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Desalination technology for optimal renovation of saline groundwater in a natural reservoir

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Abstract

Huge amounts of water are currently diverted down-stream from the Sea of Galilee (Lake Kinneret) to the rift valley, Israel. Part of the non-utilized water is saline (around 2000 mg/l chlorides) originated in the northern section of Lake Kinneret and separated from the bulk high quality water (between 200 mg/l and 250 mg/l chlorides). The flow rate of the saline water is very much affected by the level of the water in the lake that serves as the prime natural storage reservoir for water supply in Israel. The wasted amount of the diverted water can be shared, after adequate treatment, for use in the Rift Valley primarily for agricultural irrigation in the Kingdom of Jordan and the State of Israel for their mutual benefits. A management model was defined and tested towards optimal treatment of the saline water. The two major purposes of the model are (i) to delineate a methodology for economic assessment towards optimal use of membrane technology, and; (ii) to provide guidelines for optimal membrane selection in regards to the pretreatment stage. The linear model defined takes into account the cost of the feed saline water, the desalination stage, based on the reverse osmosis (RO) process, and the brine disposal. Technological constraints refer primarily to the longevity of the membrane, their performance and time dependent changes in flow-rates. Eight different saline water qualities, subject to various pretreatment options, for a tentative desalination plant for a capacity of 30,500 m^3/d close to Lake Kinneret were examined. The fmal'treated unit water cost, which is expressed by the objective function, includes investment, operation and maintenance, water intake, pretreatment, RO components, post treatment, brine removal and incentive for permeate low salinity. Analyzing various scenarios allows optimal selection of the membrane and the related pretreatment method. The cost range of the desalinated water according to the model is between $0.39/$m^3$ and $0.45/$m^3$.

Keywords: Desalination; Membranes; Optimization; Renovation; Reverse osmosis; Saline water

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1. Introduction

Spiraling demand for high quality waters, coupled with natural shortage mainly due to intensive exploitation of groundwater from aquifers and continuous deterioration of supplies, primarily in arid zones, has stimulated the search for alternative sources and water treatment methods. The gap between supply and demand can be primarily closed by implementing two major strategic directions: (i) to import water from external sources; (ii) to further develop non-conventional water sources and under specific conditions to treat the water to acceptable levels. Potential additional water treatment includes the use of membrane technology, primarily for saline and seawater however, also for treated wastewater. Desalination of brackish and seawater sounds since these waters are stable sources. However, the brine disposal is still of high concern due to potential environmental problems.

Desalination received vast attention, during past decade as a means to alleviate water shortage problems. The desalination technology based on the use of membranes mainly in reverse osmosis (RO) processes for treatment of brackish and seawater for domestic consumption [1]. However, implementing RO processes may raise issues concerning the level of raw water, membrane selection, RO stack configuration, post treatment and brine disposal. Selection of the RO membranes is therefore an integrative issue, which requires the involvement of various scientific and design disciplines [2].

2. Reverse osmosis system modeling

Management models provide effective means of rapidly testing and evaluating different scenarios for a given set of conditions [3]. Well-defined models allow examination of many hypothetical situations, which will yield perceptive insight [4]. Although model frequently deviate from real life situations; they provide preferences of optimal system selection and potential directions of processes [5,6]. These directions can be consequently interpreted by the decision-makers in project evaluation and implementation [7].

The integrative approach is based on trying to encompass all relevant aspects of the RO plant under consideration. The various aspects of desalination plant can be viewed at the following levels:

a) The local level of the isolated process. Economic, chemical and membrane performance should be taken into account in the analysis. For example, optimal selection of membrane flux and operating pressure [8] or flux decline due to gypsum precipitation on RO membranes [9].
b) At the regional level the complete picture of the water source utilization, including RO issues, has to be considered. At this level, RO membrane performance is only one link in a multi-component system. Other phases to be considered include raw water quality [10], environmental considerations for the disposal of concentrates [11] and regulation issues [12].

3. The objective function

Development of the management model is based on defining an objective function (normally an expression of the water cost) to be optimized, subject to a series of technological, environmental, chemical and operational constraints. The components of the objective function include the selection of the pretreatment method and membrane type, pretreatment costs and RO costs necessary to attain a definite permeate quality, transportation brine disposal and permeate storage costs, cost (or profit) for operation and maintenance expenses, design and

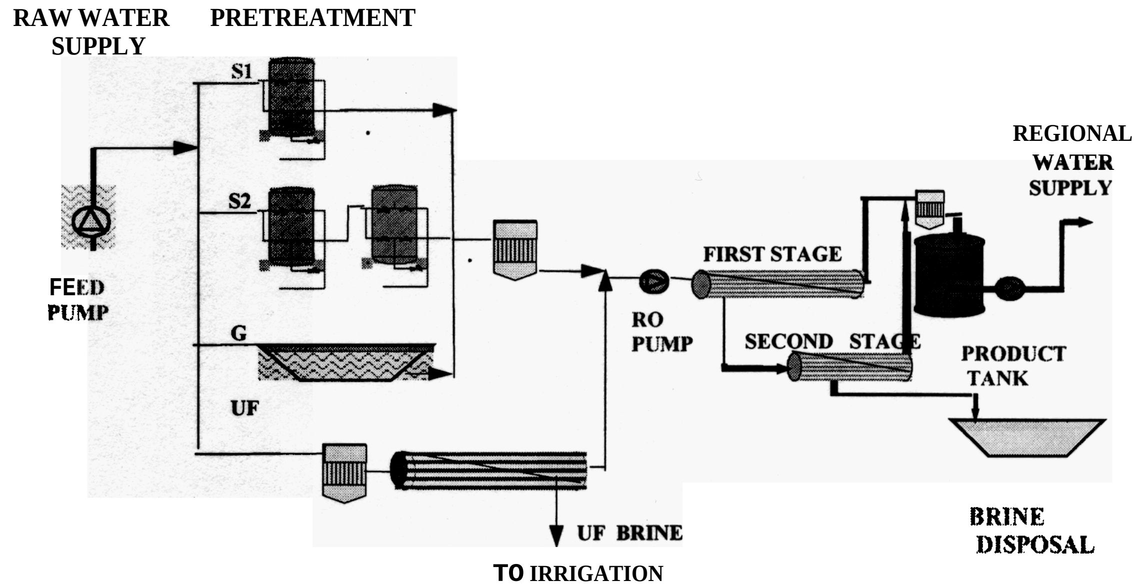

Fig. 1. Alternatives for brackish water pretreatment and plant layout for desalination.

contingency expenses. The primary benefit component in the objective function to be considered in selection of the membrane type is permeate low salinity and dilution options with low quality potable water. The objective (cost) function is given by the following general expression:

$$\begin{bmatrix}\text{Treatment}\\ \text{cost}\end{bmatrix} = \begin{bmatrix}\text{Raw}\\ \text{water}\\ \text{cost}\end{bmatrix} + \begin{bmatrix}\text{Cost of}\\ \text{pretreatment}\\ \text{system}\end{bmatrix} + \begin{bmatrix}\text{Cost}\\ \text{of}\\ \text{RO unit}\end{bmatrix} + \begin{bmatrix}\text{O \& M}\\ \text{pretreatment}\\ \text{expenses}\end{bmatrix} + \begin{bmatrix}\text{O \& M}\\ \text{RO}\\ \text{expenses}\end{bmatrix} + \begin{bmatrix}\text{Cost}\\ \text{of brine}\\ \text{disposal}\end{bmatrix} - \begin{bmatrix}\text{Return}\\ \text{for}\\ \text{permeate}\end{bmatrix} \qquad (1)$$

Where:

a) Selection of pretreatment method and membrane type takes into account the designed plant capacity, permeate salinity and experimental results in pilot plants. Commonly, selection of the treatment method and successively the membrane type is associated with defining of a set of Boolean variable, receiving 0,1 values only.

b) RO performance is based on field experience and criteria provided by related softwares [13,14].

c) Raw water cost is a function of chloride concentration and the expenses for a specific site is given by a constant parameter.

d) All annual expenses (C_{an}) for any capital investments (feed, pretreatment, RO, post treatment and brine removal) are assessed by using actual investment (C_{ac}) and the Capital Recovery Factor (CRF):

$$C_{an} = C_{ac}\,\mathrm{CRF} = C_{ac}\,\{i/[1-(1+i)^{-n}]\} \qquad (2)$$

where i is the interest rate (fractional value) and n is the life span, years.

e) All maintenance expenses M_{an} (cent/m^3) can be assessed on the basis of the capital investments (C_r) and maintenance rate M_r per year as a variable:

$$M_{an} = C_{ac}\ \alpha_m\ M_r \qquad (3)$$

Where α_m is a conversion factor to cent/m^3 and M_r is the maintenance rate per year (usually up to 5%).

f) Operational expenses that include energy, labor and chemicals. The expenses for energy include the pumping requirements for feed, RO section and permeate. The general expression for this component (C_e) is given by:

$$C_e = \alpha_{hp}\ C_e\ (Q\ H\ T_y)/(2.7\ \eta) \qquad (4)$$

Where α_{hp} is a conversion factor to kWh (α_{hp} = 0.746), Q is the flow in pumps (m^3/h), H is the pressure head required at the pump (the m decision variable), T_y is the operating hours per year and η is the pump efficiency (%).

g) A premium is credited for the permeate quality: for every 100 mg/l TDS below the concentration of 400 mg/l, a return of 2 cent/m^3 is paid.

4. The constraints

The constraints define a feasible domain in the decision space. The constraints refer to the capacity of the system (both storage and flow rates), energy losses, regime of applied reagents and aeration requirements in order to remove the concentrate. The constraints refer to restrictions placed on the pretreatment control, membrane performance and brine removal risks. All constraints are expressed in by linear functions.

The objective function and the constraints are given by a set of linear equations. Consequently, it allows using a commercially available PC software to obtain an optimal value for the objective function and the decision variables [15].

Table 1

Raw surface water characteristics from the Lake Kinneret Basin (Israel) treated by the RO plant

Quality parameter	Value
Ca, mg/l	345
Mg, mg/l	100
Na, mg/l	931
K, mg/l	36
NH_4, mg/l	0.2
Sr, mg/l	11
CO_3, mg/l	0.2
HCO_3, mg/l	293
SO_4, mg/l	182
Cl, mg/l	2,064
F, mg/l	0.5
NO_3, mg/l	17
SiO_2, mg/l	16
Operation temperature ,°C	22
pH	7.1
Permeate flow (m^3/d)*	30500
Product recovery (%)*	80
Permeate salinity (expressed in TDS)*	<400

*RO treatment plant characteristics

5. A case study

The model is illustrated by a simple, however, not obvious, case study of an RO plant located in the basin of Lake Kinneret (Sea of Galilee), Israel. The raw inlet surface water characteristics and the RO operational design criteria are given in Table 1. The life span of the system components are: 10 years for water pretreatment and control segment; 15 years for pumps, electrical equipment and service roads; 25 years for the reservoir; 30 years for pipes and 40 years for buildings. Operation and maintenance (O&M) expenses are assessed as percentages of the capital investment (e.g. 1% of the investment for pipes, roads, buildings, reservoirs, and electrical engines; 2% of the investment for accessories and pumps; 5% of the investment for water treatment equipment; 6% of the invest-

Table 2
Characteristics of the membranes examined in the model

Membrane type	Flux, $m^3/(m^2\,d)$	Salt rejection, %	pH range	Sensitivity to constituents
High flux	1.6–1	96–99.5	4–10	Oxidizing agents, free chlorine, bacteria
High resistance	1.5–1	96–99	2–12	Oxidizing agents

ment for brine removal). The interest rate is **6.5%** and the energy cost is **0.055 $/kWh. All** the variables are incorporated into simple linear expressions, thus allowing the **use** of linear programming.

Four pretreatment network alternatives for the **RO** feed were examined (Fig. 1): a sand filter and a cartridge filter **(S1);** two sand filters in series and **a cartridge filter (S2);** a gravity filter and a cartridge filter (G); an ultrafiltration unit and a cartridge filter (UF).

The **pretreatment** cost **consists** of civil engineering expenses (infrastructure, construction, soil works) and equipment cost (filters, containers and storage) and can also be found in the literature [16]. Two **types** of membranes were examined: high flux [Hydranautics **8040-ESPA2(ROHF)]** and high resistance [Filmtec **BW30-400-LW (ROHR)]** (Table **2).**

The RO component cost consists of civil engineering (infrastructure; construction) and equipment (stands, pressure vessels, membranes). The data and performance recommendations for the diverse alternatives *are* provided by the membrane manufacturers **([13,14],** Table 3).

6. Results

The management model was examined for the eight different alternative systems (Table **3).** The linear model allowed comparing the alternative proposed systems. The case study included **22** variables, **25** constraints and tested on a PC with an available **software [15].** Minimal desalination cost was obtained for the combination of two sand filters in series and a cartridge filter **(S2)** with high **flux** membranes (Fig. 2, Table **4).**

Table **3**
Characteristics of pretreatment stages and membrane type

Membrane type	Symbol	Filtration	Fine filtration	Membrane flow, m^3/d	RO feed pressure, bar	TDS permeate, ppm	Membrane replacement, y
High flux	S1+ROHF	Sand filter	Cartridge filter	12	14.4	181	3
High flux	S2+ROHF	Two sand filters in series	Cartridge filter	16.5	15.6	118	3.5
High flux	G+ROHF	Gravity filter	Cartridge filter	21	17.3	86	**4**
High flux	UF+ROHF		Cartridge filter + UF	40	26.4	41	6
High resistance	S1+ROHR	Sand filter	Cartridge filter	12	13.4	187	4.5
High resistance	S2+ROHR	Two sand filters in series	Cartridge filter	16.5	17.6	135	5
High resistance	G+ROHR	Gravity filter	Cartridge filter	21	20.1	109	***5.5***
High resistance	UF+ROHR		Cartridge filter + UF	40	31.9	67	8

*Ultrafiltration characteristics: replacement rate ~5 y; discharge ~ 27 m^3/d per element

Table 4
Sample results of the optimization model

Alternative	Raw water cost, cent/m^3	Unit water cost including intake, Pretreatment, RO components, and post treatment, cent/m^3							Cost of brine removal, cent/m^3	Cost of salinity factor, cent/m^3	Total water cost, cent/m^3
		Capital	Maintenance	Labor	Membrane	Energy	Others	Treatment			
S1+ROHF	4.9	10.7	1.6	6.0	5.9	5.7	3.6	33.4	9.1	4.4	43.1
S1+ROHR	4.9	10.8	1.6	6.0	3.9	6.0	3.6	31.9	9.1	-4.3	41.7
S2+ROHF	4.9	10.6	1.7	6.0	3.7	6.0	3.6	31.5	9.1	–5.6	39.9
S2+ROHR	4.9	10.8	1.8	6.0	2.6	6.5	3.6	31.1	9.1	–5.3	39.9
G+ROHF	4.9	11.6	2.1	6.0	2.5	6.5	3.6	32.3	9.1	-6.3	40.0
G+ROHR	4.9	12.0	2.1	6.0	2.5	7.2	3.6	33.3	9.1	–5.8	41.6
UF+ROHF	4.9	10.1	1.2	6.0	2.6	10.9	3.6	34.3	9.1	–7.2	41.1
UF+ROHR	4.9	10.7	1.2	6.0	2.4	12.2	3.6	36.0	9.1	-6.7	43.4

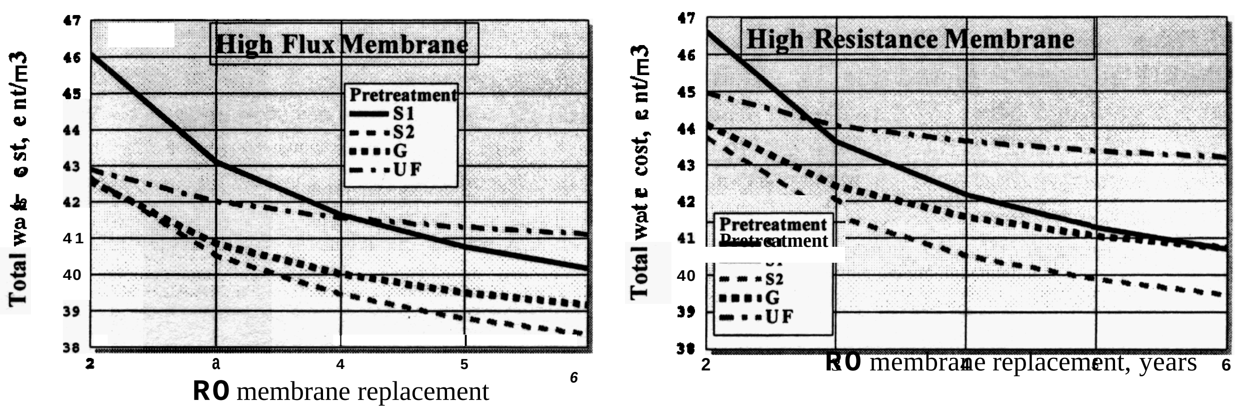

Fig. 2. Dependence of cost treatment on pretreatment, membrane type and membrane replacement frequency.

7. Sensitivity analysis

Adequate examination of linear models requires abundant data. Commonly it is expensive to obtain and utilize accurate data for management modeling. Consequently, the limited available field data and complementary information, which is published in the literature, was used. Testing a broad range of possibilities and conducting complementary sensitivity analyses can therefore confirm the validity of the linear model results. The sensitivity analysis provides an additional insight into the most effectual factors influencing the treatment process.

The sensitivity analysis of the tested case study (two sand filters in series and a cartridge filter (S2) with high flux membranes) is given in Table 5. The results indicate that the interest rate and electric power cost are the most cost-effective factors. According to the results a high resistance membrane will be selected instead of a high flux one subject to membrane replacement

Table 5
Sensitivity test of the case study solved by the linear programming model [two sand filters in series and a cartridge filter (S2) with high flux membranes (HF)]

Variables	Objective function, cent/m^3		
	Computed value	Upper value	Lower value
Interest rate, %	6.5	7.5	5.5
Permeate return, cent/m^3	39.9	40.5	39.3
Labor (number of employees)	15	24	12
Permeate return, cent/m^3	39.9	43.5	38.7
Membrane replacement, year	3.5	5	3
Permeate return, cent/m^3	39.9	38.8	40.5
Energy, $/kWh	0.055	0.06	—*
Permeate return, cent/m^3	39.9	40.5	—

*Irrelevant

frequency and permeate salinity (Fig. 2). Consequently, the decision referring to the selection of high resistance membrane depends on the following:

a) If according to the results, a high flux membrane has to be replaced after less than 3.5 years than it is recommended to substitute it with a high resistance membrane (Table 3).
b) In case the salinity of the permeate obtained in the RO process of a high flux membrane is above 188 ppm TDS than it is reasonable to use high resistance membranes (Table 3).

8. Conclusions

A management model for optimal membrane selection for brackish water desalination was defined and tested. Although available information is frequently scarce and the mathematical expressions are complex, modeling is an essential and effective tool for estimating optimal operation of RO processes. The linear model can be further used to describe integrative desalination treatment systems, namely the intake, pretreatment, RO stage, post-treatment and brine removal.

An RO treatment system design based on a combination of two sand filters in series and high flux membranes is preferable due to minimal cost. Analyzing the results verifies the sensitivity of the solution to the interest rate and cost for the required energy. Effective use of high flux membranes for brackish water desali-nation soundly depends on membrane replace-ment frequency and permeates salinity. The developed model allows further modification by changing the parameters and analyzing a broad pattern of possibilities.

9. Symbols

C_{an} — All annual expenses
C_{ac} — Actual investment
C_e — Operation expenses
CRF — Capital recovery factor
n — Life span, years.
M_r — Maintenance rate per year (usually up to 5%)
Q — Flow in pumps, m^3/h
H — Pressure head required at the pump, m (the decision variable)
T_y — Operating hours per year.

Greek

α_m — Conversion factor to cent/m^3
α_{hp} — Conversion factor to kWh (α_{hp} = 0.746)
η — Pump efficiency, %

Subscripts and superscripts

i — Interest rate

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