

Assessing the linkage between feed water quality and reverse osmosis membrane performance

Amos Bick^a, Gideon Oron^{ab*c}

^a*Department of Industrial Engineering and Management, Ben-Gurion University of The Negev, Beer Sheva 84105, Israel*

^b*Institute for Desert Research, Ben-Gurion University of The Negev, Kiryat Sde Boker 84900, Israel*

Tel. +972 (7) 659-6900; Fax +972 (7) 659-6909; email: gidi@bgumail.bgu.ac.il

^c*Water Research Institute, The Technion, Haifa 32000, Israel*

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Abstract

The scarcity of fresh water in most of the countries in the Mediterranean Basin makes desalinated seawater a valuable alternative water source. It is therefore imperative to develop and adapt reverse osmosis (RO) methods to minimize water production expenses. Management modeling allows identifying preferable directions of implementation. Usually, desalination depends on a combination of a series of controlling parameters. These include feed water quality; required resulting qualities; and operational conditions determined by the membrane characteristics, flux and operating pressure head. Frequently it is difficult to select the best membrane for the RO process due to the complexity of the processes and the abundance of information that is provided by the membrane manufacturers. Taking available data (from RO membrane manufacturer catalogues) enables defining clusters of parameters with similar properties for improved control of the desalination process. According to the analysis, it was shown that there is a similar parameterization between the Silt Density Index (SDI) and the membrane flow rate. Other clusters were found as well. This analysis can be further developed into larger clusters leading to distinguishing two major facets: (1) the permeate and (2) RO membrane rejection; each includes several parameters. This showed that corresponding managing tools can simplify the membrane selection process and ultimately diminish production expenses.

Keywords: Clusters; Desalination; Management modeling; Membrane performance; Reverse osmosis; Silt Density Index; Operational parameters

*Corresponding author.

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1. Introduction

Concern about environmental pollution and health risks when using low-quality waters, as well as water shortages due to intensive exploitation of groundwater from aquifers and others sources, have enhanced the search for alternative non-conventional water sources. Potential additional water sources include high-quality run-off water and membrane treatment of brackish, seawater and wastewater [1]. Membrane treatment [microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO)] have received great attention during the past decade as a means to alleviate water shortage problems and find better environmental solutions.

RO is a widely known technology for the production of potable water from brackish or seawater. There are two common configurations of RO membranes: spiral wound (SW) and hollow fibers (HF). Currently SW membranes are used in many RO plants. Their success is due to the development of a variety of polymer materials, high conductivity, low solute flow and high resistance to fouling processes. The configuration of SW elements and RO technology is described in the literature [2] and can be classified by the following characteristics: high flux at low pressure, high and stable salt rejection, reduced compaction, chlorine resistance, resistance to hydrolysis by acids and alkalis, and resistance to water turbidity and fouling. The common index for evaluating the fouling capacity of water is the Silt Density Index (SDI) [3].

2. The solution–diffusion model

The rate of permeate flow through a semi-permeable membrane is defined by the solution–diffusion model. According to this model [4–6], based on pure diffusion, water flux through the membrane is given by:

$$Q_w = \left(P_f - \frac{\Delta P_{fb}}{2} - P_p - \frac{Pos_f + Pos_b}{2} \right) K_w \left(\frac{S}{d} \right) \quad (1)$$

where Q_w is the permeate flow rate (g/h), P_f is the feed pressure (atm), ΔP_{fb} is the pressure drop across the membrane (atm), P_p is the permeate pressure (atm), Pos_f is the osmotic pressure of the feed (atm), Pos_b is the osmotic pressure of the brine (atm), K_w is the membrane permeability coefficient for the permeate [g/(decimeter-h)], S is the membrane surface area (decimeter²) and d is the membrane thickness (decimeter).

The osmotic pressure is given by

$$Pos = 0.081(T+273) \sum m_k \quad (2)$$

where Pos is the osmotic pressure (atm), T is the temperature (°C) and $\sum m_k$ is the sum of molar concentrations of all k constituents in the solution (molar).

An approximation of the osmotic pressure can be made by assuming that 1000 ppm of total dissolved solids (TDS) equals about 11 psi (0.76 bar) of the osmotic pressure [7]. Accordingly, the rate of solute flow is obtained, and the membrane can be defined by Eq (3):

$$Q_s = K_s(\Delta C) \left(\frac{S}{d} \right) \quad (3)$$

where Q_s is the solute rate flow (g/h), ΔC is the salt concentration difference across the membrane (mol) and K_s is the membrane permeability coefficient for salt [g/(decimeter-h-mol)].

The following can be concluded from Eqs. (1) and (3):

- Each membrane is defined by two equations: permeate flow and solute flow
- the rate of water flow through a membrane is proportional to the net pressure difference across the membrane.

The solution–diffusion model is immature in several points: (1) The equations do not relate to water quality, membrane performance and fouling processes [8], and (2) there is limited explanation for the new membranes that were developed over the last few years and have an improved flux at low operating pressure [9].

The purpose of the paper is to distinguish and validate the concept applied for RO membranes and consequently to depict relationships among clusters of similar properties, in particular those that relate to water quality and membrane performance. Hence, the following objectives are expected to be achieved in the framework of this paper: (1) development of a conceptual approach enabling to present raw water quality interactions with membrane treatment process, (2) discrimination between essential transport and salt rejection processes, and (3) comparison of the results of the proposed model with those of the solution–diffusion model.

3. Management modeling and model formulation by facet analysis

Management models provide effective means for rapidly testing and evaluating different scenarios for a given set of conditions [10]. Well-defined models allow the examination of many hypothetical situations which can yield perceptive insights [11]. Although models frequently deviate from real-life situations, they provide preferences of optimal system selection and potential directions of processing [12,13]. These directions can be consequently interpreted by the decision-makers for project evaluation and implementation [14].

Facet analysis is a research approach which has been found to be effective in the depiction and analysis of complex systems where a large number of mutual interacting variables are involved [15,16]. This powerful methodology helps to clarify membrane system performance.

It is assumed that the performance of an RO membrane system can be described by a production function Z . This function can be divided into two major facets: (1) the permeate and (2) RO membrane rejection; where each of them includes several parameters. Usually, the final results of the production function allow the selection of the set of conditions leading to maximum benefits.

$$Z = F\langle C_s \rangle + Q \cdot b_1 \langle C_s \rangle + Q \cdot (C_p - C_{p0}) \cdot b_2 \langle C_s \rangle \quad (4)$$

where Z is the production function (\$/y), Q is the permeate production rate (m^3/y), C_s is the feed salinity (dS/m), b_1 is the production expenses as function of feed quality (\$/m³), C_p is the permeate salinity (dS/m), C_{p0} is the reference permeate salinity (dS/m) and b_2 are the production expenses as a function of feed salinity [\$/ (dS/m)].

Matrix “A” is considered:

$$A = a_{il}, \quad i = 1, \dots, N; \quad l = 1, \dots, P \quad (5)$$

where i is a membrane index ($N=62$) and l denotes a variable index ($P=12$). The data include the following variables: flow, salt rejection, feed salinity, feed pressure, test recovery, maximal feed pressure, maximal SDI, maximal temperature, maximal chlorine tolerance, pH range and maximum feed flow.

The similarity coefficient is defined by Eq. (6) [17]:

$$\mu_{lm} = \frac{\sum_{i=1}^N \sum_{j=1}^N (a_{il} - a_{jl})(a_{im} - a_{jm})}{\sum_{i=1}^N \sum_{j=1}^N |a_{il} - a_{jl}| |a_{im} - a_{jm}|} \quad i \neq j, \quad l \neq m \quad (6)$$

where μ_{lm} is the similarity coefficient of the l^{th} and m^{th} variables and a_{il} is the value of the variable.

Similar structured maps can be characterized as follows: given a set of similarity coefficients, μ_{lm} for a set of objects (membranes), $i, j = 1, \dots, N$, mapping into a two-dimensional space is defined:

$$\mu_{lm} = f[d_{lm}(X)] \quad \text{for all } \mu_{lm} \quad (7)$$

where $d_{lm}(X)$ is an Euclidean distance and f is a function (typically a weak descending monotone function or a linear function). If Eq. (7) does not hold, an optimal solution is searched for that minimizes the loss function. The loss function expresses stress [18] and is defined by:

$$St = \sqrt{\frac{\sum_{l < m} [f(\mu_{lm}) - d_{lm}(X)]^2}{\sum_{l < m} d_{lm}^2}} \quad (8)$$

where St is the stress function.

Solving the mapping problem thus involves finding a layout of points that defines the distances, d_{lm} , and finding a function f of the distances for similar data that minimize the stress. It is a composite optimization problem; however, there are algorithms that almost definitely find the best solution [19,20].

4. Empirical results

Data concerning 8" SW membranes obtained from various membrane producers (Desal, Dupont, Filmtec, Hydranautics, Osmonics, Toray, and UOP) were used. The data include nor-normalized data (flow, salt rejection, feed salinity, feed pressure, test recovery) and operating conditions (maximal feed pressure, maximal SDI, maximal temperature, maximal chlorine tolerance, pH range and maximal feed flow).

Table 1
Similarity coefficient matrix for 12 membrane performance variables [Eq. (6)]

Variable	Flow											
Flow, m ³ /d	—	Salt rejection										
Salt rejection, %	-0.69	—	Feed salinity									
Feed salinity, ppm NaCl	-0.95	0.95	—	Feed pressure								
Feed pressure, psi	-0.80	0.85	1.00	—	Recovery							
Recovery, %	0.77	-0.71	-0.97	-0.95	—	Max. pressure						
Max. pressure, psi	-0.78	0.67	0.99	0.96	-0.80	—	Max. SDI					
Max. SDI	0.66	-0.88	-0.68	-0.71	0.26	-0.62	—	Max. temp.				
Max. temp., °C	-0.46	0.63	0.19	0.02	-0.28	0.48	0.30	—	Max Cl tolerance			
Max Cl tolerance, ppm	0.50	-0.24	-0.87	-0.35	0.02	-0.35	0.53	-0.15	—	pH min.		
Min. pH	0.55	-0.70	-0.42	-0.37	0.75	-0.26	0.85	-0.35	0.11	—	pH max.	
Max. pH	-0.18	0.37	0.49	-0.05	0.06	0.32	0.67	0.90	-0.73	-0.03	—	Max feed flow
Max feed flow, m ³ /h	0.51	0.09	-0.74	-0.21	-0.19	-0.49	0.12	0.39	0.76	-0.15	-0.45	—

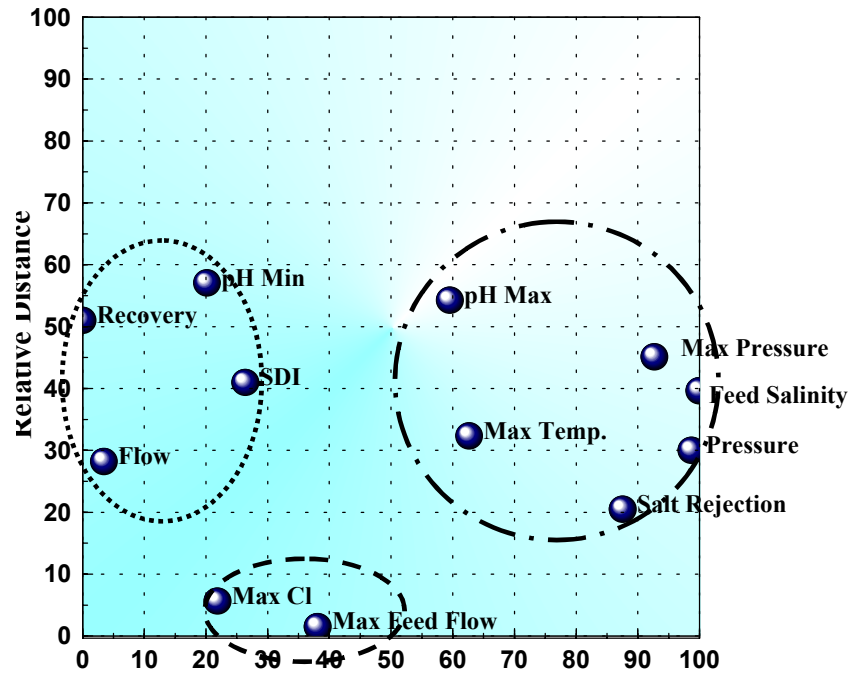


Fig. 1. Mapping of 8" spiral-wound RO membrane performance properties.

Table 2
Empirical location of 12 membrane performance variables [Eq. (7)]

Variable	Distance from centroid	Coordinate X	Coordinate Y
Flow, m ³ /d	47.8	3.5	28.2
Salt rejection, %	38.9	87.6	20.5
Feed salinity, ppm NaCl	19.4	100	39.6
Feed pressure, psi	47.9	98.7	30.0
Recovery, %	53.8	0	51.0
Max. pressure, psi	43.3	92.7	45.1
Max. SDI	25.6	26.4	40.9
Max. temp., °C	11.8	62.7	32.3
Max. Cl tolerance, ppm	40.4	21.9	5.6
Min. pH	38.6	20.2	57.0
Max. pH	22.2	59.5	54.2
Max feed flow, m ³ /h	36.1	38.1	0.8

Table 1 presents the matrix of the similarity coefficients for the observed variables. It is worth noting that some of the correlation coefficients

among the 12 variables are negative. The negative signs correspond to variables of different clusters.

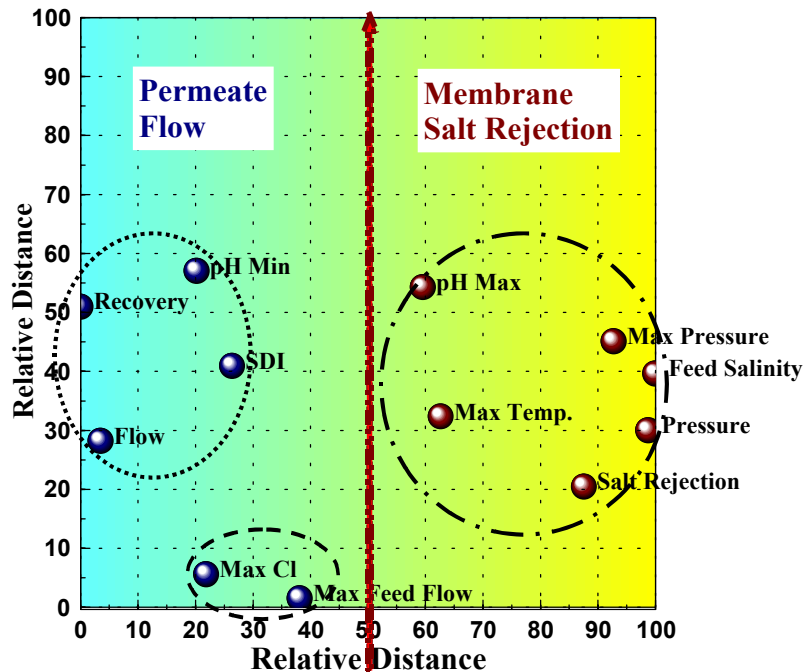


Fig. 2. Partitioning mapping of product flow and product salinity variables.

The mapping was carried out subject to the following conditions: the greater the correlation between two variables, the closer their points on the map. According to the result, the SDI is the closest variable to the membrane flow and high temperature is the closest variable to the salt passage (and influences permeate salinity). The main factor, which influences membrane flow, is the fouling tendency of the raw water.

The results of a two-dimensional facet analysis for the 12 variables are shown in Table 2 and Fig. 1. A straight line (Fig. 2) can divide the variables: one region includes the variables of product flux and the second one includes variables of salt rejection and product salinity.

The temperature affects the diffusion rate of water and dissolved ions across a membrane. There is a water flux increase of about 3% for every additional centigrade. Above 25°C, increasing feed water temperature will result in an increase in solute flow. Since RO units are

designed to operate at constant product flow rate, an increase in water temperature is compensated by a decrease in feed pressure with subsequently higher permeate salinity [21].

5. Conclusions

A management model was developed, defining clusters of similar membrane operational regions. The model provides a first approximation of membrane behavior by means of facet analysis. Membrane performance is discussed in terms of measured variables, permeate flow and salt passage. The analysis provides the rationale for an hypothesis concerning the interrelationships among components of water quality and membrane operational characteristics. The model predicts that permeate flow is mainly characterized by SDI while salt passage is influenced by high temperatures.

6. Symbols

A	— A matrix
a_{il}	— Value of variable
b_1	— Production expenses as function of feed quality, \$/m ³
b_2	— Production expenses as function of feed salinity, \$/dS/m
C_p	— Permeate salinity, dS/m
C_{p0}	— Reference permeate salinity, dS/m
C_s	— Feed salinity, dS/m
d	— Membrane thickness, decimeter
$d_{lm}(X)$	— Distance (Euclidean distance)
f	— Model function (typically a weak descending monotone function or a linear function)
K_s	— Membrane permeability coefficient for salt, g/(decimeter-h-mol)
K_w	— Membrane permeability coefficient for the permeate, g/(decimeter-h)
m_k	— Sum of molar concentration of all k constituents in the solution, molar
N	— Total number of components (membranes)
Q_w	— Permeate flow rate, g/h
P	— Number of variables
P_f	— Feed pressure, atm
P_p	— Permeate pressure, atm
Pos	— Osmotic pressure, atm
Pos_b	— Osmotic pressure of the brine, atm
Pos_f	— Osmotic pressure of the feed, atm
Q_s	— Solute rate flow, g/h
Q_w	— Permeate production, m ³ /y
S	— Membrane surface area, decimeter ²
St	— Stress function
T	— Temperature, °C
Z	— Production function, \$/y

Greek

ΔC	— Salt concentration difference across the membrane, mol
ΔP_{fb}	— Pressure drop across membrane, atm

μ_{lm}	— Similarity coefficient of variables l and m
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Indices

i, j	— Index (membrane)
k	— Constituents in the solution, molar
l, m	— Variables

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