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Analysis and Simulation Performance of a Reverse Osmosis Plant in the Al-Maqal Port

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ABSTRACT

The Basrah province (southern of Iraq) was interested in establishing desalination plants to provide drinking water due to the high levels of salinity in its water resources. This work was carried out in order to evaluate and simulate the functionality of the reverse osmosis plant in the Al-Maqal port. From the field and laboratory measurement, this study concluded that the considered parameters of product water by reverse osmosis (RO) plant were within the Iraqi standard (IRS) limits. The calculation of operation indices showed that the recovery rate of plant (72%) and the permeate flux of plant (20 lmh) was within for limitation of brackish surface water. In turn, the plant has a low salt rejection (90.1%) and a high pressure drop (5 bar); therefore, the membranes require backwashing or chemical cleaning. Then, the performance of RO membrane was simulated by the Winflows software. The best operating parameters were identified. The coefficient of determination (R^2) between simulated and measured TDS was 0.83. Therefore, the simulated TDS of permeate multiplied by 5.3 was given a good estimation for actual TDS within acceptable an error rate of 17%.

Keywords: reverse osmosis, Iraq, Basrah, Shatt Al-Arab, TDS, winflows.

INTRODUCTION

Water is an indispensable substance for the maintenance of life on the Earth and the source of continuous progress and development of human society. Although water is a natural renewable resource, the freshwater resources on the Earth only account for a small part of the total water resources, and the proportion of easily developed freshwater resources is even smaller, so the freshwater resources are very scarce. Due to population growth, rapid urbanization and global climate change, traditional water sources closely related to human life such as lakes, rivers and groundwater resources are insufficient to meet the increasing demand for high-quality drinking water [Zioui et al., 2018; Zhu et al., 2019; Wang et al., 2021]. For different causes, several nations are now experiencing a shortage of drinking water. Therefore, it is also necessary to invest the waters of the seas and oceans, as they constitute more than 97% of the globe waters through desalination processes [Idrees, 2020; Lin et al., 2021]. One of these nations is Iraq, where surface water shortage is a major issue in many provinces. As a result, several provinces have begun to experiment with alternate supplies, like brackish water [Taha et al., 2021].

Desalination is a separation procedure that reduces the dissolved salt content of saline water to an acceptable level. Desalination was first performed by boiling salt water, chilling it, and condensing it as fresh water. Multi-Stage Flash (MSF), Multi-Effect Distillation (MED), and Vapor Compression (VC) are the most well-known thermal methods. Freezing the water to remove the salt was more viable in colder climes, such as the locations bordering the Arctic Ocean. When saltwater freezes, the salt ions settle to the bottom over time, leaving freshwater on top that can be melted or shaved off [Kucera, 2014]. Membrane treatment is the most recent commercial desalination method. Brackish Water Reverse Osmosis (BWRO), also known as Sea Water Reverse

Osmosis (SWRO), is the fastest-growing desalination technique, with the most installations all over the world; it is quickly gaining a foothold in existing and future desalination markets. Its energy usage is typically 70% lower than comparable evaporation methods [Al-karaghouli & Kasmerski, 2010; Kucera, 2014]. The original and most fundamental membrane separation technique, reverse osmosis, for desalination of seawater and brackish water, might be called the most basic. Because it is the most efficient and cost-effective desalination method available [Al-karaghouli & Kasmerski, 2010; Qiu & Davies, 2012; Sarai Atab et al., 2016], its applications have grown rapidly [Lawrence K.Wang & Yung-Tse Hung, 2007; Vaithilingam et al., 2021]. Desalination via membrane is a physical process that separates salt molecules from water. The semipermeable membrane is pressed to transmit raw water through it. The RO membrane is a porous tube wrapped in a permeable sheet. Small molecules with a molecular size smaller than the membrane pores can pass through the microporous membrane [Lilane et al., 2020]. Organics, inorganics, and other substances in the water can clog these micropores [Hamad et al., 2013].

In comparison to alternative desalination systems, Al-Karaghouli and Kazmerski (2010) found that RO produces the most dependable, cost-effective, and energy-efficient fresh water. It is the fastest-growing desalination technology, having more installations across the world than any other [Al-karaghouli & Kasmerski, 2010]. The driving mechanism of RO is water pressure, which passes across the membrane to split the feed line into two additional lines with variable concentrations. The temperature of the water influences this pushing force [Agashichev et al., 2009]. As a result, precise details regarding maximum and lowest feed water temperatures, as well as plant performance temperature, are unquestionably required [Chu et al., 2020]. The rate at which raw water travels through the membrane module is equal to the pressure differential that exceeds the natural osmotic pressure differential [Charcosset, 2009]. The continued operation of a plant necessitates preventive and remedial actions. These corrective and preventive measures are necessary, based on the properties of the source water, as well as the properties of the treated water. For example, following desalination, charge is formed in the treated water, which can induce corrosion in the associated equipment [Hu et al., 2011]. These periodic measures, which can be used in pre-treatment approaches, intra-treatment modifications, and post-treatment requirements, will help and permit in the performance analysis. According to Miranda and Infield (2003), operating RO during broad operational windows is critical [Miranda & Infield, 2003].

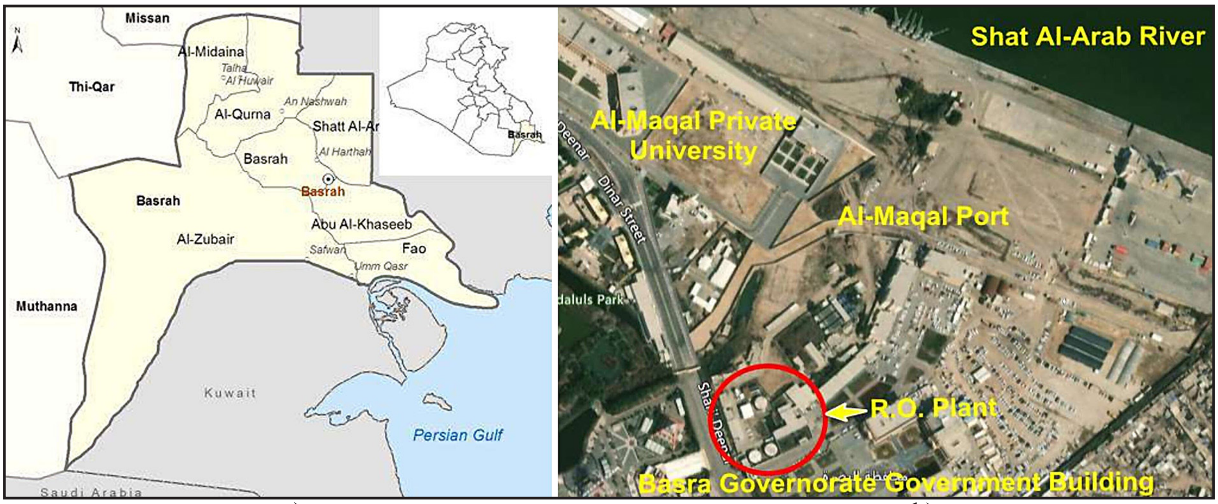
According to Greenlee et al. (2009), the RO membrane technology is dominant for new desalination installations, and it is used to treat a wide range of salt water resources with custom pretreatment and membrane system design. There are two types of RO desalination: seawater RO and BWRO [Greenlee et al., 2009]. The salt rejection and permeate flux are important elements to consider when evaluating the performance of reverse osmosis systems. Membrane fouling has a major negative effect on the operation performance of RO plants [Jamaly et al., 2014]. The salt rejection rate of a membrane system can also be utilized to evaluate the membrane function. All membrane manufacturers give a particular salt rejection rate to measure membrane performance [Greenlee et al., 2009; Wasfy, 2017].

The aim of this study was to assess and simulate the performance of the reverse osmosis plant in Al-Maqel, Basrah province, southern Iraq. The performance assessment of plant was conducted in terms of specific water parameters to understand the compliance and agreement the water product of plant based on the national guidelines standard. The performance simulation of plant was achieved by the Winflows software using past recorded measurements. This study is necessary to assist plant operators and managers in improving the quantity and quality of water produced.

MATERIALS AND METHODS

Study area

This study was conducted around the reverse osmosis plant, which is located in the port of Al-Maqal (30°33’14.9” N, 47°47’57.0” E), Basrah province, southern Iraq (Figure 1a). The Al-Maqal port is located on the right side of the Shatt Al-Arab in the center of Basra city, as shown in Figure 1b. This plant has been in construction since 2010 and began operating in 2013. The production capacity of this plant is 1500 m^3/day (62.5 m^3/hr). The objective of establishing this plant was to provide the workers in the port of Al-Maqal with clean drinking



a) b)

Figure 1. Location of the RO plant in the Al-Maqal port; a) Barash province; b) The RO plant with neighboring sites

water. Currently, this plant is managed by the General Company for Ports of Iraq.

The RO plant

The desalination process is carried out by reverse osmosis process. The process of RO is defined as the process of reverse transfer of fresh water from the more concentrated solution to the less concentrated solution (the solution is separated by a semipermeable membrane) that allows the water to pass through while preventing the salt from passing. The desalination process of the RO plant in the Al-Maqal port takes place in basic stages, as shown in Fig. 2, which are described as follows.

Pretreatment Unit

Primary treatment means preparing the feed water to enter the membrane assembly (modules) by removing turbidity, suspended particles, and preventing the sedimentation and growth of living organisms on the membranes, which is very important because the feeding water will pass through the narrow passages of the membranes, during the process of separating the fresh water from the brine. The water resource of this plant is from the Shatt al-Arab River. The pretreatment processes of water before the RO unit are included the following processes:

Coagulation process

This process is carried out in two rectangular basins, in which chlorine and alum are added and mixed with raw water.

Flocculation process

This process is carried out in two rectangular basins in the middle of the two coagulation basins, in which the relatively large suspended

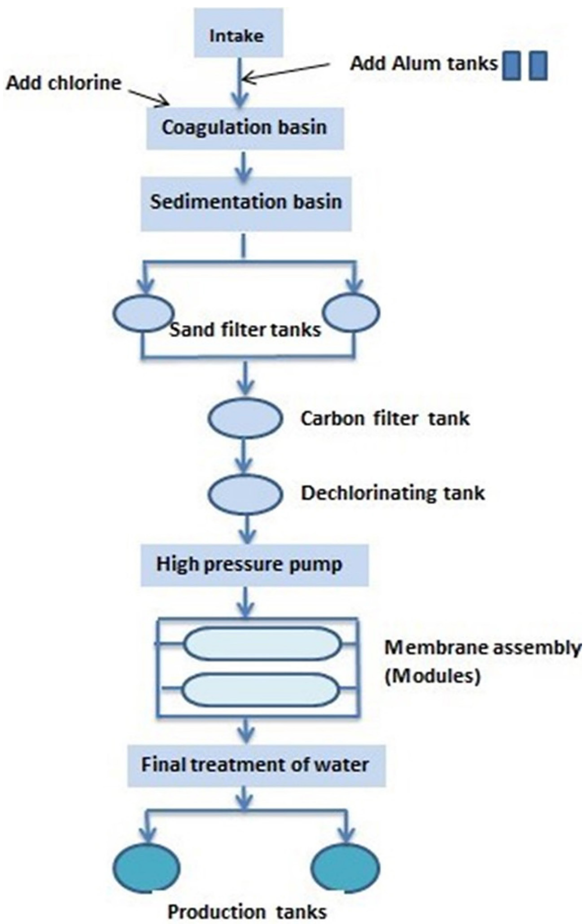


Figure 2. Flowchart of the RO plant in the Al-Maqal port

particles are settled at the bottom of the basins and then supernatant water is withdrawn to the next process.

Filtration process

This process consists of two sand filter tanks and one activated carbon filter tank. This process is carried out through the passage of water through pumps and air compressors to the sand filter tank and then to the activated carbon filter tank. The filtered water from this process is collected in a collection tank to be ready for use in the RO membrane unit.

RO membrane unit

DE chlorinating process

This process takes place in a DE chlorinating tank to remove the excess chlorine, as it has a negative effect on the membranes.

High pressure pump

In this process, the feed water is pumped at high pressure by a high pressure pump for forcing the water to permeate through the microspores of the RO membranes and separate the salts particles in the reject water which is also called the concentrate water. For this plant, the pressure and flow rate of the high-pressure pump ranges between 15–30 bars and 62.5–127 m^3/hr, respectively.

Membrane assembly (Modules)

The membrane assembly modules consist of 16 pressure vessels and each vessel contains 6 RO membranes of spiral –wound type. Backwash of membranes is done if required. The principle of the backwash is very easy, even though it requires some supplies such as a pump, a tank, and water hoses in addition to certain chemicals, such as NaOH and EDTA for alkaline washing and HCl, $C_6H_8O_7$ for acid washing. The process is done by circulating the required liquid into the membrane tubes and from them to the tank for a period of not less than an hour, after which the membranes are washed with clean water, the connections are reconnected and the plant is switched on again.

Final treatment unit

It includes preserving the properties of water and preparing it with the specifications required for use. This treatment includes adjusting pH and adding required dose of chlorine. Then, the water is transferred to store in the production tanks.

Data collection

The water samples were collected during April and May 2020 from each process of the purification and desalination plant. The samples were taken in plastic bottles of 0.5 L capacity that were rinsed several times with the sample before filling. Three samples were collected from each sampling point. The sample points were given the following numbers as sample no. 1, 2, 3, 4, and 5 for raw water, coagulation, flocculation, filtration, product (permeate) water, respectively. The samples were analyzed according the standard methods of examination water [Federation, 1999] by the laboratory of the Marine Science Center – University of Basrah to investigate of Electrical conductivity (EC), Calcium (Ca^{+2}), Magnesium (Mg^{+2}), Potassium (K^+), Bicarbonate (HCO_3), total alkalinity (TA), Chloride (Cl^-), and total hardness (TH) as $CaCO_3$ (TH) as $CaCO_3$. Other parameters, such as total dissolved solids (TDS), turbidity (TUR), and pH have been analyzed according to the standard methods at the laboratory of Civil Engineering Department – University of Basrah. Temperature of water samples was measured instantly in the WTP. Other data for previous dates were taken based on the history of daily recorded data by the staff in the treatment plant.

Field measurements of operation condition and parameters for the RO unit were collected. These operating conditions include pH, temperature, pressure, flow rate, TDS, and EC for feed, permeate, and concentrate water. Previous operation measurements of the plant were collected from the historical operation recorded for one year in order to simulate the performance of the plant. These recorded data included TDS of feed water and TDS of permeate water.

Tools of analysis

Winflows version 4.04 (developed by SUEZ group for water technologies and solutions) was used as a main tool for analysis and simulating the performance of RO plant. In addition, XL-STAT software (version 2016.02.28451) was used for statistical analysis and “Excel Statistics 2013” (SSRI Co. Ltd. 2013) was mainly used to generate graphs.

RESULTS AND DISCUSSIONS

Overall performance of plant

The average value of the studied parameters for raw water (from intakes) and product water (permeate water from RO) were listed Table 1. The values of pH, Turbidity (TU), Total Alkalinity (TA), Total hardness (TH), Total Dissolved Solid (TDS), electrical conductivity (EC), chloride (Cl^-), Bicarbonate (HCO_3^-), Potassium (K^+), Magnesium (Mg^{+2}), and Calcium (Ca^{+2}) for the raw water and product water are presented in Figure 3. The results showed that the values of these studied parameters were lower than the corresponding of inlet values. On the basis of the standard values of Iraq (Table 1), the values of these studied parameters in the product water were within the allowable concentrations for Iraqi standard [Hasan & Taleb, 2020]. Figure 4 shows that the arrangement of the studied parameters according to the efficiency

Table 1. Measured (average) and Iraqi standard values value of the studied parameters for drinking water (IRS)

Parameter	Unit	Raw water	Product water	Removal efficiency (%)	IRS
pH	--	7.3	6.8	6.21	6.5–8.5
Turbidity	NTU	45.7	0.48	98.95	5
TA	mg/L	208	80	61.54	200
TH		460	80	82.61	100
TDS		2620	259	90.11	1000
EC	μs/cm	4050	405	90.00	1500
Cl^-		950	106	88.84	250
HCO^3		164	49	70.24	150
K^+		36	16	55.00	20
Mg^{+2}		68	24	64.26	50
Ca^{+2}		130	32	75.38	75

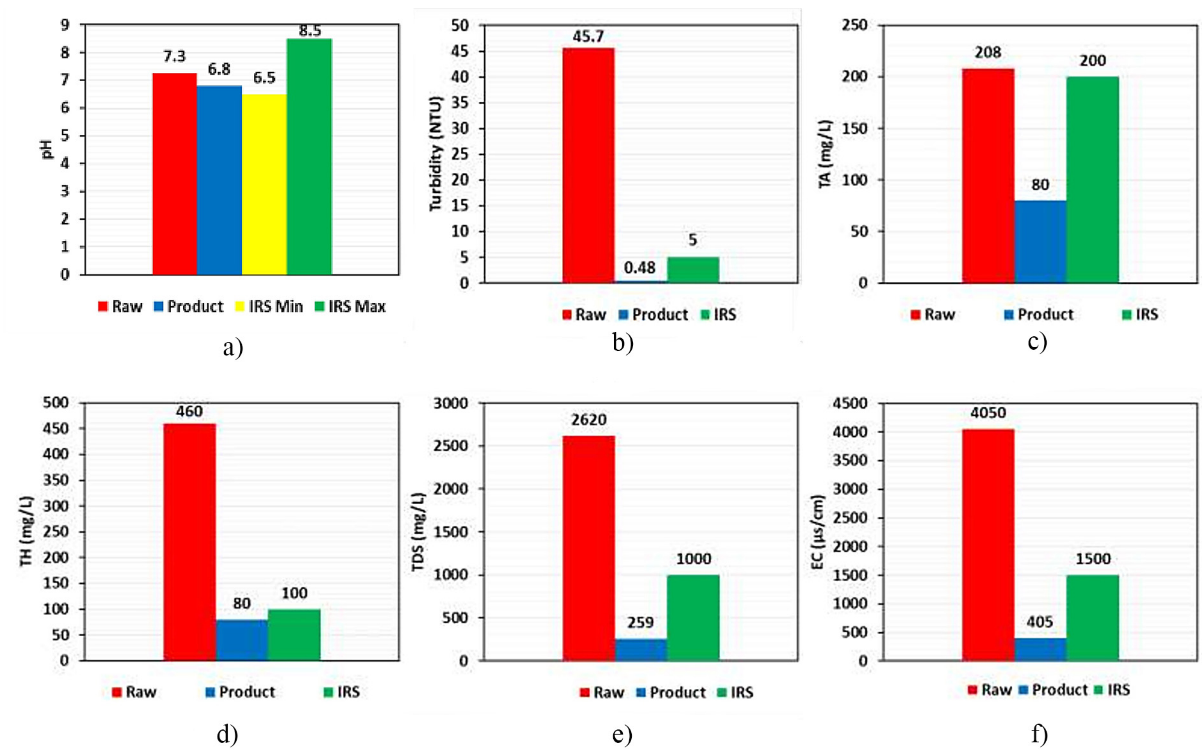


Figure 3. Average measured values of the studied parameters for raw and product water compared with the Iraqi standard values for drinking water. Note that all values are expressed in mg/L except pH (dimensionless), EC (μs/cm)

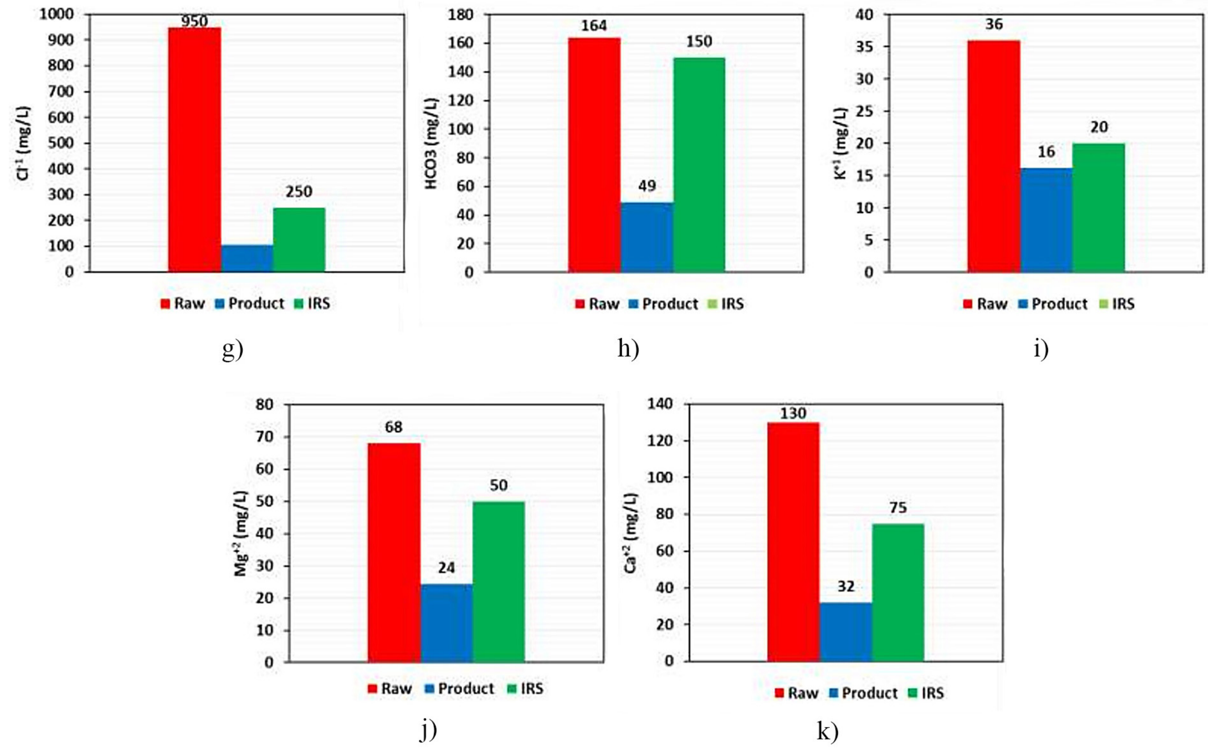


Figure 3. Cont. Average measured values of the studied parameters for raw and product water compared with the Iraqi standard values for drinking water. Note that all values are expressed in mg/L except pH (dimensionless), EC (µs/cm)

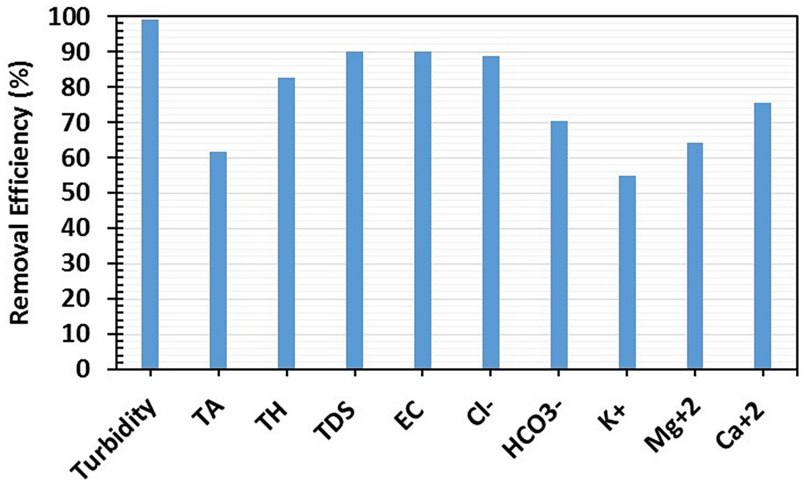


Figure 4. Overall removal efficiency of all the studied parameters for desalination plant

of the removal ratio from largest to smallest was 98.95%, 90.11%, 90%, 88.84%, 82.61%, 75.38%, 70.24%, 64.26%, 61.54%, and 55% for Turbidity, TDS, EC, Cl^-, TH, Ca^{+2}, HCO_3^-, Mg^{+2}, TA, and K^+, respectively.

Turbidity removal processes

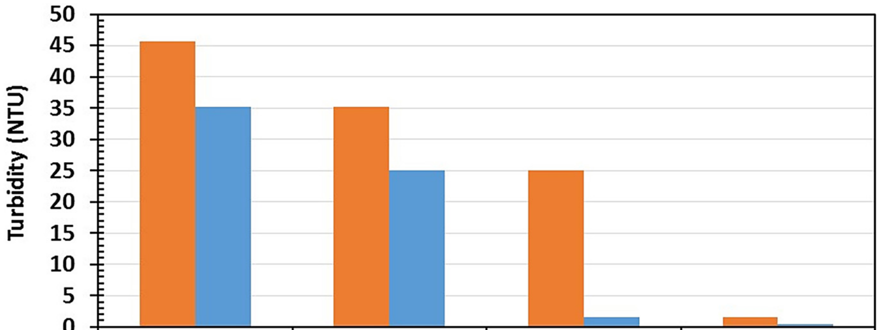
Turbidity control is crucial in water treatment, since it is the most obvious type of pollution. Increased turbidity encourages microbial development, resulting in contaminated water. The following processes can operate more smoothly and effectively if the turbidity levels are monitored and taken into account, especially before passing the water to the RO system. RO membrane fouling could be major limitation for surface brackish water with high turbidity. Therefore, this section will deal with investigating and ensuring the efficiency of the all processes in removing turbidity before the RO membranes.

Turbidly in inlet and outlet water of coagulation, fluctuation, cartridge filter, and RO membranes were measured as shown in Figure 5. From this figure, it is clear that the turbidity value decreased from 45 NTU in raw water to 35 by the coagulation process, then to 25 NTU by the flocculation process, and finally to 1.5 NTU by the cartridge filter. According to previous studies, the maximum limits are turbidity of 1 NTU to avoid fouling that will be reduce operating efficiency and membrane life, and ultimately increases the operating and maintenance costs of membrane filtration [Zhang et al., 2020]. Therefore, the turbidity (1.5 NTU) in the filtered water before entering the membranes is considered a little high and will lead to more frequent and shorter backwashing period for the RO membranes.

The self and overall removal efficiencies of turbidity by each process of the desalination plant are shown in Figure 6. From this figure, it is clear that there is a linear increase in the values of overall removal efficiency of processes from the coagulation process (23.19%) to the cartridge filter (96.72%), while past them through the membranes there is a small increase in the removal efficiency (98.85%). Moreover, the self-removal efficiency by the processes also show that there is an increasing in the efficiency (23.18%, 28.77%, and 94%) of all the processes (coagulation, flocculation, and cartridge filter, respectively) except for the membranes in which the removal efficiency (68%) decreases in relation to the rest of the processes. The reason behind this result is due to due to the significant decrease in the amount of turbidity entering the RO membranes by the previous processes. The maximum self-removal efficiency was 94% by the cartridge filter. This result confirms the great role of the cartridge filter to trap and prevent the passage the fine suspended particles to the membranes.

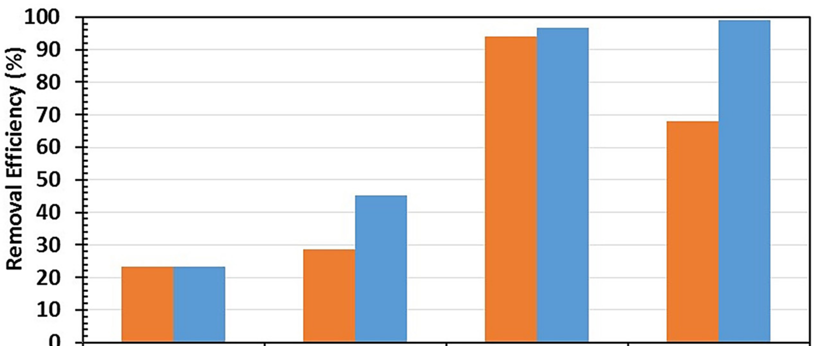
Operation conditions of RO membranes unit

The measured operation conditions are listed in Table 2. These operating conditions include



	Coagualtion	Flucolation	Catridge Filter	RO membrane
Before process	45.7	35.1	25	1.5
After process	35.1	25	1.5	0.48

Figure 5. The measured turbidity before and after each process of the RO plant



	Coagualtion	Flucolation	Catridge Filter	RO membrane
By the process	23.19	28.77	94.00	68.00
At end of the process	23.19	45.30	96.72	98.95

Figure 6. Self and overall removal efficiency of turbidity by each process of the RO plant

pH, temperature, pressure, flow rate, TDS, and EC for feed, permeate, and concentrate water.

Calculations for RO Performance

A few calculations are used to evaluate the performance of a RO system as well as design issues. Therefore, Table 2 includes the average values of the operating parameters that were measured to estimate the performance efficiency of an RO system.

Flow rate

When analyzing the performance of a reverse osmosis plant, the flow rate is a critical component to evaluate, because it is the major attribute that is directly influenced. According to equation 1, the feed water Q_f is separated into two parts: permeate Q_p and concentrate Q_c [Kucera, 2015].

$$Q_f = Q_p + Q_c \tag{1}$$

Recovery rate

Recovery rate (R) is the percentage of water that is being 'recovered' as a good permeate water or product water (Equation 2) [Kucera, 2015]. The higher the recovery means that less water is sent to drain as concentrate and more permeate water is saved. It is critical to keep track of the recovery rate when evaluating the membrane performance. However, if the recovery rate is too high for the RO design, scaling and fouling might occur, causing more serious issues. Membrane recovery can decrease over time because of scaling and fouling. As a result, the optimal recovery rate for a RO is determined by the purpose for which it was intended. It can be immediately established if the system is running outside of its original design by evaluating the recovery rate.

$$R = \frac{Q_P}{Q_f} \times 100 \tag{2}$$

As listed in Table 3, the calculations showed that the recovery rate of the studied plant was 72%, Then, for every 100 m^3 of feed water entering the RO system, 72 m^3 will be recovered as useable permeate water and 28 m^3 will be drained as concentrate. Depending on the input water parameters and other design considerations, brackish RO systems generally operate within a range 50% – 85% of recovery rate [Wenten & Khoiruddin, 2016]. Therefore, the recovery rate of plant is within the run limitations.

Permeate flux

The quantity of water that flows across a RO membrane in liters per square meter per hour (l/m^2/hr or lmh) is expressed as permeate flux (J). Permeate flux was calculated through dividing the permeate water flow (Q_p) by total surface area of all membranes (A_M). The total surface area of all membranes surface Area of one membrane (A_m) multiplied by the number of membranes (N_m) [Kucera, 2015]. However, Permeate flux (J) can be calculated by equation 3 for the singular membrane modules or a single membrane vessel with numerous membrane modules connected by a spacer.

$$J = \frac{Q_P}{A_M} = \frac{Q_P}{N_m \times A_m} \tag{3}$$

A larger flux indicates that more water passes through the RO membrane. To guarantee that the water passing through the RO membrane is

Table 3. Calculated performance indices of the RO membrane unit

Operation condition	Value
Flow rate (Q)	Q_f = 62.5 m^3/hr, Q_p = 45 m^3/hr, Q_c = 17.5 m^3/hr
Recovery ratio (R)	72%
Permeate flux (J)	20 l/m^2/hr (lmh)
Salt passing (S_P)	9.9%
Salt rejection (S_R)	90.1%
Pressure drop (ΔP)	5 bar
Surface area of membrane (A_m)	37.1 m^2

Table 2. Measured operation conditions of the RO membrane unit

Parameters	Unit	Feed water	Permeate water	Reject water
pH	–	7.3	7.0	7.2
TDS	mg/L	2620	260	8680
EC	μS⁄cm	4050	400	13500
Pressure	bar	15	0.5	10
Flow rate	m^3/hr	62.5	45	17.5
Temperature	°C	20	20	20

either excessively fast or sluggish, the RO systems are designed to function within a specified flux range. For brackish surface water, the RO systems typically flux ranges from 14 to 24 lmh [Henkens & Smit, 1979]. As listed in Table 3, the calculations showed that the permeate flux was 20 lm/hr for the study plant that had 6 RO vessels and each vessel contain 6 membranes type FILMTEC-SW30HRLE-400. This indicates that each RO membrane passes 20 liters of water per square meter every hour. Therefore, this value of permeate flux of plant was considered acceptable for limitation of brackish surface water.

Salt passing (S_P) and salt rejection (S_R)

Percent salt passing (S_P) is a metric for how many salts flow through the RO feed water to the permeate water. Therefore, Percent salt passing (S_P) is the percentage ratio between the TDS of permeate water (C_p) to the TDS of feed water (C_f) as presented in equation 4 [Kucera, 2015]. This is the quantity of salts that travel through the RO system, represented as a percentage. The better the system performs, the lower the salt passage. A high salt passage might indicate that the membranes need to be cleaned or replaced.

$$S_P = \frac{C_p}{C_f} \times 100 \tag{4}$$

On the other hand, salt rejection (S_R) is simply the inverse of salt passing or in other way S_R is 100 minus S_p. Therefore, S_R is described in the equation 5 [Kucera, 2015].

$$S_R = 1 - S_P = \left(1 - \frac{C_p}{C_f}\right) \times 100 \tag{5}$$

The higher the salt rejection, the better the system performs. A low salt rejection can mean that the membranes require cleaning or replacement. The majority of feed water salt will be rejected by a well-designed RO system with properly working RO membranes, which will reject 95%–99% of the salt. [Henkens & Smit, 1979]. For the study plant, salt passing and salt rejection were 9.9% and 90.1% (Table 3). Therefore, this plant has a low salt rejection (90.1%) which means the membranes require backwashing or chemical cleaning.

Pressure drop (ΔP)

Pressure drop (ΔP) through membrane is the difference between the pressure of feed water (P_f) and the pressure of concentrate water (P_c) which calculated using equation 6 [Kucera, 2015].

$$\Delta P = P_f - P_c \tag{6}$$

Pressure drop and fouling extent often rise over time as salts build on the membrane surface and the membrane ability to resist physical choking declines. An increase in the number of membrane in one vessel is another factor that contributes to a higher pressure drop. The highest allowable pressure drop is 4 bar per 6-element array [Srivathsan et al., 2014]. For the study plant, pressure drop (ΔP) was 5 bar (Table 3). From this result, it is clear that the plant has a pressure drop slightly higher than the maximum permissible limit; therefore, it needs backwashing.

Simulation of the plant

The Winflows version 4.04 model was used to simulate the performance of RO plant in producing pure water for drinking purposes. Therefore, a sensitivity analysis was conducted as a first step to know the variation effect of the operating parameters on the quantitatively and qualitatively performance of plant in terms of the recovery rate *R* (quantitatively) and the salt rejection (qualitatively). Another objective of the sensitivity analysis was to identify and determine the optimal values of operating parameters.

Sensitivity analysis

The model was run on the average values of the current plant operating parameters that were mentioned in Table 2. Then, one of the operating parameters was changed without changing the rest of the parameters to find out the effect of variation this parameter on the recovery rate and salt rejection, as well as, identify the optimum value for this parameter. Figure 7a shows the effect of feed water temperature (T) variation on the recovery rate and salt rejection. From this figure, it is clear that when the temperature is increased from 5°C to 30°C, there is a continuous increase in the rate of recovery and a continuous decrease in the percentage of salt rejection. Then, when the temperature increases more than 30°C, there is a small decrease in the rate of recovery and a small increase in the percentage of salt rejection. Moreover, it was concluded from this figure that the best operating temperature value is 20°C, at which the recovery rate and the salt rejection rate are 60% and 97.8%, respectively.

Figure 7b shows the effect of feed pH variation on the recovery rate and salt rejection. From this figure, it can be seen that the recovery rate increases by a very small amount (0.1%) when the pH value increases from 4 to 5, while when the pH value increases from 5 to 6, it does not cause any change in the value of the recovery rate. When the pH value increases from 6 to 7, there is a significant increase (0.3%) in the value of the recovery rate, while it decreases significantly when the pH value increases from 6 to 7. Finally, when the pH value increases from 8 to 10, it does not cause any noticeable change in the value of the recovery rate. Therefore, it is clear that the maximum value of the recovery rate was 71.1% at a pH value of 6. On the other hand, the value of the salt rejection fluctuated when the pH value changed from 4 to 10. The maximum value of the salt rejection was approximately 97.4% at the two pH values of 6 and 8. Therefore, the best value for pH was 7 at which the recovery rate and salt rejection were 71.1% and 97.3%, respectively. Figure 7c shows the effect of feed TDS variation on the recovery rate and salt rejection. From this figure, it is clear that the recovery rate decreases almost linearly when the feed TDS value increases from 1700 ppm to 6500 ppm. On the other hand, the value of the salt rejection increases when the value of the feed TDS value increases from 1700 ppm to 3000 ppm, while when the value of the TDS value increases more than 3000 ppm, a decrease in the value of the salt rejection ratio occurs. Therefore, the best feed TDS value is 2500 ppm, at which the recovery rate value and the salt rejection ratio are 71% and 97.4%, respectively.

Figure 7d shows the effect of feed flow rate variation on the recovery rate and salt rejection. From this figure, it is clear that the recovery rate

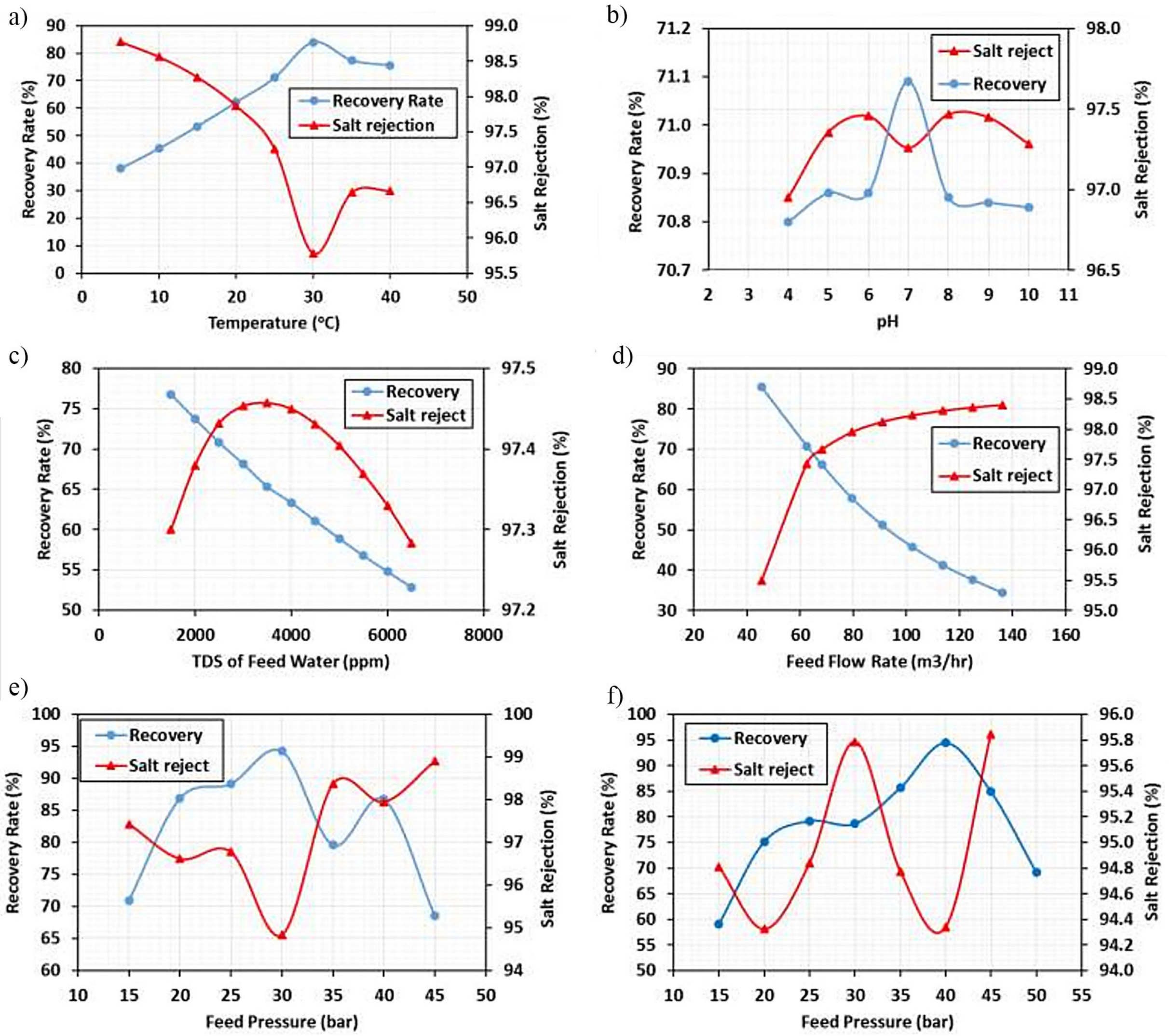


Figure 7. Effect a) water temperature; b) pH; c) TDS; d) feed flow rate on recovery rate and rejection. Effect of feed pressure on recovery rate and salt rejection for feed e) TDS = 250 ppm; f) for feed TDS = 5000 ppm

decreases almost linearly when the value of the feed flow rate increases from 45 m^3/hr to 138 m^3/hr, while the salt rejection rises with rapidly rate in the beginning until the flow rate becomes 60 m^3/hr, after which the increase rate of the rejection rate was reduced gradually with increase the flow rate from 60 m^3/hr to 138 m^3/hr. Therefore, the best value for the flow rate is 60 m^3/hr; then the value for the recovery rate and the salt rejection rate are 70% and 97.5%, respectively. The effect of feed pressure on the plant production was studied for two cases of salt concentration were 2500 ppm and 5000 ppm, due to the fluctuation of salts in the raw water. Figure 7e shows the effect of feed pressure variation on the recovery rate and salt rejection for the case of feed TDS was 2500 ppm. From this figure, it is clear that there is a fluctuation in the values of the recovery rate and salt rejection when the feed pressure changes from 15 to 45 bar. The highest value of the recovery rate was 95%, while the lowest value of the salt rejection rate was 94.8%, both of which were obtained at a pressure value of 30 bar. Therefore, the best pressure value is 17 bar, at which the recovery rate and salt rejection are 80% and 97%, respectively.

Figure 7f shows the effect of feed pressure variation on the recovery rate and salt rejection for the case of feed TDS was 5000 ppm. From this figure, it is clear that the value of the recovery rate increases until it reaches its maximum value of 95% at a feed pressure of 40 bar, while after increasing the pressure to more than 40 bar, a decrease in the value of the recovery rate occurs. On the other hand, there is a fluctuation in the value of the salt rejection ratio when the pressure value changes from 15 to 45 bar. The highest value of the salt rejection percentage was 95% at a feed pressure of 30 bar, while at a feed pressure of 20 bar the lowest value of the salt rejection percentage was obtained. Therefore, the best feed pressure is 30 bar, at which the recovery rate and salt rejection are 80% and 95.8%, respectively.

Effect of membrane age

Membrane age is the number of years to use from the beginning of its installation in the vessel of the plant. It is expected that the old membrane will be less efficient than the new membrane because using the membrane for several years without replacing will exposed it to the effect of fouling and scaling. Therefore, the Winflows software was used for the purpose of studying the effect of increasing the membrane age on various performance parameters of the plant.

Figure 8a shows the effect of membrane age on the recovery rate and salt rejection. From this figure, it is clear that the increase in the membrane age lead to an almost linear decrease in the recovery rate, while the salt rejection was a relatively low rate of decreasing before 5 years and after 5 years a significant deterioration in the salt rejection will occur. Therefore, the period of use of the membrane should not exceed 5 years, at which time the recovery rate and the percentage of salt rejection were 55% and 94%, respectively. Figure 8b shows the effect of membrane age on the TDS of permeate

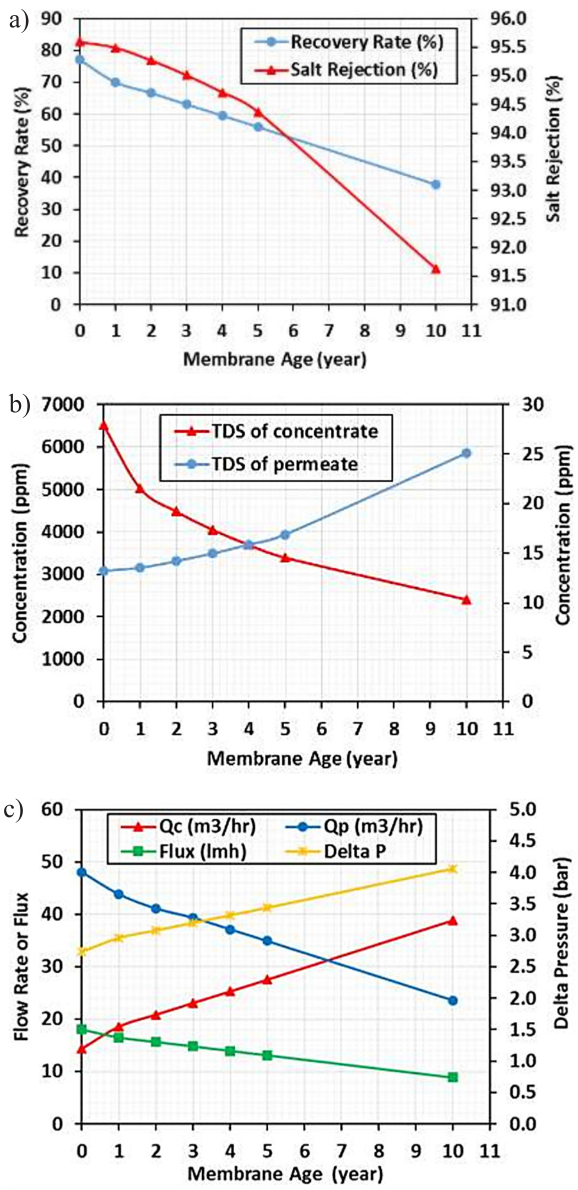


Figure 8. Effect of increasing the membrane age on: a) the recovery rate and salt rejection, b) TDS of permeate and TDS of concentrate, c) the feed flow, concentrate flow, flux, and pressure drop

and concentrate. From this figure, it is clear that the increase in the membrane age causes an increase in the TDS of permeate water and a decrease in the TDS of concentrate water. Over the age of 5 years, the TDS of permeate water was increased from 13 ppm to 16 ppm, while the TDS of concentrate water was decreased from 6,500 ppm to 3,000 ppm. Figure 8c shows the effect of membrane age on the feed flow, concentrate flow, flux, and pressure drop. This figure shows that increasing the membrane age will lead to a linear increase in the pressure drop and concentrate flow (Q_c), while the permeate flow (Q_p) and membrane flux will decrease with increasing membrane age. Over the age of 5 years, the pressure drop was increased from 32 bar to 40 bar and the concentrate flow was increased from 15 m^3/hr to 28 m^3/hr, while the permeate flow was decreased from 48 m^3/hr to 35 m^3/hr and membrane flux was decreased from 19 lmh to 12 lmh.

Simulation of permeate TDS

Finally, the Winflows model was applied to previous recorded measurements to see how well the model represented them and to compare the simulated results of the model with the previous measurements. The closeness or congruence between the measured and simulated values was determined using the coefficient of determination R^2. Then, the relationship between the measured and represented values was identified. Figure 9 shows a time-series diagram between the measured TDS of feed and permeate water for the RO unit during year of 2021. From this figure, it was noted that the TDS of permeate water are significantly lower than the TDS of feed water. Moreover, this figure shows that the TDS records of feed water fluctuated continuously. The minimum and maximum TDS of the feed water were 1020 ppm and 7000 ppm, respectively.

The TDS of permeate water for each day of the year 2021 was calculated using the Winflows software by entering the corresponding TDS of feed water, as well as by entering the values of the operating parameters of the RO unit that mentioned in Table 2. Figure 10 represents a time-series diagram between the measured and simulated TDS of permeate water for the RO unit during year of 2021. From this figure, it is clear that the simulated values of TDS were lower than the measured values,

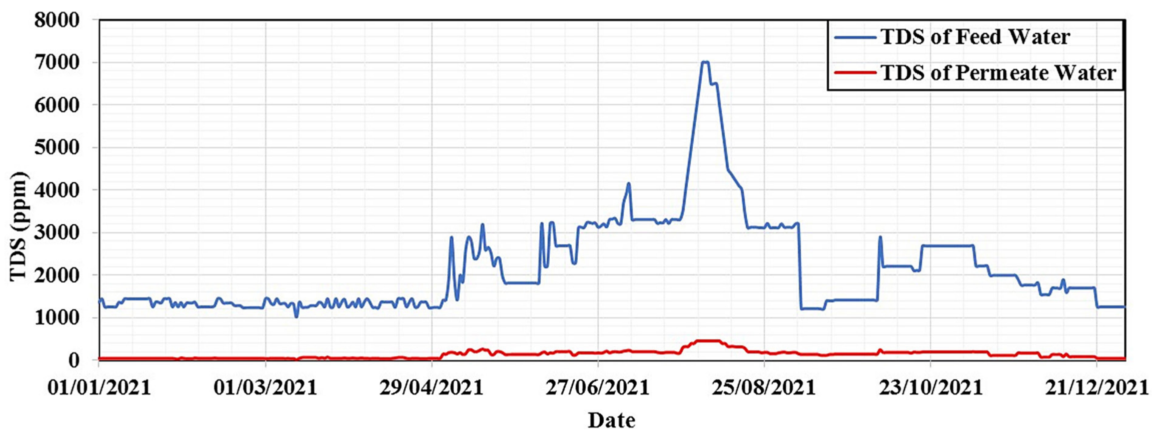


Figure 9. Measured TDS of the feed and permeate water of the plant

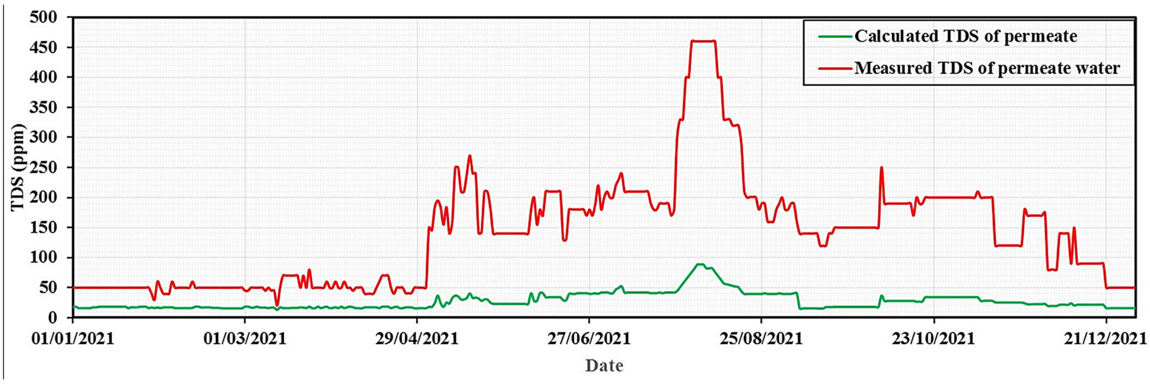


Figure 10. Measured and simulated TDS of the permeate water for the plant

which indicates that the results of the Winflows software were underestimated in relation to the actual value. The reason behind this result may be due to the old age of the membranes and their exposure to fouling and scaling. In order to reveal the relationship between the simulated and measured TDS values, scatter plot correlation between them was drawn, as presented in Figure 11. Through this figure, it is shown as an average that the measured TDS was equal to 5.3 multiplied by the simulated within an error rate of approximately 17% (R^2 = 0.83).

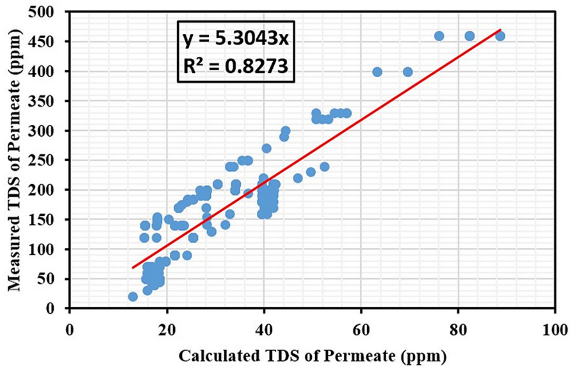


Figure 11. The relationship between the measured and simulated TDS of the permeate water for the plant

CONCLUSIONS

This study was conducted to assess and simulation the performance of the reverse osmosis plant in the Al-Maqal port, Basrah province, southern Iraq. Within the limitations and hypotheses of this study, the following conclusions can be drawn. This study concluded that the studied parameters (pH, Turbidity, TA, TH, TDS, EC, Cl^-, HCO_3^-, K^+, Mg^{+2}, and Ca^{+2}) of product water by the RO plant in AL-Maaqel port were within the Iraqi standard limits. Therefore, the product water was suitable for drinking and other domestic uses. In addition, the study concluded the effectiveness of pretreatment processes in removing turbidity from water before entering the membranes to protect them from fouling. The percentage of turbidity removal reached 98% at the last process before the membranes, which is the filter cartridge. Nevertheless, the value of turbidity was 1.5 NTU this means that more follow-up is required to make the turbidity less than 1 before the membranes. The recovery rate of plant (72%) was within the run limitations for Brackish RO systems (50–85%). The permeate flux of plant (20 lmh) was considered acceptable for limitation of brackish surface water (14–24 lmh). The plant has a low salt rejection (90.1%) lesser than the limit (95%) for properly functioning RO membranes. Moreover, the plant has a pressure drop (5 bar) slightly higher than the maximum permissible limit (4 bar); therefore, the membranes require backwashing or chemical cleaning. For maximum performance of the plant (maximum recovery rate and salt rejection), the best operating parameters for temperature, pH, feed TDS, feed flow rate, feed pressure for feed TDS of 2500 ppm, and feed pressure for feed TDS of 5000 ppm were 20°C, 7, 2500 ppm, 60 m^3/hr, 17 bar and 30 bar. Moreover, the age membrane should not exceed 5 years. From the simulation results of plant, the simulated TDS by Winflows software was underestimated for the measured TDS by 5.3. The coefficient of determination (R^2) between the simulated and measured TDS was 0.83. Therefore, the simulated TDS of permeate multiplied by 5.3 was given a good estimation for actual TDS within an acceptable error rate of 17%

REFERENCES

1. Agashichev S., Almalek S., Almazrouei A., Osman E., Kumar J., Ali T., Abdulla M. 2009. The influence of seawater temperature on the net driving force and CP degree in reverse osmosis. Desalination and Water Treatment, 6(1–3), 276–280.
2. Al-karaghouli A., Kasmerski L. 2010. Economic and Technical Analysis of a Reverse-Osmosis Water Desalination Plant. National Renewable Energy Laboratory [Internet], 1(3), 318–328. http://www.wrri.nmsu.edu/conf/conf11/reverse_osmosis_deep.pdf
3. Charcosset C. 2009. A review of membrane processes and renewable energies for desalination. Desalination, 245(1–3), 214–231.
4. Chu K.H., Lim J., Kim S.J., Jeong T.U., Hwang M.H. 2020. Determination of optimal design factors and operating conditions in a large-scale seawater reverse osmosis desalination plant. Journal of Cleaner Production, 244.
5. Federation WE. 1999. Standard Methods for the Examination of Water and Wastewater Standard Methods for the Examination of Water and Wastewater. Public Health, 51(1), 940–940. http://www.ajph.org/cgi/doi/10.2105/AJPH.51.6.940-a
6. Greenlee L.F., Lawler D.F., Freeman B.D., Marrot B., Moulin P. 2009. Reverse osmosis desalination: Water sources, technology, and today's challenges. Water Research, 43(9), 2317–2348.
7. Hamad J.Z., Ha C., Kennedy M.D., Amy G.L. 2013.

Application of ceramic membranes for seawater reverse osmosis (SWRO) pre-treatment. Desalination and Water Treatment, 51(25–27), 4881–4891.

8. Hasan Z.I., Taleb A.H. 2020. Assessment of the Quality of Drinking Water for Plants in the Al-Karkh, Baghdad, Iraq. Ibn AL- Haitham Journal For Pure and Applied Sciences, 33(1), 1.
9. Henkens W.C.M., Smit J.A.M. 1979. Salt rejection and flux in reverse osmosis with compactible membranes. Desalination, 28(1), 65–85.
10. Hu J., Cao S.A., Han J., Hao X. 2011. Research on corrosion factors and corrosion prevention measure of carbon steel in produce water of reverse osmosis in power plant. In: Asia-Pacific Power and Energy Engineering Conference, APPEEC.
11. Idrees M.F. 2020. Performance Analysis and Treatment Technologies of Reverse Osmosis Plant – A case study. Case Studies in Chemical and Environmental Engineering, 2.
12. Jamaly S., Darwish N.N., Ahmed I., Hasan S.W. 2014. A short review on reverse osmosis pretreatment technologies. Desalination, 354, 30–38.
13. Kucera J. 2014. Introduction to Desalination. Desalination: Water from Water, 9781118208, 1–37.
14. Kucera J. 2015. Reverse osmosis: Industrial processes and applications.
15. Lilane A., Saifaoui D., Hariss S., Jenkal H., Chouiekh M. 2020. Modeling and simulation of the performances of the reverse osmosis membrane. In: Materials Today: Proceedings, 24, 114–118.
16. Lin S., Zhao H., Zhu L., He T., Chen S., Gao C., Zhang L. 2021. Seawater desalination technology and engineering in China: A review. Desalination, 498.
17. Miranda M.S., Infield D. 2003. A wind-powered seawater reverse-osmosis system without batteries. Desalination, 153(1–3), 9–16.
18. Qiu T., Davies P.A. 2012. Comparison of configurations for high-recovery inland desalination systems. Water (Switzerland), 4(3), 690–706.
19. Sarai Atab M., Smallbone A.J., Roskilly A.P. 2016. An operational and economic study of a reverse osmosis desalination system for potable water and land irrigation. Desalination, 397, 174–184.
20. Srivathsan G., Sparrow E.M., Gorman J.M. 2014. Reverse osmosis issues relating to pressure drop, mass transfer, turbulence, and unsteadiness. Desalination, 341(1), 83–86.
21. Taha A.H., Joshi H., Garg M.C., Manhee H.K. 2021. Case Study of Evaluation RO Desalination Systems for Potable Water in Safwan, Iraq. Journal of Geoscience and Environment Protection, 9(2), 158–181.
22. Vaithilingam S., Gopal S.T., Srinivasan S.K., Manokar A.M., Sathyamurthy R., Esakkimuthu G.S., Kumar R., Sharifpur M. 2021. An extensive review on thermodynamic aspect based solar desalination techniques. Journal of Thermal Analysis and Calorimetry, 145(3), 1103–1119.
23. Wang L.K., Yung-Tse Hung N.K.S. 2007. Advanced Physicochemical Treatment Technologies.
24. Wang Z., Zhang Y., Wang T., Zhang B., Ma H. 2021. Design and energy consumption analysis of small reverse osmosis seawater desalination equipment. Energies, 14(8).
25. Wasfy K.I. 2017. Brackish water desalination using reverse osmosis system. Misr Journal of Agricultural Engineering, 34(4), 1783–1800.
26. Wenten I.G., Khoiruddin. 2016. Reverse osmosis applications: Prospect and challenges. Desalination, 391, 112–125.
27. Zhang H., Sun H., Liu Y. 2020. Water reclamation and reuse. Water Environment Research, 92(10), 1701–1710.
28. Zhu Z., Peng D., Wang H. 2019. Seawater desalination in China: An overview. Journal of Water Reuse and Desalination, 9(2), 115–132.
29. Zioui D., Aburideh H., Tigrine Z., Hout S., Abbas M., Merzouk N.K. 2018. Experimental Study on a Reverse Osmosis Device Coupled with Solar Energy for Water Desalination. In: Proceedings of 2017 International Renewable and Sustainable Energy Conference, IRSEC 2017.