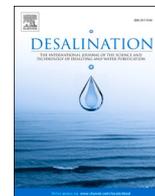# bradscholars

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Simulation and optimisation of a medium scale reverse osmosis brackish water desalination system under variable feed quality: Energy saving and maintenance opportunity

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HIGHLIGHTS

- Simulation and optimisation of a medium scale brackish water desalination plant are presented.
- Impact of pressure, flow rate, and temperature on performance are evaluated.
- Optimisation results in 19 % reduction in specific energy and 4.46 % gain in productivity.
- Optimisation results in membrane cleaning and maintenance opportunity without full shutdown.

ARTICLE INFO

ABSTRACT

In this work, we considered model-based simulation and optimisation of a medium scale brackish water desalination process. The mathematical model is validated using actual multistage RO plant data of Al-Hashemite University (Jordan). Using the validated model, the sensitivity of different operating parameters such as pump pressure, brackish water flow rate and seasonal water temperature (covering the whole year) on the performance indicators such as productivity, product salinity and specific energy consumption of the process is conducted. For a given feed flow rate and pump pressure, winter season produces less freshwater that in summer in line with the assumption that winter water demand is less than that in summer.

With the soaring energy prices globally, any opportunity for the reduction of energy is not only desirable from the economic point of view but is an absolute necessity to meet the net zero carbon emission pledge by many nations, as globally most desalination plants use fossil fuel as the main source of energy. Therefore, the second part of this paper attempts to minimise the specific energy consumption of the RO system using model-based optimisation technique. The study resulted not only 19 % reduction in specific energy but also 4.46 % increase in productivity in a particular season of the year. For fixed product demand, this opens the opportunity for scheduling cleaning and maintenance of the RO process without having to consider full system shutdown.

1. Introduction

The water that covers three-fourths of the earth is, regrettably, saline water and is not good for use even for irrigation purpose (biggest consumer of the total freshwater is being used for agriculture around the world). Globally (including the Middle East), the lack of access to freshwater and the scarcity of natural resources threatens the livelihoods of people. Desalination of seawater and brackish water has been viewed as a feasible solution to meet the increasing demand for freshwater for human consumption as well as industrial applications. As a result,

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several seawater and brackish water desalination plants, particularly in places with a lack of freshwater, were built throughout the world.

The Middle East receives less rainfall than the global average of 72 cm per year—the typical range in the region is between 20 and 40 cm per year [1]. Therefore, water desalination is the natural choice to address the water scarcity in this region. Over the course of >50 years, seawater desalination plants were widely built in several Middle Eastern nations. Nearly half of the desalination capacity of the world is in the Middle East. The growth of water desalination is also linked to energy production, food security, economic considerations and health and well-being [2]. Providing clean water and sanitation is one of the 17 sustainable development goals (SDG 6). However, SDG 2 (zero hunger), SDG 3 (good health and well-being), SDG 8 (decent work and economic growth), SDG 16 (peace and justice) are all linked to sustainable supply of water. Contaminated water transmitting diseases such as diarrhoea, cholera, dysentery, typhoid, and polio and causing over half a million diarrhoeal death each year (http://www.who.int/news-room/fact -sheets/detail/drinking-water, accessed on 26/11/2022) clearly shows the link between health and water. Three out of 4 jobs that make up the global workforce are either heavily or moderately dependent on water (https://en.unesco.org/news/water-drives-job-creation-and-economic -growth-says-new-report, accessed on 27/11/2022; [3]).

The membrane technology and specifically Reverse Osmosis (RO) unit has been employed more frequently as the most used desalination method from small [4], medium [5] to large scale [6] to desalinate seawater and brackish water. The exponential rise of RO systems is due to advancements in membrane materials in terms of their durability and anti-fouling characteristics. Due to these advantages, the RO process has seen several industrial applications, including the treatment of wastewater, food processing, and the oil sector [7–9].

According to Zapata-Sierra et al. [10], the RO technology has advanced to the point where it now accounts for 80 % of desalination plants deployed worldwide and 44 % of the world's total water production capacity. The market for RO membranes was assessed at USD 5.4 billion in 2019 to USD 8.3 billion by 2024 and is anticipated to increase at a Compound Annual Growth Rate (CAGR) of 10.2 % from now until 2030, when it is predicted to generate USD 7.70 billion in revenue [11].

High pressure pumps used in the RO process during desalination uses a significant amount of energy. The energy used in the seawater desalination process utilising the RO process ranges from 2 to 5 kW per cubic meter, which is a negligible amount compared to the 15 to 25 kW per cubic meter used in MSF (thermal process) [12,13]. Over the decades, RO processes have gone through several changes, in terms of design and operation that have had an impact on the water quality generated in addition to an improvement in sustaining the process at a lower energy consumption. Since the desalination plant can be small or large depending on the location and need, the RO process has the inherent flexibility. However, it should be noted that the performance and consumption of energy of seawater and brackish water RO desalination plants are directly impacted by several critical issues such as inadequate pre-treatment, the effects of scaling and fouling and changing feed quality. Due to these, plant managers frequently have to operate the facility below optimum conditions (specifically for brackish water desalination of variable salinity), resulting in lower output and energy efficiency [14,15].

The following literatures highlight some successful studies on modelling, simulation, optimisation with a focus in reducing specific energy consumption of water desalination plants based on the RO technology.

Afonso et al. [16] assessed the technical and economical operation of a small-size brackish water RO desalination plant in the Jordan Valley Zarqa aquifer equipped with a FilmTec RO spiral wound membrane type SW30-2521. Experimentally, the authors investigated the optimal transmembrane pressure, brackish water flow rate and water temperature to attain the maximum permeate flow rate besides acquiring the lowest specific energy consumption. The results showed the positive influence of pump pressure on water flux while feed flow rate has insignificant influence on water flux. This in turn has increased the dependency on pump pressure and water temperature to secure the lowest energy usage. Specifically, the feed flow rate was taken at 4.8 m³/day (optimal value) instead of 14.4 m³/day (design value) to secure the lowest pumping energy at an elevated water productivity. Furthermore, the economical evaluation of the process with 2300 ppm feed salinity has resulted in freshwater production cost of 0.26 €/m³ (0.28 $/m³).

A thorough performance and economic evaluation (based on the specific energy consumption) of the brackish water reverse osmosis (BWRO) desalination facility of Gabes in Tunisia was carried out by Walha et al. [17]. The authors attempted to obtain freshwater with acceptable salinity (close to WHO standard of 500 ppm), maximum productivity and lowest energy usage. The economic evaluation was focused on lessening the specific energy consumption during one pass RO operation. Use of turbine as energy recovery device (ERD) reduced the overall specific energy (pumping energy) of the RO system by 15 %. It was ascertained that the specific energy consumption of Gabes desalination plant is 0.81 kWh/m³ throughout the desalination of brackish water (2677 ppm).

El-Ghonemy [18] evaluated the performance and cost analysis of two stage small-scale RO brackish water desalination systems of 50 m³/day in the northern part of Saudi Arabia (Skaka city located in *Al*-jouf Area) used to desalinate 2000 ppm ground water. The process was powered by solar energy. The cost analysis resulted in 2 US $ per cubic meter of freshwater and 3.99 kWh/m³ of specific energy consumption.

The optimisation of seawater RO process based Mixed-Integer Nonlinear Programming was utilised by Du et al. [19] to investigate the optimal design (network) of RO system for a wide range of feed salinity that ensures the lowest specific energy consumption. The RO system was equipped with a pressure exchanger (PX) to reduce the overall pumping energy. The results showed that the one stage RO system was best to desalinate 32,000 ppm feed salinity, while two stages RO system was the best option to desalinate 28,000 ppm. Furthermore, it was found that the specific energy consumption was sensitive to seawater salinity, water temperature and pump pressure. The optimum (minimum) network resulted in the lowest specific energy consumption of 2.418 kWh/m³ for 32,000 ppm.

Using an enhanced mathematical model, Ruiz-García and Ruiz-Saavedra [20] investigated the operation of a BWRO facility in the Canary Islands, Spain powered by an electrical engine. The specific goal of the study was to assess energy consumption during the operational ten years. Specifically, the increase of specific energy consumption due to membrane decay was accounted for besides assessing the efficacy of membrane replacement and chemical cleaning. The specific energy consumption and freshwater production cost was found to vary between 1.4 and 1.7 kWh/m³, and $0.39/m³, respectively.

Atab et al. [21] utilised a mathematical model based on solution-diffusion theory to characterise the influence of brackish water temperature, salinity, pump pressure, water recovery, and design parameters on the specific energy consumption of a RO brackish water desalination system powered by an electrical engine. The brackish water temperature was found to have a positive effect on the productivity and specific energy consumption despite increasing product salinity. The use of an ERD has reduced the specific energy consumption from 2.8 kWh/m³ to 0.8 kWh/m³ of freshwater. The freshwater production cost was estimated to be $0.14/m³ (£0.11/m³) (currency convertor: 25th of January 2023) for the production capacity of 24,000 m³/day.

For steady state operation of seawater and brackish water spiral wound module of RO desalination system (powered by an electrical engine) of seven elements in a pressure vessel equipped with an energy recovery device (ERD), Karabelas et al. [22] studied the influences of membrane permeability factor, friction losses, and efficiency of pump and ERD on the specific energy consumption. The specific energy consumptions of the proposed desalination system with 85 % and 95 % of

pump and ERD efficiency, respectively, used to desalinate 4000 ppm (seawater) and 2000 ppm (brackish water) were found to be 2.374 and 0.378 kWh/m³, respectively.

Alsarayreh et al. [23] investigated the effect of energy recovery device (ERD) in a medium-sized BWRO desalination plant of Arab Potash Company (APC) in Jordan (1200 m³/day) powered by an electrical engine. In this regard, the evaluation of specific energy consumption with and without an ERD was carried out using the simulation-based model. The influences of pump pressure, temperature, and flow rate on the specific energy consumption with and without an ERD were investigated besides utilising different efficiencies of an ERD. The specific energy consumption was found to be reduced between 47 and 53 % for a RO system equipped with an ERD (the specific energy consumption of original RO system is 0.837 kWh/m³).

In the Parang Islands in Indonesia, Fairuz et al. [24] analysed the energy, economic and environmental aspects of a small-scale RO system (5 m³/day) powered by PV technology. In this regard, three scenarios of the integrated system were suggested including the RO/PV with and without a storage battery and RO/diesel generator. This system consumes 3.5 kWh/m³ at the lowest freshwater production cost of $0.627/m³ with 5 years of payback period.

Table 1 summarises the features of the above studied water desalination plants based on RO process. Clearly, the cost of water or specific energy consumption using renewable energies is higher in most cases compared to those using fossil fuel-based energy. This is due to the fact that, renewable energy-based systems are still under development [30] and will take several years for full commercial implementation.

With soaring energy prices globally, freshwater production cost will no doubt increase around the globe. Although the use of renewable energy sources would be an ideal situation to combat not only the energy price but also the carbon footprint, the commercialization of renewable energy based desalination processes is still remote. Therefore, no doubt, everybody's focus will be either to reduce the current level of energy consumption or to increase productivity per unit of energy use.

Despite the utilisation of different techniques used by several researchers (discussed above) to lessening the specific energy consumption (SEC) of RO systems based seawater and brackish water desalination, this study intends to use model based simulation of brackish water desalination RO system to develop in depth understanding of the impact of various parameter on SEC and then use optimisation to determine the optimum operating conditions of the process to minimise the SEC. First, the model of the process is validated against an actual medium scale (1992.24 m³/day) brackish water multistage RO system of Al-Hashemite University (Jordan) and evaluate the performance and scope of improvement of the RO process using a model based simulation and optimisation technique. In the simulation part, we investigate the sensitivity of pump pressure, brackish water flow rate and water temperature on the water productivity, water quality and energy consumption. For the optimisation part, we aim to minimise the SEC by optimising the feed pressure and flow rate simultaneously.

2. RO process model

With reference to a simple RO process shown in Fig. 1, the process model equations are given below. RO configuration can vary widely depending on the task. Al-Obaidi et al. [31] included over 20 such RO configurations. Note, the model equations are shown for a single membrane of the RO system [31]. The model equations can be easily tailored for any configuration [2,31,32].

Eq. (1) is used to predict the permeate flow rate (Q_p) through the single membrane.

$$Q_p = A_w \, NDP_{fb} \, A_m \tag{1}$$

The net driving pressure of feed and brine (NDP_{fb}) is estimated using Eq. (2)

Table 1
A summary of the water desalination plants, associated energy usage and freshwater production cost.

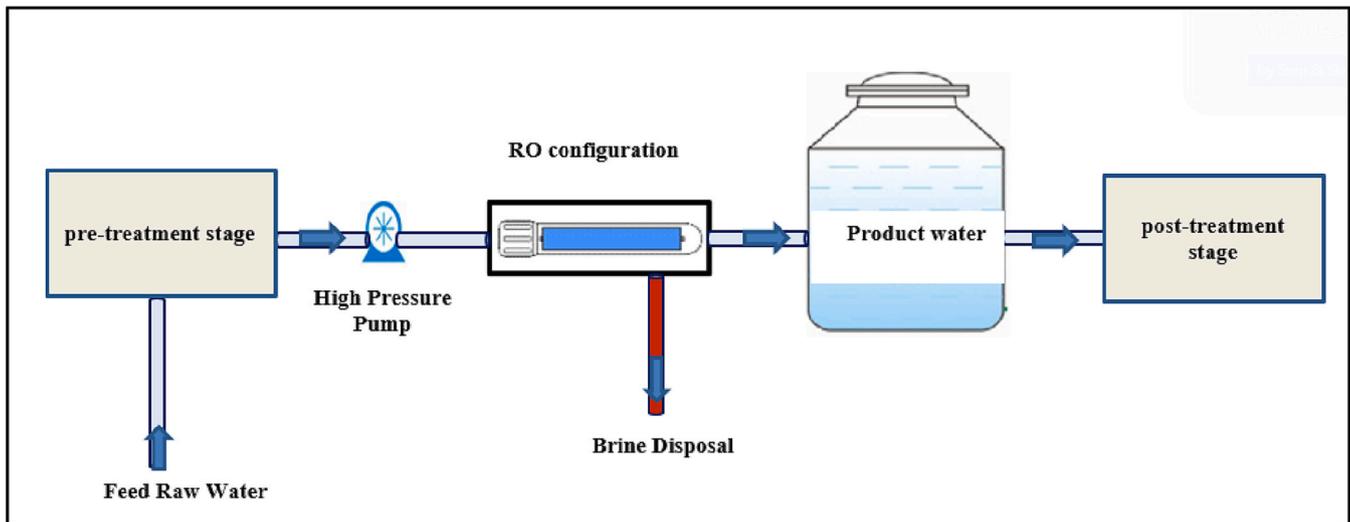| Authors	Water type		Scale				Salinity (ppm)		Capacity (m³/day)	Energy source					Energy usage (kWh/m³)	Fresh water cost ($/m³)
	Seawater	Brackish water	Small	Medium	Large		Feed water	Product water		Fossil	Solar	Wind	Integrated (Fossil/solar/wind)			
Afonso et al. [16]		✓	✓				2300	35		✓				0.81	0.28
Walha et al. [17]		✓					2677	328		✓				7.33–7.73	7.21–7.64
Helal et al. [25]	✓		✓				45,000	93–140	20		✓			3.99	2.0
El-Ghonemy [18]	✓						2000		50		✓			2.418 (Optimum)	0.502–0.597
Du et al. [19]	✓				✓		32,000–45,000	490–500	5040–7041.6	✓				5	3.693–3.812
Mokheimer et al. [26]		✓	✓						5				✓	1.4–1.7	0.39
Ruiz-García and Ruiz-Saavedra [20]		✓	✓				3144.7–7790.7	50–100	360	✓					
Atab et al. [21]		✓			✓		15,000	400	24,000	✓				0.8	0.14
Gu et al. [27]		✓	✓				35,000		0.9	✓				2.7–2.9	
Karabelas et al. [22]		✓					40,000			✓				2.374	
Karimanzira et al. [28]	✓	✓	✓				2000	777.43	185.46	✓		✓		0.378	5.578
							2500								
Alsarayreh et al. [23]	✓	✓		✓			1098	2	1200	✓				0.837	
Shalaby et al. [29]		✓	✓				1000–3000	45–250	2.27			✓			0.77–1.24
Fairuz et al. [24]		✓	✓				4000	500	5	✓				3.5	0.627
This work		✓			✓		1650.9	500	1992.24	✓				0.459	

Fig. 1. Schematic diagram of a typical RO process.

$$NDP_{fb} = P_{fb} - P_p - \pi_b + \pi_p \tag{2}$$

Eqs. (3) and (4) are used to predict the feed-brine pressure (P_{fb}) and pressure drop along the membrane element ($\Delta P_{drop,E}$), respectively.

$$P_{fb} = P_f - \frac{\Delta P_{drop,E}}{2} \tag{3}$$

$$\Delta P_{drop,E} = \frac{9.8692 x 10^{-6} \, A^* \rho_b \, U_b^2 \, L}{2 d_h \, Re^n} \tag{4}$$

The Reynolds number (Re) and bulk flow rate in the feed channel (Q_b) are estimated by:

$$Re = \frac{\rho_b d_h Q_b}{t_f \, W \, \mu_b} \tag{5}$$

$$Q_b = \frac{Q_f + Q_r}{2} \tag{6}$$

The mass and solute balance equations are given by:

$$Q_f = Q_r + Q_p \tag{7}$$

$$Q_f \, C_f - Q_r \, C_r = Q_p \, C_p \tag{8}$$

The osmotic pressure in the brine (π_b) and permeate (π_p) sides are given by:

$$\pi_b = 0.7994 \, C_b \, [1 + 0.003 \, (T - 25)] \tag{9}$$

$$\pi_p = 0.7994 \, C_p \, [1 + 0.003 \, (T - 25)] \tag{10}$$

The bulk (C_b), retentate (C_r), permeate (C_p) concentrations and solute concentration on the membrane wall (C_w) are:

$$C_b = \frac{C_f + C_r}{2} \tag{11}$$

$$C_r = C_f \, [1 - Rec]^{-Rej} \tag{12}$$

$$C_p = \frac{C_f}{Rec} \, [1 - (1 - Rec)]^{(1 - Rej)} \tag{13}$$

$$C_w = C_p + \left(\frac{C_f + C_r}{2} - C_p \right) exp \left(\frac{Q_p / A_m}{k} \right) \tag{14}$$

The water (J_w) and solute (Q_s) fluxes through the membrane are given by:

$$J_w = \frac{B_s Rej}{(1 - Rej)} \tag{15}$$

$$Q_s = B_s \left(C_w - C_p \right) \tag{16}$$

The solute rejection (Rej) is given by:

$$Rej = \frac{C_f - C_p}{C_f} \tag{17}$$

The mass transfer coefficient (k) and Schmidt number (Sc) are calculated using Eqs. (18) and (19)

$$k = 0.664 \, k_{dc} Re_b^{0.5} \, Sc^{0.33} \left(\frac{D_b}{d_h} \right) \left(\frac{2 d_h}{L_f} \right)^{0.5} \tag{18}$$

$$Sc = \frac{\mu_b}{\rho_b D_b} \tag{19}$$

The water recovery of a single membrane (Rec) is

$$Rec = \frac{Q_p}{Q_f} = \frac{(C_r - C_f)}{(C_r - C_p)} \tag{20}$$

The calculation of specific energy consumption (SEC_{RO}) is conducted using

$$SEC_{RO} = \frac{Pf \, Qf}{Qp \, \epsilon pump} \tag{21}$$

The physical properties (density (ρ_b), diffusivity (D_b), and viscosity (μ_b) of the brackish water are included below

$$\rho_b = 498.4 \, m_f + \sqrt{\left[248400 \, m_f^2 + 752.4 \, m_f C_b \right]} \tag{22}$$

$$m_f = 1.0069 - 2.757 x 10^{-4} \, T \tag{23}$$

$$D_b = 6.725 10^{-6} \, exp \left\{ 0.1546 10^{-3} \, C_b - \frac{2513}{T + 273.15} \right\} \tag{24}$$

$$\mu_b = 1.234 x 10^{-6} \, exp \left\{ 0.0212 \, C_b + \frac{1965}{T + 273.15} \right\} \tag{25}$$

The model is coded and solved using gPROMS software.

3. Model validation

In this work, we considered brackish water RO desalination system of

Al-Hashemite University, Jordan. The main causes of Jordanian's water shortage are excessive groundwater extraction and a lack of surface water sources. The ground water contains considerable concentrations of pollutants including nitrates, sulphate, sodium, chloride, potassium, fluoride, boron, etc. Thus, it is vital to effectively treat the brackish water using the most developed technologies.

The Hashemite University is located in a semi-desert area in the northwestern Jordanian Badia, 30 km northeast of the capital, Amman. The university was established in 1995 and now has >27,000 students, faculty and administrative staff. The campus consumes >600 m^3 of water per day, rest of the water being used for irrigation purposes.

3.1. Description of the process

The schematic diagram of the whole brackish water multistage RO desalination system of Al-Hashemite University and plant assembly of the pre-treatment and post-treatment are depicted in Fig. 2. The whole brackish water desalination system was designed with a capacity of 1992.24 m^3/day to produce freshwater within the Jordanian standards for drinking water (number 286/2015: product salinity should not exceed the designed value of 700 ppm but more close to 500 ppm recommended by WHO). Note, the 1992.24 m^3/day is the combination of the water productivity of RO system and the blended flow rate of 552 m^3/day as represented in Fig. 2.

The brackish water RO system contains three steps of treatments, pre-treatment, RO system and post-treatment. The pre-treatment stage comprises two steps of Microfiltration Filter (MF) where each step contains two filters. The brackish water is fed into filtration stage at > 3 bar using a feed pump (FP).

The filtered brackish water is then fed into the RO system of three stages connected in a series using a high-pressure pump (HPP) (two duty and stand by HPPs). The first, second and third stages contain six, three, and two pressure vessels (connected in a parallel) where each pressure vessel holds six membranes of spiral wound module (diameter membrane element: 8 in.) connected in a series inside the pressure vessel. The

RO system uses the retentate reprocessing mode where the retentate stream of the first stage is fed into the second stage and so on. To maintain a high productivity of the whole RO system, the booster pump is used to deliver the feed of the third stage with a high pressure. The design characteristics of these filters, RO membranes, pumps and pipes and fitting are listed in Table 2 with detailed operating conditions and water product specifications.

The retentate of the third stage represents the brine stream of the RO system, which is fed into an evaporation bond while the permeate stream of RO system (collected streams of three stages) is fed into an aeration tower (0.75 m) to remove at least 55 % of CO_2 from the permeate. The tower is made from stainless steel 304 with packing support that have a high percentage of free area to allow unrestricted countercurrent flow of down coming liquid and upward flowing vapor. Packing limiters are provided in case there is a risk of packing material movement due to high air flow rate. In addition, 500 mm opening are provided with a cover to allow easy removal of packing material. The easily removable centrifugal air fans are used for cleaning and maintenance. Air to liquid ratio is 25 m^3 of air/m^3 of water to protection grilles for both intake and outlet port.

The product water of the whole brackish water desalination plant is made up of blended brackish water (552 m^3/day) and the permeate flow rate of RO system (1440.24 m^3/day) of the RO process (Fig. 2). Table 2 presents the water productivity of the RO system (1440.24 m^3/day) and the overall water productivity of the whole desalination system (1992.24 m^3/day). Specifically, these productivities reflect high water recovery values of 90 % and 92.5 % for RO system and the whole desalination system, respectively (Table 2). In other words, the combination of product water of RO system and a part of the feed brackish water represents the whole desalination system as can be shown in Fig. 2. The water recovery rate of reverse osmosis (RO) brackish water desalination facilities can vary based on several factors such as feed water quality, type of RO membrane employed, operating circumstances, and plant design. In general, water recovery rates of >90 % are possible in RO brackish water desalination systems [33,34]. However,
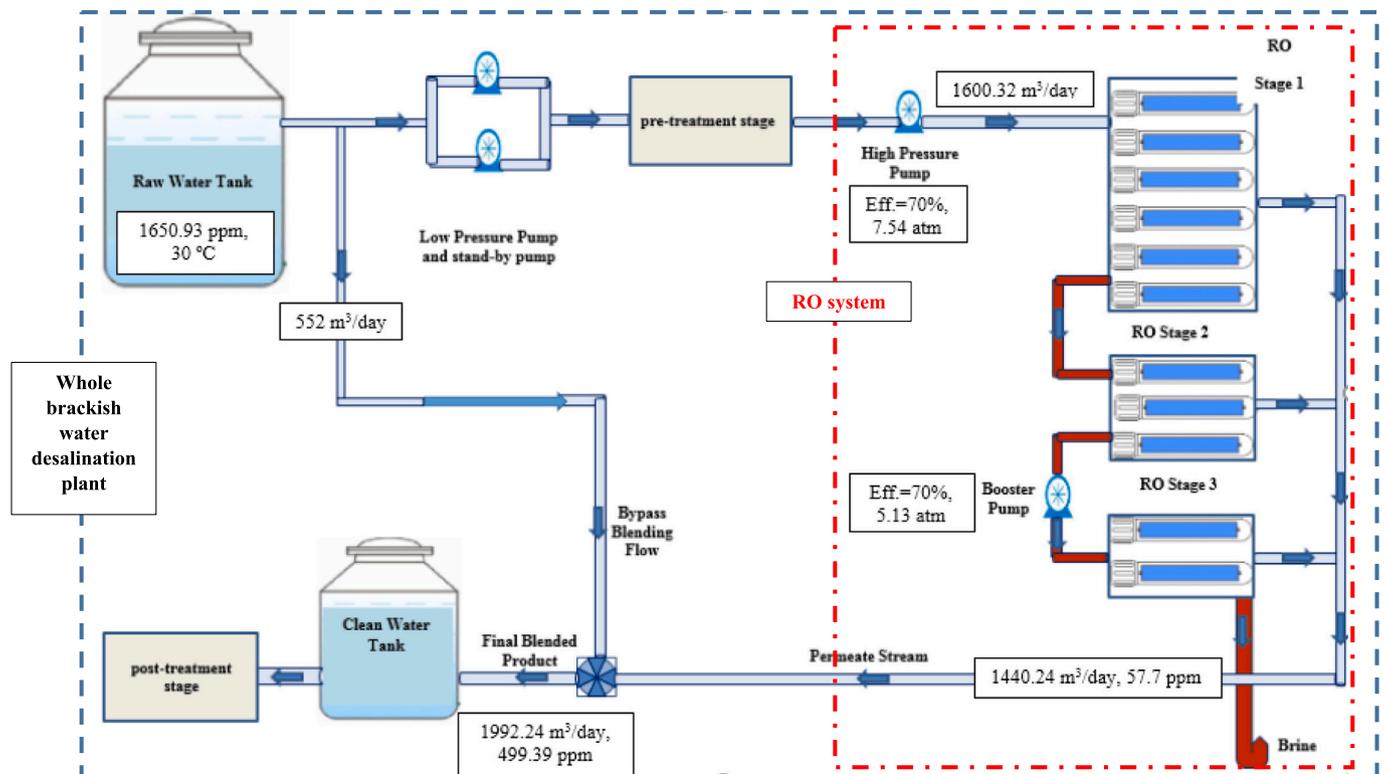

Fig. 2. Schematic diagram of the whole brackish water desalination system of Al-Hashemite University (Jordan).

Table 2
Design specification and operating data for the brackish water RO desalination plant.

Item	Specifications	
Micro filter	Type	Bag filters with universal seat that accepts most standard 7 in. diameter bags
	Nominal bag rating	First filter: 25 μm, Second filter: 5μm
	Material	Polypropylene for bags and non-metallic material for vessel certified for drinking water according to NSF/ANSI Standard 61
	Pressure rating	>3 (bar)
RO membrane	Membrane supplier	DOW FILMTEC™ ECO PRO-400 Element
	Diameter membrane element	8 (inch)
	Module type	Spiral wounded
	Material	TFC
	Min salt rejection	99.60 %
	Total area (A)	37.16 (m^2)
	Length (L)	1 (m)
	Width (W)	37.16 (m)
	Configuration	6-3-2 of six membranes per each pressure vessel
	Maximum operating conditions	Feed pressure	40.464 (atm)
		Pressure drop per element	0.987 (atm)
		Feed temperature	45 (°C)
		Feed flow rate	432 (m^3/day)
	Feed spacer type	NALTEX-129
	Spacer parameters	length of filament in the spacer mesh (L_f)	2.77×10^{-3} (m)
		Feed and permeate spacer thickness (t_f, t_p)	8.6×10^{-4} (m) (34 mils), 5.5×10^{-4} (m)
		Hydraulic diameter (d_h)	8.126×10^{-4} (m)
		A'	7.38 (−)
		n	0.34 (−)
		ε	0.9058 (−)
		k_{dc}	1.501 (−)
Feed pump (FP) and High pressure pump (HPP)	Type	Centrifugal
	Brand	316 St. St.
	Pump efficiency	70 %
	Motor type	Variable speed drive
Pipes and fitting	Material	HDPE or uPVC in the permeate side PN16
		Stainless steel in the feed-concentrate side from the HPP discharge side to the outlet of the brine
		HDPE or uPVC, PN16 between container outlet and product tank inlet
	Pipe velocity	1.5 (m/s) in HDPE or uPVC pipes, 2 (m/s) in stainless steel pipes
Operating data of RO system	Feed flow rate	1600.32 (m^3/day)
	Blending flow rate	552 (m^3/day)
	Feed pressure (inlet pressure of the 1st stage)	7.54 (atm)
	Booster pressure (inlet pressure of the 3rd stage)	5.13 (atm)
	Salinity of brackish water	1650.93 (ppm)
	Feed temperature	30 (°C)
Product water of the RO system	Average productivity	1440.24 (m^3/day)
	Water recovery	90 %
	Product water salinity	57.7 (ppm)
Product water of the whole	Average productivity (capacity)	1992.24 (m^3/day)

Table 2 (*continued*)

Item	Specifications	
desalination system	Water recovery	92.5 %
	Product water salinity	500 (ppm)

note that high water recovery rate comes with a cost in terms of energy consumption. Higher recovery rate will require higher operating pressure resulting in higher energy consumption.

The product water of CWT is fed into clear water reservoir (CWR) after passing through two dosing systems for anti-scalant and acid injection to preserve the requested pH. The dosing rate for anti-scalant is 280 mL/h so the dosing pump operates at a rate above 30 % of its capacity, and anti-scalant shall never diluted >30 %. Anti-scalant dose is usually about 1 ppm. The dosing rate for acid is 1 L/h. Also, the pH of product water should be within the Jordanian standards for drinking water of 8 ± 0.2 unit. The final post-treatment step is the chlorination system. Chlorine system is designed to be operated manually via chlorine dose. Chlorine gas will be withdrawn from a set of two cylinders connected to an electro-automated changeover device with manual bypass valve. The set is designed to be operated as one duty-one standby. Each chlorinator has a maximum capacity of feeding gas rate to ensure that the existing clear water reservoir (1500 m^3) has 1 ppm free residual Cl_2.

As shown in Section 2, the model of the whole RO system of Al-Hashemite University, Jordan (capacity of 1992.24 m^3/day) consists of a large number of algebraic, linear and non-linear equations to represent the mass and energy balances and the performance indicators. The model can predict the variables of the whole plant, each stage, each pressure vessel and each membrane in the pressure vessel.

The model equations in Section 2 are manipulated to represent the actual configuration of multistage RO system of Al- Hashemite University. The permeate of RO stages is blended to a part of feed brackish water. Thus, Eqs. (26) and (27) are used to characterise this.

$$Q_{p(RO\ system)} + Q_{f(blended)} = Q_{p(product)} \tag{26}$$

$$Q_{p(RO\ system)}\ C_{p(RO\ system)} + Q_{f(blended)}\ C_{f(blended)} = Q_{p(product)}\ C_{p(product)} \tag{27}$$

Due to the existence of a high-pressure pump and a booster pump in the RO system of Al- Hashemite University, the overall specific energy consumption ($SEC_{RO\ system}$) is calculated by Eq. (28)

$$SEC_{RO\ system} = \frac{Pf_{(Stage\ 1)}\ Qf_{(Stage\ 1)}}{Qp_{(RO\ system)}\ \varepsilon pump} + \frac{Pf_{(Stage\ 3)}\ Qf_{(Stage\ 3)}}{Qp_{(RO\ system)}\ \varepsilon pump} \tag{28}$$

3.2. Model validation

The model predictions are compared with those of the actual RO process data of the Hashemite University (Jordan). Table 3 depicts the marginal errors between the experimental data and model predictions of the most important performance indicators. Specially, for freshwater production rate, salinity and specific energy consumption for the whole process and the RO process, the difference between the actual plant data and the model predicted data were very small (highlighted in bold in Table 3). This assures the robustness of the model developed which will be used in further simulation and optimisation studies.

The simulation results presented in Table 3 will be considered as the base case to be compared against the optimisation results in the next sections.

4. Simulation of RO system of Al- Hashemite University

This section focuses on evaluating the influence of inlet parameters of RO system including feed pressure, brackish water flow rate, and temperature on the performance indicators of the whole brackish water

Table 3

Comparison between experimental data and model predictions of the RO system and whole desalination system.

Parameters	Units	Experimental data	Model predictions (base case)	Errors %
Feed salinity of 1st membrane in 1st pressure vessel of 1st stage	(ppm)	1650.93	–	–
Product salinity of 1st membrane in 1st pressure vessel of 1st stage		11.45	13.00	−13.53
Feed salinity of 2nd membrane in 1st pressure vessel of 1st stage		1835.45	1837.02	−0.08
Product salinity of 2nd membrane in 1st pressure vessel of 1st stage		14.13	15.25	−7.92
Feed salinity of 3rd membrane in 1st pressure vessel of 1st stage		2049.99	2057.94	−0.38
Product salinity of 3rd membrane in 1st pressure vessel of 1st stage		17.61	18.10	−2.78
Feed salinity of 4th membrane in 1st pressure vessel of 1st stage		2301.42	2322.48	−0.91
Product salinity of 4th membrane in 1st pressure vessel of 1st stage		22.19	21.84	1.57
Feed salinity of 5th membrane in 1st pressure vessel of 1st stage		2598.63	2641.33	−1.64
Product salinity of 5th membrane in 1st pressure vessel of 1st stage		28.31	26.88	5.05
Feed salinity of 6th membrane in 1st pressure vessel of 1st stage		2952.80	3026.64	−2.50
Product salinity of 6th membrane in 1st pressure vessel of 1st stage		36.65	33.93	7.42
Product salinity of 1st stage		20.69	20.70	−0.04
Product salinity of 2nd stage		59.20	63.98	−8.07
Product salinity of 3rd stage		178.76	172.59	3.45
Salinity of permeate of RO system (Total of 3 stages)	(ppm)	57.7	53.9	6.58
Total water productivity of RO system	**(m³/ day)**	**1440.24**	**1406.97**	**2.31**
Specific energy consumption of RO system	**(kWh/ m³)**	**0.459**	**0.482**	**−4.79**
Total system water recovery (product flow rate of RO system and bypass blended flow rate)	**(%)**	**92.56**	**91.01**	**1.67**
Total water productivity (product flow rate of RO	**(m³/ day)**	**1992.24**	**1958.98**	**1.66**

Table 3 (*continued*)

Parameters	Units	Experimental data	Model predictions (base case)	Errors %
system and bypass blended flow rate) (Productivity)				
Salinity of product water (product flow rate of RO system and bypass blended flow rate)	**(ppm)**	**499.39**	**503.92**	**0.90**

Specifications of feed brackish water: Salinity (1650.93 ppm), pressure (7.54 atm), feed flow rate (1600.32 m³/day), and temperature (30 °C) and bypass blending flow rate (552 m³/day). Booster pump pressure (5.13 atm).

RO desalination system (product flow rate of RO system and bypass blended flow rate) using simulation. Specifically, the feed pressure and flow rate will be varied by 50 % at fixed inlet brackish water salinity, brackish water temperature and bypass blending flow rate while the overall water productivity and product salinity of the whole desalination system and specific energy consumption of the RO system will be estimated. Also, the influence of brackish water temperature on the performance metrics will be investigated based on the seasonal temperature variations in the region.

4.1. Influence of feed pressure

The feed pressure is varied between 6 atm to 9 atm (increase by 50 %) on the performance indicators of the whole RO desalination system (Productivity, Salinity of product, $SEC_{RO\ system}$) at fixed feed flow rate of 1600.32 m³/day, fixed blended flow rate of 552 m³/day, fixed brackish water salinity of 1650.93 ppm, and fixed feed temperature of 30 °C. The simulation results for water productivity and product salinity are shown in Fig. 4. Clearly, it can be stated that increasing feed pressure by 50 % would positively enhance the water productivity and product salinity of the whole brackish water desalination plant. Statistically, this is an increase of 10.6 % of water productivity and decrease of 7.3 % of product salinity. Increasing feed pressure at fixed feed flow rate would elevate the driving force of water flux through the membrane pores and therefore causes a reduction of permeate salinity in the permeate channel as illustrated in Fig. 4. Fig. 5 shows the specific energy consumption (SEC) profile against the feed pressure. As the feed pressure increases, the SEC decreases with pressure until 7 atm. However, above 7 atm, SEC increases with feed pressure. This observation can be attributed to a sudden increase of water productivity of the whole desalination system due to increasing feed pressure from 6 to 7 atm at fixed brackish water flow rate, which then followed by a steady increase of water productivity (Fig. 4). Furthermore, Fig. 6 introduces the water flux through the first membrane of each pressure vessel in the 1st, 2nd, 3rd stages. Fig. 6 shows different behaviors of water flux of the associated stages. Specifically, the water flux of the first membrane increases as a result to increasing pump pressure from 6 to 9 atm. Also, the water flux of the first membrane of the second stage decreases after increasing feed pressure from 7 to 9 atm. This can be attributed to a clear reduction of feed flow rate of the second stage at 9 atm (174.10 m³/day) compared to at 8 atm (225.76 m³/day) and 7 atm (280.39 m³/day). Indeed, the feed flow rate of the second stage corresponds to the brine flow rate of the first stage and its circumstances. However, the increase of water flux in the first membrane of the third stage is due to the existence of a booster pump that raises the operating pressure considerably. The simulation results show the feed pressure of the first membranes of the stages 1, 2, and 3 as 9, 8.68, and 13.6 atm, respectively when the pump pressure is 9 atm. The specific energy consumption has both a direct relationship with feed pressure and inverse relationship with permeated water (see Eq. (21) in Section 2).
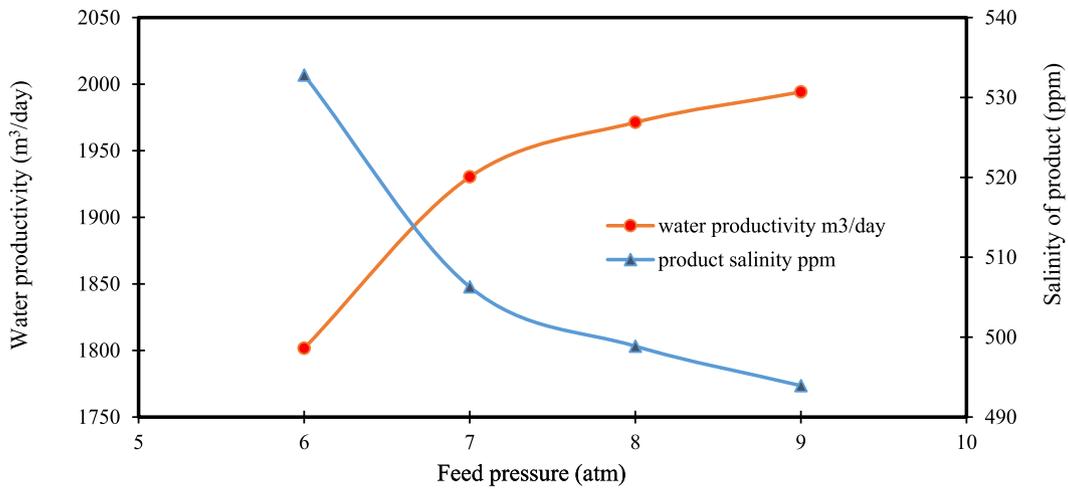
Fig. 4. Influence of 50 % increase of feed pressure on the water productivity and product salinity of the whole desalination system at fixed other inlet conditions.
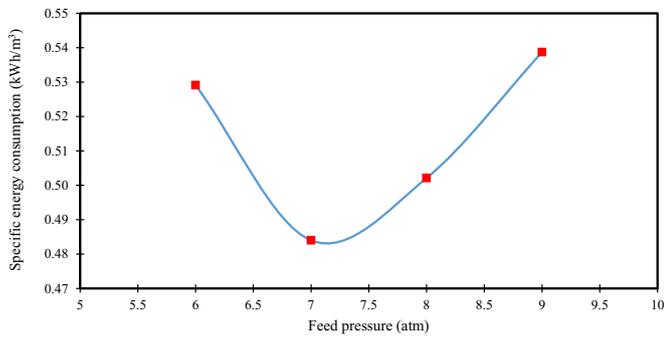

Fig. 5. Influence of 50 % increase of feed pressure on the specific energy consumption of RO system at fixed other inlet conditions.

Fig. 7. Influence of 50 % increase of brackish water flow rate on the water productivity and product salinity of the whole desalination system at fixed other inlet conditions.

concentration on the membrane wall. This is clearly depicted in Fig. 8 that shows the enhancement of water flux of the first membrane of each pressure vessel in the 2nd and 3rd stages of RO system due to increasing brackish water flow rate from 1400 m³/day to 2100 m³/day at fixed feed pressure and temperature. Here, it should be noted that the brackish water flow rate has insignificant influence on water flux of the first membrane of 1st stage (Fig. 8). This is due to having the highest feed flow rate in the 1st stage compared to the 2nd and 3rd stages. Increased feed flow rate means a lower residence time of the fluid, which has no much influence on water flux compared to a lower residence time practice.

The increase of water productivity of the whole desalination system
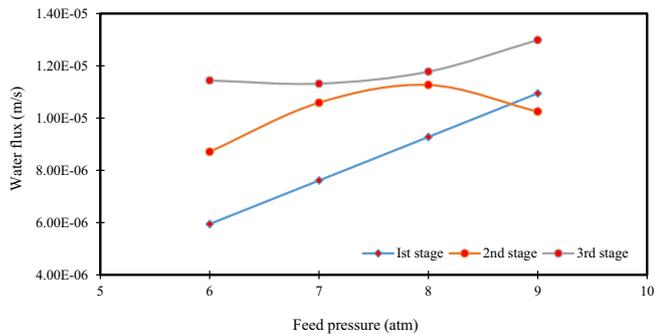

Fig. 6. Influence of 50 % increase of feed pressure on the water flux of the first membrane of 1st, 2nd, 3rd stages of RO system at fixed other inlet conditions.

4.2. Influence of feed flow rate

The feed flow rate is varied between 1400 m³/day and 2100 m³/day (increase by 50 %) at fixed feed salinity of 1650.93 ppm, fixed feed pressure of 7.54 atm, fixed blended flow rate of 552 m³/day, and fixed feed temperature of 30 °C on the performance indicators of the whole desalination system (Productivity, Salinity of product, $SEC_{RO\ system}$). The simulation results of water productivity and product salinity are depicted in Fig. 7. Fig. 7 shows that an increase in feed flow rate by 50 % causes an increase of 25.8 % of water productivity besides a reduction of 21.5 % of product salinity. Increasing feed flow rate has strengthened the turbulence inside the module, which retards the concentration polarization and enhances water flux due to a reduction of solute
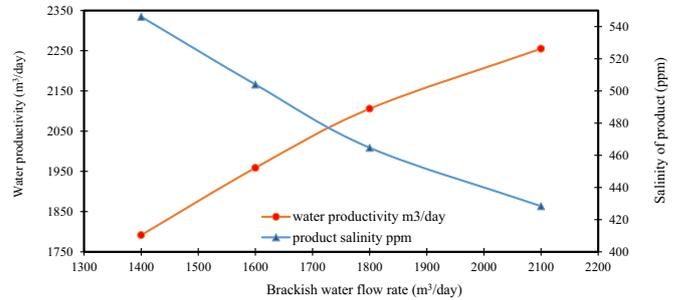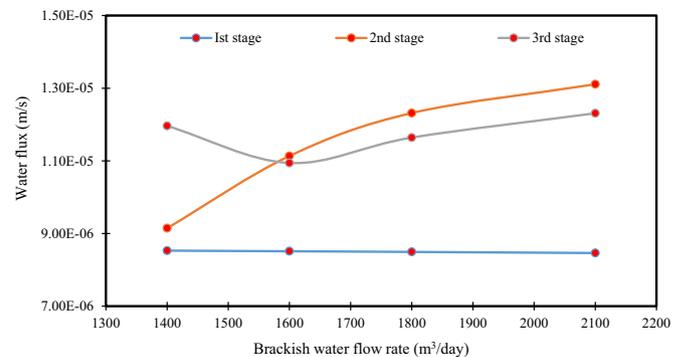

Fig. 8. Influence of 50 % increase of brackish water flow rate on the water flux of the first membrane of 1st, 2nd, 3rd stages of RO system at fixed other inlet conditions.

due to increasing feed flow rate by 50 % at a fixed pressure has nearly gain 2.5 times the water productivity profit due to increasing feed pressure by 50 % at fixed feed flow rate. Furthermore, Fig. 7 depicts a reduction of product salinity by 21.5 % due to increasing feed flow rate by 50 % at a fixed feed pressure.

Fig. 9 shows that increasing feed flow rate by 50 % at fixed pump pressure, brackish water salinity and temperature and fixed blended flow rate has got the same fluctuated behavior noticed for the influence of pump pressure. There is a decrease of specific energy consumption at 1600 m³/day and then increases steadily. It should be noted that there is a direct relationship between the feed flow rate and specific energy consumption as indicated by Eq. (21) in Section 2.

Referring to the simulation results of Figs. 4 and 7 and the tested ranges of feed pressure and brackish water flow rate, it can be stated that the feed flow rate is the vital variable, which has the most profound contribution for brackish water RO system (water productivity and product salinity) if compared to feed pressure. As stated in the above discussions, the change of feed flow rate at fixed pressure has caused the highest improvements in water productivity and product salinity compared to a change of feed pressure at fixed feed flow rate. However, Figs. 5 and 9 introduced the fact of having optimal feed flow rate and feed pressure to guarantee the lowest specific energy consumption of RO system. Note, the selected values of pressure and feed flow in this investigation are within the membrane manufacturer's recommended limits.

4.3. Influence of seasonal variable of temperature

The actual plant data (Table 2) available to us implies that the plant operates at a fixed feed water temperature of 30 °C. Also, the plant configuration (Fig. 2) does not show if there is an additional plant item (such as heat exchangers) to keep the feed temperature at a constant temperature. Therefore, it is assumed that feed temperature varies throughout the year and according to literature, the feed temperature impacts the productivity, product salinity, specific energy consumption [2]. Therefore, it will be interesting to analyse the impact of brackish water temperature on the performance metrics of the whole desalination system of RO process. We considered four seasons winter (17.5 °C), spring (27 °C), summer (38.5 °C), and autumn (35 °C) around the plant location.

The seasonal variation of brackish water temperatures of the RO system throughout an operational year was collected from AccuWather website (https://www.accuweather.com/en/jo/as-safi/222077/janua ry-weather/222077?year=2022). The simulation was carried out at fixed values of the pump pressure (7.54 atm), brackish water salinity (1650.93 ppm), brackish water flow rate (1600.32 m³/day), and blended flow rate (552 m³/day), and the Productivity, Salinity of product, $SEC_{RO\ system}$) are calculated for four different brackish water temperature as shown in Figs. 10 and 11.
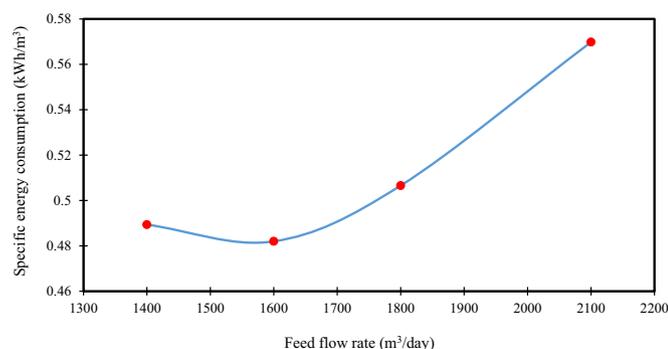

Fig. 9. Influence of 50 % increase of feed flow rate on the specific energy consumption of RO system at fixed other inlet conditions.

Fig. 10 shows that an increase in the brackish water causes a growth in water productivity. Thus, summer has got the maximum productivity compared to that in winter with the lowest productivity. This would be an advantage as the water consumption usually increases in the summer. The behavior of increasing productivity with increasing feed water temperature (Fig. 10) can be attributed to having low solution viscosity besides increasing the solution osmotic pressure. In this regard, osmotic pressure rises when water temperature rises because the diffusion rate of water molecules over a semipermeable membrane rises with temperature, resulting in a greater pressure difference across the membrane [35]. Thus, the salt diffusivity will increase through the membrane pores which results in increasing product salinity (Fig. 10). Note, the increase of product water salinity in summer has not significantly exceeded the WHO recommended limit of 500 ppm. The increase of brackish water temperature from 17 °C in winter to the maximum 38.5 °C in summer has resulted in 3.43 % improvement of water productivity.

As the operating pressure remains the same for all cases, the pump energy also remained the same. However, according to Eq. (21) increase in water productivity with feed water temperature decreases the specific energy consumption as shown in Fig. 11 resulting in 9.3 % reduction in the specific energy consumption of the RO system in summer compared to that in winter.

In summary, the simulation results presented and discussed above provide a clear understanding of the impact of selected variables on the performance indicators of the process. For a given feed water temperature (i.e. a particular season of the year), it will be interesting to optimize the other parameters (considered in the simulation) in order to reduce the specific energy consumption of the process.

4.4. Influence of variable brackish water salinity

Pre-treatment presents a challenge for brackish water desalination facilities as the quality of feed might change over a period. Sources of brackish water are prone to changes in salinity, suspended particles, dissolved solids, and other pollutants. Sandrin et al. [36] noted a variation of brackish water salinity between 10 % to 32 % due to natural erosion, or as a result of seawater mixing with river water or groundwater, human activities and agricultural irrigation practices. These various elements have the potential to seriously foul and scale the desalination system without the use of efficient pre-treatment procedures like filtering, sedimentation, and chemical dosing. Thus, this section intends to evaluate the influence of variable brackish water salinity on the performance indicators of the whole RO desalination system (Productivity, Salinity of product, $SEC_{RO\ system}$) at fixed feed flow rate of 1600.32 m³/day, fixed blended flow rate of 552 m³/day, fixed pump pressure of 7.54 atm, fixed booster pump at 5.13 atm, and fixed water temperature of 30 °C. It is assumed that the brackish water salinity might increases by 30 % from the base case of 1650.93 ppm to 2146.21 ppm over a period of time.

The simulation results of water productivity and product salinity are depicted in Fig. 12. Fig. 12 demonstrates a reduction of 3.75 % in water productivity and an increase of around 25.8 % in product salinity due to an increase of 30 % in brackish water salinity at fixed other operating conditions. Increasing brackish water salinity has a direct influence on promoting the osmotic pressure, which retards the water flux throughout the membranes as demonstrated for the first membranes of 1st, 2nd, and 3rd stages in Fig. 13. Accordingly, it can be assured that increasing brackish water salinity would negatively affect the specific energy consumption. Fig. 14 depicts this fact as in almost increases linearly by 13.6 % due to the associated reduction of water productivity. In this aspect, it can be assured that an increase of specific energy consumption can lead to higher operational costs and energy requirements for brackish water desalination. Also, further increase of brackish water salinity based on the original value will further deteriorate the performance indicators of RO system.
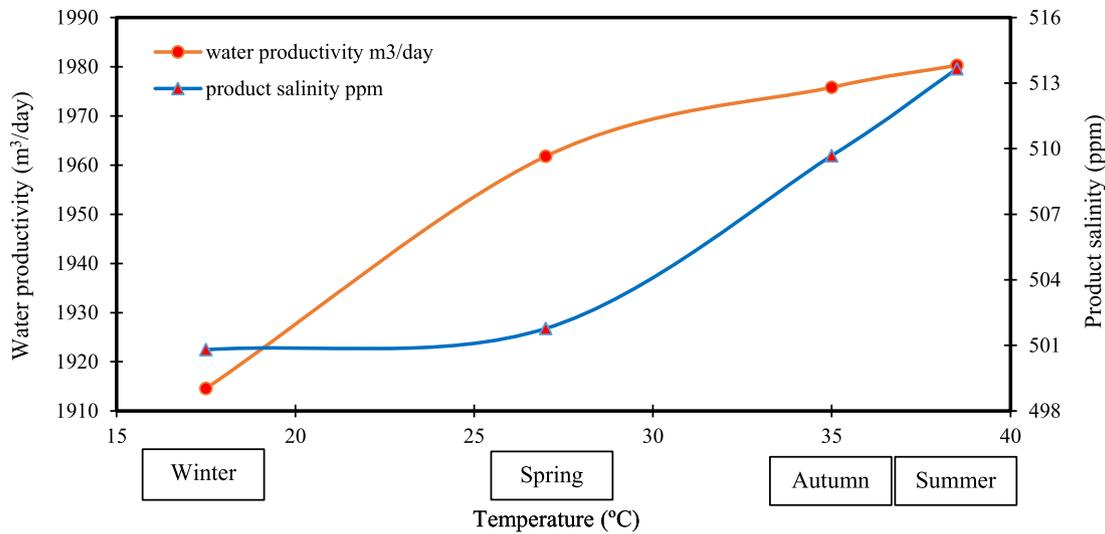
Fig. 10. Influence of temperature variation of brackish water on the water productivity and product salinity of the whole desalination system at fixed other inlet conditions.
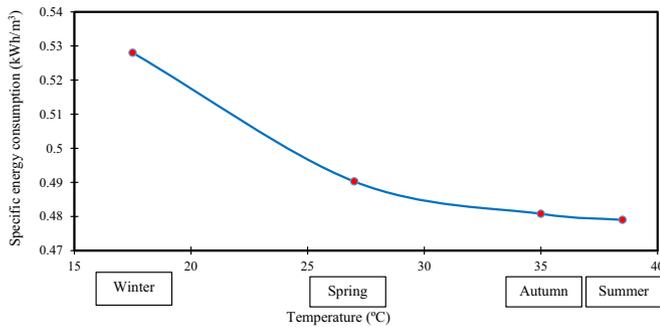

Fig. 11. Influence of temperature variation of brackish water on the specific energy consumption of RO system at fixed other inlet conditions.

5. Optimisation of RO system

5.1. Formulation of optimisation problem

This section focuses on the optimisation of operating conditions such as the feed flow rate and pump pressure of the first stage of RO system and booster pressure of the third stage while minimising the specific

energy consumption of the RO system (Eq. (28)). Here, the brackish water salinity and the feed water temperature are considered to be 1650.93 ppm and 30 °C (representing weather in between Spring and Summer and also in between Summer and Autumn), respectively. Lower and upper bounds of the decision variables are considered as follows:

- The feed pressure of RO system ($P_{f(Stage\ 1)}$) is optimised between a lower and upper specified limits of the membranes used for brackish water desalination. In other words, the inlet pressure varies between the design bounds of the manufacturer of the membrane.
- The boost pressure of third stage ($P_{f(Stage\ 3)}$) (contains two pressure vessels in a vertical configuration) varies between 1 and 10 atm.
- The feed flowrate of RO system ($Q_{f(Stage\ 1)}$) is also taken between a upper and lower bound. These bounds were determined based on the upper and lower limits of feed flowrate of each membrane (as specified by the manufacturer) inside the pressure vessel accounting the number of pressure vessels in the first stage (contains six pressure vessels in the first stage with vertical configuration).
- The efficiency of the pump is an important parameter to reduce the specific energy consumption Karabelas et al. [22]. The efficiency of most medium and larger centrifugal pumps ($\varepsilon pump$) varies between 70 and 93 % [37–39]. Thus, the maximum pump efficiency will be taken as 90 % from an engineering considerations.
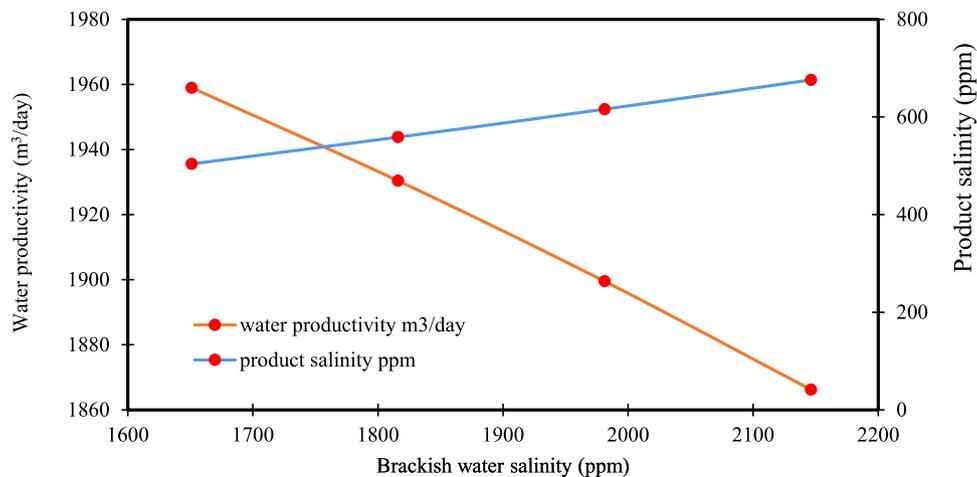

Fig. 12. Influence of brackish water salinity on the water productivity and product salinity of the whole desalination system at fixed other inlet conditions.
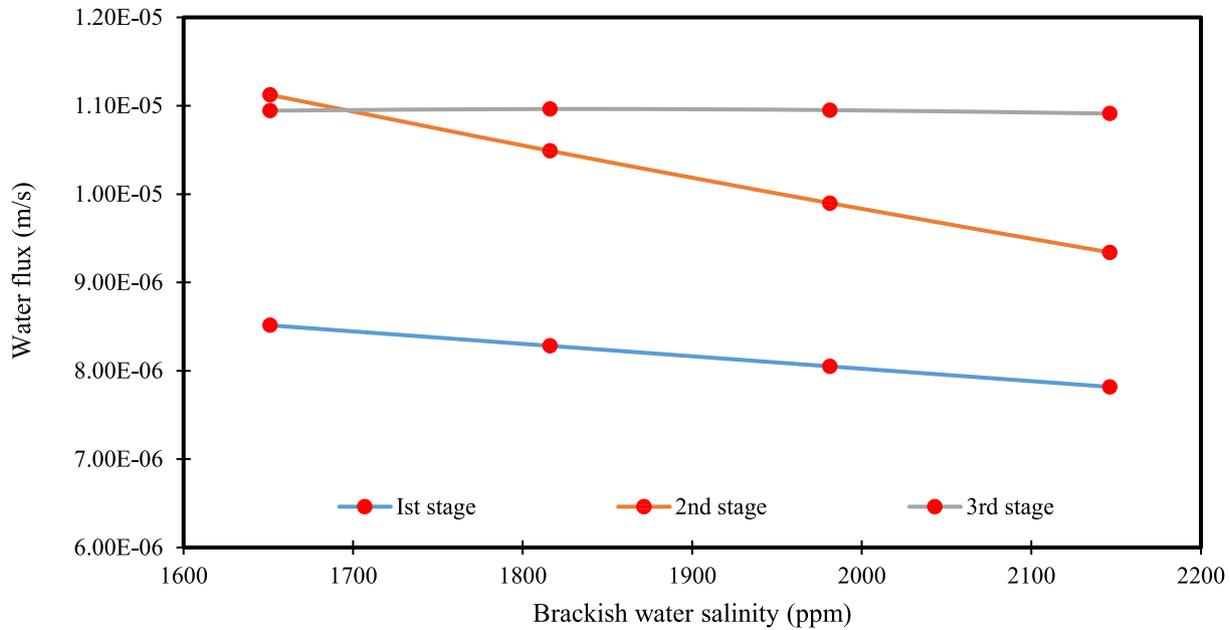
Fig. 13. Influence of 50 % increase of brackish water salinity on the water flux of the first membrane of 1st, 2nd, 3rd stages of RO system at fixed other inlet conditions.
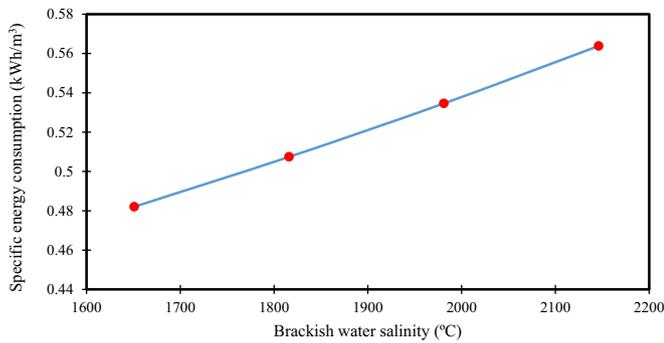

Fig. 14. Influence of brackish water salinity on the specific energy consumption of RO system at fixed other inlet conditions.

To ensure safe operation of the RO process, a number of other constraints are also considered as follows;

- The upper and lower limits of feed flowrate of each membrane in each pressure vessel of each stage ($Q_{f(Membrane)}$). This has been taken based on the manufacturer details
- The whole desalination system produces 500 ppm of drinking water. Therefore, a specific constraint was considered to maintain this value as the product water in the collected tank ($C_{p(Product\ tank)}$) (the combined stream of permeate water of RO system and blended brackish water).

Based on the above description, the optimisation problem can be mathematically represented below:

Min $SEC_{RO\ system}$

$P_{f(Stage\ 1)}, P_{f(Stage\ 3)}, Q_{f(Stage\ 1)}, Q_{f(Blended)}$

Subject to:
Equality constraints:

Process Model : $f(x, u, v) = 0$

Inequality constraints:

(5 atm) $P_{f(Stage\ 1)}{}^{L} \leq P_{f(Stage\ 1)} \leq P_{f(Stage\ 1)}{}^{U}$ (15 atm)

(1 atm) $P_{f(Stage\ 3)}{}^{L} \leq P_{f(Stage\ 3)} \leq P_{f(Stage\ 3)}{}^{U}$ (10 atm)

(522.719 m^3/day) $Q_{f(Stage\ 1)}{}^{L} \leq Q_{f(Stage\ 1)} \leq Q_{f(Stage\ 1)}{}^{U}$ (2780.640 m^3/day)

(70 %) $\varepsilon pump^{L} \leq \varepsilon punp \leq \varepsilon pump^{U}$ (90%)

End-point constrain:

(86.4 m^3/day) $Q_{f(Membrane)}{}^{L} \leq Q_{f(Membrane)} \leq Q_{f(Membrane)}{}^{U}$ (432 m^3/day)

$C_{p(Product\ tank)} \leq 500$ ppm

L and *U* are the lower and upper limits, respectively.

Note, the blended feed flowrate of the brackish water ($Q_{f(Blended)}$) will remain at the designed value 552 m^3/day with salinity of 1650.93 ppm, to secure the salinity of the product water within 500 ppm.

5.2. Optimisation results and discussion

Table 4 presents the base case (Table 3) of the whole desalination system and RO system and the optimisation results for comparison purposes. The optimisation results show an improvement of water productivity of the whole brackish water desalination system and RO system by 4.46 % and 6.22 %, respectively while minimising the SEC of the RO system to 0.39 kWh/m^3 demonstrating a reduction of 19 % compared to the base case. To achieve the minimum specific energy consumption, the decision variables should be maintained at the optimal levels as represented in Table 4. Specifically, the feed pressure of the 1st stage has to be increased by 6.6 % from 7.54 atm (plant data) to 8.04 atm. Furthermore, the booster pressure of the third stage has to be reduced by 2.96 % from 5.13 atm (plant data) to 4.98 atm. Fig. 4 shows that increasing feed pressure has a positive influence on water productivity besides Fig. 5 shows the importance of locating the optimal pressure that fits the lowest specific energy consumption.

It is also interesting to note that the brackish water feed flow rate of the 1st stage should be increased by 5.8 % from the actual plant value of 1600.32 m^3/day to 1693.34 m^3/day. This is an important action to be carried out to maintain a higher permeation rate of freshwater from the whole RO stages with improving the salinity of permeate by 7.6 %

Table 4
Experimental and optimisation results and the associated benefits.

Decision variables			Performance indicators			Benefits %
Actual plant data		Optimal values	Simulation data (base case)		Optimal values	
Pressure of the 1st stage	7.54 atm	8.04 atm	Productivity of the whole brackish water desalination plant	1958.98 m^3/ day	2046.58 m^3/ day	4.46
Booster pressure of the 3rd stage	5.132 atm	4.98 atm	Productivity of the RO system	1406.97m^3/ day	1494.58 m^3/ day	6.22
Feed flow rate of the 1st stage	1600.32 m^3/ day	1693.34 m^3/day	Specific energy consumption of RO system	0.482kWh/m^3	0.39 kWh/m^3	19
Bypass blending flow rate	552 m^3/day	552 m^3/day (fixed at design value)	Salinity of permeate of RO system	53.9 ppm	49.8 ppm	7.6
Pump efficiency	70 %	90 %	Salinity of product water of whole desalination system	503.92 ppm	481.5 ppm	4.45

compared to the simulation plant data (Table 4). This in turn would inevitably enhance the specific energy consumption due to improving the overall permeate flow rate of RO system. The optimum feed flow rate of the 1st stage is consistent with the findings of Fig. 9 that introduced a specific region of feed flow rate that assures the lowest specific energy consumption. However, the bypass blending flow rate of brackish water has almost fixed at its design value of 552 m^3/day to ensure product water salinity <500 ppm. In this regard, the optimisation results depict the improvement of product water salinity by 4.45 % from 503.92 ppm to 481.5 ppm.

The simultaneous influences of feed flow rate and pump pressure have gained an improvement in the specific energy consumption of RO system. The specific energy consumption decreases from the base case value of 0.482 kWh/m^3 to 0.39 kWh/m^3 resulting in 19 % reduction. However, there is a necessity to replace the current pumps of the first and third stages with another type of high-pressure pumps of 90 % efficiency. Note the actual pump efficiency is 70 % (Table 2).

Clearly, the optimisation results presented above shows 4.46 % overproduction of freshwater (although at a reduced salinity) in a particular season in the whole process (i.e., in between Spring and Summer and also in between Summer and Autumn). As mentioned earlier, there is >27,000 students, faculty and administrative staff. The campus consumes >600 m^3/day; the rest of the water being used for irrigation purposes. Thus, the additional water (87.41 m^3/day) of the whole desalination system can support the irrigation water or the university might reconsider the design of the freshwater tank in the worst case. Alternative options are presented in the next section.

Note, the optimisation is carried out at feed water temperature of 30 °C. According to the simulation results presented earlier in Section 4.3, with the optimum feed flow rate and pumps pressures, winter (17.5 °C) will produce less fresh water from the RO plant and summer (38.5 °C) will produce more freshwater from the RO plant in line with the assumption that water demand in winter will be less than that in summer.

5.3. On-spec product at different feed salinity

It would be interesting to investigate how freshwater product quality of 500 ppm or less can be achieved for Hashemite campus when feed brackish water salinity can increase by up to 30 % from the base case. Fig. 12 presented earlier shows that the product salinity has exceeds the required freshwater quality of Hashemite when brackish water salinity is above 1800 ppm. The optimisation problem presented in Section 5.1 is resolved for 10 %, 20 %, and 30 % increase in brackish water salinity with 70 % pump efficiency and feed water temperature of 30 °C. The RO system configuration remained the same as before. The results are presented in Table 5 which shows different optimal operating conditions of pump pressure, booster pump, feed flow rate, and blended flow rate that should be applied to maintain the product salinity on-spec. Table 5 also provides the performance indicators of productivity and the lowest

specific energy consumption for each scenario of brackish water salinity.

While guaranteeing on-spec product salinity ($< 500ppm$), the optimisation results of Table 5 shows that an increase of brackish water salinity has a negative effect on water productivity and specific energy consumption. Furthermore, the optimisation of these scenarios has introduced an elevated water productivity compared to the one presented in Table 3. This can be attributed to the utilisation of higher pump pressure and booster pump and feed flow rate compared to the ones presented in Table 3.

5.4. Cleaning and maintenance opportunity

Here, we refer to the results presented in Section 5.2. Based on the optimum values of pump pressure (8.04 atm), booster pump pressure (4.98 atm), feed flow rate (1693.34 m^3/day), and pump efficiency (90 %) as presented in Table 4, several blending options can be introduced to ensure base case productivity of 1958.98 m^3/day and to offer cleaning and maintenance of the membranes of the RO system at 30 °C. Undoubtedly, continuous maintenance option is the more practical suggestion for a running a plant without having to have shut down for maintenance.

Table 6 presents the first option which is the base case of the whole brackish water desalination plant (see Table 3). The second option is the utilisation of the optimal operating conditions of RO system (Table 4) except the moderation of the blend flow rate (reduced) to assure a fixed water productivity of the whole brackish water desalination plant.

The third option utilises the freeing up of one pressure vessel from the first stage (contains 6 pressure vessels) while keeping the other stages same. This option would provide therefore a cleaning and maintenance opportunity while keeping a fixed water productivity of 1958.98 m^3/day. However, option 3 requires RO system to produce less than the optimal value. The same trend of these results is concluded after relaxing two pressure vessels from the first stage. Despite the salinity of the produced water increases as the number of relaxed pressure vessels increases, the salinity of produced water is below 500 ppm compared to the simulation base case value.

This strategy for maintenance can be scheduled throughout the year even while operating at other feed water temperature.

6. Conclusions

One of the primary sources of freshwater that can be produced by water desalination procedures is brackish water. However, the brackish water contains a number of contaminants, effective treatment technology is needed. In this regard, desalinating brackish water via the RO method is a common practice, particularly in arid regions. Due to an incredible increase of energy prices, the intention of this study was to minimise the specific energy consumption using model-based optimisation technique of medium scale multistage RO process.

The influence of the inlet conditions of the RO system (pump

Table 5
Adapted inlet conditions of three scenarios of brackish water salinity and associated performance indicators.

Brackish water salinity (ppm)	Pump pressure (atm)	Booster pump (atm)	Feed flow rate (m³/day)	Blended flow rate (m³/day)	Salinity of product water of whole desalination system (ppm)	Productivity of the whole brackish water desalination plant (m³/day)	Specific energy consumption (kWh/m³)
(10 %) 1816.023	11	10	2780.640	551.807	354.76	3114.151	0.664
(20 %) 1981.116	11	10	2773.211	551.808	388.26	3079.487	0.689
(30 %) 2146.209	11	10	2740.854	551.807	425.97	3023.590	0.711

Table 6
Different blend options based fixed water productivity of the whole brackish water desalination system.

Blending options	Permeate flow rate of RO system (m³/day)	Permeate salinity of RO system (ppm)	Blend flow rate (m³/day)	Blend salinity (ppm)	Total productivity of freshwater (m³/day)	Freshwater salinity (ppm)
1 (Base case) Table 3	1406.97	53.9	552.00	1650.93	1958.98	503.92
2 (Table 4)	1494.58	49.8	464.4	1650.93	1958.98	429.4
3 (Relaxing 1 PV)	1483.10	46.6	475.87	1650.93	1958.98	436.3
4 (Relaxing 2 PVs)	1450.12	38.5	508.84	1650.93	1958.98	457.3

pressure, brackish water flow rate, water temperature, and brackish water salinity) was investigated using model-based simulation of the process. The feed flow is found to positively influence more on the performance metrics (water productivity and product water salinity) compared to the pump pressure. Furthermore, the simulation results showed varying specific energy consumption due to variation in pump pressure, brackish water flow rate and salinity. Also, the seasonal variation in temperature has more positive influence on the specific energy consumption compared to other operating conditions.

The optimisation (considering variable pump pressure and feed flow rate at a particular season and brackish water salinity) resulted in 19 % reduction in specific energy of RO system and 4.46 % in the water productivity of the whole brackish water desalination system, besides maintaining a high quality product water. The gain in productivity has enabled us to suggest different options of membrane cleaning and maintenance of RO system at a fixed water productivity.

Finally, further improvement of the performance, especially reduction in specific energy consumption can be made by adding an energy recovery device to the RO system. Also, use of alternative energy sources [29] and design (Fairuz et al. [24] would be of interest.

Nomenclature

A_m	Effective membrane area (m²)
A_w	Water transport parameter (m/atm s)
A'	Spacer characteristics (dimensionless)
B_s	Solute transport parameter (m/s)
C_b	Bulk solute concentrations at the feed channel of a membrane module (kg/m³)
C_f	Feed solute concentrations at the feed channel of a membrane module (kg/m³)
C_w	Solute concentration on the membrane wall (kg/m³)
C_p	Permeate solute concentration at the permeate channel of a membrane module (kg/m³)
$C_{p(Product\ tank)}$	Salinity of fresh water in the product tank (kg/m³)
C_r	Retentate solute concentration of a membrane module (kg/m³)
D_b	Solute diffusion coefficient of feed at the feed channel (m²/s)
d_h	Hydraulic diameter (m)
F_f	Fouling factor (dimensionless)
J_w	Water flux of a membrane module (m/s)

k	Mass transfer coefficient (m/s)
k_{dc}	Spacer parameter. Constant in Eq. (11) (dimensionless)
L	Membrane length (m)
L_f	Length of filament in the spacer mesh (m)
m_f	Constant in Eq. (22)
n	Spacer parameter (dimensionless)
NDP_{fb}	Net driving pressure of feed and brine of a membrane module (atm)
P_{fb}	Feed-brine pressure of a membrane module (atm)
P_p	Permeate pressure of a membrane module (atm)
Q_b	Bulk flow rate of a membrane module (m³/s)
Q_f	Feed flow rate of a membrane module (m³/s)
Q_p	Permeate flow rate of a membrane module (m³/s)
Q_r	Retentate flow rate of a membrane module (m³/s)
Q_s	Solute flux through the membrane pores (kg/m² s)
Re_b	Reynolds number of the bulk at the feed channel (dimensionless)
Rec	Water recovery of a membrane module (dimensionless)
Rej	Solute rejection of a membrane module (dimensionless)
Sc	Schmidt number (dimensionless)
SEC_{RO}	Specific energy consumption of R system (kWh/m³)
T	Feed temperature (°C)
t_f	Height of feed channel (m)
t_p	Height of permeate channel (m)
U_b	Bulk velocity in the feed channel of a membrane module (m/s)
W	Membrane width (m)

Subscript

μ_b	Bulk viscosity of a membrane module (kg/m s)
ρ_b	Bulk density at the feed channel of a membrane module (kg/m³)
$\Delta P_{drop,E}$	Pressure drop along the membrane module (atm)
π_b	Bulk osmotic pressure of a membrane module (atm)
π_p	Osmotic pressure at the permeate channel of a membrane module (atm)
ϵ	Spacer parameter. Void fraction (dimensionless)
$\varepsilon punp$	Pump efficiency (dimensionless)

CRediT authorship contribution statement

All authors contributed equally in all aspects of this paper.

Declaration of competing interest

There is no conflict of interests.

Data availability

No data was used for the research described in the article.

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