Water Research 170 (2020) 115282

Contents lists available at ScienceDirect

Water Research

journal homepage: www.elsevier.com/locate/watres

A modeling framework to evaluate blending of seawater and treated wastewater streams for synergistic desalination and potable reuse

Xin Wei [a], Zachary M. Binger [b], Andrea Achilli [b], Kelly T. Sanders [a], Amy E. Childress [a,*]

[a] Sonny Astani Department of Civil and Environmental Engineering, University of Southern California, Los Angeles, CA, 90089, United States
[b] Department of Chemical and Environmental Engineering, University of Arizona, Tucson, AZ, 85721, United States

ARTICLE INFO

Article history:
Received 27 July 2019
Received in revised form
4 November 2019
Accepted 4 November 2019
Available online 9 November 2019

Keywords:
Seawater desalination
Wastewater reclamation
Modeling framework
Energy requirements
Membrane processes
Reverse osmosis

ABSTRACT

A modeling framework was developed to evaluate synergistic blending of the waste streams from seawater reverse osmosis (RO) desalination and wastewater treatment facilities that are co-located or in close proximity. Four scenarios were considered, two of which involved blending treated wastewater with the brine resulting from the seawater RO desalination process, effectively diluting RO brine prior to discharge. One of these scenarios considers the capture of salinity-gradient energy. The other two scenarios involved blending treated wastewater with the intake seawater to dilute the influent to the RO process. One of these scenarios incorporates a low-energy osmotic dilution process to provide high-quality pre-treatment for the wastewater. The model framework evaluates required seawater and treated wastewater flowrates, discharge flowrates and components, boron removal, and system energy requirements. Using data from an existing desalination facility in close proximity to a wastewater treatment facility, results showed that the influent blending scenarios (Scenarios 3 and 4) had several advantages over the brine blending scenarios (Scenarios 1 and 2), including: (1) reduced seawater intake and brine discharge flowrates, (2) no need for second-pass RO for boron control, and (3) reduced energy consumption. It should be noted that the framework was developed for use with co-located seawater desalination and coastal wastewater reclamation facilities but could be extended for use with desalination and wastewater reclamation facilities in in-land locations where disposal of RO concentrate is a serious concern.

1. Introduction and background

1.1. Seawater reverse osmosis desalination

As of 2018, there were 5328 operational seawater desalination plants with a total global desalination capacity of approximately 58 million m^3/day (Jones et al., 2019). Of the seawater desalination technologies, reverse osmosis (RO) is the most dominant process (Amy et al., 2017; Greenlee et al., 2009), producing 56% of the global seawater desalination product (Jones et al., 2019). Although RO is the most widely adopted commercial seawater desalination technology, seawater RO (SWRO) has several drawbacks, including that it produces a brine stream, requires seawater intakes, and has high energy requirements.

Global brine production by SWRO in 2018 was approximately 44 million m^3/day, or 16.0 billion m^3/year (Jones et al., 2019). The discharge of RO brine into ocean environments can have ecosystem impacts. Because of its high density, contaminants can be carried to the ocean floor where benthic organisms may be harmed because there is minimal wave propagation for mixing and dilution (Tularam and Ilahee, 2007). In some countries (e.g., USA, Australia, Japan, UAE, and Oman), dilution and/or diffusers are required prior to/during discharge of RO brine to the ocean (Jenkins et al., 2012) to reduce and attenuate brine concentration (Rodman et al., 2018).

Entrainment and impingement of marine organisms by seawater intake systems is also a major environmental concern (Missimer and Maliva, 2018). Subsurface intakes can be used to mitigate the effects of intake systems on aquatic communities (Henthome and Boysen, 2015). Because subsurface intakes also provide some pre-treatment, their use in small systems may be beneficial; however, for large systems, their installation significantly increases capital costs and construction time (Missimer et al., 2013). Additionally, the ability to install subsurface intakes depends on the presence of proper geology and sediment characteristics

* Corresponding author.
E-mail address: amyec@usc.edu (A.E. Childress).

https://doi.org/10.1016/j.watres.2019.115282

such as sand and gravel with sufficiently high porosity and transmissivity (Missimer and Maliva, 2018).

In addition to these concerns, there are also concerns with the high energy requirement of SWRO. Although RO is the most energy efficient commercial seawater desalination technology, it still requires a relatively high amount of energy to achieve the pressures necessary to overcome the osmotic pressure of seawater (Elimelech and Phillip, 2011; Lin and Elimelech, 2015). Energy recovery devices (ERDs) with efficiencies greater than 95% are commonplace and reduce energy consumption by as much as 60% (Penate and Garcia-Rodriguez, 2011). With ERDs, current state-of-the-art SWRO facilities consume between 3 and 3.5 kW h/m^3 (Ng et al., 2015).

If second-pass RO is required for boron removal, energy consumption increases further. Typically, boron concentrations in seawater are approximately 4–6 mg/L (Park et al., 2012) and SWRO only rejects approximately 83–92% (Shultz and Freger, 2018). US states such as California and Florida, and countries such as Israel, Saudi Arabia, and Japan have regulations or guidelines for maximum boron levels ranging from 0.4 to 1 mg/L. For example, the California State Notification Level is 1 mg/L. Thus, second-pass RO for all or part of first-pass product water may be required (Alnouri and Linke, 2014; Du et al., 2015, 2016; Sassi and Mujtaba, 2013).

1.2. Synergistic opportunities in coastal water system

SWRO facilities may be co-located with wastewater treatment facilities that also discharge a stream to the ocean. Currently, the only synergistic use of these waste streams is to use the treated wastewater to dilute the SWRO brine stream prior to discharge (Fig. 1). The *2019 Amendment to California Ocean Plan* (California Environmental Protection Agency, 2019) defines this blending as the preferred technology, with the goal being that the resulting blended solution is positively buoyant (Voutchkov, 2011). In this way, the supply of treated wastewater could define the amount of seawater that can be desalinated. However, discharge of treated wastewater to the ocean could be considered a waste of the water resource within this stream.

Instead of using treated wastewater to dilute the RO brine, a possible future scenario is to blend the treated wastewater (after additional advanced treatment processes) with the intake seawater. By blending the treated wastewater with the intake seawater upstream of the RO process, not only will the SWRO feed stream be diluted, but the SWRO brine stream will also be more dilute. This scenario represents a raw water augmentation approach to direct potable reuse of treated wastewater (National Water Research Institute, 2018) and has been considered briefly in the literature (e.g., Cath et al., 2005; Hancock et al., 2012, 2013; Linares et al., 2016; Shaffer et al., 2012).

The objective of the current study is to evaluate synergistic blending of the waste streams from SWRO and wastewater treatment facilities. Four scenarios – two discharge blending and two influent blending – were considered. A modeling framework was developed to evaluate required seawater and treated wastewater flowrates, discharge flowrates and components, boron removal, and system energy requirements. The best blending scenarios that meet SWRO brine discharge requirements were determined.

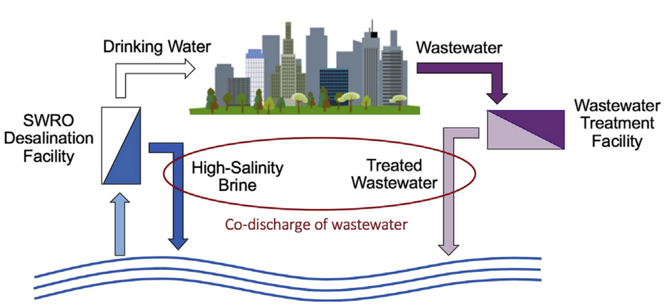

Fig. 1. Schematic of coastal water system.

2. Material and methods

2.1. System model framework

All scenarios were modeled based on a medium-size 1.14×10^4 m^3/d (3 million gallons/day (MGD)) SWRO facility, the Charles E. Meyer Desalination Plant (Santa Barbara, CA) and a 3.03×10^4 m^3/d (8 MGD) secondary wastewater treatment facility, the El Estero Wastewater Treatment Plant (Santa Barbara, CA), which are 0.2 km apart. Approximately half of the treated wastewater (1.63×10^4 m^3/d) is further treated with tertiary processes to provide non-potable reuse water. The other half of the treated wastewater (1.40×10^4 m^3/d) is used to dilute the brine from the SWRO facility. The blended stream is discharged into a pipeline that extends 2.4 km into the ocean.

Brine discharge regulations that exist around the world range from salinity increments above ambient (e.g., 1 part per thousand (ppt)) to absolute levels (e.g., 40 g/L) (Jenkins et al., 2012). These limits typically apply at the boundary of a mixing zone that has dimensions on the order of 50–300 m surrounding the discharge (Jenkins et al., 2012). The *2019 Amendment to California Ocean Plan* (California Environmental Protection Agency, 2019) states that discharges to the receiving water body shall not exceed a daily maximum of 2 ppt above the natural background salinity measured no further than 100 m horizontally from the discharge point. Accordingly, the Claude "Bud" Lewis Carlsbad desalination facility in Carlsbad, CA and a new facility in late-stage permitting in Huntington Beach, CA have absolute limits of less than 40 ppt at a compliance point of 305 m (1000 ft) from the discharge location (California Water Resources Control Board, 2012). In the current framework, the limitation for discharge salinity was set at 40 g/L.

2.2. Overview of scenarios

This section provides an overview of the four scenarios considered (Fig. 2). Detailed discussion and depiction of the scenarios can be found in Supplementary Information (Figs. S1 - S4). The scenarios included a brine blending scenario (blending treated wastewater with RO brine) (Fig. 2a), a scenario with extraction of salinity gradient energy (SGE) during brine blending (Fig. 2b), an influent blending scenario (blending treated wastewater with seawater influent to RO) (Fig. 2c), and a scenario with osmotic dilution as a treatment process during influent blending (Fig. 2d).

In Scenario 1, the baseline scenario, treated wastewater is blended with SWRO brine prior to discharge (Fig. 2a and detailed schematic in Fig. S1). The objective of this scenario is to use treated wastewater to dilute the RO brine stream to maintain a discharge salinity of 40 g/L. Because the treated wastewater is used only for brine dilution prior to disposal and not for beneficial reuse purposes, this scenario does not make full use of the value of the water resource embedded within the treated wastewater.

In Scenario 2 (Fig. 2b and detailed schematic in Fig. S2), the RO brine stream is used as a draw solution to extract high quality water from the treated wastewater under isobaric conditions. The result is a diluted RO brine stream and a concentrated wastewater stream, as well as the capture of SGE (Achilli and Childress, 2010; Han et al., 2013; She et al., 2012; Straub et al., 2014; Achilli et al., 2014a,b). In this study, SGE capture was modeled using pressure-retarded osmosis. In pressure-retarded osmosis, a semi-permeable

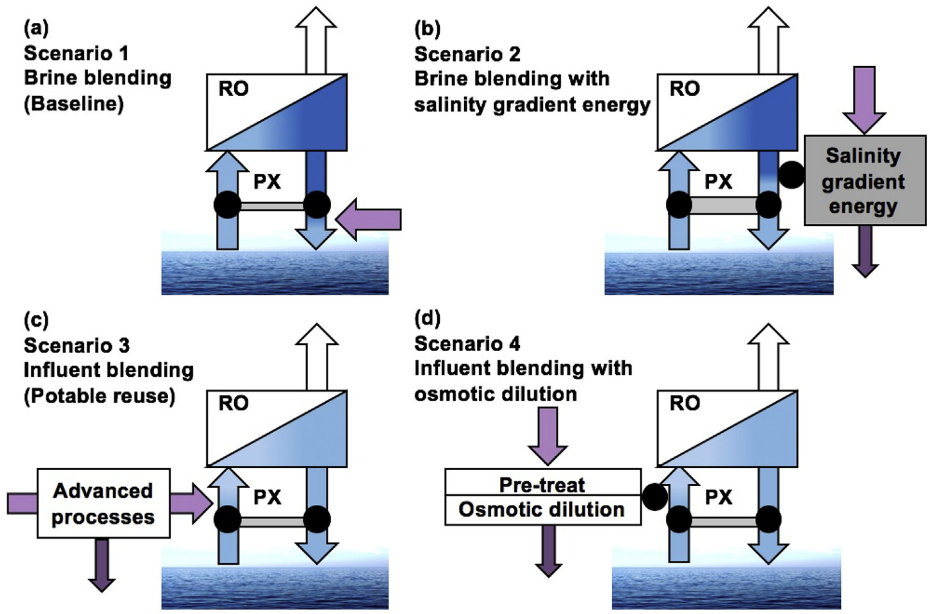

Fig. 2. Four scenarios to evaluate synergistic use of SWRO brine and treated wastewater streams.

membrane separates the pressurized, high-salinity draw solution (i.e., the RO brine) from the low-salinity feed solution (i.e., the treated wastewater). Through osmosis, water permeates from the feed solution to the draw solution against the pressure gradient, diluting the RO brine (Achilli et al., 2014a,b; Prante et al., 2014). A portion of the chemical potential between the draw solution and the low-salinity feed solution is transformed into hydraulic pressure as water is transferred; energy is recovered through depressurization (Plata and Childress, 2019). The concentrated wastewater stream can then be blended with the diluted RO brine stream that is discharged to the ocean or it can be sent back to the wastewater treatment facility.

In Scenario 3 (Fig. 2c and detailed schematic in Fig. S3), treated wastewater is blended with the intake seawater, creating a diluted feed stream for the RO process. This scenario is considered as direct potable reuse since treated wastewater is an influent to the RO process that ultimately produces water for a potable supply (Linares et al., 2016). This scenario is expected to be advantageous over Scenarios 1 and 2 because the volume of seawater influent required is reduced. This reduction in seawater influent flowrate requirement has direct implications for reduced infrastructure requirements for seawater intake systems. Additionally, the energy requirements for RO decrease as the salinity of the feed solution decreases. However, this scenario does require additional processes and monitoring to ensure that the water quality of the RO permeate meets potable reuse regulations (National Water Research Institute, 2018).

In Scenario 4 (Fig. 2d and detailed schematic in Fig. S4), the intake seawater is used as a draw solution to extract high-quality water from the treated wastewater using osmotic dilution. In osmotic dilution, the driving force for transport across a forward osmosis membrane is the osmotic pressure difference between the treated wastewater and the seawater (Cath et al., 2006, 2010). As in Scenario 3, the diluted seawater becomes the influent to the RO process and the concentrated wastewater stream can either be blended with the brine stream that exits the RO process or it can be sent back to the wastewater treatment facility. Although this process increases system capital and operating costs, the additional treatment barrier that it provides may be necessary to achieve regulatory requirements for pathogen removal. In addition, the forward osmosis process provides a low-energy, high-quality pre-treatment process for the treated wastewater (Hancock et al., 2011; Morrow and Childress, 2019; Shaffer et al., 2012; Zou et al., 2016; Cath and Childress, 2011). Thus, Scenario 4 is expected to require fewer additional processes than Scenario 3 to ensure that the water quality of the RO permeate meets direct potable reuse regulations.

2.3. Process models

Each process in the treatment train (e.g., pre-treatment, reverse osmosis, engineered osmosis, and post-treatment) was modeled individually to determine flowrates and energy consumption.

2.3.1. Pre-treatment

In the four scenarios, UF was used as pre-treatment for SWRO, and also as pre-treatment for the treated wastewater prior to RO, forward osmosis, and pressure-retarded osmosis. The UF process was modeled using Dow Chemical Company's *DOW™ WAVE Design Software - version 1.64* (Dow Chemical Company, 2019). Similar to studies from the literature (e.g., Kahler et al., 2015; Nakatsuka et al., 1996; Qin et al., 2004), a recovery of 90% was assumed for the UF process; 100% of the feed water was converted to filtrate; however, 10% of the filtrate was used to backwash the UF membranes.

2.3.2. Reverse osmosis

The RO process was modeled using both *DOW™ WAVE Design Software* and *Power Model* (Energy Recovery Inc, 2019) because all scenarios incorporated an RO pressure exchanger to reduce energy consumption. A PX Q300 pressure exchanger (Energy Recovery Inc., San Leandro, CA) was selected because of its high efficiency.

In Scenarios 1 and 2, there is no dilution of the RO influent with treated wastewater so the RO influent consists of 100% seawater. In Scenarios 3 and 4, when the RO influent is diluted with treated wastewater, the RO influent consists of a blend of seawater and treated wastewater (hereafter referred to as the SW:WW influent ratio). For example, a 40:60 SW:WW influent ratio represents a blend of 40% seawater and 60% treated wastewater as the RO influent.

The RO recovery rate was set at 50% when the SW:WW influent ratio is 100:0 and the RO recovery rate was set at 80% when the SW:WW influent ratio is 0:100. These are typical water recovery values for those systems (Altaee et al., 2014; Gilron, 2014; Linares et al., 2013). For blended RO influent streams, the RO recovery rate (R_{RO}) is a weighted average between 50 and 80% and calculated according to:

$$\boldsymbol{R_{RO}} = \boldsymbol{SW\%} \times \boldsymbol{R_{RO-sw}} + \boldsymbol{WW\%} \times \boldsymbol{R_{RO-ww}} \tag{1}$$

where $SW\%$ is percentage of seawater in the RO influent; R_{RO-sw} is RO recovery rate when the RO influent is 100% seawater; $WW\%$ is percentage of treated wastewater in the RO influent; and R_{RO-ww} is RO recovery rate when the RO influent is 100% treated wastewater. Based on the RO recovery rate, the required RO influent flowrate ($\boldsymbol{F_{RO-influent}}$) is:

$$\boldsymbol{F_{RO-influent}} = \frac{\boldsymbol{F_{PW}}}{\boldsymbol{R_{RO}}} \tag{2}$$

where F_{PW} is RO permeate flowrate. F_{PW} is held constant at $1.14 \times 10^4\ m^3/d$ for all scenarios. As the SW:WW influent ratio decreases (i.e., as the percentage of treated wastewater increases), the RO recovery rate increases according to Equation (1) and the RO influent flowrate requirement decreases according to Equation (2). The RO influent flowrates of seawater and treated wastewater required to achieve the product flowrate of $1.14 \times 10^4\ m^3/d$ are shown in Fig. 3. A SW:WW influent ratio of 100:0 represents seawater desalination only (no wastewater reclamation) and a SW:WW influent ratio of 0:100 represents wastewater reclamation only (no seawater desalination).

2.3.3. Second-pass RO for boron removal

In the current framework, the boron concentration limit is assumed to be 1 mg/L; second-pass RO is deemed necessary when the boron concentration in the RO permeate exceeds this value. *DOW™ WAVE Design Software* was used to calculate the energy consumption of full second-pass RO and then a linear relationship between energy consumption difference and influent boron concentration from Du et al. (2015) was used to estimate a value for only partial second-pass RO.

2.3.4. Engineered osmosis

Forward osmosis and pressure-retarded osmosis were modeled

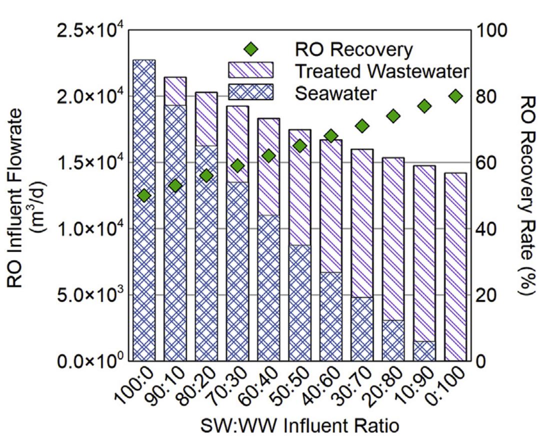

Fig. 3. RO influent flowrate requirements to achieve desired product water flowrate of $1.14 \times 10^4\ m^3/d$ for seawater:treated wastewater (SW:WW) influent ratios.

using Engineered Osmosis Processes (EOP) solver, which is a module-scale solver that considers key aspects of spiral wound membrane modules and directly estimates mass transfer and pressure losses in forward osmosis and pressure-retarded osmosis. In EOP, the forward osmosis process was operated at a recovery rate of 90% and the pressure-retarded osmosis process was operated at a recovery rate of 95%. Similar recovery rates for forward osmosis and pressure-retarded osmosis processes are found in the literature (Linares et al., 2013; Tan and Ng, 2010).

2.3.5. Post-treatment

Advanced oxidation using UV light coupled with hydrogen peroxide (UV/H_2O_2) is an industry-standard post-treatment process in potable reuse applications (National Water Research Institute, 2018; Yin et al., 2018). UV/H_2O_2 degrades neutral-charged, low-molecular-weight organics that pass through the RO membrane (Kimura et al., 2003; McCurry et al., 2017). A UV dose of at least $300\ mJ/cm^2$ is necessary for 6-log removal of all known pathogens (National Water Research Institute, 2018) and a UV dose of $900\ mJ/cm^2$ is used to destroy disinfection by-products such as N-nitroso-dimethylamine (Gerrity et al., 2015). In the current study, UV/H_2O_2 was modeled as a post-treatment process for the RO permeate in the influent blending scenarios (Scenarios 3 and 4) with the dose varying between 300 and $900\ mJ/cm^2$ depending on the SW:WW influent ratio.

2.4. Estimation of energy consumption

For each scenario, specific energy consumption (SEC) and specific energy savings (SES) were calculated for the individual processes. SEC values for RO ($\boldsymbol{SEC_{RO}}$) and UF ($\boldsymbol{SEC_{UF}}$) were calculated using *DOW™ WAVE Design Software* and SEC values for forward osmosis ($\boldsymbol{SEC_{FO}}$) were calculated using EOP Solver. SEC values for UV/H_2O_2 ($\boldsymbol{SEC_{UV/AOP}}$) were estimated based on the literature (e.g., (Holloway et al., 2016; Tang et al., 2018)), which shows that $\boldsymbol{SEC_{UV/AOP}}$ has a linear relationship with UV dose and ranges from 0.04 to 0.13 kW h/m³. SES values were calculated for the PX ($\boldsymbol{SES_{PX}}$) by *Power Model* and for the pressure-retarded osmosis process ($\boldsymbol{SES_{PRO}}$) by EOP Solver.

Net specific energy consumption ($\boldsymbol{SEC_{Net}}$) was calculated for each scenario using:

$$\text{Scenario 1: } \boldsymbol{SEC_{Net}} = \boldsymbol{SEC_{UF}} + \boldsymbol{SEC_{RO}} - \boldsymbol{SES_{PX}} \tag{3}$$

$$\text{Scenario 2: } \boldsymbol{SEC_{Net}} = \boldsymbol{SEC_{UF}} + \boldsymbol{SEC_{RO}} - \boldsymbol{SES_{PX}} - \boldsymbol{SES_{PRO}} \tag{4}$$

$$\text{Scenario 3: } \boldsymbol{SEC_{Net}} = \boldsymbol{SEC_{UF}} + \boldsymbol{SEC_{RO}} + \boldsymbol{SEC_{UV/AOP}} - \boldsymbol{SES_{PX}} \tag{5}$$

$$\text{Scenario 4: } \boldsymbol{SEC_{Net}} = \boldsymbol{SEC_{UF}} + \boldsymbol{SEC_{RO}} + \boldsymbol{SEC_{UV/AOP}} + \boldsymbol{SEC_{FO}} - \boldsymbol{SES_{PX}} \tag{6}$$

All SEC and SES values are in units of kWh per cubic meter of product water (PW) (kWh/m³-PW), where product water is RO permeate. The energy consumption of the UF process per cubic meter of product water (SEC_{UF}) is calculated according to:

$$SEC_{UF} = \frac{SEC_{UF-filtrate} \times F_{UF-filtrate}}{F_{PW}} \tag{7}$$

where $SEC_{UF-filtrate}$ is the energy consumption of the UF process per cubic meter of UF filtrate and $F_{UF-filtrate}$ is UF filtrate flowrate.

3. Results and discussion

3.1. RO brine salinity

The RO brine salinity for each SW:WW influent ratio is shown in Fig. 4. RO brine salinity decreases as the SW:WW influent ratio decreases because the salinity of the treated wastewater (0.6 g/L) is much less than that of seawater (35 g/L). The horizontal line in Fig. 4 indicates the limitation for discharge salinity (40 g/L) set in the current study. It can be seen that to maintain a discharge salinity of 40 g/L without discharge dilution, the SW:WW influent ratio must be 30:70 or less; at SW:WW influent ratios from 100:0 to 40:60, discharge dilution is necessary alongside influent dilution.

3.2. Treated wastewater flowrates in hybrid systems

The data in Fig. 5 show treated wastewater flowrates required to meet the limitation for discharge salinity. Because there is no influent dilution in Scenarios 1 and 2, these scenarios are represented only by the 100:0 SW:WW influent ratio (Fig. 5a). In Scenarios 1 and 2, to maintain a discharge salinity of 40 g/L, 8.19×10^3 m^3/d of treated wastewater must be blended with the RO brine.

In Scenario 3 (Fig. 5b), there is no data point for SW:WW influent ratio 100:0 because the case of no influent dilution is already represented by Scenario 1. As the SW:WW influent ratio decreases, the treated wastewater flowrate requirement increases. At SW:WW influent ratios greater than 40:60, some treated wastewater is used for influent dilution and some for discharge dilution. For example, when the SW:WW influent ratio is 50:50, even when the seawater influent is diluted by 50% with treated wastewater, the RO brine still requires dilution to achieve 40 g/L or less. According to Equation (1), the RO recovery rate is 65% (not 50%), thus the RO brine salinity prior to effluent dilution is 50 g/L (not 40 g/L) (Fig. 4).

At influent ratios of 40:60 and less, discharge dilution is no longer needed to maintain a discharge salinity of 40 g/L. This is important because when treated wastewater is used for influent dilution, the value of the water resource is fully realized; when treated wastewater is used for discharge dilution, much of the value in the water resource is lost. At SW:WW influent ratios of 10:90 and less, achieving the desired product water flowrate of 1.14×10^4 m^3/d requires more treated wastewater than is available, thus Scenario 3 is not feasible at SW:WW influent ratios less than or equal to 10:90.

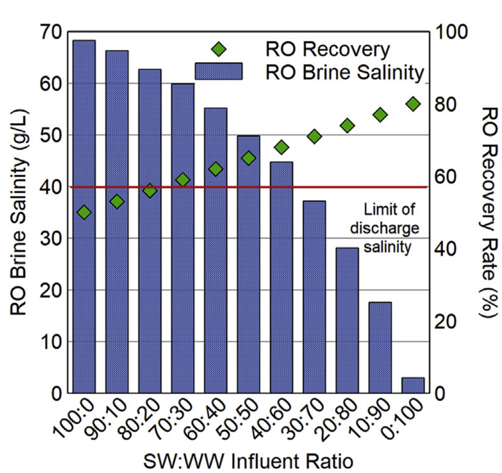

Fig. 4. RO brine salinity for seawater:treated wastewater (SW:WW) influent ratios. The horizontal line indicates the limitation for discharge salinity (40 g/L) set in the current study. Operation at SW:WW influent ratios of 40:60 or greater requires discharge blending to meet the salinity limit; operation at SW:WW influent ratios of 30:70 or less does not require discharge blending.

In Scenario 4 (Fig. 5c), osmotic dilution is used to achieve influent dilution and pre-treatment for the RO process. There are no data points for SW:WW influent ratios less than or equal to 30:70 because the seawater flowrates for these ratios are too low to extract wastewater through the forward osmosis process. Similar to Scenario 3 (Fig. 5b), as the SW:WW influent ratio decreases, the treated wastewater flowrate requirement increases.

Comparing the treated wastewater flowrate requirements for Scenarios 3 and 4 for SW:WW influent ratios from 90:10 to 60:40, the total treated wastewater flowrates for Scenarios 3 and 4 are exactly the same even though the forward osmosis process has a recovery rate of 90%. This is because all forward osmosis concentrate is used for discharge dilution. At the SW:WW influent ratio of 50:50, Scenario 4 requires 5% more treated wastewater than Scenario 3 because only a portion of the forward osmosis concentrate is needed for discharge dilution (i.e., the forward osmosis concentrate flowrate exceeds the flowrate needed for discharge dilution). At the SW:WW influent ratio of 40:60, Scenario 4 requires 10% more treated wastewater than Scenario 3, because no treated wastewater is needed for discharge dilution.

If the goal is to operate a SWRO facility that meets a 40 g/L limitation for discharge salinity and does not waste the water resource in the treated wastewater (i.e., all treated wastewater is used for influent dilution) then Scenarios 3 and 4 would be operated at SW:WW influent ratios of 40:60 and 50:50. At these blending ratios, no discharge dilution is needed. Thus, a SW:WW influent ratio of 40:60 in Scenario 3 and a SW:WW influent ratio of 50:50 in Scenario 4 were selected to represent Scenarios 3 and 4 in later discussion.

3.3. Discharge flowrates in hybrid systems

Discharge flowrates are depicted in Fig. 6. The total discharge flowrates are similar in magnitude for each SW:WW influent ratio, regardless of scenario, but the total discharge flowrates decrease substantially with decreasing SW:WW influent ratio. In Scenarios 1 and 2, the combined flowrates of UF retentate, treated wastewater, and pressure-retarded osmosis concentrate (Scenario 2 only) are almost equal to the flowrate of RO brine. In Scenario 3, at SW:WW influent ratios greater than 40:60, UF retentate alone is not enough to dilute the RO brine to 40 g/L, thus, treated wastewater is also required. At SW:WW influent ratios less than or equal to 40:60, UF retentate alone is enough to dilute the RO brine. In Scenario 4, forward osmosis concentrate is also used for discharge dilution. Similar to Scenario 3, at SW:WW influent ratios less than or equal to 50:50, UF retentate and forward osmosis concentrate are enough to dilute the RO brine and no additional treated wastewater is required.

In Scenarios 3 and 4, at lower SW:WW influent ratios, where discharge dilution is not necessary, the less UF retentate and less forward osmosis concentrate, the less wasted discharge. Thus, at these conditions, operation at higher UF and forward osmosis recovery rates would be preferred.

3.4. Boron concentration in RO permeate

From Fig. S5 in Supplementary Information, the concentration of boron in the RO permeate decreases from 1.32 to 0.24 mg/L as SW:WW influent ratio decreases from 100:0 to 0:100. At SW:WW influent ratios greater than 60:40, because the boron concentration exceeds 1.0 mg/L, partial second-pass RO was added to the model; the resulting increase in energy consumption is discussed in the

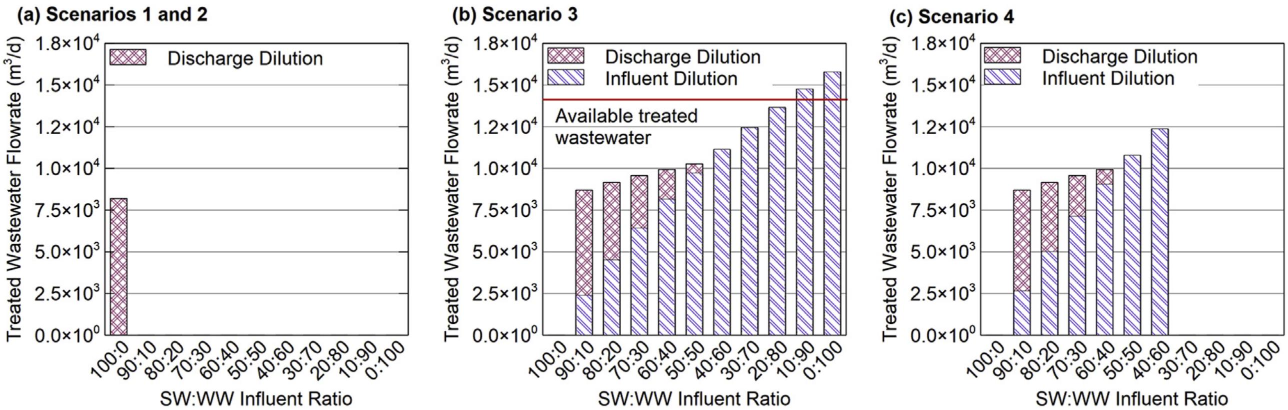

Fig. 5. Required treated wastewater flowrates for both influent dilution and discharge dilution for all seawater:treated wastewater (SW:WW) influent ratios in (a) Scenarios 1 and 2 (the brine blending scenarios), (b) Scenario 3 – the influent blending scenario, and (c) Scenario 4 – the influent blending scenario with osmotic dilution. The horizontal line in Scenario 3 (Fig. 5b) indicates the available amount of treated wastewater in the current study.

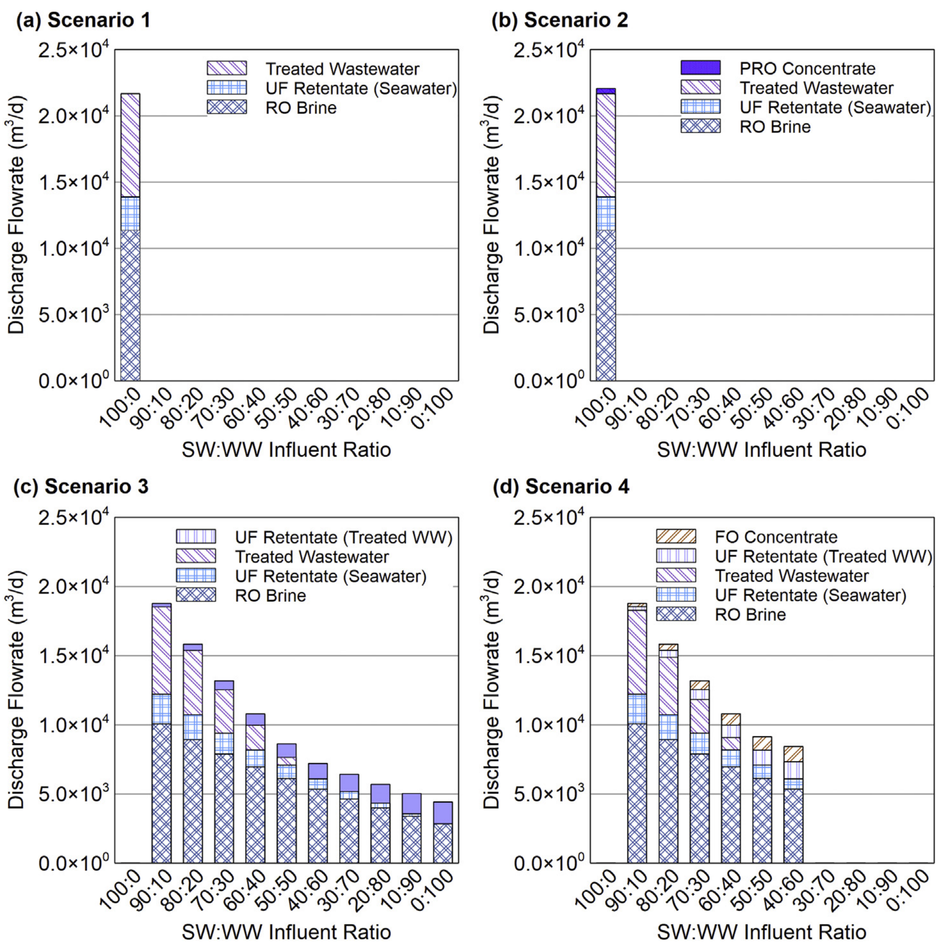

Fig. 6. Discharge flowrates for seawater:treated wastewater (SW:WW) influent ratios in (a) Scenarios 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4.

next section. For SW:WW influent ratios of 60:40 or less, additional treatment is not required to reduce the boron concentration.

3.5. Specific energy consumption and specific energy savings in hybrid systems

3.5.1. Specific energy consumption of RO

The RO SEC values for each SW:WW influent ratio are shown in Fig. 7. For SW:WW influent ratios greater than 60:40, when partial second-pass RO (Pass 2) is required, the RO SEC increases by 34% specifically due to the second pass. For influent ratios of 60:40 and less, because second-pass RO is not required to reduce the boron concentration, there are no Pass 2 energy requirements.

3.5.2. Energy consumption of pre-treatment and post-treatment

UF is used for pre-treating seawater in all scenarios and for pre-

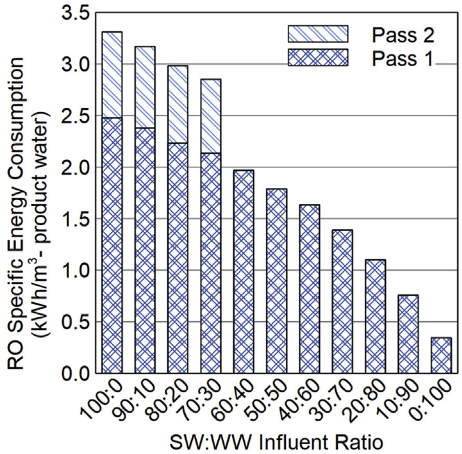

Fig. 7. RO specific energy consumption for seawater:treated wastewater (SW:WW) influent ratios.

treating treated wastewater in Scenarios 3 and 4. The UF SEC decreases as the SW:WW influent ratio decreases from 100:0 to 0:100 (Fig. S6 in Supplementary Information). This decrease is not because the UF SEC for pre-treatment of seawater is higher than that of treated wastewater; in fact, they are assumed to be the same (both are 0.07 kW h/m^3). Instead, total UF SEC decreases because a higher RO recovery rate can be used when the seawater is diluted with treated wastewater (Fig. 3) so the UF influent flowrate is reduced.

UV/H_2O_2 is modeled as a post-treatment process for the RO permeate in Scenarios 3 and 4. The UV dose increases linearly from 300 to 900 mJ/cm^2 with decreasing SW:WW influent ratio (Table S1 in Supplementary Information). In Scenario 3, the UV SEC increases from 0.04 to 0.13 kW h/m^3. Pertaining to Scenario 4, it has been demonstrated in previous studies that forward osmosis rejection is greater than 40% for tested organic compounds in bench-scale experiments and greater than 60% for tested organic compounds in pilot-scale experiments (Hancock et al., 2011). Based on this, rejection of organic compounds by forward osmosis in this study is assumed to be 50%. Thus, with the additional barrier provided by osmotic dilution in Scenario 4, the UV dose is set to range from 300 to 450 mJ/cm^2 only (Table S1 in Supplementary Information); over this range, the UV SEC increases from 0.04 to 0.06 kW h/m^3.

3.5.3. Integration into system-scale model

Net SEC values calculated from Equations (3)–(6) are shown in Fig. 8. In Scenario 1 (the baseline scenario), the net SEC is 3.5 kW h/m^3. This overall energy consumption is approximately two times the theoretical minimum energy of RO (1.8 kW h/m^3 (Elimelech and Phillip, 2011)) due to the need for partial second-pass RO, UF, and UV/H_2O_2 processes. In Scenario 2, the net SEC is 0.42 kW h/m^3 less than that in Scenario 1 due to energy recovery by pressure-retarded osmosis. Based on the available flowrates and concentrations of the RO brine and treated wastewater streams, 0.60 kW h/m^3 of specific energy is theoretically available for the pressure-retarded osmosis system to recover (Yip and Elimelech, 2012). The difference between the theoretical thermodynamic potential and the modeled result (30%, or 0.18 kW h/m^3) is due to unutilized energy and friction losses (O'Toole et al., 2016). In Scenario 3, as the SW:WW influent ratio decreases from 90:10 to 0:100, the net SEC decreases from 3.4 to 0.6 kW h/m^3. The SW:WW influent ratio of 0:100 in Scenario 3 represents the condition where the RO influent consists of 100% treated wastewater. In this case, the energy consumption is 0.6 kW h/m^3, which is lower than the energy consumption values for the blended RO influents. However, as can be seen in Fig. 5b, the available treated wastewater flowrate is not sufficient to achieve the desired product water flowrates, which would necessitate use of a blended influent. In Scenario 4, the net SEC values are slightly less than those in Scenario 3 due to the lower UV doses required in Scenario 4. All in all, decreasing the percentage of seawater has a much greater effect on decreasing net SEC than the choice of scenario.

3.5.4. Composition of net SEC

The data in Fig. 9 show the SEC percentages for each process. In Scenario 1 (Fig. 9a), the RO and UF contributions to net SEC are 95.9 and 4.1%. In Scenario 2, the RO contribution decreases to 93.9% because the pressure-retarded osmosis sub-system reduces the overall SEC by recovering SGE from blending the RO brine with the treated wastewater. In addition, in Scenario 2, the UF contribution to net SEC increases to 6.1% because Scenario 2 replaces the direct blending in Scenario 1 with a pressure-retarded osmosis process, which requires UF as pre-treatment. In Scenario 3, as the SW:WW influent ratio decreases from 90:10 to 0:100 and the percentage of treated wastewater increases, the RO contribution to net SEC decreases and the contributions of UF and UV/H_2O_2 increase. In Scenario 4, the UF contribution to net SEC is slightly higher than

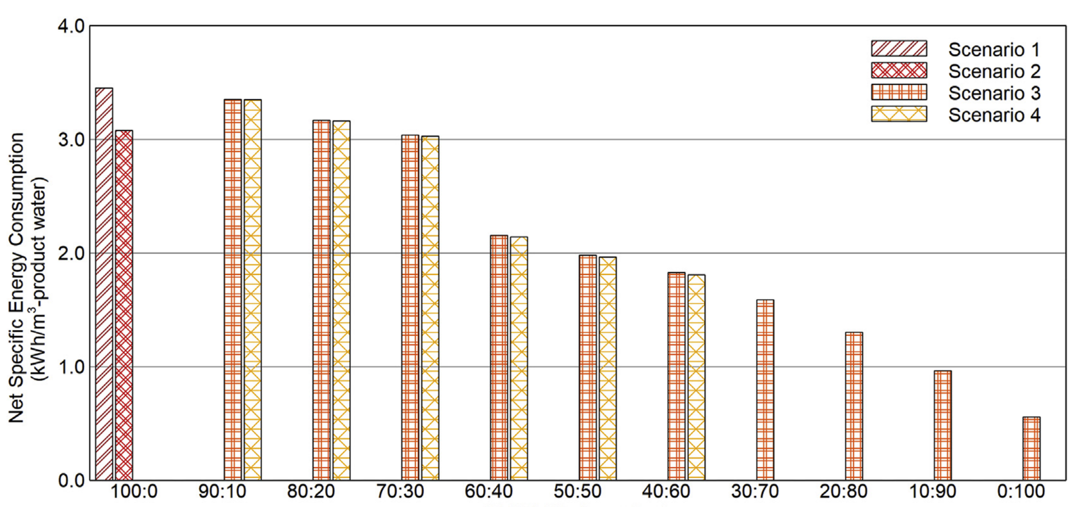

Fig. 8. Net SEC comparison for seawater:treated wastewater (SW:WW) influent ratios in four scenarios.

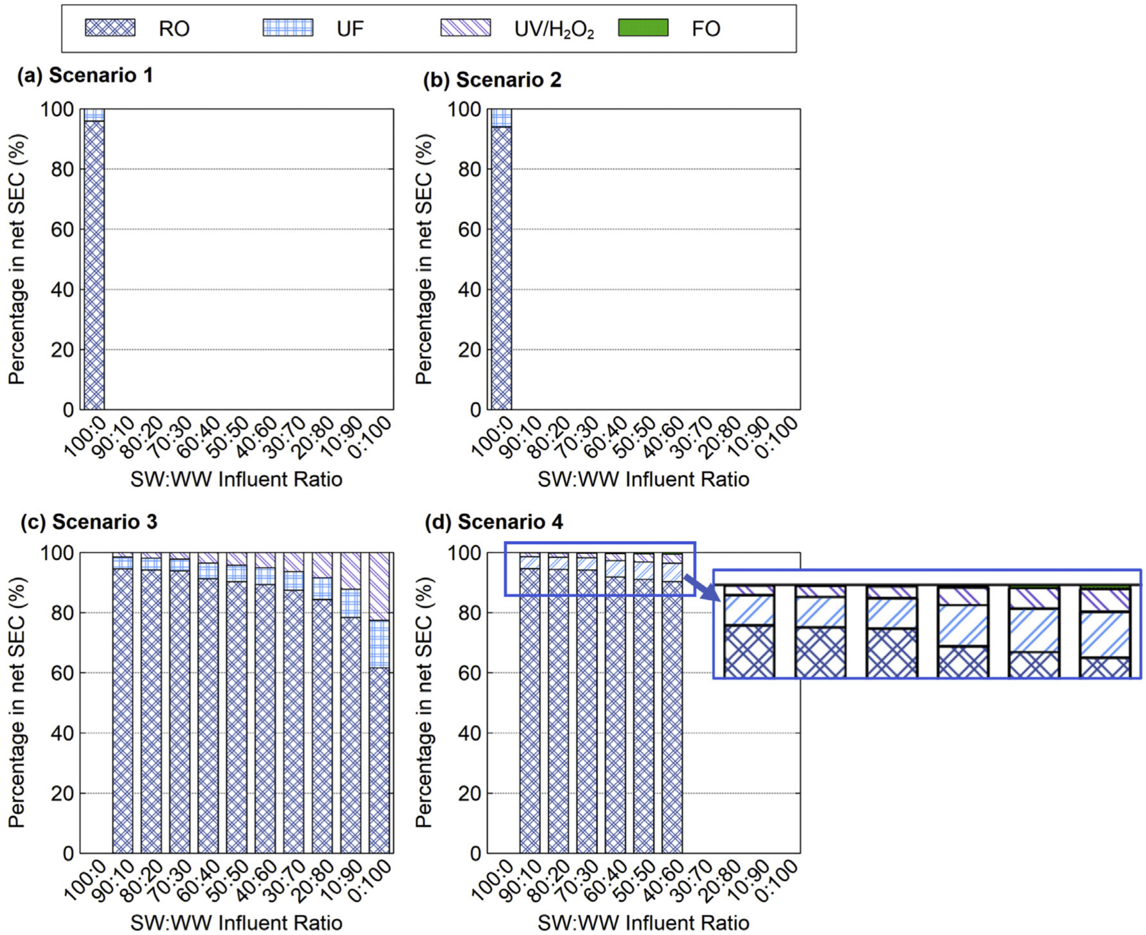

Fig. 9. Percentage of RO, UF, UV/H_2O_2, and forward osmosis (FO) in net SEC for seawater:treated wastewater (SW:WW) influent ratios in (a) Scenario 1, (b) Scenario 2, (c) Scenario 3, and (d) Scenario 4.

Scenario 3 because Scenario 4 replaces the direct blending in Scenario 3 with forward osmosis that is operated at 90% recovery. Thus, compared to Scenario 3, more treated wastewater needs to be pre-treated by UF prior to the forward osmosis process in Scenario 4. The contribution of UV/H_2O_2 to net SEC in Scenario 4 is 29% lower than it is in Scenario 3 on average, because the additional barrier provided by osmotic dilution reduces the UV dose requirement. Also, considering that the additional wastewater foulants in the RO influent are being rejected at higher pressure than are typically used in RO for wastewater reuse, the high-quality pre-treatment offered by forward osmosis in Scenario 4 may be valuable. In addition, forward osmosis only contributes negligibly (less than 0.5%) to the SEC.

3.5.5. Specific energy comparison for select conditions of four scenarios

Energy consumptions in all scenarios are depicted in Fig. 10. SEC values for all processes are shown above the x-axis and SES values are shown below the x-axis. Also shown for each scenario is the net SEC (the sum of SEC values minus the sum of SES values). As mentioned in Section 3.2, for Scenarios 3 and 4, 40:60 and 50:50 are selected to compare with Scenarios 1 and 2 because they represent conditions that meet the limitation for discharge salinity but do not waste the water resources in the treated wastewater (i.e., all treated wastewater is used for influent dilution). In Scenarios 1 and 2, the RO SEC is greater than in Scenarios 3 and 4 because with no influent dilution, the RO operates at higher pressure in first-pass RO and

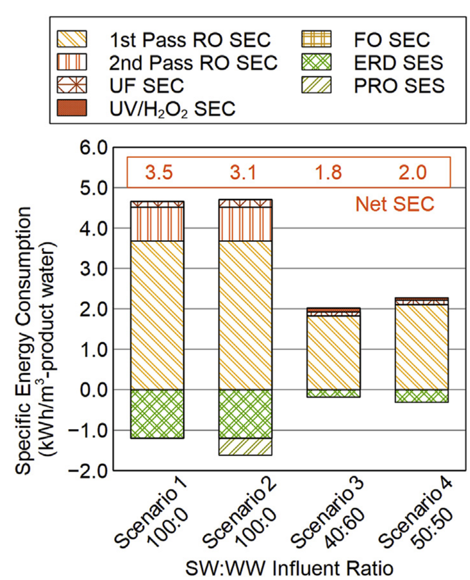

Fig. 10. RO, UF, UV/H_2O_2, and forward osmosis (FO) specific energy consumptions, and pressure-retarded osmosis (PRO) and ERD specific energy savings for Scenarios 1–4. The net SEC is calculated by subtracting total SES from total SEC.

also, second-pass RO is required for boron control. In Scenario 4, forward osmosis provides a highly selective pre-treatment with only 11% increase in SEC when compared to Scenario 3.

3.6. Summary for select conditions of four scenarios

The data in Fig. 11 shows the seawater intake flowrates, treated wastewater flowrates, discharge flowrates, and SECs for the selected SW:WW influent ratio conditions. It is important to note that the product water flowrate is constant across all scenarios. Compared to Scenarios 1 and 2 (without influent dilution), seawater influent flowrates, discharge flowrates, and net SECs in Scenarios 3 and 4 are approximately 66, 63, and 42% lower. The reason is that when treated wastewater is used for influent dilution, rather than discharge dilution, a larger fraction of treated wastewater can be recovered as product water. In addition, the treated wastewater flowrates in Scenarios 3 and 4 are 34% higher than that of Scenarios 1 and 2 (but not as much as double) mainly because the reduced influent salinity of RO in Scenarios 3 and 4 allows greater RO recovery. In Scenario 2, the pressure-retarded osmosis subsystem reduces energy consumption without requiring additional treated wastewater.

3.7. Concerns for application of blending scenarios

Comparing the brine blending scenarios (Scenarios 1 and 2) with the influent blending scenarios (Scenarios 3 and 4), there will be increased likelihood of fouling, and in particular, biological fouling (or “biofouling”) on the RO membrane in Scenarios 3 and 4. Considering this, Scenario 4 may have a better lifecycle outlook as the forward osmosis process provides additional pretreatment to the treated wastewater by removing most of the dissolved and colloidal carbon species that are typically only marginally removed by a UF membrane (Fan et al., 2008; Morrow et al., 2018). With regard to RO membrane and module selection for Scenarios 3 and 4: although feed channel spacers are necessary to create turbulence and alleviate concentration polarization, which can ultimately lead to increased salt passage through the membrane, biofouling of the spacers may be problematic. Module feed spacers that minimize biofouling (Linares et al., 2014; Matin et al., 2011; Siddiqui et al., 2017) and associated pressure drop in the feed channels (Siddiqui et al., 2017; Vrouwenvelder et al., 2010) are desirable.

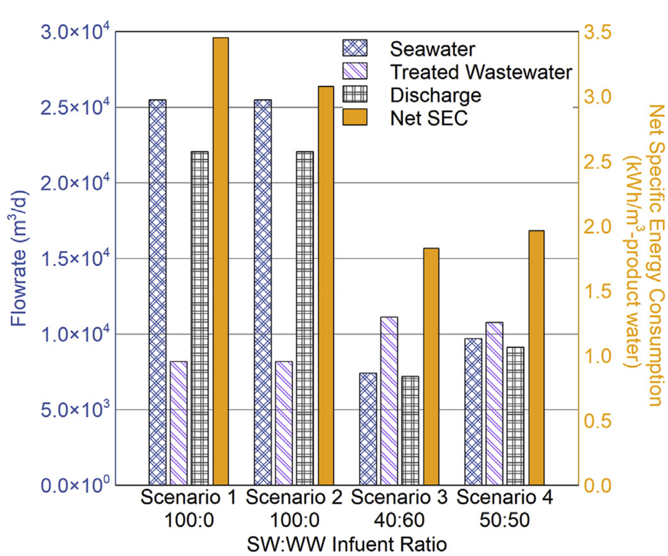

Fig. 11. Required seawater, required treated wastewater, and discharge flowrates comparison as well as net SEC comparison for four scenarios.

4. Conclusion and implication

Given the multiple benefits of the influent blending scenarios (Scenarios 3 and 4), including that: (1) seawater intake and discharge requirements are reduced, (2) second-pass RO for boron control is no longer required, (3) energy consumption is reduced, (4) seawater and treated wastewater constituents in the brine to be disposed are diluted (5) land footprint is saved, and (6) pumping volumes are saved, the advantages of these scenarios are clear. Even though SGE recovered in Scenario 2 decreases the overall energy consumption, the saving is not as significant as the RO energy savings that occur at lower seawater percentages in the influent blending scenarios (Scenarios 3 and 4). Beyond the framework, technical and societal challenges associated with direct potable reuse must be considered. With consideration of developing regulatory requirements for potable reuse (National Water Research Institute, 2018; California State Water Resources Control Board, 2019), the benefits of osmotic dilution over other advanced processes must be considered. If real-time membrane failure detection is available for forward osmosis (Desormeaux, 2017), the ability to achieve additional log removal value credits would provide significant value.

Although the framework was developed for use with co-located seawater desalination and coastal wastewater reclamation facilities, its use can be extended to co-located, or close proximity, desalination and wastewater reclamation facilities in in-land locations. At these facilities, disposal of RO concentrate is an equally serious concern. Considering the large number of seawater and brackish water RO facilities that are in planning, construction, and operation in the US west and other arid regions of the world, the developed framework could have a broad reach.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

This work was supported by the Electric Power Research Institute (EPRI). XW was also supported by the University of Southern California’s Theodore and Wen-Hui Chen Endowed Fellowship, the University of Southern California’s Viterbi/Graduate School PhD Fellowship. ZMB was also supported by a National Science Foundation Bridge to Doctorate Graduate Fellowship.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.watres.2019.115282.

References

Achilli, A., Childress, A.E., 2010. Pressure retarded osmosis: from the vision of Sidney Loeb to the first prototype installation - Review. Desalination 261 (3), 205–211.
Achilli, A., Childress, A.E., Cath, T.Y., 2014a. Osmotically-assisted Desalination Method and System. U.S. Patent: US8801934B2.
Achilli, A., Prante, J.L., Hancock, N.T., Maxwell, E.B., Childress, A.E., 2014b. Experimental results from RO-PRO: a next generation system for low-energy desalination. Environ. Sci. Technol. 48 (11), 6437–6443.
Alnouri, S.Y., Linke, P., 2014. Optimal seawater reverse osmosis network design considering product Water boron specifications. Desalination 345, 112–127.
Altaee, A., Zaragoza, G., van Tonningen, H.R., 2014. Comparison between forward

osmosis-reverse osmosis and reverse osmosis processes for seawater desalination. Desalination 336, 50–57.
Amy, G., Ghaffour, N., Li, Z.Y., Francis, L., Linares, R.V., Missimer, T., Lattemann, S., 2017. Membrane-based seawater desalination: present and future prospects. Desalination 401, 16–21.
California State Water Resources Control Board, 2019. A proposed framework for regulating direct potable reuse in California. https://www.waterboards.ca.gov/drinking_water/certlic/drinkingwater/documents/direct_potable_reuse/dprframewkseced.pdf.
Cath, T.Y., Childress, A.E. (2011) Systems and Methods for Purification of Liquids. U.S. Patent: US8083942B2.
Cath, T.Y., Childress, A.E., Elimelech, M., 2006. Forward osmosis: principles, applications, and recent developments. J. Membr. Sci. 281 (1–2), 70–87.
Cath, T.Y., Gormly, S., Beaudry, E.G., Flynn, M.T., Adams, V.D., Childress, A.E., 2005. Membrane contactor processes for wastewater reclamation in space Part I. Direct osmotic concentration as pretreatment for reverse osmosis. J. Membr. Sci. 257 (1–2), 85–98.
Cath, T.Y., Hancock, N.T., Lundin, C.D., Hoppe-Jones, C., Drewes, J.E., 2010. A multi-barrier osmotic dilution process for simultaneous desalination and purification of impaired water. J. Membr. Sci. 362 (1–2), 417–426.
Desormeaux, E., 2019. Porifera: creating a world with less waste, water reuse instead of discarded, concentrated products: reducing emissions by travelling lighter. https://erik-desormeaux.squarespace.com/s/Porifera-Technology-Overview-March2017.pdf.
Dow Chemical Company, 2019. Dow chemical Company's DOW™ WAVE design software - version 1.6. https://www.dupont.com/water/design-software.html.
Du, Y.W., Liu, Y., Zhang, S.F., Xu, Y.J., 2016. Optimization of seawater reverse osmosis desalination networks with permeate split design considering boron removal. Ind. Eng. Chem. Res. 55 (50), 12860–12879.
Du, Y.W., Xie, L.X., Liu, Y., Zhang, S.F., Xu, Y.J., 2015. Optimization of reverse osmosis networks with split partial second pass design. Desalination 365, 365–380.
Elimelech, M., Phillip, W.A., 2011. The future of seawater desalination: energy, technology, and the environment. Science 333 (6043), 712–717.
Energy Recovery Inc, 2019. Energy recovery's power model. http://www.energyrecovery.com/resource/power-model/.
Fan, L.H., Nguyen, T., Roddick, F.A., Harris, J.L., 2008. Low-pressure membrane filtration of secondary effluent in water reuse: pre-treatment for fouling reduction. J. Membr. Sci. 320 (1–2), 135–142.
Gerrity, D., Pisarenko, A.N., Marti, E., Trenholm, R.A., Gerringer, F., Reungoat, J., Dickenson, E., 2015. Nitrosamines in pilot-scale and full-scale wastewater treatment plants with ozonation. Water Res. 72, 251–261.
Gilron, J., 2014. Water-energy nexus: matching sources and uses. Clean Technol. Environ. Policy 16 (8), 1471–1479.
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 Res. 43 (9), 2317–2348.
Han, G., Zhang, S., Li, X., Chung, T.S., 2013. High performance thin film composite pressure retarded osmosis (PRO) membranes for renewable salinity-gradient energy generation. J. Membr. Sci. 440, 108–121.
Hancock, N.T., Black, N.D., Cath, T.Y., 2012. A comparative life cycle assessment of hybrid osmotic dilution desalination and established seawater desalination and wastewater reclamation processes. Water Res. 46 (4), 1145–1154.
Hancock, N.T., Xu, P., Heil, D.M., Bellona, C., Cath, T.Y., 2011. Comprehensive bench- and pilot-scale investigation of trace organic compounds rejection by forward osmosis. Environ. Sci. Technol. 45 (19), 8483–8490.
Hancock, N.T., Xu, P., Roby, M.J., Gomez, J.D., Cath, T.Y., 2013. Towards direct potable reuse with forward osmosis: technical assessment of long-term process performance at the pilot scale. J. Membr. Sci. 445, 34–46.
Henthome, L., Boysen, B., 2015. State-of-the-art of reverse osmosis desalination pretreatment. Desalination 356, 129–139.
Holloway, R.W., Miller-Robbie, L., Patel, M., Stokes, J.R., Munakata-Marr, J., Dadakis, J., Cath, T.Y., 2016. Life-cycle assessment of two potable water reuse technologies: MF/RO/UV-AOP treatment and hybrid osmotic membrane bioreactors. J. Membr. Sci. 507, 165–178.
Jenkins, S., Paduan, J., Roberts, P.J.W., Schlenk, D., Weis, J., 2012. Management of Brine Discharges to Coastal Waters Recommendations of a Science Advisory Panel, Technical Report 694. Southern California Coastal Water Research Project, Costa Mesa, CA.
Jones, E., Qadir, M., van Vliet, M.T.H., Smakhtin, V., Kang, S.M., 2019. The state of desalination and brine production: a global outlook. Sci. Total Environ. 657, 1343–1356.
Kahler, A.M., Johnson, T.B., Hahn, D., Narayanan, J., Derado, G., Hill, V.R., 2015. Evaluation of an ultrafiltration-based procedure for simultaneous recovery of diverse microbes in source waters. Water 7 (3), 1202–1216.
Kimura, K., Amy, G., Drewes, J.E., Heberer, T., Kim, T.U., Watanabe, Y., 2003. Rejection of organic micropollutants (disinfection by-products, endocrine disrupting compounds, and pharmaceutically active compounds) by NF/RO membranes. J. Membr. Sci. 227 (1–2), 113–121.
Lin, S.H., Elimelech, M., 2015. Staged reverse osmosis operation: configurations, energy efficiency, and application potential. Desalination 366, 9–14.
Linares, R.V., Bucs, S.S., Li, Z., AbuGhdeeb, M., Amy, G., Vrouwenvelder, J.S., 2014. Impact of spacer thickness on biofouling in forward osmosis. Water Res. 57, 223–233.
Linares, R.V., Li, Z.Y., Abu-Ghdaib, M., Wei, C.H., Amy, G., Vrouwenvelder, J.S., 2013. Water harvesting from municipal wastewater via osmotic gradient: an evaluation of process performance. J. Membr. Sci. 447, 50–56.
Linares, R.V., Li, Z., Yangali-Quintanilla, V., Ghaffour, N., Amy, G., Leiknes, T., Vrouwenvelder, J.S., 2016. Life cycle cost of a hybrid forward osmosis low pressure reverse osmosis system for seawater desalination and wastewater recovery. Water Res. 88, 225–234.
Matin, A., Khan, Z., Zaidi, S.M.J., Boyce, M.C., 2011. Biofouling in reverse osmosis membranes for seawater desalination: phenomena and prevention. Desalination 281, 1–16.
McCurry, D.L., Ishida, K.P., Oelker, G.L., Mitch, W.A., 2017. Reverse osmosis shifts chloramine speciation causing re-formation of NDMA during potable reuse of wastewater. Environ. Sci. Technol. 51 (15), 8589–8596.
Missimer, T.M., Ghaffour, N., Dehwah, A.H.A., Rachman, R., Maliva, R.G., Amy, G., 2013. Subsurface intakes for seawater reverse osmosis facilities: capacity limitation, water quality improvement, and economics. Desalination 322, 37–51.
Missimer, T.M., Maliva, R.G., 2018. Environmental issues in seawater reverse osmosis desalination: intakes and outfalls. Desalination 434, 198–215.
Morrow, C.P., Childress, A.E., 2019. Evidence, determination, and implications of membrane-independent limiting flux in forward osmosis systems. Environ. Sci. Technol. 53 (8), 4380–4388.
Morrow, C.P., Furtaw, N.M., Murphy, J.R., Achilli, A., Marchand, E.A., Hiibel, S.R., Childress, A.E., 2018. Integrating an aerobic/anoxic osmotic membrane bioreactor with membrane distillation for potable reuse. Desalination 432, 46–54.
Nakatsuka, S., Nakate, I., Miyano, T., 1996. Drinking water treatment by using ultrafiltration hollow fiber membranes. Desalination 106 (1–3), 55–61.
National Water Research Institute, 2018. Guidance Framework for Direct Potable Reuse in Arizona. January 2018.
Ng, K.C., Thu, K., Oh, S.J., Ang, L., Shahzad, M.W., Bin Ismail, A., 2015. Recent developments in thermally-driven seawater desalination: energy efficiency improvement by hybridization of the MED and AD cycles. Desalination 356, 255–270.
O'Toole, G., Jones, L., Coutinho, C., Hayes, C., Napoles, M., Achilli, A., 2016. River-to-sea pressure retarded osmosis: resource utilization in a full-scale facility. Desalination 389, 39–51.
Park, P.K., Lee, S., Cho, J.S., Kim, J.H., 2012. Full-scale simulation of seawater reverse osmosis desalination processes for boron removal: effect of membrane fouling. Water Res. 46 (12), 3796–3804.
Penate, B., Garcia-Rodriguez, L., 2011. Energy optimisation of existing SWRO (seawater reverse osmosis) plants with ERT (energy recovery turbines): technical and thermoeconomic assessment. Energy 36 (1), 613–626.
Plata, S.L., Childress, A.E., 2019. Limiting power density in pressure-retarded osmosis: observation and Implications. Desalination 467, 51–56.
Prante, J.L., Ruskowitz, J.A., Childress, A.E., Achilli, A., 2014. RO-PRO desalination: an integrated low-energy approach to seawater desalination. Appl. Energy 120, 104–114.
Qin, J.J., Oo, M.H., Lee, H., Kolkman, R., 2004. Dead-end ultrafiltration for pretreatment of RO in reclamation of municipal wastewater effluent. J. Membr. Sci. 243 (1–2), 107–113.
Rodman, K.E., Cervania, A.A., Budig-Markin, V., Schermesser, C.F., Rogers, O.W., Martinez, J.M., King, J., Hassett, P., Burns, J., Gonzales, M.S., Folkerts, A., Duin, P., Virgil, A.S., Aldrete, M., Lagasca, A., Infanzon-Marin, A., Aitchison, J.R., White, D., Boutros, B.C., Ortega, S., Davis, B., Tran, V.N., Achilli, A., 2018. Coastal California wastewater effluent as a resource for seawater desalination brine commingling. Water 10 (3), 19.
Sassi, K.M., Mujtaba, I.M., 2013. MINLP based superstructure optimization for boron removal during desalination by reverse osmosis. J. Membr. Sci. 440, 29–39.
Shaffer, D.L., Yip, N.Y., Gilron, J., Elimelech, M., 2012. Seawater desalination for agriculture by integrated forward and reverse osmosis: improved product water quality for potentially less energy. J. Membr. Sci. 415, 1–8.
She, Q.H., Jin, X., Tang, C.Y.Y., 2012. Osmotic power production from salinity gradient resource by pressure retarded osmosis: effects of operating conditions and reverse solute diffusion. J. Membr. Sci. 401, 262–273.
Shultz, S., Freger, V., 2018. In situ modification of membrane elements for improved boron rejection in RO desalination. Desalination 431, 66–72.
Siddiqui, A., Lehmann, S., Bucs, S.S., Fresquet, M., Fel, L., Prest, E., Ogier, J., Schellenberg, C., van Loosdrecht, M.C.M., Kruithof, J.C., Vrouwenvelder, J.S., 2017. Predicting the impact of feed spacer modification on biofouling by hydraulic characterization and biofouling studies in membrane fouling simulators. Water Res. 110, 281–287.
Straub, A.P., Yip, N.Y., Elimelech, M., 2014. Raising the bar: increased hydraulic pressure allows unprecedented high power densities in pressure-retarded osmosis. Environ. Sci. Technol. Lett. 1 (1), 55–59.
Tan, C.H., Ng, H.Y., 2010. A novel hybrid forward osmosis - nanofiltration (FO-NF) process for seawater desalination: draw solution selection and system configuration. Desalin. Water Treat. 13 (1–3), 356–361.
Tang, C.Y., Yang, Z., Guo, H., Wen, J.J., Nghiem, L.D., Cornelissen, E., 2018. Potable water reuse through advanced membrane technology. Environ. Sci. Technol. 52 (18), 10215–10223.
Tularam, G.A., Ilahee, M., 2007. Environmental concerns of desalinating seawater using reverse osmosis. J. Environ. Monit. 9 (8), 805–813.
Voutchkov, N., 2011. Overview of seawater concentrate disposal alternatives. Desalination 273 (1), 205–219.
Vrouwenvelder, J.S., Picioreanu, C., Kruithof, J.C., van Loosdrecht, M.C.M., 2010. Biofouling in spiral wound membrane systems: three-dimensional CFD model based evaluation of experimental data. J. Membr. Sci. 346 (1), 71–85.
Yin, R., Zhong, Z.Z., Ling, L., Shang, C., 2018. The fate of dichloroacetonitrile in UV/Cl2

and UV/H_2O_2 processes: implications on potable water reuse. Environ. Sci. Water Res. Technol. 4 (9), 1295–1302.
Yip, N.Y., Elimelech, M., 2012. Thermodynamic and energy efficiency analysis of power generation from natural salinity gradients by pressure retarded osmosis. Environ. Sci. Technol. 46 (9), 5230–5239.
Zou, S.Q., Yuan, H.Y., Childress, A., He, Z., 2016. Energy consumption by recirculation: a missing parameter when evaluating forward osmosis. Environ. Sci. Technol. 50 (13), 6827–6829.
California Water Resources Control Board, 2012. Management of brine discharges to coastal waters recommendations of a science advisory panel. https://www.waterboards.ca.gov/water_issues/programs/ocean/desalination/docs/dpr051812.pdf.
California Environmental Protection Agency, 2019. Amendment to California ocean plan. https://www.waterboards.ca.gov/water_issues/programs/ocean/docs/oceanplan2019.pdf.