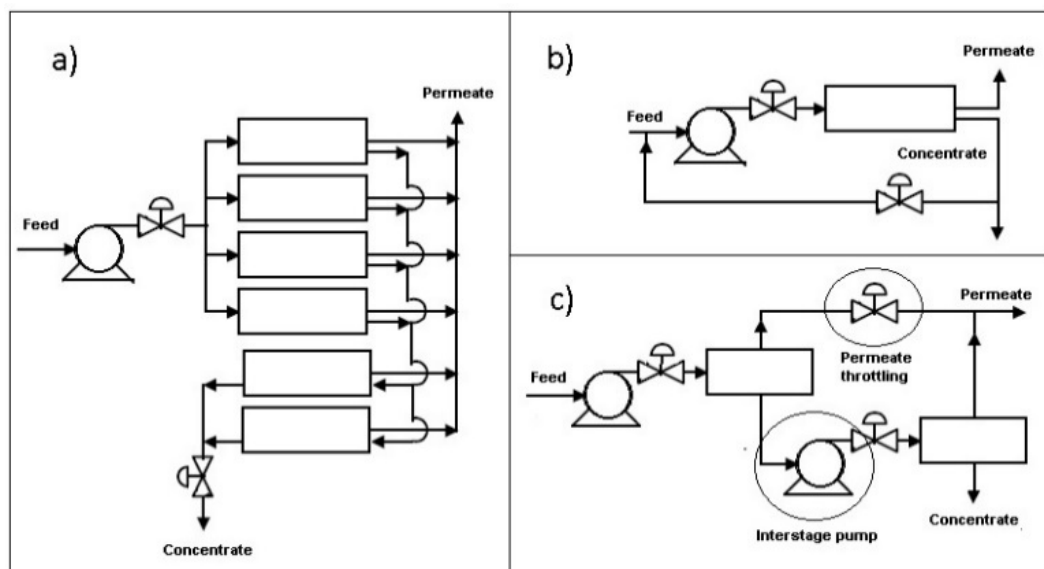


Figure 1. System flow configurations for concentrate reduction: a) pyramidal design b) concentrate recirculation c) membrane-in-series (modified from Hydranautics)^[6]

Reuse of wastewater for irrigation is widely used in countries where fresh water resources are becoming insufficient. Nutrient content of secondary effluents and the relative cost of

reclaiming water for irrigation unlike reclaiming for drinking purposes make this process favorable [7]. Also, some studies showed that the amount of irrigation water is the first to be decreased rather than drinking or process water when the water supplies started to be insufficient. That being said, water reclamation for agricultural irrigation gains even more importance[8]. However, reclaimed water should obey to water quality guidelines for agricultural irrigation which requires development of a proper water management strategy. For this purpose, some concepts such as soil permeability and salinity of irrigation water should be checked carefully.

High sodium concentration disperses the soil clay and causes the soil to become hard and compact when the soil is dry and reduces the rate of water penetration when the soil is wet. The low infiltration rate can cause deficiencies of several nutrients. In contrast, the effect of calcium and magnesium is to cause flocculation of soil clay, thus promoting and maintaining good soil structure. Thus, the Sodium Adsorption Ratio (SAR) is a standart indicator of the flocculation or dispersion of aggregates in soil, which is directly influencing the structure of the soil and hence the permeability. SAR is defined in Equation 1 as an expression of the sodium hazard of irrigation water [8].

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (\text{Equation 1})$$

where the concentrations are in meq/L. Infiltration of irrigation water to the soil is not only connected to SAR but also to electrical conductivity (EC). FAO and WHO guidelines offer a relation between SAR and EC to assess the suitability of irrigation water.

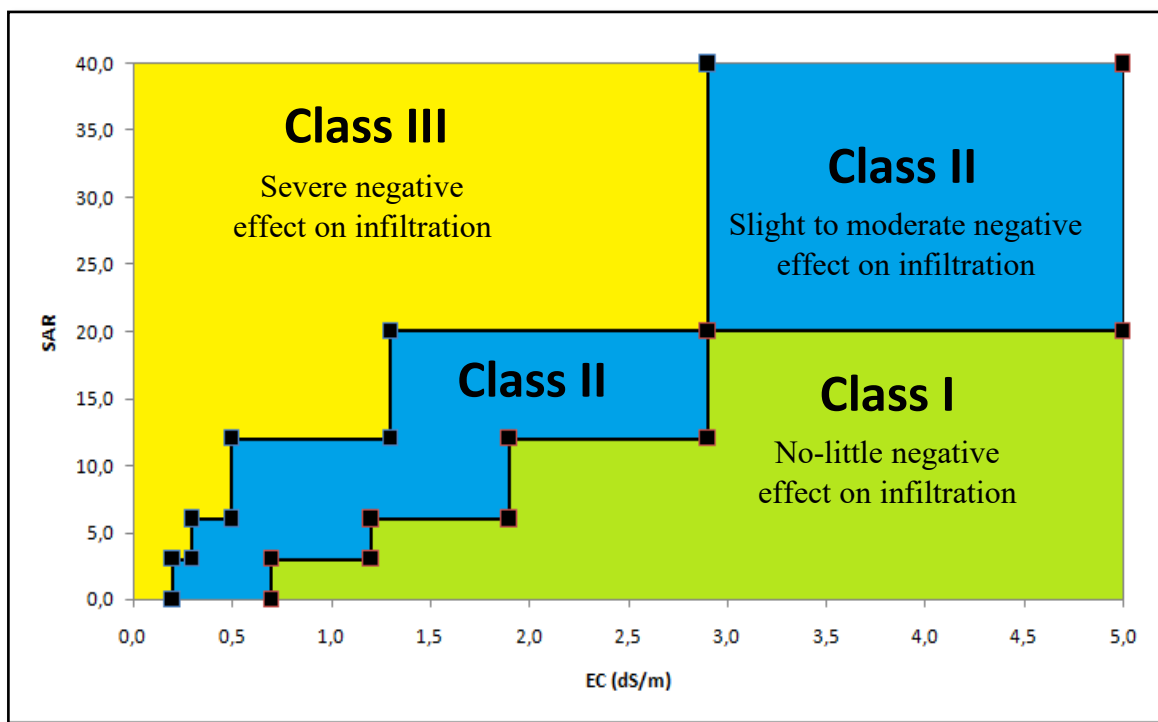
The values given in Table 1 were illustrated in Figure 2 for better understanding of the effect of irrigation water on soil permeability. Classes I, II and III correspond to degrees of restriction on use as none, slight to moderate and severe, respectively. It must be noted that Class I water means the water will not have negative effects on soil permeability but does not say anything about salinity. While high EC can toxicate plants, low EC will mean low amount of minerals for plant to sustain its life. Therefore, a suitable irrigation water should obey to both SAR-EC classification and salinity criteria.

Potassium adsorption ratio (PAR) is another parameter to be investigated to assess the effect of potassium ion to soil clay dispersion, which is calculated by Equation 2[11].

Table 1. Classification of irrigation water regarding soil permeability [9]

Parameter	Degree of Restriction on Use		
	None	Slight to Moderate	Severe
SAR	EC (mS/cm)		
0-3	>0.7	0.2-0.7	<0.2
3-6	>1.2	0.3-1.2	<0.3
6-12	>1.9	0.5-1.9	<0.5
12-20	>2.9	1.3-2.9	<1.3
20-40	>5.0	2.9-5.0	<2.9

98



99

100

Figure 2. Illustration of SAR-EC classification for irrigation water ^[10]

101

102

103

104

105

106

$$PAR = \frac{[K^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (\text{Equation 2})$$

FAO, WHO and USEPA guidelines and regulations offers also other parameters for assessing suitability of water for agricultural irrigation. Three documents are cross-checked and Table 2 contains standards that fit with all of them.

Table 2. Standard limits for agricultural irrigation ^[12-14]

Parameter	Unit	Degree of Restriction on Use		
		None	Slight to Moderate	Severe
EC	mS/cm	<0.7	0.7-3	>3
SAR	-	Check Table 1		
TDS	g/L	<0.45	0.45-2	>2
NO ₃ -N	mg/L	<5	5-30	>30
TN	mg/L	<5	5-30	>30
PO ₄ -P	mg/L	-	<2 or <5	-
PAR	-	<5	5-10	>10
HCO ₃	mg/L	<90	90-500	>500
Boron	mg/L	<0.7	0.7-3	>3
Chloride	mg/L	<106.5	>106.5	-
Sodium	mg/L	<69	>69	-
Free Cl	mg/L	<1	1-5	>5
TSS	mg/L	<50	50-100	>100
pH	-	6-9		
Turbidity	NTU	<2		

It must be noted that chloride and sodium standards are taken for sprinkler irrigation since it is already more efficient than surface irrigation.

Although different plants have different tolerance levels to various components of water (fruit plants have low tolerance to ion toxicity and boron while harsh-climate plants like date palm are highly resistant), Table 2 can be used as a preliminary information for the evaluation.

Previously, we checked the desalination performances of different NF and RO membranes by using a cross-flow flat-sheet membrane test unit. Permeates of RO membrane (GE-Osmonics AG membrane) and NF membranes (GE-Osmonics HL, DL membranes) were compared with

irrigation water standards for its reuse in irrigation ^[15]. Elsewhere, application NF and RO processes for reclamation and reuse of industrial wastewater treated with MBR process was investigated using a mini-pilot scale membrane test system. The qualities of permeates obtained by BW30-RO and NF-90 membranes were evaluated according to irrigation water standards ^[16]. At the same time, effect of membrane type on product water quality for industrial usage as cooling and boiling feed water as well as process water in paper and textile industries was studied ^[17]. Also, effect of pressure on desalination of MBR effluents with high salinity by using NF and RO processes for reuse in irrigation was reported ^[18].

Concentrate management in pressure driven membrane processes is an important and challenging task to be solved. Besides the product water, the brine generation from the membrane filtration processes is of important environmental concern. Indeed, an appropriate concentrate management is required to avoid serious negative effects on environment ^[5].

Ocean concentrate disposal is possible if specific discharge regulation are observed ^[19]. Another method to eliminate the generated brine is leaving it to natural evaporation process creating a solid waste ^[20]. However, this process requires high time and area and can be not feasible when high amounts of concentrate are to be treated ^[21]. Therefore, is necessary to reduce, as much as possible, the concentrate amount before further treatments or discharge.

Many different flow configurations of RO systems were utilized to reduce the brine generation. Membrane modules can be connected in series with or without an interstage pump or permeate throttling, connected in a pyramidal design, etc. Also the concentrate recirculation configuration allow to increase the water recovery recycling part of the concentrate stream ^[6]. These configurations are shown in Figure 1.

In our previous study, effect of concentrate recirculation on the product water quality of integrated MBR+ NF processes in sequential mode was investigated for wastewater reclamation and industrial reuse ^[22]. Using the same membrane tests system, MBR-treated industrial wastewater was further processed by BW30, a brackish water RO membrane in concentrate recirculation configuration. Membrane and system performances were assessed, including product water quality and the concentrate retention ratio ^[23]. The aim of this study is to reduce the amount of concentrate stream of RO and NF processes while assessing alternative use of the permeate stream for agricultural irrigation and hence to establish a two-way solution for problems of industrial-scale operations. For this, various combinations of different membrane pairs were employed in batch mode of operation by feeding concentrate stream of the first membrane to the second membrane in membrane-in series mode.

2. MATERIAL AND METHODS

In this study, three different membranes (NF90, NF270 and BW30) were used in such two membrane-in series configurations as NF90+NF90, BW30+BW30, BW30+NF270 combinations using the same mini pilot system for water recovery from MBR effluent at wastewater treatment plant of ITOB Organized Industrial Zone, Menderes-Izmir, Turkey. The concentrate stream of the second membrane and the total permeate were recycled to the feed tank to operate in batch mode. Concentrate stream of the first membrane was fed to the second membrane in this membrane-in-series configuration to increase the water recovery (as shown in Figure 1c without throttling or interstage pump). Properties and informations about the membranes employed are given in Table 3.

Table 3. Membrane properties ^[24]

Membrane	Manufacturer	Material	NaCl rejection (%)	pH Interval	Max Temperature (°C)	Max Pressure (bar)
BW30-RO	Dow-Filmtec	Polyamide Thin-Film Composite	99.5	2-11	50	41
NF90-NF	Dow-Filmtec	Polyamide Thin-Film Composite	95.0	2-11	45	41
NF270-NF	Dow-Filmtec	Polyamide Thin-Film Composite	50.0	2-11	45	41

Experiments were carried out using a mini pilot system installed at wastewater treatment plant. Photographs of the mini pilot membrane test system are given in Figure 3.

MBR effluent discharged from wastewater treatment plant was used as feed stream for the membrane tests using mini pilot membrane test system. Properties of MBR effluent used as feed are given in Table 4.

The flow configuration used during membrane tests is depicted in Figure 4. It must be noted that while this pilot test system has six membranes, only five of them (two NF 90, two BW 30 and one NF 270) were used for tests.

The MBR effluent utilized as feed was collected in a 500 L of feed tank and pumped to the membrane test system. Average feed flow rate supplied by the pump was 4.33 L/min varied by 6% margin. Permeate and concentrate streams were fed back to the feed tank and experiments were carried out in batch mode for 6 h. The applied pressure at the inlet of the first membrane of the pair is 20 bar for all experiments.

Samples of feed, permeate and concentrate streams were taken at each hour for lab analysis while the field analysis (EC, TDS, salinity, pH) were performed online by means of a conductometer and a pH-meter for all samples at each 15 min. The quality parameters such TSS, color, turbidity, COD, SiO₂, total nitrogen, nitrite-N, phosphate-P and ammonium-N concentrations were measured by using Hach-Lange chemical measurement kits by means of DR 3900 benchtop VIS model spectrophotometer. Most cation (Ca²⁺, Mg²⁺, K⁺ and Na⁺) concentrations were measured by an atomic absorption spectrometer (Shimadzu AA-7000) while anion concentrations (NO₃⁻, Cl⁻ and SO₄²⁻) were measured by an ion chromatography (Shimadzu LC-10Ai). Bicarbonate concentration was measured by titrating samples with 0.05 M HCl solution using methyl orange indicator. Permanent hardness were measured by titration of samples with pre-prepared 0.01 M Na₂EDTA solution while using eriochrome black T as indicator.



Figure 3. Photographs of mini pilot membrane test system

Table 4. Properties of the MBR effluent used as feed for membrane tests

MBR Effluent	Two membrane-in series tests		
Parameter	BW30 to BW30	NF90 to NF90	BW30 to NF270
TSS (mg/L)	1.3 ± 0.2	2.0 ± 0.3	1.0 ± 0.2
Color (mg/L Pt-Co)	12.0 ± 1.4	25.5 ± 3.2	9.0 ± 1.5
Turbidity (NTU)	0.2 ± 0	1.1 ± 0.2	0.5 ± 0.2
COD (mg/L)	19.6 ± 1.5	17.5 ± 1.3	20.4 ± 1.5
SiO ₂ (mg/L)	5.9 ± 1.9	7.2 ± 2.5	6.8 ± 2.3
HCO ₃ (mg/L)	16.8 ± 0.9	15.0 ± 1.0	15.3 ± 0.9
Na (mg/L)	395 ± 17	399 ± 21	462 ± 23
Ca (mg/L)	101 ± 5	100 ± 5	113 ± 5
K (mg/L)	130 ± 12	139 ± 13	92.0 ± 12
Mg (mg/L)	22.8 ± 0.9	25.5 ± 1.1	34.7 ± 1.4
SO ₄ (mg/L)	339 ± 41	406 ± 43	442 ± 37
Cl (mg/L)	488 ± 35	495 ± 34	497 ± 39
Hardness (mg/L CaCO ₃)	367 ± 9	358 ± 11	448 ± 12
NO ₃ -N (mg/L)	35.0 ± 1.2	38.0 ± 1.1	35.6 ± 1.2
Total Nitrogen (TN) (mg/L)	36.8 ± 3.4	38.5 ± 4.1	38.5 ± 3.6
NO ₂ -N (mg/L)	0.03 ± 0	<0.02	0.03 ± 0

PO₄-P (mg/L)	<0.5	<0.5	<0.5
NH₄-N (mg/L)	<0.2	<0.2	<0.2
EC (μS/cm)	4200 ± 75	4300 ± 78	3800 ± 74
TDS (mg/L)	1400 ± 21	1400 ± 19	1500 ± 18
Salinity (‰)	1.4 ± 0	1.4 ± 0	1.5 ± 0
pH	7.7 ± 0.3	7.6 ± 0.3	7.7 ± 0.3

210

211

212

213

214

215

216

217

218

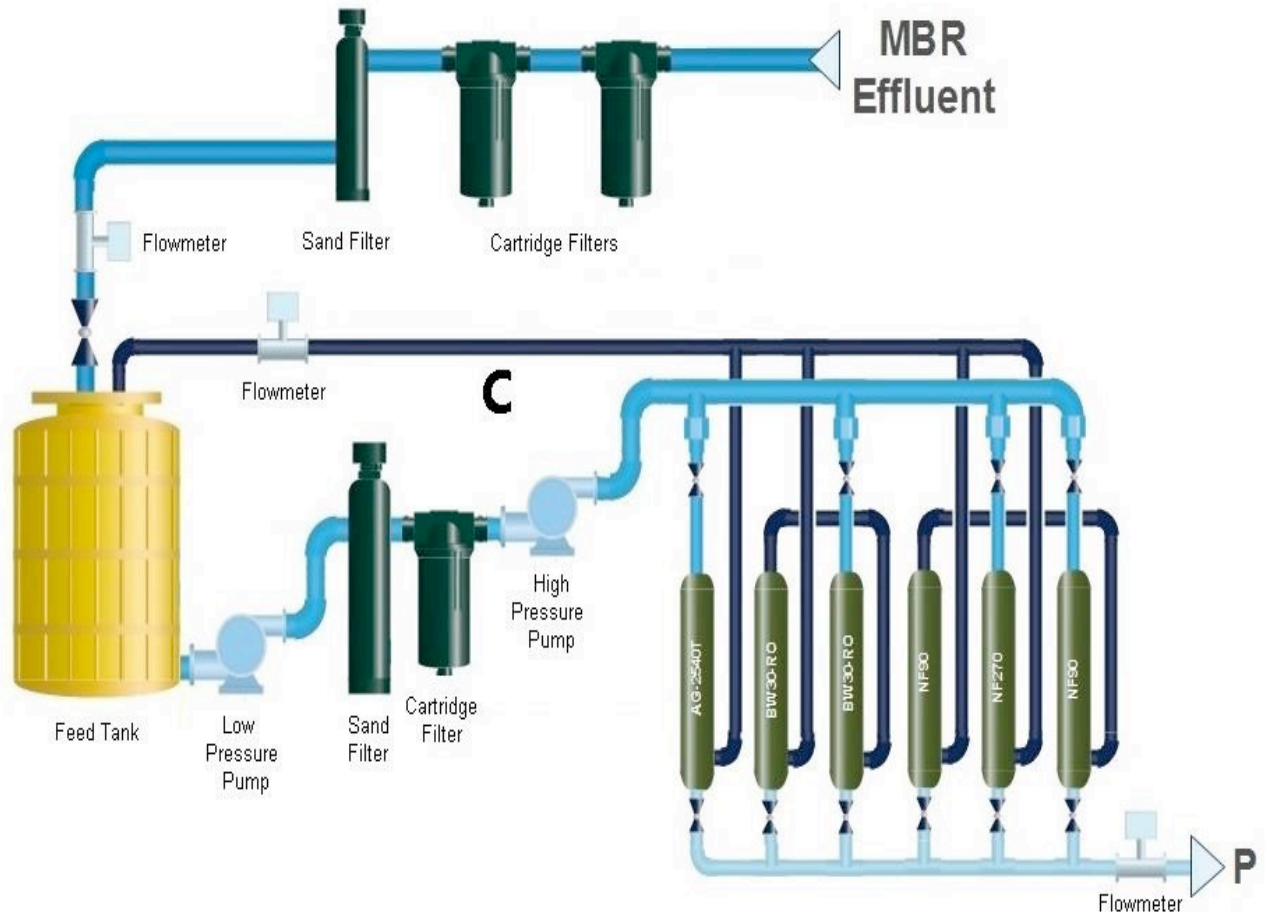


Figure 4. Flow congifuration in mini-pilot membrane test system
(F: Feed, C: Concentrate, P: Permeate)

Water recovery is calculated by Equation 3:

$$\text{Water recovery (\%)} = \frac{P}{M} \quad (\text{Equation 3})$$

Permeate flux is calculated by Equation 4. Permeate fluxes are normalized according to a standart temperature via Equation 5:

$$J_P \left(\frac{L}{m^2 \cdot h} \right) = \frac{P}{A} \quad (\text{Equation 4})$$

$$J_{P_{adj}} = \frac{J_P}{1.03^{(T-25)}} \quad (\text{Equation 5})$$

Rejection for any parameter is calculated by Equation 6

$$R (\%) = \frac{C_f - C_p}{C_f} \quad (\text{Equation 6})$$

where P is permeate flow rate, M is MBR effluent flow rate, J_p is the permeate flux, A is the active membrane surface area, T is temperature ($^{\circ}\text{C}$), R is the rejection of a component/parameter, C_f and C_p are concentrations or values of any parameter in feed and permeate, respectively.

Water recovery of individual membranes were calculated by manual flow readings of permeate streams and concentrate stream of the first membrane performed in each 10 min with 30 s of sampling time. Manually calculated permeate flow rates are then divided with the feed amount to each membrane (feed flow rate to the first membrane, concentrate flow rate produced by the first membrane to the second membrane) to calculate water recoveries.

MBR effluent and product waters obtained from various two membrane-in series configurations (NF90+NF90, BW30+BW30, BW30+NF270) were also evaluated for their reuse in agricultural irrigation according to FAO, WHO and USEPA guidelines and regulations.

3.0 RESULTS AND DISCUSSION

The system performances for different two membrane-in series configurations were compared in terms of permeate flux, solute rejections and permeate quality. System water recoveries were kept almost constant as 81.5-81.6%. Average permeate flux was only slightly higher for the NF90+NF90 combination compared to the BW30+BW30 system, while the salinity removal was 92.9% in the first case and 97.4% in the second one. This was due to the high performances of NF90 membrane, which are close to typical performances of brackish water RO membranes. Significant increase in the permeate flux was obtained with a BW30+NF270 system. However, the permeate quality was severely affected, obtaining 42.9% of salinity rejection.

Table 5. System performances in the different configurations

System configuration		BW30 to BW30	NF90 to NF90	BW30 to NF270
Average water recovery (%)	1 st Membrane	48.5%	39.4%	28.4%
	2 nd Membrane	64.0%	69.6%	74.3%
	TOTAL	81.5%	81.6%	81.6%
Average normalized permeate flux (L/m ² .h)	1 st Membrane	51.5 ± 0.5	60.5 ± 0.6	43.2 ± 0.4
	2 nd Membrane	35.1 ± 0.4	65.0 ± 0.7	80.9 ± 0.8
	TOTAL	86.6	125.6	124.1
Salinity rejection (%)*		97.4	93.7	42.9

*Individual salinity rejections of the membranes are unknown because the system configuration does not allow to take samples between membranes but only to measure flux.

Since by definition, water permeability is the inverse of the resistance of the membrane to the permeate flow (closely related to pore diameters), permeate flux of NF270 is much bigger than NF90 and BW30. While the salt rejection of NF90 is defined close to reverse osmosis membranes with its nearly 200 Da; NF270 is loosest NF membrane produced by Dow with its 400 Da, hence lower salt rejection was already expected [25].

Although the fluxes of NF90+NF90 and BW30+BW30 combinations are nearly equal and salinity rejection performance of BW30+BW30 pair is higher, it must also be noted that NF membranes require lower applied pressure than RO membranes. In this case, 20 bar of operating pressure was applied for effective comparison between membranes. However, 10-15 bar of operating pressure is mostly used in real NF applications.

Average rejections of some selected parameters from MBR effluent using various two membrane-in series configurations are given in Table 6.

Table 6. Percent average rejections of some selected quality parameters

Parameter	BW30 to BW30	NF90 to NF90	BW30 to NF270
TSS	~100	~100	~100
Color	~100	~100	88.9 ± 0.8
Turbidity	64.2 ± 3.4	74.8 ± 3.5	49.3 ± 2.4
COD	29.8 ± 3.5	49.7 ± 7.1	75.5 ± 9.1
SiO₂	87.8 ± 2.5	90.3 ± 2.3	13.2 ± 0.4
HCO₃	84.2 ± 1.1	87.1 ± 1.5	47.9 ± 0.9
Na	94.7 ± 0.6	91.2 ± 1.2	50.4 ± 0.8
Ca	98.5 ± 1.1	98.7 ± 1.2	62.1 ± 1.0
K	96.1 ± 2.0	92.2 ± 2.3	40.7 ± 1.5
Mg	>99.9	>99.9	83.9 ± 1.9
SO₄	>99.5	>99.5	>99.5
Cl	97.3 ± 1.1	94.0 ± 1.4	21.7 ± 0.7
Hardness	>99.7	97.5 ± 0.5	76.1 ± 0.9
NO₃-N	89.1 ± 1.3	77.1 ± 1.1	13.0 ± 0.4
TN	86.2 ± 7.4	71.7 ± 6.7	18.6 ± 3.1
Conductivity	97.0 ± 0.4	92.9 ± 0.3	41.4 ± 0.3
TDS	97.3 ± 0.4	93.4 ± 0.3	42.6 ± 0.3
Salinity	97.4 ± 0.5	93.7 ± 0.3	42.9 ± 0.3

Feed and permeate compositions along with their evaluations for degrees of restriction on agricultural irrigation were given in Table 7.

Table 7. Average feed and permeate compositions compared with agricultural irrigation standards

Parameter	Unit	Average Feed	Permeate			Degree of Restriction on Use		
			BW30 to BW30	NF90 to NF90	BW30 to NF270	None	Slight to Moderate	Severe
EC	mS/cm	4.1	0.1	0.2	1.7	<0.7	0.7-3	>3
SAR	-	8-10	3.8	7.7	8.6			
TDS	g/L	1.4	<0.1	0.1	0.9	<0.45	0.45-2	>2
NO ₃ -N	mg/L	36.2	3.8	8.7	31.0	<5	5-30	>30
T-N	mg/L	37.9	5.1	10.9	31.3	<5	5-30	>30
PO ₄ -P	mg/L	<0.1	<0.1	<0.1	<0.1	-	<2 or <5	-
PAR	-	1.0	0.3	0.8	1.2	<5	5-10	>10
HCO ₃	mg/L	15.7	2.7	1.9	7.9	<90	90-500	>500
B	mg/L	2.3	<0.5	1.1	2.0	<0.7	0.7-3	>3
Cl	mg/L	493.3	13.4	29.6	389	<106.5	>106.5	-
Na	mg/L	418.7	21.0	35.2	229	<69	>69	-
Free chlorine	mg/L	<0.1	<0.1	<0.1	<0.1	<1	1-5	>5
TSS	mg/L	1.4	0	0	0	<50	50-100	>100
pH	-	7.7	6.4	6.8	7.2	6-9		
Turbidity	NTU	0.6	0.1	0.3	0.2	<2		

It is obvious that MBR effluent is not suitable for agricultural irrigation due to excessive amounts of sodium and chloride ions (causing ion toxicity), salinity and nitrate. BW30+NF270 combination produced water with excess sodium, chloride and nitrate ions although their concentrations are not as much as in MBR effluent. The permeates of BW30+BW30 and NF90+NF90 pairs are good irrigation waters for boron-sensitive and salinity-sensitive plants.

Previous studies ^[10, 26, 27] suggested to mix permeate streams with MBR effluent in certain amounts to increase its soil permeability and to remineralize it. Therefore, theoretical mixtures are calculated for both permeate of NF90+NF90 combination with MBR effluent and permeate of BW30+BW30 combination with MBR effluent. Soil permeability (SAR-EC classification) graphs were shown in Figures 5 and 6.

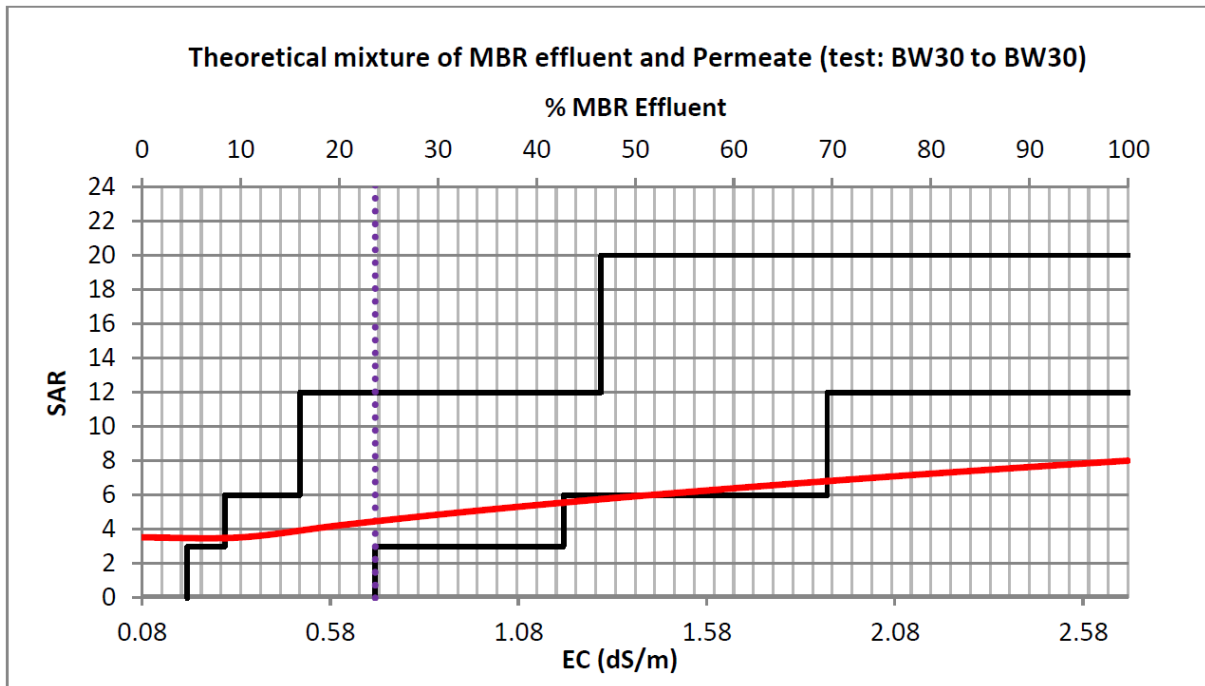


Figure 5. SAR-EC classification of theoretical mixture of MBR effluent and permeate of BW30+BW30 combination

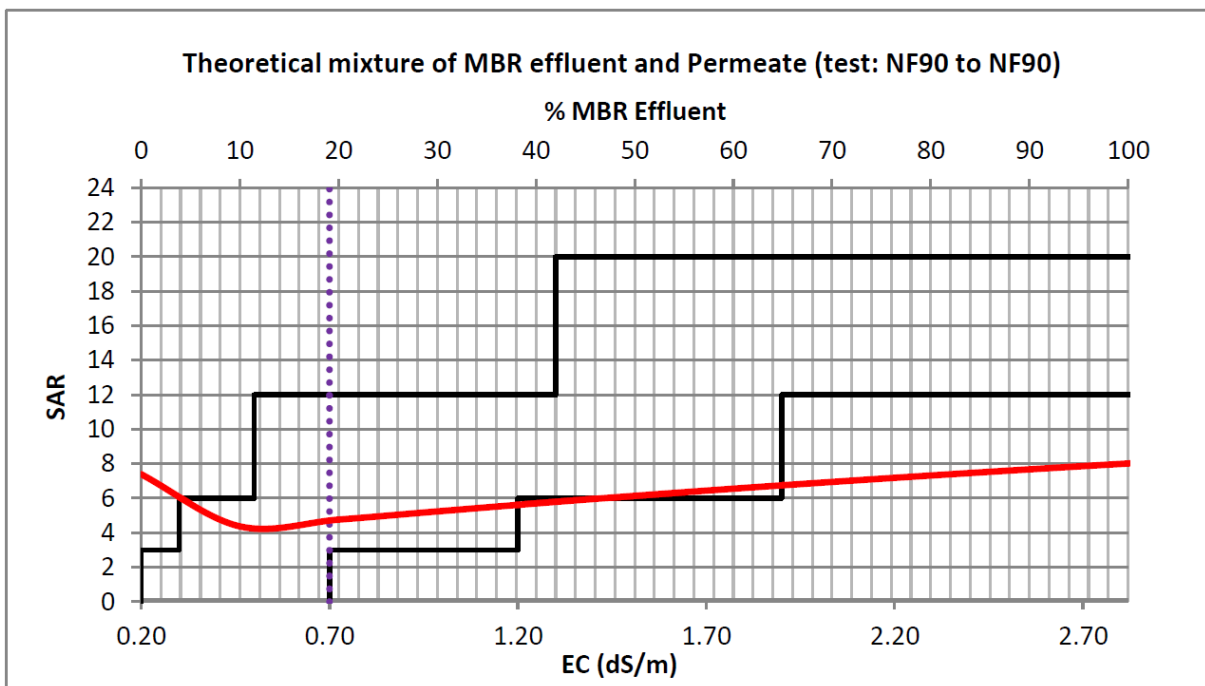


Figure 6. SAR-EC classification of theoretical mixture of MBR effluent and permeate of NF90+NF90 combination

Water with a first class soil-permeability seems to be unachievable without high salinity (vertical dotted lines are salinity criteria), but close to first class soil-permeability together with a fit to other irrigation standards which are achievable. This can be obtained by a theoretical mixtures of 85-95% of NF90+NF90 and BW30+BW30 permeates mixed with 15-5% of MBR effluent. Percentage of MBR effluent can be increased if the resistance of the plant for salinity and boron is high.

While MBR effluent is toxic to the plants, especially for salt-sensitive plants, NF90 and BW30 permeates do not include enough minerals to sustain the plant life. Theoretical mixtures using 15-5% of MBR effluent and 85-95% of BW30+BW30 or NF90+NF90 permeates are thought to solve this problem and create useable water for agricultural irrigation.

Findings are partially in contrast with the findings of other researchers using theoretical mixtures approach for the agricultural irrigation although their focus was on the treatment of domestic wastewaters, while this study is based on secondary-treated industrial wastewaters. While they thought the sustainability of plant life would be better if the permeate is re-mineralized via addition of some MBR effluent, but there was no any indicator for its effect on soil permeability.

SAR values –when combined with EC values- mathematically proved the comments of other researchers and shows the need of demineralization of NF90 and BW30 pair permeates for agricultural irrigation purposes. Figures 5 and 6 (created from placement of research findings on Figure 2) show a plausible way to assess the suitability of use of any type of water in agricultural irrigation.

Table 8. Properties of optimum theoretical mixtures of NF90+NF90 and BW30+BW30 permeates with MBR effluent

Two membranes-in series configuration	Unit	BW30+BW30	NF90+NF90
MBR effluent (%)		12	9
EC	mS/cm	0.4	0.4
SAR	-	3.9	4.3
TDS	g/L	0.2	0.2
NO ₃ -N	mg/L	7.6	11.3
TN	mg/L	8.9	13.4
PO ₄ -P	mg/L	0.1	0.1
PAR	-	0.4	0.5
HCO ₃	mg/L	8.9	13.4
B	mg/L	<0.5	0.5-1.0
Cl	mg/L	70.3	71.4
Na	mg/L	65.8	68.0
Free chlorine	mg/L	<0.1	<0.1
TSS	mg/L	0.2	0.2
pH	-	6.5	6.9
Turbidity	NTU	0.1	0.3

SAR-EC criteria of those theoretical mixtures can be checked from Figures 5 and 6 showing that they are in second class of water quality which is close to the first class of water quality.

4.0 CONCLUSIONS

Water recoveries were obtained as 81.5% for BW30+BW30 pair and 81.6% for other two pairs (NF90+NF90, BW30-NF270) by the application of membrane-in-series configuration which are much higher than water recovery that is usually obtained by one membrane at around 40-50% without considerable fouling.

Among various two membrane-in series configurations, NF90+NF90 and BW30+BW30 combinations are found to be favorable with 93.0% and 97.4% of conductivity rejections, respectively while BW30+NF270 pair was not successful to decrease salinity of MBR effluent with its only 42.4% of conductivity rejection.

Even though the concentrate stream is more saline than the feed solution (MBR effluent), its amount is reduced more than 81.5%. The rest (less than one fifth of before) would be easier to be dealt with natural evaporation or any other waste management option.

Theoretical mixtures of MBR effluent and BW30+BW30 or NF90+NF90 permeate as 15-5% of MBR effluent and 85-95% of permeate of BW30+BW30 or NF90+NF90 pair were found suitable theoretical mixture for use in agricultural irrigation.

5.0 ACKNOWLEDGEMENTS

The financial supports of Ministry of Science, Industry and Technology of Turkish Republic (03.STZ.2013-02) are greatly acknowledged. We sincerely thank to ITOB-OSB for their support to conduct pilot membrane tests in wastewater treatment plant. Acknowledgement is also given to the European Union for the Erasmus plus scholarship awarded to Horacio Reynaldo Tomasini and to the TUBITAK (Project No. 114Y500) for the scholarship awarded to Mert Can Hacifazlıoğlu.

6.0 REFERENCES

- 1) D. Norton-Brandão, S. M. Scherrenberg, J. B. Van Lierf, Reclamation of used urban waters for irrigation purposes e A review of treatment technologies, *Journal of Environmental Management* 122 (2013) 85-98.
- 2) E. Can Dogan, A. Yasar, U. Sen, C. Aydiner, Water recovery from treated urban wastewater by UF and RO for landscape irrigation, *Urban Water Journal* 13 (6) (2015) 553-568.
- 3) J. Arévalo, L. M. Ruiz et al., Wastewater reuse after treatment by MBR. Microfiltration or ultrafiltration, *Desalination* 299 (2012) 22–27.
- 4) S.S. Shenvi, A.M. Isloor, A.F. Ismail, A review on RO membrane technology: Developments and challenges, *Desalination*, 368 (2015) 10-26.
- 5) S.H. Joo, B. Tansel, Novel technologies for reverse osmosis concentrate treatment: A review, *Journal of Environmental Management*, 150 (2015) 322-335.
- 6) Hydranautics, Flow Configuration, (January 23, 2001), Retrieved from <http://membranes.com/docs/trc/flowcon.pdf>.
- 7) C. A. Quist-Jensen, F. Macedonio, E. Drioli, Membrane technology for water production in agriculture: Desalination and wastewater reuse. *Desalination* 364 (2015) 17–32.
- 8) C. J. Smith, J. D. Oster, G. Sposito, Potassium and magnesium in irrigation water quality assessment, *Agricultural Water Management* 157 (2015) 59–64.
- 9) Technical Procedure Declaration for Wastewater Treatment Plants, Ministry of Environment and Urbanization, Republic of Turkey, 2010, pp. 91–93.
- 10) N. J. Falizi, M. C. Hacifazlıoğlu, İ. Parlar, N. Kabay, T. Ö. Pek, M. Yüksel, Evaluation of MBR treated industrial wastewater quality before and after desalination by NF and RO processes for agricultural reuse, *Journal of Water Process Engineering*, 22 (2018) 103-108.
- 11) A. G. Marchuk, P. Rengasamy, Cation ratio of soil structural stability (CROSS), 19th World Congress of Soil Science, Soil Solutions for a Changing World (2010) Australia.
- 12) WHO, Water quality for irrigation, Table A1.1. (2016).
- 13) FAO, Wastewater quality guidelines for agricultural use, (1992), Table 9: Guidelines for interpretation of water quality for irrigation.
- 14) USEPA, USEPA guidelines for water reuse, (2014), Tables 2-7. Recommended limits for constituents in reclaimed water for irrigation (Table 4-13 suggested guidelines for water reuse, types of reuse: urban reuse).

428 15) G. Sert, S. Bunani, E.Yörükoğlu, N.Kabay, O. Egemen, M. Arda, M. Yüksel, Performances
 429 of some NF and RO membranes for desalination of MBR treated wastewater, Journal of Water
 430 Process Engineering 16 (2017) 193–198.

431 16) G.Sert, S. Bunani, N. Kabay, O. Egemen, M. Arda, T.O. Pek, M. Yüksel, Investigation of
 432 mini pilot scale MBR-NF and MBR-RO integrated systems performance—Preliminary field
 433 tests, Journal of Water Process Engineering 12 (2016) 72–77.

434 17) M. Gündoğdu, Y.A. Jarma, N.Kabay, T.Ö. Pek, M.Yüksel, Integration of MBR with NF/RO
 435 processes for industrial wastewater reclamation and water reuse-effect of membrane type on
 436 product water quality, Journal of Water Process Engineering 29 (2019) (Article No: 100574) *in*
 437 *press*.

438 18) M.C. Hacıfazlıoğlu, H.R. Tomasini, N. Kabay, L. Bertin, T.Ö. Pek, M. Kitiş, N. Yiğit, M.
 439 Yüksel, Effect of pressure on desalination of MBR effluents with high salinity by using NF and
 440 RO processes for reuse in irrigation, Journal of Water Process Engineering 25 (2018) 22-27.

441 19) N. Voutchkov, Overview of seawater concentrate disposal alternatives, Desalination 273
 442 (2011) 205-219.

443 20) M. Ahmed, W. H. Shayya, D. Hoey et al., Use of evaporation ponds for brine disposal in
 444 desalination plants, Desalination 130 (2000) 155-168.

445 21) M. Mickley, R. Hamilton et al., Membrane Concentration Disposal, American Water Works
 446 Association Research Foundation (1993), USA.

447 22) M. Gündoğdu, N. Kabay, N. Ö. Yiğit, M. Kitiş, T.O. Pek, M.Yüksel, Effect of concentrate
 448 recirculation on the product water quality of integrated MBR-NF process for wastewater
 449 reclamation and industrial reuse, Journal of Water Process Engineering 29 (2019) (Article No.
 450 100485) *in press*.

451 23) H. R. Tomasini, M.C. Hacıfazlıoğlu, N. Kabay, L. Bertin, T.O. Pek, M. Yuksel, Concentrate
 452 management for integrated MBR-RO process for wastewater reclamation and reuse-
 453 preliminary tests, Journal of Water Process Engineering 29 (2019) (Article No: 100455) *in*
 454 *press*.

455 24) Lenntech: Water treatment and purification products (2015)
 456 (<https://www.lenntech.com/products/index.htm>)

457 25) Dow Chemical, What is the MWCO of FILMTEC NF90 and NF20 Reverse Osmosis
 458 Elements? (2019) ([https://dowac.custhelp.com/app/answers/detail/a_id/4925/~/_filmtec-](https://dowac.custhelp.com/app/answers/detail/a_id/4925/~/_filmtec-membranes---nanofiltration---mwco)
 459 [membranes---nanofiltration---mwco](https://dowac.custhelp.com/app/answers/detail/a_id/4925/~/_filmtec-membranes---nanofiltration---mwco))

- 460 26) S. Shanmuganathan, S. Vingeswaran, T.V. Nguyen, P. Loganathan, J. Kandasamy, Use of
461 nanofiltration and reverse osmosis in reclaiming micro-filtered biologically treated sewage
462 effluent for irrigation, *Desalination*, 364 (2015) 119-125.
- 463 27) S. Bunani E. Yörükoğlu, Ü. Yüksel, N. Kabay, M. Yüksel, G. Sert, Application of reverse
464 osmosis for reuse of secondary treated urban wastewater, *Desalination*, 364 (2015) 68-74.