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Optimization of wastewater desalination

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ABSTRACT

The shortage of water in Israel and concern about the quality of groundwater resources have led to awareness that a national wastewater reclamation program should be developed. Such a program could cover a major portion of the agricultural water demand and also include water reuse for other applications such as aquifer recharge and industrial uses. The implementation of Integrated Membrane System (IMS) contributes to the success of treating wastewater effluents. The system comprises UF pretreatment for RO followed by NF desalination. Evaluation of the performance of UF and RO membranes was conducted by monitoring the effect o multiple variables including pretreatment, feed quality and operating flux. Trials were conducted to determine the optimum operating conditions for the entire system. The results achieved within this study indicate significant cost benefits in the range of approximately 20% for medium and large scale wastewater desalination systems. This paper presents the research activity over the last 3 years in advanced tertiary treatment: desalination of secondary effluents after activated sludge process by IMS consisting of immersed UF technologies and RO. Large demonstration-sized pilot plants, located at the biggest WWTP in Israel, the Shafdan, were used for the research. Results of the evaluation and optimization of UF technology are conveyed. Data obtained from the operation of the RO membrane system and an RO/NF hybrid system at high fluxes and high (up to 90%) recovery ratios are also detailed.

Keywords: Ultrafiltration; Secondary effluent; Desalination; Antiscalant; Biocide; Biofouling

1. Introduction

In wastewater desalination RO recovery rates of 80–82% and sometimes greater, up to 85%, are typically achievable [1,2]. It is rather well known that increasing the recovery even further, up to 90% would be of great value [3]. Operation at higher recovery translates to the minimization of the pretreatment system size, maximization of the water source use and minimization of the environmental concerns surrounding brine waste disposal.

When increasing RO recovery, two problems are encountered:

1. Dissolved organic compounds will be more likely adsorbed on the membranes surface as they are more concentrated.

2. Certain ionic species can scale the membranes. Among them the most common in wastewater treatment is calcium phosphate.

Adequate pretreatment could enable the desired high recovery operation. This study revealed that a properly

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designed and operated UF system could provide the level of pretreatment required to achieve the high recovery operating mode of the RO membrane system. It can be challenging to maintain stable operation at high fluxes and minimal cleaning with varying influent water quality.

The primary goal of the research was to optimize the IMS operating parameters in order to reduce the wastewater desalination cost. This was done by demonstrating high UF operating fluxes and high (up to 90%) RO recovery. The latter was achieved by applying the latest developments in wastewater desalination including the use of a hybrid RO/NF system, proprietary antiscalants aimed to prevent specific scales like calcium phosphate's and utilizing a new type of biocide aimed to prevent biofouling of the RO membranes.

2. Field testing

The pilot tests were performed in a demonstration facility that consisted of a UF/RO pilot plant with a daily capacity of 600 m^3. The study, which started in 2006, is being performed in cooperation between the Mekorot Water Company and GE Water & Process Technologies, supported by the Canada–Israel Industrial Research and Development Foundation.

2.1. Set-up description

Secondary effluent from the Shafdan wastewater treatment facility is fed through a 300 micron self-cleaning filter to protect the UF pretreatment system. This is not necessary prior to the pretreatment system as it has no impact on the operation of the UF. The pretreatment system utilizes the commercially available ZeeWeed® 1000 UF membrane [4]. The UF section consists of one cassette housing 24 individual ZeeWeed® 1000 membrane modules at 450 ft^2, each totaling 10,800 ft^2. The main characteristics of the membranes are shown in Table 1.

The desalination system, fed by UF filtrate, consists of three stages with 35 8-inch commercial RO elements. A special for calcium phosphate precipitation prevention antiscalant was injected prior to the RO membranes together with pH adjustment by acid addition. RO membranes were operated in all three stages for the first portion of the testing and for the second portion a combination of RO and NF membranes was utilized [5]. RO membranes remained in the first two stages and NF membranes were installed in the third stage. The pretreatment capacity is 960 m^3/d and RO capacity is 600 m^3/d. The process flow diagram of the pilot is presented in Fig. 1.

Table 1
Characteristics of ZeeWeed 1000 WW membranes

UF model	ZeeWeed® 1000
Type	Immersed
Area, ft^2	450
Configuration	Outside–in
Nominal pore diameter, μ	0.02
Max. TMP, kPa	69
Filtration principle	Dead-end

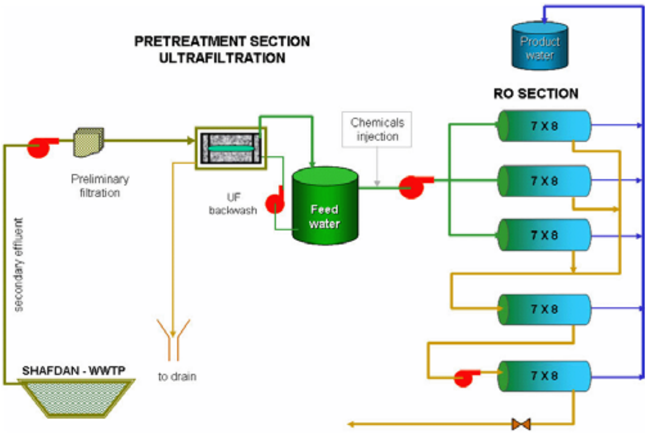

Fig. 1. Schematic diagram of the demonstration plant.

Table 2
Main secondary effluents characteristics

Parameter	After secondary treatment		
	Avg.	Max.	Min.
Turbidity, NTU	3	7	1.8
Suspended solids 105°C, mg/l	5	18	3
BOD, mg/l	7	10.0	5.0
COD, mg/l	44	63.0	39.0
DOC, mg/l	14	30.0	11.0
TOC, mg/l	12	33.0	8
UV 254 absorbance, cm^{-1}×10^3	216	233	211
Color, unit	50	75.0	35.0
Ammonia, as N, mg/l	1.5	3	0.5
Kjeldahl nitrogen, mg/l	5	20	4.5
Nitrate, as N, mg/l	0.34	0.6	0.1
Nitrite. as N, mg/l	1	2.3	0.2
Phosphates, as P, mg/l	1.5	2.8	0.9
Total dissolved solids 105°C, mg/l	899	1047	800
Calcium, mg/l	85	90.0	82.0
Magnesium, mg/l	32	35.0	27.0
Chloride, mg/l	314	364.0	248.0
pH	7.6	7.9	7.5
Total bacteria, count/ml	7.E+05	8.E+06	5.E+05
Coliforms, count/100 ml	8.E+05	8.E+06	5.E+05
Fecal coliforms, count/100 ml	4.E+04	4.E+05	6.E+03

2.2. Feed water characteristics

The secondary effluent is characterized in Table 2. It can be seen that all the parameters related to the organic compounds concentration (BOD, COD, TOC, DOC, UV, color, N organic) have relatively high concentration values. High phosphate concentrations and relatively high calcium concentrations indicate that RO chemical pretreatment optimization is required to better control calcium phosphate precipitation. A wide range of SS, turbidity and organic matter are observed during the winter period (up to 35 ppm, 21 NTU and 20 ppm accordingly).

3. Results and discussion

3.1. Pretreatment–UF membranes

3.1.1. Optimization test

The test protocol called for starting up the ZeeWeed system at low operating fluxes to establish operational stability and to determine a baseline for the program. The fluxes were then increased over time to determine the optimal flux for this particular application. The initial operating conditions are listed below:

- Flux: 25 lmh
- Filtration duration: 30 min
- BW duration 1 min 30 s with air and another 30 s with air and filtrate backpulsing through the membrane in the reverse direction
- Tank drain every BW
- Daily maintenance clean procedure (MC), including recirculation of UF filtrate mixed with 100 ppm of sodium hypochlorite through the membranes in the forward direction for 10 min
- Recovery cleaning procedure of soaking the membrane in 500 ppm sodium hypochlorite solution for 5 h

The demonstration facility was started up on September 13, 2006. Stable and low TMP values were demonstrated during the initial testing period at fluxes of 25 lmh and 30 lmh (Fig. 2). When the flux was increased up to 35 lmh, the TMP began to rise. The first recovery clean was performed in November, restoring the TMP to its initial value but the membranes began to foul again shortly afterwards as depicted in Fig. 2.

The unstable performance of the ZeeWeed membrane occurred during the winter months when fluctuations in turbidity were observed, although only slightly and seemingly insignificant at times. This high rate of fouling was initially dealt with by often conducting recovery cleans. The recovery cleans showed complete TMP recoverability but proved to be costly and impacted membrane life. Maintenance cleans, which were conducted daily, did not restore the TMP as needed and only decreased the TMP no more than 25%. This was not significant enough to impact the system operation positively.

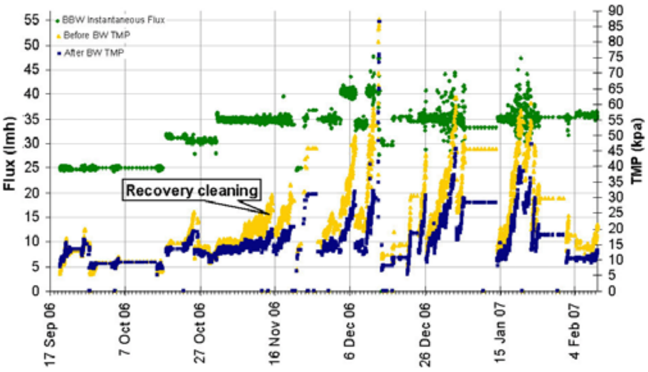

Fig. 2. TMP at fluxes of 20– 35 lmh, ZeeWeed 1000 V, Shafdan pilot plant.

It was found that the seasonal increased turbidity in the winter is due to organic matter increase. In the rainy season, the rain water penetrates the sewage system, adversely affecting the biological treatment and thus causing the rise in turbidity. The flocs formed during the secondary treatment are not weak and unstable. The precipitation rate decreases and therefore the flocs remain in the secondary effluents. These flocs stick to the surface of the UF membrane, which cause the TMP to increase rapidly.

Following this evaluation, the MC procedure was modified to improve the fouling rate. The membranes were backpulsed for 10 min with a UF filtrate mixed with sodium hypochlorite at a concentration of 100 ppm. These long, disinefecting backwashes flushed the flocs from the membrane surface and returned the TMP to its original value of −10 kPa. When there was an increase of turbidiy in the raw water, this procedure was applied (manually) instead of the regular automatic MC procedure. This new procedure was named the “BW extended procedure”.

Once this fouling was under control, the permeate flux optimized continues and the flux was increased in steps while observing the TMP and permeate quality (Fig. 3). As shown in Fig. 3, the TMP was very stable at fluxes 40 and 45 lmh throughout February, March and April 2007 (until April 20). There were two peaks in TMP that were related to an error in the MC cleaning procedure where the MC was unknowingly performed with raw water instead of UF permeate. This was immediately corrected.

From April 20 to May 10, the TMP value spiked reaching 75 kPa (the four peaks on Fig. 3). This period was characterized by significant SS and turbidity increases in the raw water (SS reached to 20 ppm). A visual test showed a large amount of flocs in the feed water. The extended backwash procedure could not be conducted on the weekends when there were no operators on site

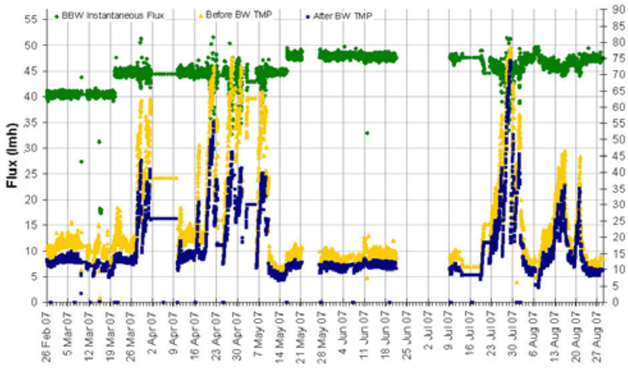

Fig. 3. TMP at fluxes 40–50 lmh, ZeeWeed 1000 V, Shafdan pilot plant.

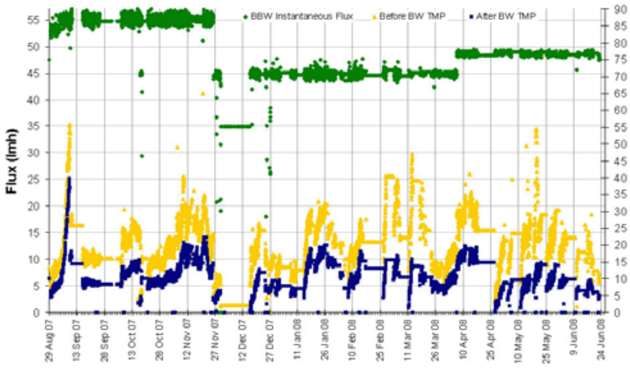

Fig. 4. TMP at fluxes 45–55 lmh, ZeeWeed 1000 V, Shafdan pilot plant.

because it is a manual operation. However, when conducted, the BW extended procedure always restored the TMP to the initial values without a recovery clean.

The TMP declines as the feed water quality improves starting May 10 and therefore the flux is increased up to 48–50 lmh. From May 2007 until the end of June 2008, the UF membrane system operated at high fluxes from 45 up to 55 lmh with stable TMP from -13 kPa to -25 kPa and low recovery cleaning frequency (once per 6–8 months) (Fig. 4). At this time the filtration duration was increased from 30 min to 40 min, which is very significant for the overall system cost reduction as it increases the recovery of the system while reducing the number of backwashes and thus downtime. This improvement and the flux improvement were possible primarily due to the application of the BW extended procedure to control the TMP fouling during upset conditions in the upstream processes.

3.1.2. UF permeate quality

During the test, the turbidity and SDI of the membrane were monitored. The turbidity remains stable at 0.1 NTU throughout the testing regardless of the feed water quality. When the feed SDI could not be measured, even in 2 min, the average UF permeate SDI remained between 2.2 and 3 independent of the feed quality.

Table 3
UF permeate main parameters and removal percentages

Parameters	UF feed	UF permeate	Removal, %
SDI (15)	—	2.2–3.0	—
Turbidity, NTU	3–5	0.1–0.2	96–98
SS, 105°C	3–8	0.2–0.4	85–99
TOC, ppm	10	8–11, peaks to 17	10–15
COD, ppm	40	30–45	10–20
UV 254 Abs., $\text{cm}^{-1}\times10^3$	190	200–218	5–6
NKj, ppm	4.5–20	4.4–15	3–25
PO_4, as P, ppm	1.3–3.0	0.9–2.7	10

The main UF permeate parameters and the removal values are presented in Table 3, showing a high level of suspended solids (SS) and turbidity removal. Organic removal is not high since 86–90% of the organics are dissolved and thus pass through the UF membrane.

Regarding bacteriological quality, 4–5 logs removal of total bacteria count, coli and fecal, was achieved (from 10^6–10^7 cfu/1 ml of TBC and 10^6 cfu/100 ml of coli and fecal in the feed).

3.2. Desalination system operation

The main goal of the investigation is to achieve stable RO system operation at maximum recovery rate. In order to reach high recovery of up to 90%, a treatment intended to mitigate the $Ca_3(PO_4)_2$ precipitation was evaluated. The treatment comprised a special antiscalant together with pH adjustment by HCl addition [5].

- TEST 1: RO membrane Type 1 in all stages
- TEST 2: Hybrid RO/NF system: RO membrane; Type 1 in first and second stages, NF membrane in third stage

3.2.1. $Ca_3(PO_4)_2$ precipitation mitigation

PO_4 is a trivalent anion also knows as orthophosphate. The inorganic form of phosphorus found in secondary effluents at concentration of 1.5–3 ppm as P. Phosphate can be problematic for the RO system when it combines with calcium to form tricalcium phosphate [$Ca_3(PO_4)_2$] scale with a fifth-order reaction:

$$3\,[\mathrm{Ca}] + 2\,[\mathrm{PO_4}] = \mathrm{Ca_3(PO_4)_2}$$

$$\text{Saturation level} = [\mathrm{Ca}]^3\,[\mathrm{PO_4}]^2/K_{\mathrm{spc}}$$

Because tricalcium phosphate saturation is fifth order, small changes in free phosphate concentration, or even smaller changes in calcium concentration [6], significantly affect the calculated saturation level. Studies have shown, that scale inhibitor (antiscalant) alone is insufficient to control calcium phosphate scaling when pH exceeds 7 [7]. However, a reduction in pH will decrease the saturation level to a point where calcium phosphate specific antiscalant can be effective.

Due to the combination of high recovery (85–90%) and high calcium concentration (Table 2), pH to RO was reduced to 6.5. A new specific for calcium phosphate precipitation prevention antiscalant was added in RO feed. In addition, it was observed [8,9] that the tendency of $Ca_3(PO_4)_2$ precipitation in RO membranes intensified when biofilm formed on the membranes. Therefore, biocide (chloramines or another one) addition is important for calcium phosphate mitigation.

Chloramines forms in the RO feed water due to a relatively high content of ammonia in the secondary effluents, usually fluctuating between 3–8 ppm as N, when a certain portion of sodium hypochlorite is added to the RO feed. Due to the oxidizing nature of chloramines, their presence in the RO feed is considered satisfactory for disinfection purposes. However, it was found that the ammonia content in the secondary effluent fluctuates and reaches very low concentration of 0.5–0.8 ppm at times, which causes a chlorine free reaction yielding hypochlorite which penetrates into the RO membranes. Therefore, the experiments with hypochlorite addition were stopped and evaluation of a new biocide started.

The biocide kills microbes that eventually produce slime on the RO membranes but does not dissolve any established slime. Hence, it is important to add Aqucar RO-20 as a preventive treatment and not as a curative one [10]. Micro-organisms that come into contact with the biocide are rapidly killed by a mechanism that appears to involve a reaction with the protein fraction of the cell membrane and inactivation of enzyme systems. The most frequently used mode was an intermittent dosage to the RO feed twice per week for 1 h.

TEST 1, RO membrane type 1 in all of the stages — The RO system ran for 1680 h with a stepwise increase in recovery from 78% to 88%; 88% is the maximum possible recovery in the existing RO configuration related to the manufacturer's strict limitation on the minimal brine flow. The permeate flux ranged between 17 lmh to 20.7 lmh. The pH was decreased as the recovery increased (Fig. 5) to prevent $Ca_3(PO_4)_2$ precipitation.

It can be seen in Figs. 6 and 7 that the membrane performance was stable at all of the stages of the test regarding pressure drop and salt passage. The normalized permeate flow of the first stage decreased by 15%; however, in the second and the third stages it decreased by 6–7% only (Fig. 8), a typical result of compaction of the new membrane. Once decreased, the permeate flow of the second and the third stages remained stable along the test.

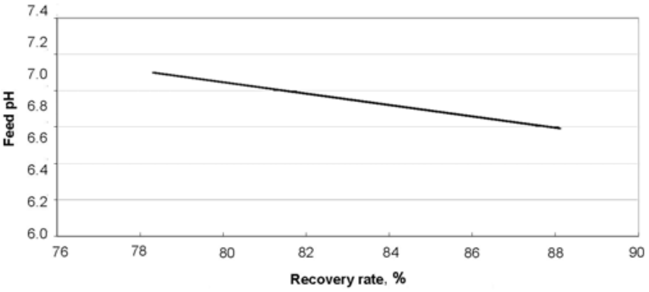

Fig. 5. Feed pH vs. recovery rate.

Table 4
Rejection of Ca and PO_4 in RO and RO/NF systems

	Ca rejection, %	PO_4 rejection, %
TEST 1, RO	98.6	99.3
TEST 2, Hybrid RO/NF	97.3	93.0

The permeate flow of the first stage showed a slight declining tendency. The most probably reason for this is biofouling on the membrane surface. The successful result of chemical cleaning at pH of 12 confirmed this assumption. Biocide was added into the RO feed twice/week for a duration of 1 h each time.

TEST 2, hybrid RO/NF system — After witnessing stable operation at 88%, the configuration was changed so that a higher recovery could be tested. The RO membranes in the third stage were replaced by NF membranes manufactured by Hydranautics, type ESNA LF1. This membrane is characterized by a more open structure and consequently, lower rejection than ROs [11]. In this way, more Ca and PO_4 ions could penetrate to the product, resulting in their lower concentration in the brine and thus decreasing the risk of $Ca_3(PO_4)_2$ precipitation.

The laboratory analyses of Ca and PO_4 concentration in the feed, the brine and the product of RO, performed during TEST1 and TEST2, permitted to compare ions rejection by the RO membranes and the hybrid RO/NF (Table 4). In spite of the fact that the contribution of the NF membranes to the total product produced by RO/NF system is only 17%, it had a considerable effect on the ions rejection, especially PO_4. This enabled the system to operate at a higher pH, from 6.5 to 6.8–6.9, resulting in a 25% decrease of chemical usage.

The brine flow from the NF membrane can be lower than from the RO Type 1 membrane (according to the manufacturer's instructions) which allowed a recovery rate increase up to 90%. It should be stressed that the membranes demonstrated remarkable stability regarding the permeate flow, salt passage and pressure drop in all the stages (Figs. 6–8). The permeate flow of the first stage decreased by 6% during TEST 2.

Table 5
Chemicals cost for RO pretreatment (recovery = 90%)

Feed pH	Chemicals	Price, \$/ton	Dosing, g/m^3 feed	Cost, ¢/m^3 feed	Dosing, g/m^3 prod.	Cost, ¢/m^3 prod.
6.5	H_2SO_4 (98%)	96	114.5	1.10	127.22	1.22
6.9	H_2SO_4 (98%)	96	55.8	0.54	62.0	0.60
6.5; 6.9	Antiscalant	2800	4	1.12	4.44	1.24
Total for pH = 6.5						2.46
Total for pH = 6.9						1.84

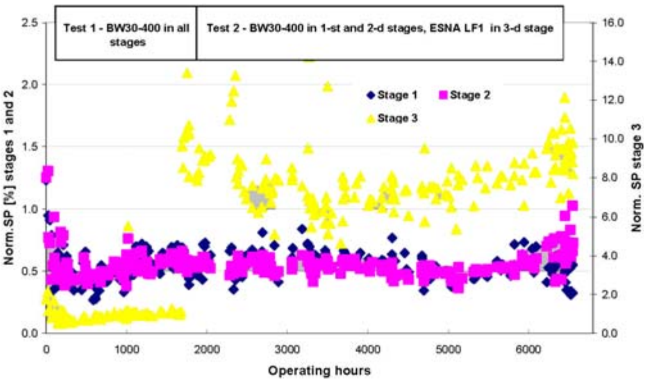

Fig. 6. Normalized salt passage, RO system, Shafdan pilot plant.

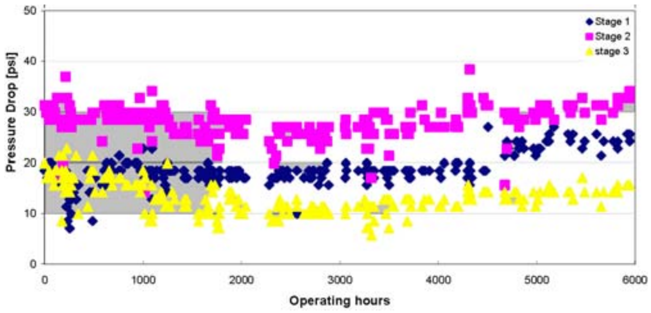

Fig. 7. Pressure drop across RO membrane, Shafdan pilot plant.

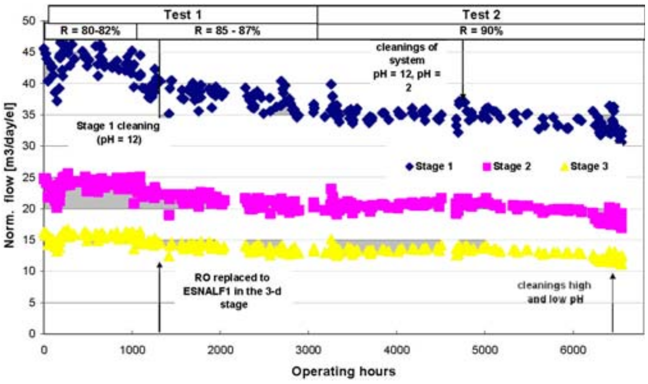

Fig. 8. Normalized flow of all RO stages, Shafdan pilot plant.

During TEST 2 a phenomenon of sudden feed pressure and pressure drop rise in the third stage occurred several times. The pressure was restored to the initial value by immediately adding acid to the feed water (to a pH of 2.5) and then using that water to flush the NF membranes for 15 min. The success of this procedure indicates $Ca_3(PO_4)_2$ precipitation in the third stage related to the fluctuations of phosphate concentration in the secondary effluent from 0.8 up to 2.7 ppm as P, especially during the winter months. The precipitation was intensified by increasing the pH up to 6.9.

In an industrial plant, flushing of the last RO system stage with acidic feed should always be performed when the pressure increases. This procedure can be performed without stopping the plant, with the first stages operating. The contribution of the last stage to the total product flow is approximately 17–18%.

3.3. *Improved design for desalination of secondary effluents*

The optimization work conducted during this testing enabled the overall system to operate at a higher product recovery, lower specific energy consumption and lower chemical consumption. The cost savings associated with this optimization is summarized in Table 6. The results of this experiment have led to an improved design for desalination of secondary effluents at the Shafdan site, with a capacity of 20,000 m^3/day. The unit water desalination cost of the improved design will be lower by approximately 20% than the unit water cost of the conservative design that would have been used without the experience of the research.

Table 6
Optimization UF/RO system tests effect on unit water cost

	Conservative design	Improved design	Δ, %
UF membrane flux, lmh	25	50	+100
RO product recovery, %	80	88–90	+10
RO specific energy,	1.1	0.8–0.9	−20
kWh/m^3	6.0	5	
UF+RO chemicals cost,	455	383	−17
¢/m^3	37.1	30.1	
Specific investment[a],			−16
\$/m^3.day			
Unit water desalination			−19
cost[a], ¢/m^3			

[a] In 20,000 m^3/day plant.

4. Conclusions

The integrated membrane system solution has proven successful under difficult conditions of high TOC content, fluctuation of phosphates, high bacteria, coli and fecal load. The combination of UF pretreatment, antiscalant for $Ca_3(PO_4)_2$ precipitation prevention, hybrid RO/NF system and successful biocide for biofouling control is a cost-effective solution for secondary effluents desalination at high recovery rates.

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