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Case Study of Evaluation RO Desalination Systems for Potable Water in Safwan, Iraq

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Abstract

Iraq faces water scarcity due to a shortage of surface water resources. People in Safwan (Basrah, Iraq) and its environs use brackish groundwater as alternative resource. To improve water quality, small reverse osmosis (RO) plants have been established. The water selling price is (1.3 $/m^3$)* which does not cover the product cost which is (2.4 $/m^3$)*. Data were collected from eight plants, and a techno-economic assessment was conducted to explore the ideal cost. The known effective factored considered in this case, recovery ratio, temperature and total dissolved solids (TDS). From the other side, membrane replacement and energy cost were significantly effect, when their portions of the total production cost were 30.98%* and 48.38%* respectively as shown in Figure 10. In addition, software analysis was used to predict the scaling potential in raw water samples. Its results showed a high inorganic fouling (scaling) potential. Scaling has a permanent influence on operations and maintenance costs. These identified major cost influencers will be incorporated into the experimental design of the next phase of this ongoing research programme.

Keywords

Reverse Osmosis, Recovery Ratio, Total Dissolved Solids, Energy Consumption, Scaling

1. Introduction

Many countries, at present, are suffering from potable water scarcity for various reasons. One of the those is Iraq whereas the surface water scarcity is the main

* Note: the numbers are taken of plant no. 1.

problem in its middle and south areas. As a result, some governorates (provinces) have initiated use of alternative resources, such as brackish water. Safwan (Basrah Province) totally depends on brackish groundwater as its main water resource. Small plants of RO desalination system were the only recourse for this area.

Reverse osmosis (RO), for desalination of seawater and brackish water, might be considered the original, as well as the most fundamental of membrane separation techniques. Because the process is most effective and economic among all desalination processes available (Al-Karaghouli & Kazmerski, 2012; Saria Atab, Samallbone, & Roskilly, 2016; Qiu and Davies, 2012), its applications have grown rapidly (Barbosa-Canovas, 2012; Wang, Hung, & Shammas, 2007). Recently, studies have applied techno-economic evaluations to RO, to optimise performance while trying to reduce water costs. However, the studies have mostly involved surface water (Al-Karaghouli & Kazmerski, 2012; Saria Atab, Samallbone, & Roskilly, 2016; El-Emam & Dincer, 2013; Romero-Ternero, Garacia-Rodriguez, & Gomez-Camacho, 2004). Many of these studies adopted thermodynamic methods integrated with exergy analysis (Qureshi & Zubair, 2015; Qureshi & Zubair, 2016; Saria Atab, Samallbone, & Roskilly, 2016; El-Emam & Dincer, 2013). Unfortunately, these techniques depend on seawater properties, like enthalpy and entropy (Millero, 2010). (El-Dessoudy & Ettouney 2002) their book chapter seven explain the RO system in details, such as RO characteristics, Ro membrane types, RO model and system variables, and designing data, while chapter eight mentions RO feed treatment, biofouling and membrane cleaning, and finally chapter ten the economic analysis of desalination process. It is considered as the main reference of the fundamental information of RO in this work as well the economic analysis and water cost calculation. (Atikol & Aybar, 2005) used the amortisation factor to assess water cost from an established RO plant, and compared the major components for a similarly constructed and operated plant. Amortisation factor has been considered in this study with various interest values (Helal, Al-Malek, & Al-Katheeri, 2007) evaluated and compared economically three different types of RO small capacity plants: diesel solar assisted, fully diesel driven, and fully solar driven to discover the ideal alternative among them. (El-Emam & Dincer, 2013) defined the design parameters depending on mass flow rate, salinity of source water, and molar and mass fractions of salt at each point of the RO system (feed, permeate and reject stream). The work effort was calculated and minimised by applying the first and second law of thermodynamics. The exergy efficiency of a desalination system was defined, whilst the economic analysis was considered in terms of volume flow rate from the seawater source. (Saria Atab, Samallbone, & Roskilly, 2016) developed a model RO system, using Matlab/Simulink Thermlib blocks software tools, with a recovery device used to predict system performance, and support optimisation of permeable quality and flow rate. (Qureshi & Zubair, 2015) considered seven different RO desalination system configurations, six with various energy recovery devices, and one without, to compare the relative performance. A model was developed by applying the first and second laws of thermodynamics, and, as for the previous study, exergy efficiency was used to evaluate the systems' performances. The previous studies used to extract designing data to calculate the water product cost to select the suitable values for this study and to evaluate the missed data reasonably. The interest rate value, membrane life time, operation and maintenance cost, membrane replacement factor, levelized cost and plant life time.

(Romero-Ternero, Garacia-Rodriguez, & Gomez-Camacho, 2004) made an extensive economic study of a Santa Cruz desalination plant, by considering the effect of irreversibility and fixed costs on the exergoeconomic cost. Thermodynamic fundamentals, the economic setting, investment costs, operation and maintenance (O & M) costs, fixed costs, exergoeconomic costs of the flow, and skid equipment costs were used for the economic evaluation of the plant. To realize the percentage, share of each item in water product cost the idea of previous study applied. (Wade, 1993) compared three desalination systems in a techno-economic evaluation: multistage flash distillation (MSF), multiple effect distillation (MED) and an RO system. This study gives the right vision for membrane replacement time taking in consideration some realistic reasons such as the membrane manufacturing. Also explain the advantage and disadvantage of each desalination method showing at the end the superiority of RO system.

All these studies emphasised the importance of applying techno-economic analyses to evaluate a project or optimise plant performance. The significance of operational and performance factors was variable; however, feed water salinity, operational energy, and recovery ratio consistently played major roles in these studies.

Our study was divided into two parts. The objective of the first part (the present work) was to identify the major reasons why the Safwan plants have been unable to cover water production costs. The second part (future work) will be to apply these factors as independent parameters to design experiments using Response Surface Methodology RSM software to optimise plant performance.

In order to understand the operational management of the Safwan RO plants, information was collected, analysed, and interpreted. Sensitivity analyses were carried out by evaluating five factors: temperature, total dissolved solids (TDS), lifetime (project lifespan), interest ratio, recovery ratio, and plant availability. The availability deals with the duration of running time of operation. Due to the unavailability of some information from some plants, such as maintenance costs and pressure data, sensitivity analysis for TDS was conducted for three plants only. ROIFA excel spreadsheet software was used to predict the inorganic fouling potential of raw composite samples. (El-Manharawy & Hafez, 2005) reported fouling loads by estimating the combination of soluble hardness salts and their relative fouling fractions, at a given chloride ion (Cl^-) concentration. The water was classified according to its ionic molar ratio (SO_4/HCO_3). The formation of inorganic fouling was attributed to the hydration of scale-forming species, which did not require that their concentration was in the super saturation zone. ROIFA excel sheet programme has been used by El-Manharawy et al. and shows in this programme the fouling types and chemical materials which are needed for membrane treatment.

2. General Description of RO Plants in Safwan and the Study Area

Water samples were collected from eight private, small capacities (between 60 to 198 m^3/day) RO plants in the Safwan area. All were single stage, conventional configuration RO systems, as shown in Figure 1. Each plant was diesel powered, and had four main process components: a pre-treatment system, a booster pump, a high-pressure pump, and a membrane system.

The solid and organic contents in the feed water were reduced by pre-treatment systems comprising a three-layer, multimedia filter (MMF), with anthracite coal, sand and garnet layers, and a gravel supporting layer on the bottom of the tank. High-pressure pumps pressurised the feed water. The membrane systems consisted of two parts, the pressure vessels, arranged in parallel, and the spiral-wound membrane elements [20.3 cm (8") (d) × 101.6 cm (40") (l)], inside them.

Safwan is located in southern Iraq, in the Basrah governorate, between latitudes 30˚05'00" - 30˚10'00" and longitudes 47˚40'00" - 47˚47'00", and has an area of 8872 km^2. It has been suffering from potable water shortages for an extended period. Analysis of samples collected from this area indicated that the water was brackish, with salinity between 7700 and 13,000 mg/l. Some earlier local and regional studies have reported significant variations in groundwater levels and quality (Al-Tememi, 2015). The locations of the private plants, the government plant, and Jabal Sanam are shown in Figure 2. Jabal Sanam is considered the groundwater salinity source for the area.

3. Calculation of Production Water Cost and Sensitivity Analysis

The purpose of our study was to calculate water production cost and identify the major factors which intensively affect it. Some studies applied software to estimate

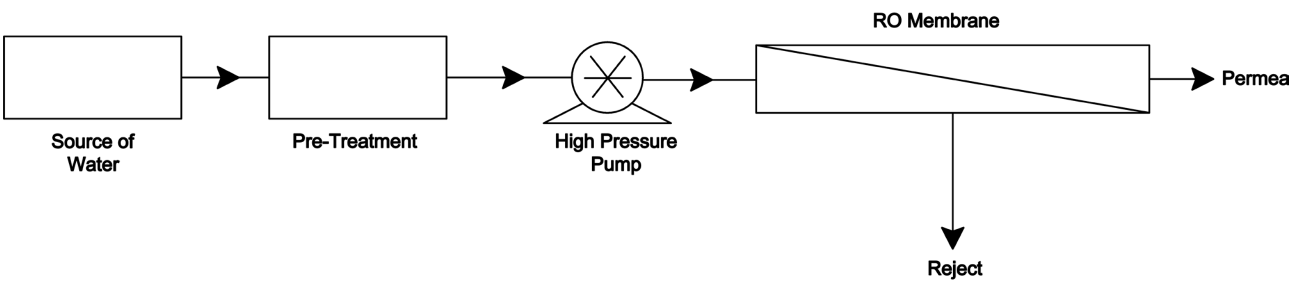

Figure 1. General layout of reverse osmosis system.

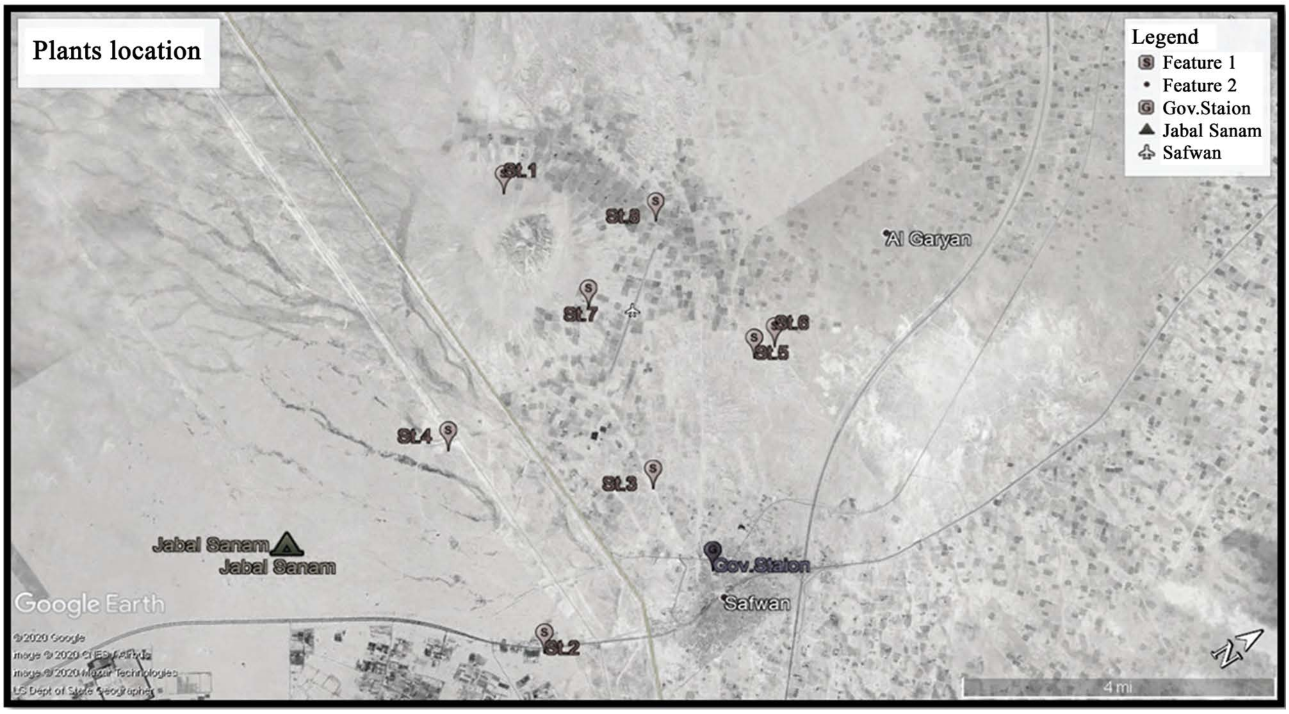

Figure 2. Locations of the Safwan plants; the circular shape is the government plant, rectangular one is Jabal Sanam, and the other marks are locations of the private plants.

water product cost, such as WTCost© and DEEP, which provide cost estimates with different accuracies, and whose application relies on specific conditions (Ghafour, Missimer, & Amy, 2013).

In our study, temperature, pH, and electrical conductivity were measured with each study sample Table 1. For laboratory analyses in Iraq, composite samples were prepared, by mixing equal volumes of feed water, permeate water, and rejected water for each category considered. Physico-chemical and biological analyses were performed using standard methods. Operational, economic, and other general information was collected and is summarised in Table 2 and Table 3.

3.1. Water Cost Calculation

For calculating water production cost, the amortization method was used. The capital cost (CAPEX) included the cost of the RO system, installation cost, generator cost, well drilling cost, and motor and building costs. The major operational and maintenance costs (O & M costs) included membrane replacement, energy, and chemicals costs. Other costs, such as maintenance costs for generators, high-pressure pumps, and other mechanical equipment, such as motors and booster pumps, were taken as a percentage of CAPEX (El-Emam & Dincer, 2013; Romero-Ternero et al., 2004). Table 4 shows the parameters included in water cost calculations.

3.1.1. Amortization Factor

The amortization factor was calculated to divide the water cost into equal,

Table 1. Temperature, pH and electrical conductivity values for collected samples.

Plant no.	Stream	Temp. ˚C	PH	EC µS/cm		
	Feed	32	7.78	11,740	Max. EC feed water	17,010
1	Permeate	32	8.111	337		
	Reject	33	7.48	15,500	Min. EC feed water	10,040
	Feed	33	7.86	12,310		
2	Permeate	32	8.28	321		
	Reject	32	7.77	11,430		
	Feed	31	7.51	14,400		
3	Permeate	33	7.6	411		
	Reject	32	7.7	20,700		
	Feed	31.5	7.75	14,210		
4	Permeate	34	7.35	445		
	Reject	33	7.63	23,000		
	Feed	31	7.817	11,390		
5	Permeate	34	6.73	270		
	Reject	32.5	7.76	14,910		
	Feed	32	7.72	10,040		
6	Permeate	34	7.4	163.2		
	Reject	32	7.744	10,975		
	Feed	31	7.63	17,010		
7	Permeate	32	8.25	727		
	Reject	32	7.4	21,000		
	Feed	31	7.4	15,630		
8	Permeate	32	7.3	588		
	Reject	32	7.63	23,100		

Table 2. Economic information of Safwan plants.

Items	Unit	Plant 1	Plant 2	Plant 3*	Plant 4*	Plant 5	Plant 6*	Plant 7	Plant 8
The RO system cost	$	35,000	27,000	35,000	32,000	40,000	28,600	25,400	45,000
RO system installation cost	$	7,000	5,000	7,000	6,500	0	5,000	4,500	0
Generator power	kVA	40	40	40	40	40	40	40	40
Well drill cost with motor cost	$	1300	1300	1300	1300	1300	1300	1300	1300
Building cost (15 × 7) m	$	22,245.8	22,245.8	22,245.8	22,245.8	22,245.8	22,245.8	22,245.8	22,245.8
Fuel consuming by generator	litre/hr	9	7	9	9	9	7	7	9
Daily working hour of plant	hr	10	10	10	22	8	20	22	22
Membrane element cost	$	850	850	850	850	850	850	850	850
Number of elements	No.	16	16	12	12	9	6	6	12
Replacement period in months	Month	12	12	12	5	12	9	6	5
The selling price of water	$\$/m^3$	1.69	1.69	0.64	0.85	1.69	0.85	1.69	1.69

*Plants nearest to the government owned plant.

Table 3. General information about Safwan plants.

Items	Unit	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8
Latitude		30˚15'11.6"	30˚20'75.43"	30˚7'3.81"	30˚6'48.02"	30˚5'41.49"	30˚7'25.6"	30˚15'17.92"	30˚6'35.16"
Longitude		47˚36'0.71"	47˚67'28.95"	47˚42'21.93"	47o44'37.86"	47˚47'27.6"	47o43'58.87"	47˚38'34.36"	47˚42'51.72"
Inlet water temperature	˚C	32	33	31	31.5	31	32	31	30
Treated water temperature	˚C	32	32	33	34	34	34	32	29
Outlet water temperature	˚C	33	32	32	33	32.5	32	32	31
Feed flow rate	m^3/hr	20	30	35	36	33	15	32	67
Permeate flow rate	m^3/hr	8	6	6	9	8	3	8	31
Reject stream flow rate	m^3/hr	12	21	28	27	25	12	24	36

Table 4. Parameters of water cost calculation.

Parameters used for water cost calculations	
Interest rate, *i*% (El-Dessoudy & Ettouney, 2002)	5%
Generator installation cost	10%
O & M cost for generator (Romero-Ternero et al., 2004)	3%
O & M of high-pressure pump (Romero-Ternero et al., 2004)	2%
Other equipment O & M costs (Saria Atab et al., 2016; El-Emam & Dincer, 2013; Romero-Ternero et al., 2004)	2%
Effective discount rates, i_{eff} (Saria Atab et al., 2016; El-Emam & Dincer, 2013)	8%
Nominal escalation rate, r_n (El-Emam & Dincer, 2013)	5%
Diesel cost	750 ID
Building cost	250,000 ID/m^2

smaller amounts, over the lifetime of the project.

$$a = \frac{i(1+i)^n}{(1+i)^n - 1} = 1/\text{year} \tag{1}$$

In (1), i = Interest rate (%), n = Life time of plant (yr.).

After calculating total CAPEX, the summation was multiplied by the amortization factor (Helal, Al-Malek, & Al-Katheeri, 2007; Atikol & Aybar, 2005)

$$A1 = \text{Total capital cost} \times a = \$/\text{year} \tag{2}$$

In (2), $A1$ = Annual cost ($/year)

3.1.2. OPEX

Field information from Safwan, such as fuel costs, membrane replacement and chemicals costs, were used to calculate these costs, as in (3), (4) and (5).

$$Fc = Cf \times AOH \times fc \times 365 \tag{3}$$

In (3), Fc = Fuel annual cost ($/year), AOH = Actual operating hours (day), Cf = fuel cost ($/litre), fc = fuel consumption per hour (litre/hr).

$$Rcm = p \times Cm \times NE \tag{4}$$

In (4), Rcm = Annual membrane replacement cost ($/year), p = Annual period of membrane replacement (month), Cm = Membrane cost ($/element) and N = Number of membrane elements.

$$Chc = Qf \times AOH \times Cch \times 365 \tag{5}$$

In (5), Chc = Annual chemical cost ($), Qf = Feed flow rate (m^3/hr), Cch = Chemical material cost/m^3.

3.1.3. Constant Escalation Levelization Factor

The O & M costs were levelised (El-Emam & Dincer, 2013; Kotub & Zaky Abdelaa, 2016) using a factor which reflected the effect of inflation on the O & M cost (as using CAPEX as the source for percentage calculations would be accurate for only the year of the CAPEX (Romero-Ternero et al., 2004), as shown in (6).

$$CELF = CRF \cdot \frac{K\left(1-k^{n}\right)}{1-k} \tag{6}$$

In (6), n = System lifetime (years.), $CELF$ = Constant escalation levelisation factor, CRF = Capital recovery factor (see (8)),

k = Constant. (derived using (7)).

$$K = \frac{1+r_n}{1+i_{eff}} \tag{7}$$

In (7), r_n = Nominal escalation rate, i_{eff} = Effective discount (difference between the future value and present value) (Kotub & Zaky Abdelaa, 2016), see **Table 4**.

$$CRF = i_{eff} \cdot \frac{\left(1+i_{eff}\right)^{n}}{\left(1+i_{eff}\right)^{n}-1} \tag{8}$$

CRF factor was used to identify the annuities as a series of equal transactions made up by dividing the known present value by the number of years in the economic lifetime (El-Emam & Dincer, 2013).

3.2. Factors Affect Water Cost

Among the factors that could have been responsible for high water costs, we reviewed interest rates, recovery ratio, lifetime (plant lifespan) and availability, temperature, and inorganic loads or TDS.

3.2.1. Interest Rates

To identify the effect of interest rate on water production cost, selected values (0% (no interest rate), 3% (less than the average) and 5% (average)) were considered. Earlier studies had reported interest rates ranging from 3% to 8% (El-Dessoudy & Ettouney, 2002; Al-Karaghouli & Kazmerski, 2012; Saria Atab, Samallbone, & Roskilly, 2016; Helal, Al-Malek, & Al-Katheeri, 2007), however, in the present study, it was decided to adopt the 5% value (El-Dessoudy & Ettouney, 2002) as the levelised cost.

3.2.2. Recovery Ratio and Plant Capacity

Percent recovery is the ratio of permeate flow to feed flow (El-Dessoudy & Ettouney, 2002; Saria Atab, Samallbone, & Roskilly, 2016; Lewabrane, 2012). The applied feed pressure should be greater than the permeate pressure, otherwise the permeate flux will decrease, and perhaps stop, when the salt concentration reaches a value where the osmotic pressure of the concentrate is as high as the applied feed pressure (DOW, FILMTEC TM Membranes, Form No. 609-02003-1004). For the purposes of our study, a hypothetical situation was assumed in which the feed pressure was constant (9).

$$\text{Recovery } \%(Y) = \frac{Q_p}{Q_f} \times 100\% \quad (9)$$

In (9), Q_p = Permeate flow rate (m^3/hr), Q_f = Feed flow rate (m^3/hr).

Several studies have reported recovery ratios varying from 50% - 90% (Qiu & Davies, 2012; Ghafour, Missimer, & Amy, 2013; Qureshi & Zubair, 2015; Shenvi, Isloor, & Ismail, 2015) for single stage, brackish water reverse osmosis (BWRO) plants. However, as our test waters were brackish, our recovery ratio was determined to be ≤75%, taking the increase in concentration factor into consideration (Helal, Al-Malek, & Al-Katheeri, 2007; Wade, 1993).

3.2.3. Effect of Availability on Water Production Cost

Availability, as a variable, is a measure of the proportion of time that the plant is online and functional (Barringer, Barringer, & Associates, Inc. Humble, 1997) Availability was tested against the water costs for the plants, when availability was <80%. Plants no. 4, 6, 8, and 9 were excluded from this test, as their availability was >80%.

3.2.4. The Effect of Lifetime

Studies have reported different RO plant lifetimes, including 20 years (El-Emam & Dincerm, 2013; Romero-Ternero, Garacia-Rodriguez, & Gomez-Camacho, 2004), 25 years (Helal, Al-Malek, & Al-Katheeri, 2007), and 30 years (El-Dessoudy & Ettouney, 2002; Atikol & Aybar, 2005). For our study, RO system lifetime was fixed at 16 years (Saria Atab, Samallbone, & Roskilly, 2016), noting that neither the equipment quality nor the membrane lifetime were particularly good. As the case is here the plants are small and the construction time is short so the life time result will be negligible and not so affected.

3.2.5. Membrane Replacement

Membranes lasted from 6 to 12 months in the Safwan plants. Equations (10) and (11) were used to compare their capital cost with the actual membrane replacement value, to evaluate the membrane performance.

$$Rm = 10\% \times Cm \quad (10)$$

In (10), Rm = Membrane replacement cost and, Cm = Membrane capital cost. Or, using investment cost instead of capital cost, we apply (11).

$$Rm = 8\% \times TCC \tag{11}$$

In (11), TCI = Total investment cost, and TCC = Total capital cost.

3.2.6. The Effect of Temperature on Permeate Flux

The effect of temperature on permeate flux was tested, as the flux was seen to vary in response to different operating temperatures. Actual plant capacities were available from the field, and the membrane section areas were available for 20.3 cm (8") elements, so the actual permeate flux could be calculated as shown in (12) (Water Environment Federation (WEF), 2006).

$$J_v = \frac{Q_p}{A} \tag{12}$$

In (12), A system = Surface area of the membrane system (m^2).

The standard RO operating temperature in this study was taken as 25˚C. The effect of temperature on flux was then evaluated using Equation (13) (Water Environment Federation (WEF), 2006).

$$JT = (J25) \times 1.03(T - 25) \tag{13}$$

In (13), JT= Flux at temperature T (˚C), and $J25$ = Flux at standard temperature 25˚C (77˚F).

Flux is affected by the water temperature, which, for study purposes, is often normalised to a standard temperature of 25˚C (77˚F) to account for fluctuations in water viscosity.

3.2.7. The Effect of Salinity (TDS)

The TDS effect was tested for plants 1, 2 and 3, as these were the only plants with fully functional temperature and pressure gauging. The TDS effect was considered depending upon the variation in osmosis pressure value with respect to increased or decreased feed water TDS concentration, and its subsequent effects on the net driving pressure and water permeate flux. Hydraulic pressure, temperature, and recovery ratio were assumed to be constant. The computational model for calculating the effect of salinity on permeate flux and product water cost is further discussed below.

The water flux, Jv, is linked with the pressure and concentration gradients across the membrane by the function shown in Equation (14) (Baker, 2012).

$$Jv = Kw(\Delta p - \Delta \pi) \tag{14}$$

In (14), Jv = Water flux (lit/m^2·day), Kw = Water permeate factor (lit/m^2·day·bar), Δp = Transmembrane pressure (TPM) (El-Emam & Dincer, 2013; El-Dessoudy & Ettouney, 2002), $\Delta \pi$ = Difference between feed and permeate pressures.

Osmotic pressure, π, of a solution can be determined experimentally by measuring the concentration of dissolved salts in solution, as shown in (15).

$$\pi = 1.19(T + 273) * \sum(mi) \tag{15}$$

In (15), π = Osmotic pressure (psi), T = Temperature (˚C), and $\sum(mi)$ =

Sum of molal concentration of all constituents in solution (El-Dessoudy & Ettouney, 2002; Al-Mutaz & Al-Ghunaimi, 2001). An approximation for π may be given by Equations (16)-(18) (El-Emam & Dincer, 2013; Al-Mutaz & Al-Ghunaimi, 2001).

$$\pi = \frac{0.0385C(T+273)}{1000-\frac{C}{1000}} \tag{16}$$

In (16), π = Osmotic pressure (psi), T = Temperature (˚C), C = Water stream concentration (ppm).

$$\Delta p = 0.5(Pf + Pc) - Pp \tag{17}$$

$$\Delta\pi = 0.5(\pi f + \pi c) - \pi p \tag{18}$$

In (17) and (18), P = Hydraulic pressure, f = Feed side, c = Concentrate side (reject stream), p = Permeate side.

The osmotic pressure of the permeate stream can be neglected as it has little salt content (Liu, Zhang, Meng, & Zhang, 2008; McGovern & Lienhard, 2016; Baker, 2012) and differentiation between the hydraulic and osmotic pressure can be evaluated using Equations (19) and (20).

$$\Delta p = 0.5(Pf + Pc) \tag{19}$$

$$\Delta\pi = 0.5(\pi f + \pi c) \tag{20}$$

As Pc could not be measured in field, another relation needed to be applied to solve the above equations.

However, pressure drop equation for the concentrated brine or reject stream pressure could be defined as in (21),

$$dp = Pf - Pc \tag{21}$$

where dp = Pressure drop (as bar or psi).

Equation (22), developed by Filmtec, was used to estimate the pressure drop across a 20.3 cm (8") diameter, seawater RO membrane (Altaee, 2012; DOW, FILMTEC TM Membranes, Form No. 609-02057-604).

$$\Delta Pfc = 0.01n(qfc)1.7 \tag{22}$$

In (22), ΔPfc = Concentrate side pressure drop (psi), qfc = Arithmetic average of concentrate-side flow rate (gpm) (=1/2 (feed flow + concentrate flow). However, another equation (Equation (23), from Lewabrane) was applied to compare the results (Lewabrane, 2012)

$$dp = a \times \{(Qf + Qc)/2\} b \tag{23}$$

In Equation (23), a and b were constants, with values of 0.014 and 1.3, respectively, for a 20.3 cm (8") dia. membrane, Qf and Qc = Feed and concentrate flow rates (m^3/hr). When this equation is applied, it gives nearly the same value of pressure drop.

Finally, after solving all the equations, a Kw value was established for the actual study conditions. By then assuming that Kw was constant, permeate fluxes for various feed water concentrations were determined.

3.3. Sharing-Cost Constituents

The RO system total cost was divided into its components, as percentages of the total investment cost (TIC), to identify the relative magnitude of each component (Romero-Ternero, Garacia-Rodriguez, & Gomez-Camacho, 2004).

3.4. Fouling Problem

Membrane fouling is an important factor that has an adverse effect on RO performance. Major fouling agents have been categorised into four classes: biological fouling, organic fouling, colloidal/particulate fouling, and scaling agents (Santosh, Jegatheesan, Baskaran, & Shu, 2012; Hilal, Al-Zoubi, Darwish, Mohammed, & Abu Arabi, 2004; Wang, Chen, Hung, & Shammas, 2011) Based on their size and physico-chemical properties, these agents can occur individually or together. To investigate feed water quality and its effect on membrane lifetime, a fouling evaluation was conducted. RO inorganic fouling assessment software (ROIFA) was used to calculate probable salt combinations, fouling fractions, fouling loads, and fouling fluxes (El-Manharawy & Hafez, 2005).

4. Result and Discussion

4.1. Calculation of Water Cost Using Various Interest Rates

Water costs were calculated from the information presented previous Tables 2-4. These have been presented in Table 5, which shows the water cost calculations with respect to various interest rates, and with levelised O & M costs for an interest rate of 5%.

As shown in Figure 3, the differences in water production costs were observed

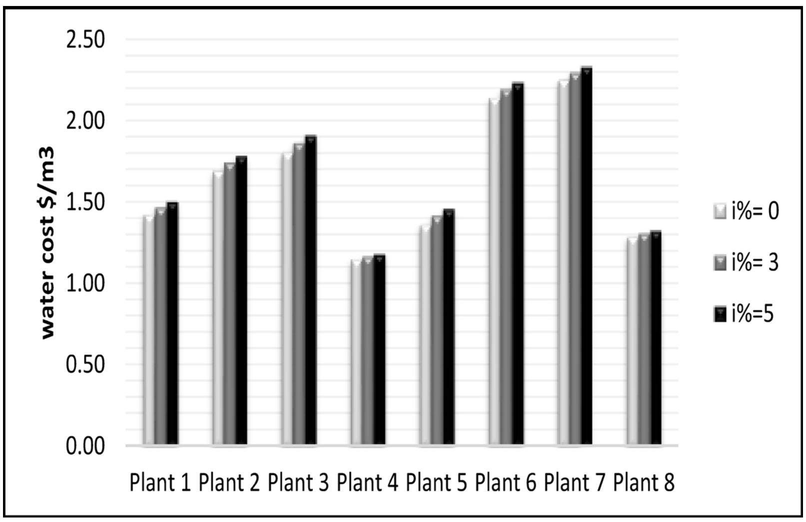

Figure 3. Effect of interest rate on water cost.

Table 5. Calculation of the water production costs, with various interest rates and CELF.

items	Units	Plant 1	Plant 2	Plant 3*	Plant 4*	Plant 5	Plant 6*	Plant 7	Plant 8
Installation cost of generator (10% of generator cost)	$	700	700	700	700	700	700	700	700
The sum of capital cost	$	73,246	63,246	73,246	69,746	71,246	64,846	61,146	76,246
System life time	Years	16	16	16	16	16	16	16	16
Capital cost calculation									
A1 according to 0% interest rate	$/year	4577.9	3952.9	4577.9	4359.1	4452.9	4052.9	3821.6	4765.4
A1 according to 3% interest rate	$/year	5831.2	5035.0	5831.2	5552.5	5671.9	5162.4	4867.9	6070.0
A1 according to 5% interest rate	$/year	6758.4	5835.7	6758.4	6435.4	6573.8	5983.3	5641.9	7035.2
Operation & maintenance cost:									
Fuel cost per litre	$/litre	0.6466	0.6466	0.6466	0.6466	0.6466	0.6466	0.6466	0.6466
Plant Capacity	m^3/day	2960	2556	2960	2818	2879	2620	2471	3081
Chemical cost per m^3	$/$m^3$	0.025	0.025	0.025	0.025	0.025	0.025	0.025	0.025
A2—Fuel cost	$/year	21,239	16,519	21,239	46,726	16,991	33,039	36,343	46,726
A3—Membrane replacement cost	$/year	13,600	13,600	10,200	24,480	7,650	6,800	10,200	24,480
A4—Chemical cost	$/year	1847	2770	3232	7314	2438	2770	3657	6501
Sum of other O & M cost									
Case 0%	$/year	320.45	276.70	320.45	305.14	311.70	283.70	267.51	333.58
Case 3%		408.18	352.45	408.18	388.68	397.04	361.37	340.75	424.90
Case 5%		473.09	408.50	473.09	450.48	460.17	418.83	394.93	492.46
Cost per m^3 of product water for i = 0%	$/$m^3$	1.42	1.69	1.81	1.15	1.36	2.14	2.25	1.29
Cost per m^3 of product water for i = 3%	$/$m^3$	1.47	1.75	1.87	1.17	1.42	2.20	2.30	1.31
Cost per m^3 of product water for i = 5%	$/$m^3$	1.50	1.79	1.91	1.18	1.46	2.24	2.33	1.33
Levelised cost per m^3 of product water for i = 5%	$/$m^3$	2.06	2.45	2.61	1.66	1.97	3.09	3.25	1.86

*These plants are those nearest to the government plant.

to be very small. With the increase in the interest rate from 0% to 5%, whereas (El-Dessoudy & Ettouney, 2002) consider the value of i% from (3% to 8%) but considering value was 5% as the average, water cost increased from 3% to 7%. As the target plants were small, the effect of interest rate changes was limited, on the basis that their initial CAPEX was also relatively small, in contrast with larger plants, where construction may take many years (Atikol & Aybar, 2005). Thus, for small plants, the capital cost was not considered to be high. While the levelized cost is noticeably higher than the non levelized one according to the O & M cost escalation with respect to the RO plant life time (El-Emam &Dincer, 2013).

4.2. Water Cost Reduction by Predict Recovery Ratio Effect

In general, the recovery ratio was linked to plant capacity. Increasing the recovery ratio has been considered as an effective water cost reduction factor (Helal, Al-Malek, & Al-Katheeri, 2007; Saria Atab, Samallbone, & Roskilly, 2016;

El-Emam & Dincer, 2013) as it affects product flow (permeate flux) (Baker, 2012; DOW, FILMTEC TM Membranes, Basics of RO and NF: Principle of Reverse Osmosis and Nanofiltration; Kim & Balaban, 2012) and that by increasing plant capacity. (Saria Atab, Samallbone, & Roskilly, 2016; El-Emam & Dincer, 2013) show how significantly this ratio affecting the water product cost. **Table 6** shows the relationship between increased recovery ratio and decreased water cost. From this table at recovery ratio 75% all plants can cover the water product cost and some of them keep some profits.

4.3. Water Cost Reduction by Predict Availability Effect

An increase in availability not only increases the O & M cost but also affects plant capacity. We can see from **Table 7**, however, that increased availability did not reduce the water cost as significantly as an improved recovery ratio did. This factor maybe has not been taken in another study as they assumed the availability is 100% or in another expression, the working time is 24 hours.

4.4. Water Cost Reduction by Predict Membrane Replacement Effect

The performance of membrane modules was seen to have a major influence on

Table 6. Recovery ratio effect on water cost.

Recovery ratio value	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8
	water cost $/m^3							
10%	8.22	4.89	4.47	4.14	4.78	6.18	5.41	4.64
20%	4.11	2.45	2.24	2.07	2.39	3.09	2.70	2.32
30%	2.74	1.63*	1.49	1.38	1.59*	2.06	1.80	1.55*
50%	1.64*	0.98	0.89	0.83*	0.96	1.24	1.08*	0.93
75%	1.10	0.65	0.60*	0.55	0.64	0.82*	0.72	0.62
Actual recovery ratio	2.06	2.45	2.61	1.66	1.97	3.09	3.24	1.85
Selling price	1.69	1.69	0.64	0.85	1.69	0.85	1.69	1.69

*Recovered water cost.

Table 7. Effect of availability on water cost.

Availability	Plant 1	Plant 2	Plant 3	Plant 5
40%	2.09	2.50	2.65	1.84
50%	1.90	2.25	2.44	1.71
60%	1.77	2.08	2.30	1.62*
70%	1.68*	1.97	2.20	1.56
80%	1.61	1.88	2.13	1.52
WSP**	1.69	1.69	0.64	1.69

*Recovered water cost. **WSP: water selling price.

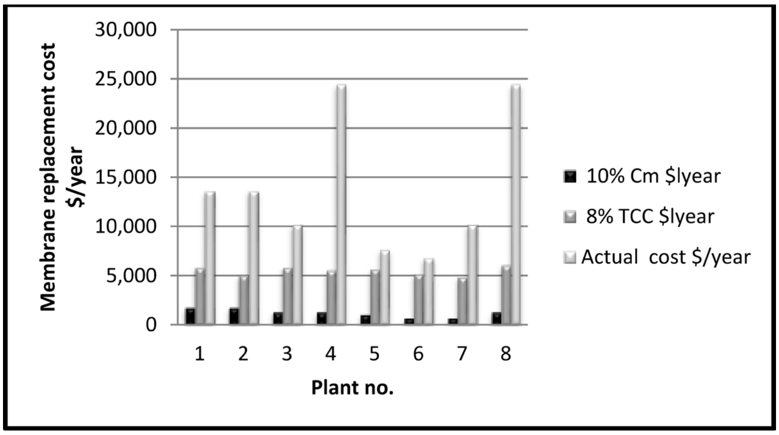

Figure 4. Comparison between membrane replacement cost according to Equations (10) and (11), and the actual replacement cost.

energy cost and water production quality (Jiang, Wang, Lin, Cheng, & Wang, 2017) **Figure 4** shows how the membrane replacement enormously affects the water cost due to Equations (10) and (11). In Safwan, membranes were observed to have a short lifespan, although, according to many studies, membrane life spans ranged from 1 to 5 years (Al-Karaghouli & Kazmerski, 2012; Saria Atab, Samallbone, & Roskilly, 2016; Helal, Al-Malek, & Al-Katheeri, 2007; DOW, FILMTEC TM Membranes, Form No. 609-02003-1004). Thin film, composite polyamide membranes (PA) have been developed to be efficient in term of flux, salt rejection, and fouling (Shenvi, Isloor, & Ismail, 2015). While some referred to membrane replacement rates as ranging from 5% to 15% of membrane elements capital cost, these results depended on feed water quality, pre-treatment conditions and operating stability. Which obviously showed slit increase in water product cost as (Romero-Ternero, Garacia-Rodriguez, & Gomez-Camacho, 2004) referred in their study. Common operational factors affecting membrane lifespan included use of improper cleaning solutions and disregarding regular inspection and maintenance schedules for scaling or inorganic fouling (El-Dessoudy & Ettouney, 2002). From **Figure 4**, plants' no. 4 and 8 membrane replacement cost are approximately 25,000 $/year which so higher than the value of 10% of membrane cost and 8% of total capital cost.

4.5. Water Cost Reduction by Predict the Effect of Temperature on Permeate Flux and Recovery Ratio

Increased temperature leads to increased flux, permeate flow and subsequent recovery ratio, without the need for higher pressure, although increased temperature also facilitates increased salt passage (Al-Karaghouli & Kazmerski, 2012; Saria Atab, Samallbone, & Roskilly, 2016; Baker, 2012). In **Figure 5** of plant no. 1 shows how increased temperature accompanied with increasing in water flux and decreasing in water cost. A 5˚C increase in temperature increased water flux by 15.9%, while the water cost decreased by 13.74%. **Figure 6** shows that increasing temperature by 5˚C led to improve the recovery ratio in Plant no. 3 by

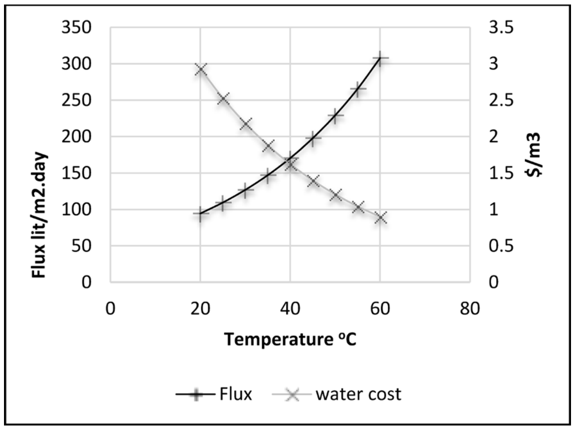

Figure 5. Effect of temperature on water flux and water cost for Plant no. 1.

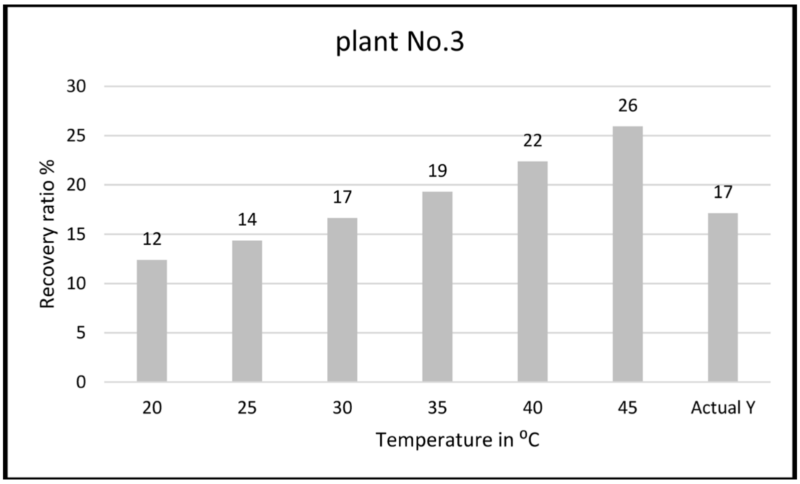

Figure 6. Effect of temperature on recovery ratio for Plant no. 3.

Table 8. Effect of temperature on water production cost.

Temp. ˚C	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8
	Water cost $/m³							
20	2.93	3.59	3.61	2.33	2.73	4.41	4.50	2.57
25	2.53	3.10	3.12	2.01	2.36	3.80	3.88	2.22
30	2.18	2.67	2.69	1.73	2.03	3.28	3.34	1.91
35	1.88	2.31	2.32	1.49	1.75	2.83	2.89	1.65*
40	1.62*	1.99	2.00	1.29	1.51*	2.44	2.49	1.42
45	1.40	1.72	1.73	1.11	1.30	2.11	2.15	1.23
Selling price	1.69	1.69	0.64	0.85	1.69	0.85	1.69	1.69

*Recovered water cost.

16%. Higher feed water temperature increased the average pore diameter of the membrane and changes in the water structure and viscosity assisted water passage through the membrane, and significantly reduced energy consumption (Saria Atab, Samallbone, & Roskilly, 2016; Al-Mutaz & Al-Ghunaimi, 2001; Abdelaziz, Karameldin, Mekhamer, & Adbelmonem, 2006).

Table 8 shows the effect of temperature on water cost, although for our purposes, we considered the maximum operating temperature to be 45˚C, which is the maximum operating temperature of polyamide membranes. However only two plants cover the water product cost at 40˚C temperature, and only one plant cover the cost at 35˚C temperature.

4.6. The Effect of Salinity (TDS) on Plant Capacity and Water Cost

Figure 7 shows how the TDS negatively affected the water permeate flux of Plant no. 1, and how water cost was increased by the increasing salinity. Water cost decreased by 50% and water flux was increased by 105% when the TDS was reduced to 1000 mg/L.

Groundwater of the Safwan area was found to be highly brackish, having TDS of up to 13,000 mg/L, which affected the water cost.

With increased salinity, higher pressures are needed to overcome the higher osmotic pressure (Al-Karaghouli & Kazmerski, 2012; Baker, 2012) To achieve the necessary higher pressure, specific energy consumption (SEC) increased accordingly (Abdelaziz, Karameldin, Mekhamer, & Adbelmonem, 2006). Thus, increased water salinity caused a predictable increase in the cost per unit volume of potable water produced (El-Emam & Dincer, 2013; Saria Atab, Samallbone, & Roskilly, 2016) emphasize the salinity negative effect on water product.

Figure 8 demonstrates how high TDS levels affected fuel costs. Increased O&M costs were also observed when feed water concentration increased SEC, as discussed previously. Table 9 shows the actual TDS values and water fluxes for plants no. 1, 2 and 3.

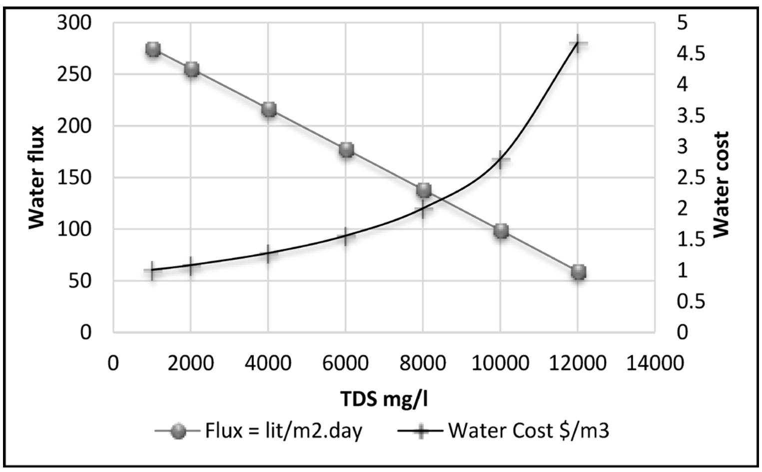

Figure 7. Salinity effect on water flux and cost, for Plant no. 1.

Table 9. Actual feed water salinity (TDS) and water flux.

Plant No.	1	2	3
Actual water flux (l/m^2·day)	134	101	134
Actual feed water TDS (mg/l)	9025	8787	11,070

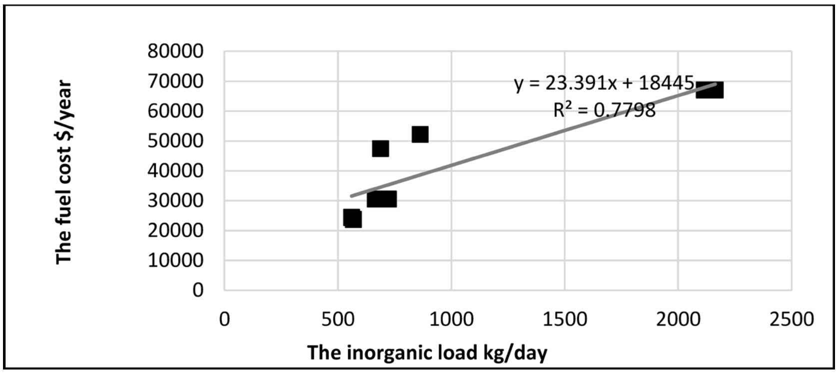

Figure 8. Inorganic load effect on fuel cost of product water.

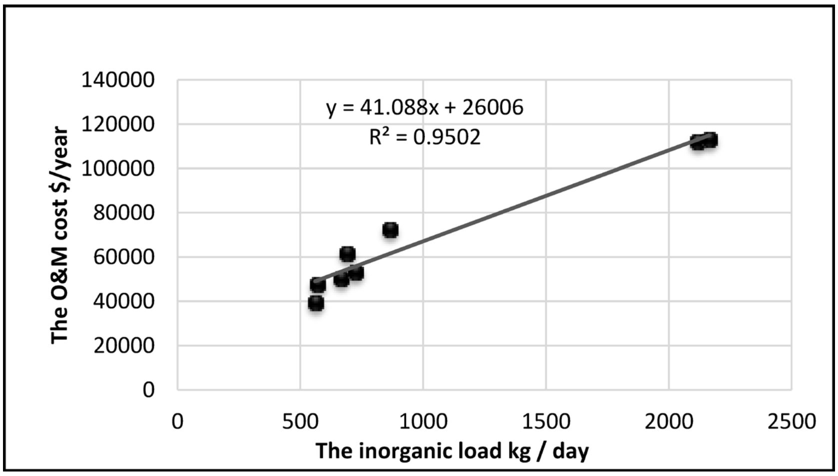

Figure 9. Inorganic load effect on O&M cost of product water.

It was also apparent that increased TDS concentration increased fouling potential and membrane replacement cost, required the system to be cleaned more often, and increased chemical treatment costs. The relationship between TDS and O & M costs for the Safwan plants is shown in Figure 9.

4.7. The Major and Minor Water Product Cost Components for Safwan Plants

The final step was to divide the total investment cost, with each component share in the TIC represented by a percentage of the total cost (Romero-Ternero, Garacia-Rodriguez, & Gomez-Camacho, 2004). Figure 10 shows that the components affected the water product cost of plant no. 1 as example. The figure shows major and minor components that affect the water cost in this study. The average membrane replacement cost and the fuel, were 25% and 54% respectively. (Helal, Al-Malek, & Al-Katheeri, 2007) study referred to the enormous effect of fuel on water cost. The RO system capital cost is 6%, while building cost varies from 2.4% to 6% and chemical costs vary from 4.21% to 8.57%. The average value of RO system installation cost is 1% and that is near to the average of generator cost is 1.35%. While the other components contribution was very small. Table 10 shows each component's share of the total cost, as a percentage.

Table 10. The percentage share of each constituent in water production cost.

Components	Units	Plant 1	Plant 2	Plant 3	Plant 4	Plant 5	Plant 6	Plant 7	Plant 8
The RO system cost	%	7.34	6.35	7.69	3.45	10.79	5.37	4.16	4.86
Ro system installation cost.	%	1.47	1.18	1.54	0.70	0.00	0.94	0.74	0.00
Generator cost.	%	1.47	1.65	1.54	0.75	1.89	1.31	1.15	0.76
Generator installation.	%	0.15	0.16	0.15	0.08	0.19	0.13	0.11	0.08
Well drill cost with motor cost.	%	0.27	0.31	0.29	0.14	0.35	0.24	0.21	0.14
Building cost (15 × 7) m.	%	4.66	5.23	4.89	2.40	6.00	4.18	3.64	2.40
Fuel cost.	%	48.38	42.23	50.71	54.72	49.84	67.43	64.64	54.83
Membrane replacement cost.	%	30.98	34.77	24.35	28.67	22.44	13.88	18.14	28.73
Chemical cost.	%	4.21	7.08	7.72	8.57	7.15	5.65	6.50	7.63
Generator other O & M costs.	%	0.46	0.45	0.48	0.23	0.58	0.37	0.30	0.25
O & M of high-pressure pump.	%	0.31	0.30	0.32	0.15	0.39	0.24	0.20	0.17
Other mechanical equipment O & M cost.	%	0.31	0.30	0.32	0.15	0.39	0.24	0.20	0.17
Sum		100.00	100.00	100.00	100.00	100.00	100.00	100.00	100.00

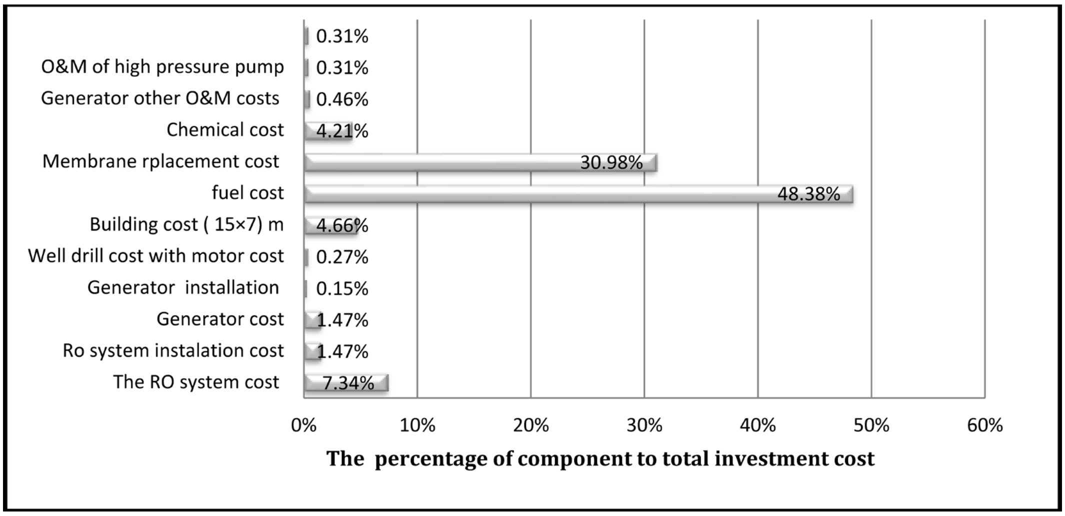

Figure 10. Percentage share for each component of water product cost of plant no. 1.

4.8. ROIFA Result

According to ROIFA excel spread sheet, the inorganic fouling flux, of 1.3105E+18 Molecules/0.1cc. s, was in the high fouling range. While the Carbonate and Sulphate proportions were 24.803% and 75.1967% respectively, both were in the low range, although according to the molar ratio (SO_4/Alk), the Sulphate fouling potential was very high. Table 11 presents detailed ROIFA guidelines.

RO membrane fouling can take three general forms: 1) build-up of feed water constituents on the membrane surface, 2) formation of chemical precipitates due to the chemistry of the feed water, and 3) damage to the membrane due to the

Table 11. ROIFA Guidelines.

<table>
<tr><td colspan="7">Guideline for Inorganic Fouling Flux</td></tr>
<tr><td colspan="4">Inorganic Fouling Flux Range (Molecules/0.1cc. s)</td><td colspan="2" rowspan="2">Fouling Potential</td><td rowspan="2">Remarks</td></tr>
<tr><td colspan="2">From</td><td colspan="2">To</td></tr>
<tr><td colspan="2">1.00E+18</td><td colspan="2">1.50E+18</td><td colspan="2">High Fouling</td><td>Anti-scaling, + Short Chemical Cleaning</td></tr>
<tr><td colspan="7">Guideline for the Carbonate & Sulphate Saturation Factor (%)</td></tr>
<tr><td colspan="4">Saturation Factor (%)</td><td colspan="2" rowspan="2">Fouling Potential</td><td rowspan="2">Remarks</td></tr>
<tr><td colspan="2">From</td><td colspan="2">To</td></tr>
<tr><td colspan="2">0%</td><td colspan="2">100%</td><td colspan="2">No Fouling</td><td>No treatment is required</td></tr>
<tr><td colspan="7">Guideline for Molar Ratio (SO_4/Alk) and Scaling Potential</td></tr>
<tr><td>Water Type</td><td>Proposed Name</td><td>TDS Range* (mg/Kg)</td><td>Chloride Range (mMol/kg)</td><td>Molar Ratio (SO_4/Alk**)</td><td>Carbonate Fouling Potential</td><td>Sulphate Fouling Potential</td></tr>
<tr><td>Type-09</td><td>Medium Salty Water</td><td>10,000-15,000</td><td>100-200</td><td>12-15</td><td>Very low</td><td>Very high</td></tr>
</table>

*TDS (in mg/kg) is approximated for guidance purpose. **Alk.: sum of alkalinity ions (=OH + CO_3 + HCO_3, in mMol/kg).

presence of either chemical substance that can react with the membrane, or biological agents that can colonise it (Santosh, Jegatheesan, Baskaran, & Shu, 2012). In the present study, scaling was more prominent than fouling, with precipitation of dissolved salts in the concentrate stream being the major cause of the scaling.

5. Conclusion and Recommendation

From our results, the components that have largest share of the water product cost were membrane replacement and fuel/energy costs. The membrane replacement cost was high due to the high TDS values observed in Safwan (reaching up to 13,000 mg/L). The plants used BWRO membranes, for which the recommended TDS ranges are between 1000 and 7000 mg/L. Ideally, RO membrane life may be 5 years or more if proper pre-treatment was applied, indicating that the shorter lifetime in the small remote Safwan plants may be due to a combination of poor design and faulty operation.

Membranes may have their life prolonged life in various ways, including effective feed pre-treatment, conservative design and well-trained operators, and these factors were seen to be absent in our study area. Improving the recovery ratio showed an impressive effect on water production cost reduction.

The remedy from application of ROIFA software in this case was application of ‘anti-scaling + short chemical cleaning to reduce scaling factor.

The other two effective factors were the TDS and temperature, the first one dramatically increased the water product cost while the other decrease it. Increasing feed water temperature in a country like Iraq is not an issue, if the owner makes a group of water tanks out the building and the sunshine will complete the task perfectly.

The ideal of desalination with low energy costs may be reached by the following two options: 1) the optimisation of factors and minimisation of energy consumption, and 2) use of non-conventional energy sources.

The operators of the Safwan area need skill training, particularly for aspects such as smooth operations and improved maintenance capability—particularly on factors such as identification of fouling symptoms by observing either a 10% - 15% decrease in the normalised water flow, or an increase in the pressure drop by 10% - 15%. Operators also need to understand membranes better, including appreciation that they may be damaged by low pH, by high chlorine concentrations, or by aggressive chemical compounds.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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Acronyms

AOH = Actual operation hours hr/day.

C = Solution concentration ppm.

CFu = Fuel consuming by generator, (l/hr).

Cfm = Mean salt concentration in feed mg/l.

Cch = Chemical cost, $/m^3.

Chc = Chemical cost $/year.

CF = Concentration factor.

Cm = Membrane element cost, $.

Cp = Permeate solution in mg/l.

Fc = Fuel cost $/year.

fc = Fuel cost($/l).

n = Life time in years.

N = Number of membrane element in one series.

NE = No. of membrane elements.

p = 12/period of change in month during one year.

Pf = Feed pressure in bar.

Pc = Concentrate pressure in bar.

Pp = Permeate pressure in bar.

Posm = osmosis pressure bar or psi.

Qf = Feed flow rate m^3/hr.

Qp = Permeate flow rate m^3/hr.

Rcm = Membrane replacement cost, $/year.

RO = Reverse osmosis system.

SR = Salt rejection %.

Sp = Salt passage %.

TCC = Total capital cost $.

TDS: Total dissolved solid mg/l.

TIC = Total investment cost $.

T = Temperature OC.

R = Recovery ratio %.

Greek Symbols

πf = Osmosis pressure for feed water in bar.

πc = Osmosis pressure for concentrate or (brine or Rejected) water in bar.

πp = Osmosis pressure for permeate water in bar.