DESALINATION

Desalination 187 (2006) 335–345

www.elsevier.com/locate/desal

A two stage membrane treatment of secondary effluent for unrestricted reuse and sustainable agricultural production

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Received 27 December 2004; accepted 29 April 2005

Abstract

Field experiments are in progress for secondary wastewater upgrading for unrestricted use for irrigation and sustainable agricultural production. The integrative treatment system for the secondary effluent polishing is based on implementing in series of two main treatment stages: ultrafiltration (UF) and reverse osmosis (RO) membrane treatment. The pilot system has the capacity of around 8 m^3/h. The UF effluent is used to feed the RO membrane stage. Different mixtures of UF and RO permeates are subsequently applied for drip irrigation of various agriculture crops. The field results indicate the importance of the UF component in the removal of the organic matter and the pathogens that are still contained in the secondary effluent (the secondary effluent is obtained from a waste stabilization pond treatment system). Under specific conditions, when the dissolved solids content is relatively low, the UF effluent can be applied directly for unrestricted irrigation. In the successive RO stage most nutrients are removed, allowing applying the effluent without jeopardizing the soil fertility and the aquifers. Preliminary economic assessment indicates that the extra cost for effluent polishing via the UF stage only is in the range of 8–12 US cents/m^3. The extra cost for the RO stage is as well assessed at 8–12 US cents/m^3. The additional treatment expenses depend to a large extent on the quality of the incoming raw secondary effluent and local requirements at the command agricultural production sites.

Keywords: Effluent; Hybrid membrane systems; Renovation; Unrestricted Reuse; Economic assessment

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Presented at the International Conference on Integrated Concepts on Water Recycling, Wollongong, NSW Australia, 14–17 February 2005.

1. Introduction

Water shortage in arid and semi-arid regions has stimulated the search for alternative solutions. The alternative non-conventional water sources include primarily saline waters, high quality run-off water and treated wastewater [1]. The growing demand for water and increasing environmental awareness reinforces today's intensive efforts towards improving the treatment and reuse of surface waters and domestic wastewater. Reuse of treated wastewater, primarily for agricultural irrigation, solves simultaneously disposal problems and environmental issues. The efforts associated with effluent reuse include additional studies regarding pathogens viability (bacteria, viruses and parasites) and possibilities of dissolved solids removal. Pathogens content in the disposed or applied effluent is related to their impact on the soil and agricultural raw eaten products. The human communities ultimately consume these products. The nutrients content in the effluent (primarily ammonia, phosphate and potassium) and additional constituents might have adverse effects on agricultural productivity, both in the long and short term. The additional constituents that have to be seriously considered include sodium, calcium and manganese, allowing the assessment of the sodium absorption ratio (SAR) of the effluent and related impact on the soil. Heavy metals (e.g. selenium and boron) that are occasionally contained in the effluent might devastate the soil structure, have adverse toxic effects and ultimately cause a reduction in productivity. The long-term effects are primarily related to the accumulation of the various dissolved solids in the soil, plants and groundwater.

Consequently, the on-going research focuses simultaneously on several related topics for increasing the availability and improving the value of waters of original low qualities. These include improved treatment of domestic, industrial and agricultural wastes, yielding high quality effluent with minimal health and environmental risks. The advanced treatment methods should be based on combined biological, chemical and mechanical processes, including membrane technology and disinfection processes with minimal by-products generation. Advanced water application methods, primarily drip irrigation for agriculture, for the improved disposal and reuse of the effluent are in progress.

1.1. Membrane technology

Concerning environmental pollution, and health risks when reusing treated wastewater, as well as water shortage due to intensive exploitation of groundwater from aquifers and others water sources, has enhanced the search for advanced high level and reliable wastewater treatment [2]. Conventional wastewater treatment methods, and even advanced filtration and disinfection not often can comply with water quality requirements. Membrane treatment [microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO)] have received abundant attention during the past decade as a means to alleviate water shortage problems and of better environmental control.

UF membranes is a widely-known technology used for the treatment of surface water, effluent, brackish and seawater. Currently there are two common configurations of UF membranes: spiral wound (SW) and hollow fiber (HF). The configuration of SW elements is described in the literature [3] and can be classified by the following characteristics: (i) high flux at low pressure, (ii) high and stable organic matter removal, (iii) reduced compaction, (iv) high chlorine resistance, (v) resistance to hydrolysis by acids and alkalis, and; (vi) resistance to water turbidity and fouling processes.

1.2. Microbial effluent quality for reuse

In 1989, the World Health Organization (WHO) published the guidelines (a revision of the 1973 guidelines). According to WHO there should be ≤1,000 fecal coliforms per 100 ml in water to be used for irrigation of crops likely to be eaten uncooked, sport courts and public parks [4]. These recommendations are less stringent than the California State regulations (Title 22), which require media values for total coliforms to be ≤2.2 per 100 ml and in a single sample to be less than 240 per 100 ml [5]. In this light it is anticipated that piercing discussions will take place among experts as per terms and level of "safe" irrigation water.

1.3. Chemical effluent quality for reuse

The next emerging stage, in order to maintain sustainable agriculture production is to deal with the chemical constituents contained in the effluent. Subject to the conditions when applying secondary effluent for irrigation, the dissolved solids content has to be considered along with assessing the accumulative effects on the long-time range. The accumulative time effects are mainly important in dry regions and in areas where ground waster is located in relatively shallow depths.

2. The purpose of the work

The purpose of the on-going research project is to examine on a field scale the possibilities of polishing secondary effluent for unrestricted reuse, primarily for agricultural irrigation. In the past mainly the UF membrane technology was used for polishing of the secondary effluent in order to minimize health and environmental risks.

In this work the RO membrane treatment stage is combined with a UF stage for the removal of the dissolved solids [6]. The purpose is to remove the dissolved solids for better management of sustainable agricultural production. It will enhance better on farm irrigation management [7].

3. Materials and methods

3.1. The Arad Heights site

The Arad Heights agricultural fields encompass a total area of about 500 ha. The cultivated fields are located, around 525 m above the sea level. Mean annual precipitation during the rainy season (around four months) is around 150 mm. Mean maximal daily temperatures during the warm summer months rise to approximately 29°C. Mean minimal daily temperature during winter decrease to 6°C. The relative humidity is relatively low during the summer season, and is in the range of 15–30%. Maximal solar radiation is in the range of 1000–1100 W/m^2.

The experiments are conducted adjacent to wastewater treatment facility [waste stabilization ponds (WSP) system] located several kilometres west of the City of Arad, Israel. Secondary effluent from the WSP is used as the feed for the membrane pilot system. The secondary effluent is initially treated by a mechanical ring filter and subsequently by a UF membrane system. The permeate of the UF system is used for irrigation and also feeding the reverse osmosis (RO) stage. The RO permeate is as well applied for irrigation, adding extra amounts of fertilizers to comply with the content of the original secondary effluent. The schematic treatment system is depicted in Fig. 1.

3.2. The membrane treatment system

The ultrafiltration stage (Fig. 1) consists of a small temporary storage (5 m^3), a ring filter, a circulation pump, and three modules with twelve UF 8″ spiral-wound (SW) membranes, a flushing system and a chemical cleaning unit. Manual valves allow controlling the circulation rate in the membrane system.

The spiral-wound UF membrane consists of three layers: a polyester support web, a microporous polysulfone interlayer, and an ultra-thin barrier coating on the top surface. Two-stage spiral-wound UF membrane modules are used for irrigation and supply 10 m^3/h. Except for the chemical cleaning process, the UF plant runs automatically under the control of an on-board programmable logic controller (PLC). UF type is NIROSOFT RM10-8, 8040 spiral wound. The molecular weight cut-off (MWCO) of the

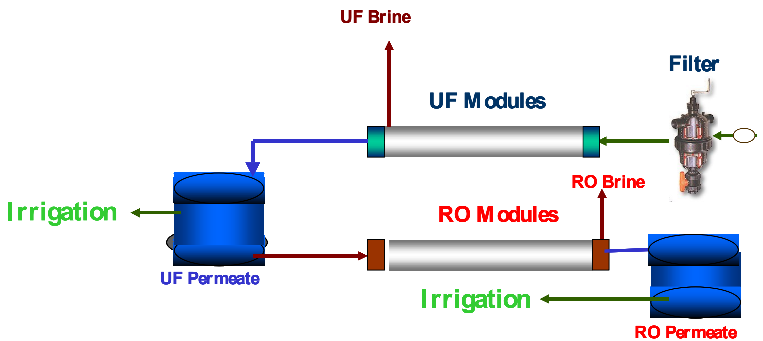


Fig. 1. The hybrid membrane wastewater polishing treatment system.

membrane is 20 KDa. The defined removal rate is 88–93% at 3 bar, 20°C, stirring cell. Other characteristics of the UF system used are given in Tables 1 and 2 [8].

Table 1
Characteristics of the UF system under operation

Parameter	Value
Membrane length, mm	1,016
Membrane diameter, mm	200
Product water tube diameter, mm	28.6
Membrane active area, m^2	37.1
Number of membranes used at stage 1	8
Number of membranes used at stage 2	4

Table 2
Characteristics of the thin-film composite UF membrane

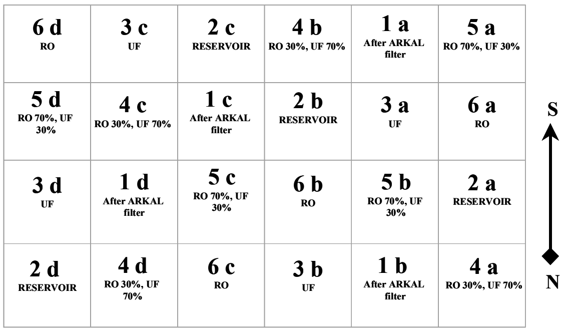
Parameter	Value
Molecular weight cut-off, Da	20,000
Max. chlorine tolerance, ppm	1,000
Max. hydrogen peroxide tolerance, ppm	1,000
Max. operating temp., °C	45
Max. operating pressure, bar	40
Max. pressure drop per element, bar	0.9
Max. pressure drop per vessel, bar	4.1
pH range, continues operation	2–11
pH range, short term cleaning (max. 45°C, 2 h/d)	1–12
Permeate flow rate, m^3/h	0.4–4.0
Max. feed flow rate, m^3/h	12
Min. concentrate flow rate, m^3/h	2.5

The membranes are operated at pH 7, inlet feed pressure is around 5 bar and the operating temperature is around 26°C. The feed water (secondary effluent) is pumped directly from Arad WSP system. The UF system was operated under feed-and-bleed mode.

The RO unit consists of a two-stage array with four 4″ membrane elements (Filmtec type FT30 4040 thin-film composite membrane in spiral-wound configuration). The membrane coating is remarkable in that it has surface pores controlled to a diameter of approximately 150 Å [8]. Except for the chemical cleaning process, the pilot runs automatically and the feed was pretreated with acid (HCl) without anti-scalant. There was no post-treatment: permeate was delivered to a reservoir and supplied to the customers. The RO elements were not back-washed: the membranes were cleaned at intervals of about 70 h with citric acid.

3.3. The irrigation system

The possibility of using several secondary effluent qualities combined with onsurface drip irrigation (ODI) technology for crops irrigation was examined in a cornfield experiment during May–August 2004. The following treatments, all purposely under ODI are (Fig. 2): (i) irrigation with secondary effluent from the ponds (SEP); (ii) irrigation with secondary effluent from the reservoir (SER); (iii) irrigation with UF effluent;



6 d RO	3 c UF	2 c RESERVOIR	4 b RO 30%, UF 70%	1 a After ARKAL filter	5 a RO 70%, UF 30%
5 d RO 70%, UF 30%	4 c RO 30%, UF 70%	1 c After ARKAL filter	2 b RESERVOIR	3 a UF	6 a RO
3 d UF	1 d After ARKAL filter	5 c RO 70%, UF 30%	6 b RO	5 b RO 70%, UF 30%	2 a RESERVOIR
2 d RESERVOIR	4 d RO 30%, UF 70%	6 c RO	3 b UF	1 b After ARKAL filter	4 a RO 30%, UF 70%

Fig. 2. The experimental field layout, Arad, May–August 2004.

(iv) irrigation with RO effluent; (v) irrigation with a mixture of 70% UF effluent and 30% RO effluent (0.7 UF + 0.3 RO), and; (vi) irrigation with a mix-ture of 30% UF effluent and 70% RO effluent (0.3 UF + 0.7 RO). Each treatment consists of 4 replications (four plots) namely, a total of 24 plots (Fig. 2). The soil texture in the experimental fields consists of about 28.8% clay, 45.2% silt and 26% sand. The field experiment consists of 6 treatments with six different effluent qualities. Each treatment consists of four plots, allowing a thorough statis-tical analysis. Each plot is 12 m × 16 m and the total experimental area is around.0.46 ha. Corn *(*corn for grains #3223) was seeded on 2 May 2004 (8 seeds per 1 m run per each row). The plants were arranged in rows on of 0.93 m wide beds. Each row was irrigated by Netafim RAM Emitting Pipe ISO 9261A-laterals. Each lateral was 16 m long. Compensating emitters with a flow rate of 1.2 L/h are 25 cm apart on the drip laterals. One drip lateral is serving each plants row.

Several issues were of concern during the irrigation part of the project: (i) verifying the effects of ODI, applying secondary effluent of diverse qualities (six qualities) on the yield, and; (ii) assessing salinity accumulation and distribution in the soil as related to the soil depth and effluent quality application.

Soil moisture content was characterized by a standard gravimetric method. Effluent and soil chemical and microbial characteristics were determined by conventional methods [9,10]. Soil samples for moisture, chemical and microbial assessment were taken at 0, 30, 60 and 90 cm depths from the equidistant on both sides of the plants, near the emitters and in the middle between two adjacent emitters.

4. Results

4.1. The field experiment effluent qualities

Data referring to the chemical and microbial characteristics of the effluent are presented in Tables 3 and 4. The effluent quality of refers both to the membrane system performance and the related impact on the agricultural irrigated field.

4.2. Irrigation and fertilization

Prior to starting on the drip irrigation, the field was sprinkler irrigated for the plants' germination: two irrigation shifts of 300 m^3/ha, each. Up from May 16 until August 8 of the field was irrigated by the ODI system. Irrigation scheduling was based on class "A" Pan evaporation monitoring and locally used crop coefficients. All treatments obtained the same amounts of effluent, as was confirmed by soil moisture profiles. Moreover, according to Analysis of Variance (ANOVA) no significant differences were detected in amounts of water accumulated in the 0–90 cm soil profile (P-value >>0.1) (11). All treatments were adjusted to one similar application level of nutrients as expressed by NPK, according to recommendations of Israeli Ministry of Agriculture. Additional amounts of fertilizers (liquid fertilizer nitrogen 14%; phosphorus 14%) were applied every irrigation and controlled according to the effluent qualities (Tables 3 and 4). After irrigation termination, the plants remained in the field for drying for about one month. The corn ears were harvested on 12 September 2004.

Table 3
Effluent quality. Arad, 20 June 2004

Sample notation	BOD (mgO_2/l)	COD (mgO_2/l)	Fecal coliform (CFU/100 ml)	pH	EC (dS/m)	TSS (mg/l)	Cl (mg/l)	Na (mg/l)	K (mg/l)	N-NH_4 (mg/l)	PO_4 (mg/l)
SEP*	123	577	2×10^5	7.7	2.25	214	313	328	49.7	47.6	9.2
UF permeate	1.2	113	6	7.9	2.19	0	311	302	46.6	40.16	5.25
UF brine	148	673	3×10^5	7.7	2.21	244	299	310	46.9	50.28	6.2
RO permeate	1.0	9.28	0	7	0.126	0	18.82	23.6	3.56	4.922	0.32
RO brine	1.4	172	2	7.9	5.03	16	738	710	141	60.12	20.4
SER**	29.1	291	1×10^2	7.4	2.43	43	322	330	55.2	48.23	39.3

*SEP — secondary effluent from stabilisation ponds
**SER — secondary effluent from reservoir

Table 4
Effluent quality, Arad, 22 July 2004

Sample notation	BOD (mgO_2/l)	COD (mgO_2/l)	Fecal coliform (CFU/100 ml)	pH	EC (dS/m)	TSS (mg/l)	Cl (mg/l)	Na (mg/l)	K (mg/l)	N-NH_4 (mg/l)	PO_4 (mg/l)
SEP*	83.2	546	2×10^5	7.6	2.11	94	265	260	67.1	43.51	20.0
UF permeate	1.8	94.5	1	7.8	1.98	4	216	246	34.2	37.67	16.8
UF brine	88.5	656	3×10^5	7.4	2.13	140	285	259	48.1	47.64	7.10
RO permeate	2.25	2.83	0	7.1	0.224	0	22.4	28.0	5.16	6.312	0
RO brine	57.5	179	3	7.9	3.67	16	520	520	20.5	61.99	48.8
SER**	78.5	278	2×10^2	7.2	2.48	21	290	290	70.0	47.02	45.6

*SEP — secondary effluent from stabilisation ponds
**SER — secondary effluent from reservoir

4.3. Plant development and yields

One of the main objectives of this part of research was to examine plants response to different qualities of applied effluent. Two parameters indicating the plants' response to effluent quality are the height and stem diameter. Measurements were contended to 40 replications for every treatment (Fig. 3). The ANOVA and Duncun multi-range tests for the plants development were very significantly affected by the qualities of effluent applied (P-values << 0.001) for corn height as well as for corn stems' diameter. The best plant development was obtained for irrigation with RO effluent and the poorest for irrigation with secondary effluent from the reservoir probably, due to the differences in irrigation water salinity (Tables 3 and 4).

Similar results were obtained for the corn yield (Fig. 4). The best yield was obtained for irrigation with RO effluent and the poorest for irrigation with secondary effluent from the reservoir. The differences in the yield of corn dry grains subject to different qualities of water applied was also significant (P-value <0.1), but less significant in comparison with the plant development characteristics. According to data obtained it can be concluded that irrigation with RO effluent with added fertilizer provides the best plant development and eventually the best yield.

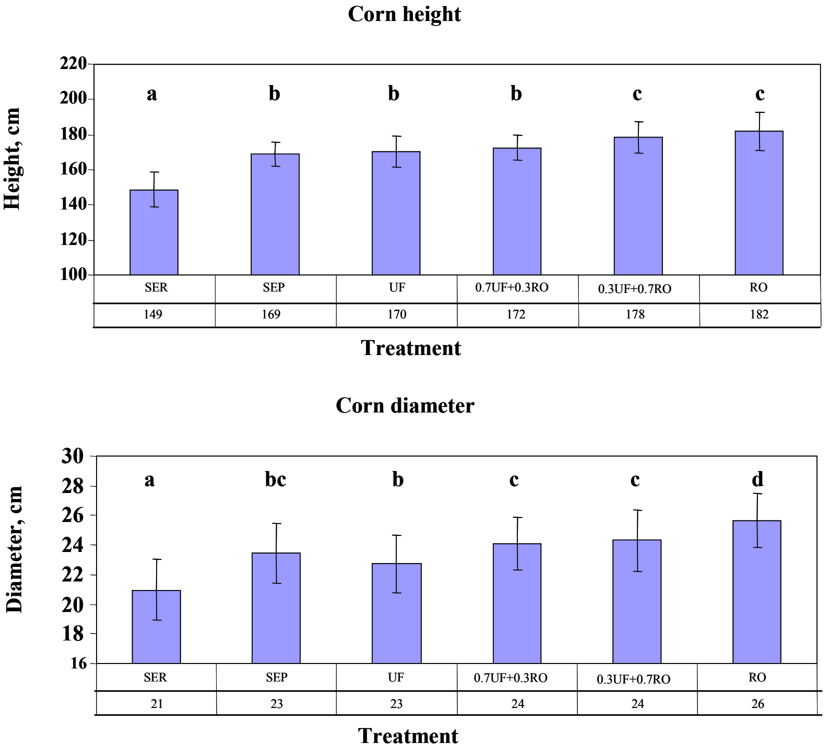


Fig. 3. Plant development characteristics subject to different qualities of water applied. Cornfield, Arad, 2004. (Letter under the columns represents results of Duncun test.) SEP — secondary effluent from the ponds; SER — secondary effluent from the reservoir; UF — UF effluent; RO — RO effluent; 0.7 UF + 0.3 RO — a mixture of 70% UF effluent and 30% RO effluent; 0.3 UF + 0.7 RO — mixture of 30% UF effluent and 70% RO effluent.

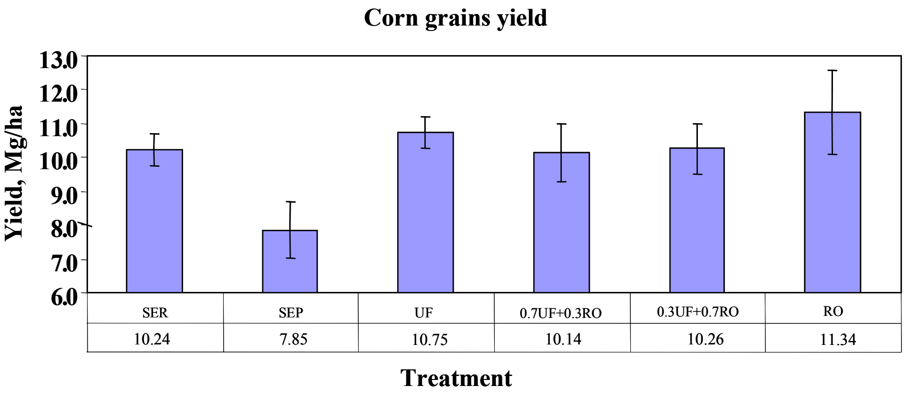


Fig. 4. Corn dry grains yield subject to different qualities of water applied, the corn field, Arad, 2004. SEP — secondary effluent from the ponds; SER — secondary effluent from the reservoir; UF — UF effluent; RO — RO effluent; 0.7 UF + 0.3 RO — a mixture of 70% UF effluent and 30% RO effluent; 0.3 UF + 0.7 RO — mixture of 30% UF effluent and 70% RO effluent.

4.4. The membrane system performance

4.4.1. Ultrafiltration

The membrane system was operated continuously from the beginning of May until the middle of August 2004. Operation was followed by continuous monitoring of main control parameters for both the UF and RO components. Related data of water qualities is presented in Tables 3 and 4. Secondary Effluent from ponds SEP was considered as the feed. Total operated duration was around 1,104 h and total amount of generated permeate was around 11,850 m^3. Data for the permeate flow rates and the system recovery is presented in Figs. 5 and 6.

During all operating period the wastewater was successfully subject to pollutants and organic matter removal (Tables 3 and 4 and Fig. 7). Effluent quality, according to the reuses criteria complied with needs, according to the crops' demands. The membranes were continuously flushed when significant decrease in permeate flow rate was noticed. Sodium hydroxide (NaOH); chloride acid (HCl) and hydrogen peroxide (H_2O_2) were used for the membrane flushing.

4.4.2. The reverse osmosis phase

Similarly, the RO membranes were operated during all experimental period. Related data for the water qualities is presented in Tables 3 and 4. The UF permeate was the feed for the RO stage. Total operated time of the RO membranes was 239 h and total amount of generated RO permeate was around 690 m^3. Chloride acid (HCl) was used for membrane flush. RO system permeate flow rate and recovery are presented in Fig. 8 proves that the RO membranes successfully removed the dissolved solids from the wastewater.

5. Conclusions

An integrated system of effluent polishing by a combined UF membrane stage and RO membrane stage for unrestricted reuse is under operation and testing in the fields of Arad-Height enterprise, near the City of Arad, Israel. Based on the data recorded it seems that UF membrane barrier guarantee over 4 log fecal coliforms removal. The tests concerning pathogens and organic matter removal indicate the efficiency of the UF stage. The RO stage guarantees dissolved solids

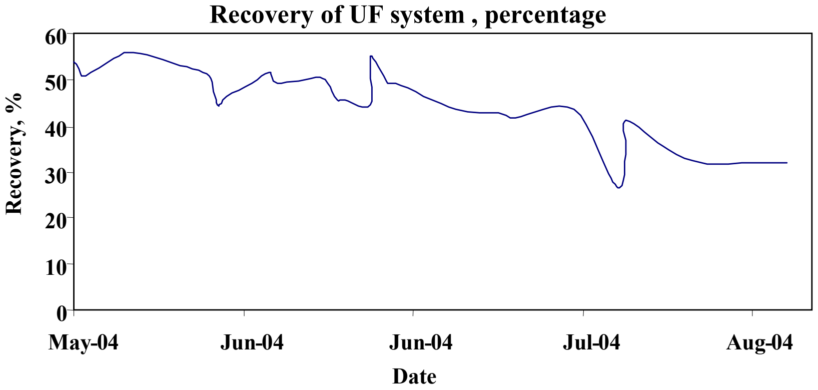


Fig. 5. UF system permeate flow rate subject to operated time. (Common flush — flush with NaOH; special flush with NaOH, then with HCl and H_2O_2.)

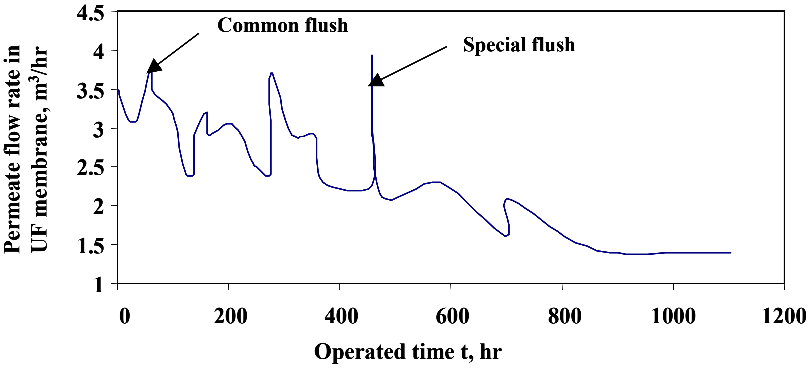


Fig. 6. The UF membrane recovery in Arad, summer 2004.

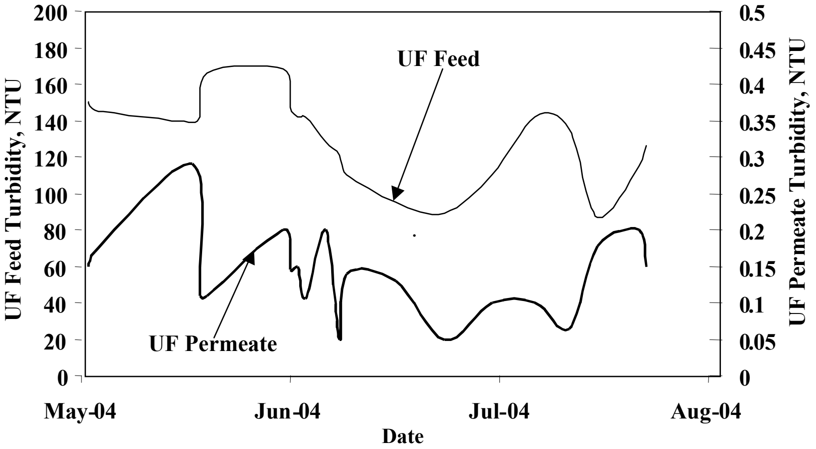


Fig. 7. Turbidity of feed and permeate of UF membranes in Arad, summer 2004.

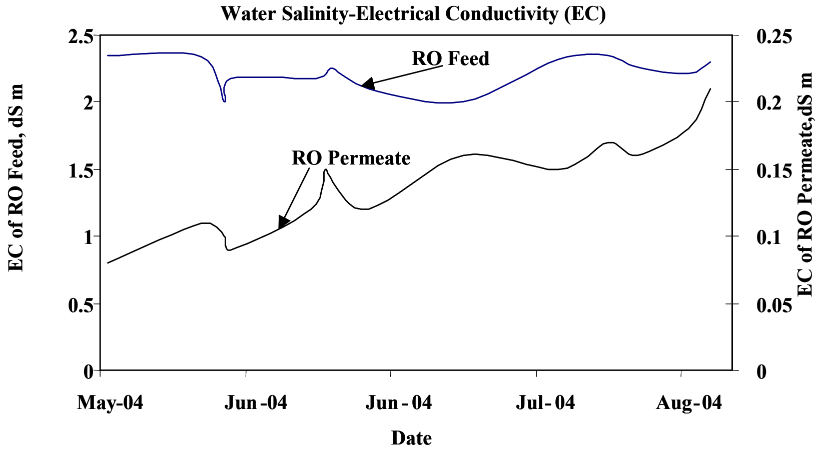


Fig. 8. Effluent salinity at the entrance and outlet of the RO phase, Arad summer 2004.

removal. Membrane flushing with sodium hydroxide solution is used to prevent bacterial re-growth, fouling phenomena and reduction in membrane flow rate.

The pilot system provided effluent for corn irrigation by an onsurface drip system. The performance of the hybrid membrane system for treatment of secondary effluent for corn production provided several preliminary conclusions: (i) UF membranes are very effective for removing soluble organic particles including coliform bacteria, (ii) permeate quality exceeds the regulations limits for irrigation, (iii) the RO permeate complies with salinity water quality; (iv) it is imperative for irrigated agriculture fields to raise a variety of products of better quality and with less wastage, and increase the value added to water, and; (v) there is a substantial need to develop and adapt management models for improved operation of agricultural farms along with improved control of the environment. According to these experiments it seems that risk of consuming agricultural products irrigated with reclaimed wastewater is minimized [12–14].

The objectives for the further work include continuous long-term pilot tests for examination of the accumulative effects on the soil and environment during application of effluent of the diverse qualities. Further work will deal with improved insight into the membrane performance for an improved economic assessment for large-scale systems. Part of the work will be associated with management modeling towards optimal operation of the hybrid pilot membrane system [15].

Acknowledgments

The work was supported by the MERC Project (M22-006) supported by USAID on Wastewater Treatment and Reuse in Agricultural Production, The Beracha Foundation, The Stephen and Nancy Grand Water Research Institute, The Technion, Haifa Israel, The Palestinian-Jordanian-Israeli Project (PJIP), on Membrane Technology for Secondary Effluent Polishing: From Raw Sewage to Valuable Waters and Other By-Products, The Levin Family Foundation, [via the Jewish National Foundation (JNF)], Dayton, Ohio, USA.

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