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# Autonomous operation and maintenance of small-scale PVRO systems for remote communities

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ABSTRACT

Solar-powered reverse osmosis desalination (Photovoltaic-powered reverse osmosis [PVRO]) is a technically feasible method of providing fresh water to many remote communities with saline water sources. To be practical, these systems must be well operated and maintained by non-experts. Their productivity is a complex function of their locations, water chemistry and demand, and the solar radiation history at their locations, which is quite variable with time. A key aspect of the maintenance program is the cleaning of the reverse osmosis (RO) membranes, including system flushing and chemical cleaning. Guidelines for cleaning from membrane manufacturers do not consider the complex, variable operating conditions for these small solar-powered systems. Local operators do not have the expertise to determine how and when cleaning should be done. While cleaning will generally improve clean water production, it is costly, requires the system to be shut down, and uses some of the clean water produced. Here, simple, physics-based models of RO membrane fouling and remediation are used to find maintenance schedules that maximize water produced by a small-scale PVRO system under deterministic conditions, such as found in large RO plants using conventional grid power. However, it is shown that for small PVRO systems working in remote locations, the large uncertainties have a significant impact on optimal cleaning schedules.

*Keywords:* Solar-powered reverse osmosis; Maintenance; Fouling; Remediation

## 1. Introduction

Photovoltaic-powered reverse osmosis (PVRO) desalination is a technically feasible method to provide fresh water to off-grid, remote communities in sunny regions with saline water sources, such as seawater or brackish ground water [1]. The Yucatan Peninsula, Mexico, is such a location (see Fig. 1). Villages in the region have very limited fresh water sources and high levels of solar insolation, averaging 5.15 kWh/m$^2$/d annually [2]. The villages do, however, have access to local brackish water sources with high concentrations of hard minerals. Field testing of a small, 1,000 L/d brackish water PVRO system is underway in the Yucatan village of La Mancalona, a community of approximately 450 people [3].

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Fig. 1. Location of the MIT FSRL PVRO field test site. Map from the United States Geological Survey [4].

Field testing of the La Mancalona system has shown that small-scale PVRO systems must be operated and maintained by non-experts with minimal training. Performances of RO membranes and pre- and post-treatment filters degrade as functions of their operation and feed water chemistry. This degradation reduces clean water production and can also reduce their useful lives. The remediation of RO membranes is particularly important and is often achieved by cleaning procedures such as system flushing and chemicals. For effective maintenance, guidelines must be provided that are based on the unique conditions found in the village, such as water chemistry, water demand, and solar power histories. While increasing water production, such cleaning procedures are costly, requiring the system to stop its production and use some of the clean water product. The supplies required by chemical cleaning also add to the operational costs. To be most effective, a PVRO system must be designed for its specific locations and water demands [5,6]. Similarly, its maintenance should be tailored to its design, location and amount of water it produces, that is a function of the variable solar radiation history it has received. Therefore, determining an optimal remediation program to maximize water production and minimize cost is not trivial, and certainly not within the skill set of local non-expert operators.

RO membrane manufacturers provide general maintenance guidelines for cleaning based on membrane type and some assumed steady operating conditions. These guidelines are not ideal for a specific system or site conditions. Too frequent remediation results in excessive product water use for cleaning. Too infrequent cleaning permits greater buildup of foulants on the membrane surface, resulting in reduced water production rates and possibly permanent degradation. Suboptimal remediation protocols will result in substantially reduced productivity and increased costs. An optimal cleaning routine is particularly important for PVRO systems that experience fluctuation in their operating power. The degradation of RO membranes under fluctuating power conditions has not been well studied. A maintenance strategy that is custom-tailored to each PVRO system is desired.

Here, model-based algorithms are explored to help non-expert operators know when and what type of cleaning should be done to optimize fresh water production and minimize water costs. Mathematical models are developed of the underlying physics of the RO degradation and cleaning processes. The two most common cleaning processes are system flushing and chemical cleaning; system flushing is typically done more frequently than chemical cleaning. Chemical cleaning requires substantially more clean water and time than system flushing. The models are used to develop optimizing operational algorithms.

The proposed method is evaluated here using numerical calculations and exhaustive search to determine an optimal maintenance program for a small-scale PVRO system operating in La Mancalona, Mexico. The system produces 1,000 L/d of clean water from brackish groundwater. A method of determining the optimal threshold for condition-based cleaning of the example system is also discussed. The example presented here demonstrates that the prescheduled maintenance program will not maximize water production under changing conditions. This motivates further research that will develop an algorithm that fuses the process models with sensor information in real time to estimate the state of the system as a function of time. The algorithm then applies optimal planning methods to anticipate when the next remediation treatment should occur. This supplies the non-expert operator with sufficient notice to implement remediation to maximize lifetime water production and minimize water costs.

## 2. PVRO basics

Reverse osmosis (RO) processes produce fresh drinking water from brackish ground water or seawater input, or other feed water, using electrical energy to power pumps that pressurize the feed water to pressures higher than the feed water's osmotic pressure. This is an energy-intensive process, so using solar energy to power the system is attractive. An RO system that uses electrical power generated by solar photovoltaic (PV) panels is called here a PVRO system [1,3–7]. See Fig. 2.

In such a system, the pressurized feed water passes into a vessel with a semipermeable membrane that is permeable to water, but not salt. Some of the water, permeate, passes through the membrane and leaves its salts behind. The remaining brine exits the pressure vessel where, in some cases, it is used to generate energy for the RO process. PVRO systems may include pre- and post-treatment microfiltration and disinfection units, such as UV lamp disinfection, to ensure biological purity of the treated water, as well as other elements, as shown in Fig. 2.

### 2.1. RO performance degradation

The performance of an RO system will degrade with time due to the accumulation of particles, micro-organisms, and films on the RO membrane surface and its internal water channels, as the water is forced through the RO membrane. The water flow across the membrane may sweep some of the previously settled particles off the membrane but, overall, there is a net increase in the mineral/bacterial layer thickness over time, resulting in what is called membrane fouling that reduces the fresh water flow through the membrane and hence system productivity.

### 2.2. Types of RO membrane fouling

There are several membrane fouling mechanisms. The first is called concentration polarization, where as the feed water is desalinated, the local concentration of salts at the membrane surface becomes higher than that of the feed water, slowing water production. In the second, soluble minerals, such as calcium carbonate, may reach supersaturated concentration at the membrane surface and precipitate onto the membrane, forming a hard mineral scale that reduces the flow of fresh water. In the third, called colloidal fouling, suspended particles in the water, called colloids, are carried onto the membrane surface by the permeate flow, where they coalesce and form a soft cake layer. These particles may also become trapped in channels between the membrane and its support structures. Finally, micro-organisms will attach to both the membrane surface and to its support

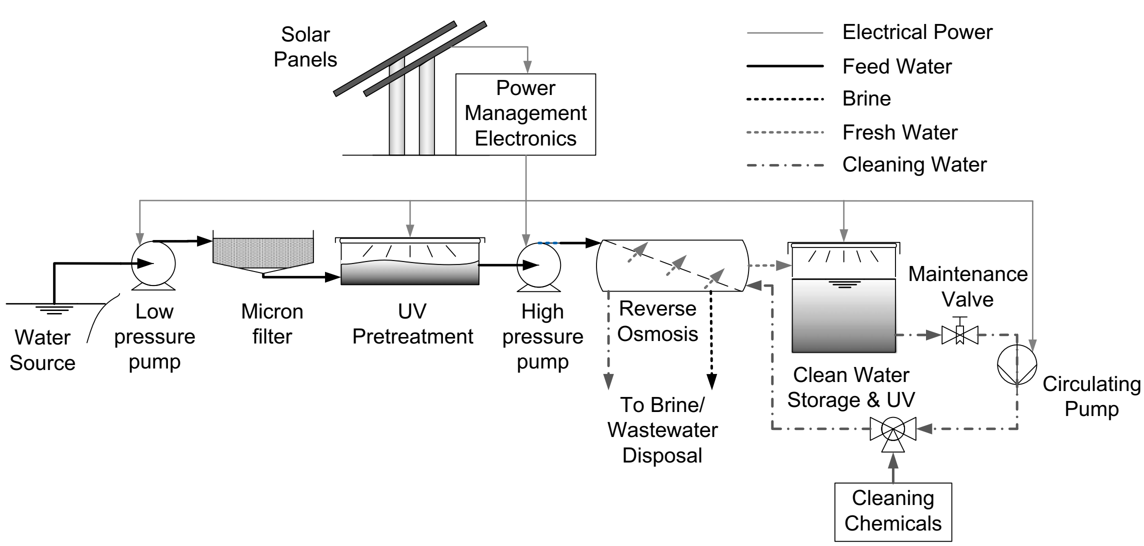


Fig. 2. A typical small-scale solar powered RO desalination system.

structure. As these bacterial colonies grow, they generate an extracellular polymeric substance layer (a biofilm) that protects the colonies and traps nutrients. Fig. 3 shows colloidal fouling and mineral scaling.

In addition, the high pressure of the feed water on the membrane over time causes membrane compaction, reducing the permeate flux. The cleaning processes discussed later in this paper cannot mitigate the effects of this mechanism.

#### 2.2.1. Fouling models

Colloidal fouling and biofouling of RO membranes have been studied and mathematical models of fouling processes have been developed [7–13]. They range from simple models that calculate the reduction in water flow rate as a function of time, to complex, finite difference, temporal–spatial models of colloidal fouling that calculate the net deposition of particles on the membrane surface while accounting for local hydrodynamics, pressure, and salt concentrations. Complex biofouling models that describe the colonization, colony growth, and detachment of micro-organisms have also been developed [12,13]. These models are generally empirical, depending heavily on experimental data.

Fouling mechanisms are not independent of one another. For example, deposition of colloids containing nutrients will promote colony growth. However, research on the interactions between colloidal fouling, mineral scaling, and biofouling is limited. Preliminary research indicates that the relationships can be complex [14–16]. In this paper, as explained later, biofouling is not as important for the small-scale system PVPO systems considered here.

### 2.3. Fouling prevention and remediation

Methods to minimize fouling of RO membranes can be divided into two kinds: pretreatment and maintenance procedures [17]. Pretreatment includes media and sand filtration, flocculation and settling of colloids, anti-scalant dosing, chlorination–dechlorination disinfection, and ultraviolet disinfection. Flocculation is the process in which particles clump together as flakes and come out of suspension in water. This may require addition of a clarifying chemical. Sand and micron filtration and flocculation can remove some of the larger colloids and particles suspended in the feed water. Anti-scalants can minimize mineral scale formation by keeping the scaling salts in solution; by changing the crystal structure of the salts as they precipitate, so they form a softer layer; or by imparting charges to the salts, so they repel one another. Chlorine dosing can kill micro-organisms that cause biofouling, but chlorine can also irreparably damage the RO membrane, so the pretreated water must also be dechlorinated before entering the RO pressure vessel. For small-scale PVRO systems, UV disinfection is practical due to the low cost of solar panels, and its use avoids the need for additional chemicals and dosing equipment.

Pretreatment cannot completely prevent fouling, so periodic maintenance is also needed. The two most common maintenance processes for RO systems are system flushing and chemical cleaning [17,18]. In system flushing, the clean water flows from the feed water inlet along the RO membrane surface, dislodging and removing loosely deposited particles, then exits through the concentrate (brine) outlet (see Fig. 4). System flushing will not remove hard scale, although it can remove scaling minerals before they harden [19].

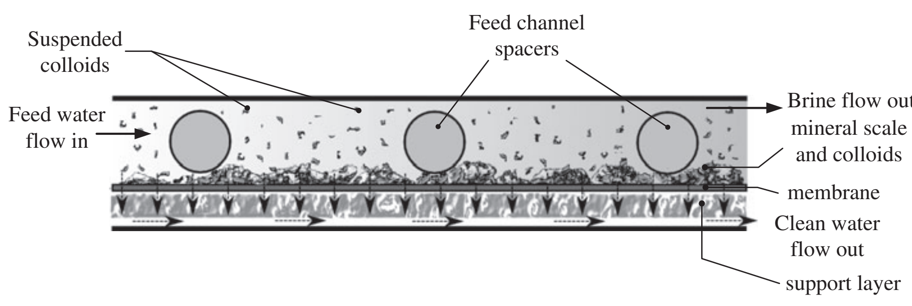


Fig. 3. Colloidal fouling and mineral scaling on a RO membrane.

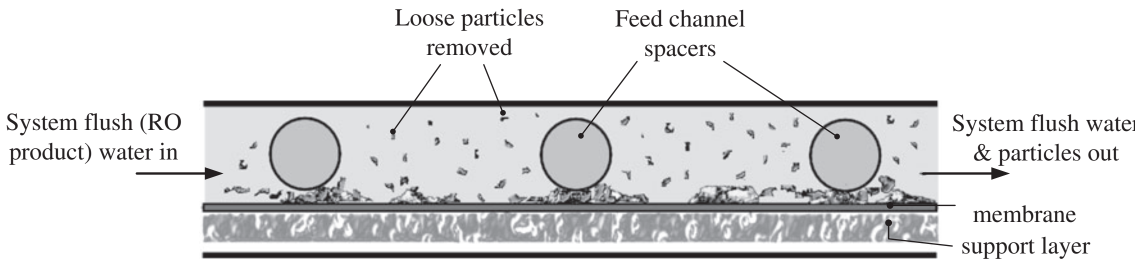


Fig. 4. System flushing a RO membrane.

Chemical cleaning processes typically consist of pre-flushing, in which there is a slow circulation of a cleaning chemical solution, followed by a 30-min to full-day soak, then followed by a high-flow rate recirculation of the cleaning solution for 30–60 min, and finally a clean-water flush for approximately 60 min [17,20]. The types of chemicals used for cleaning depend on the type of fouling. For example, alkaline solutions (high pH cleaners), such as sodium hydroxide solutions, can be used to remove sulfate scale, organic fouling, biofouling, and silica. Low pH cleaners, such as hydrochloric acid solution and sodium hydrosulfate, can be used to remove calcium carbonate scale and iron oxide deposition, respectively. Neutral pH cleaners can be used to remove biofilms. Typically, acid cleaning follows alkaline cleaning, since cleaning with acid first in the presence of biofouling or organic fouling can cause irreversible damage to the membrane. Chemical cleaning cannot perfectly remove all foulants.

After several years of operation, an RO membrane wears out due to compaction from the high-pressure feed water, from irreversible fouling, and from general deterioration. Membrane life depends on the feed water chemistry, with lifetimes of two to five years typically given in the literature, based on operator experience.

#### 2.3.1. Modeling remediation effectiveness

The system flushing and chemical cleaning processes have been modeled [19,21,22]. The change in the concentration polarization layer thickness and the change in concentration of salts during system flushing as functions of the feed and permeate concentrations, applied pressure, and feed flow rate have been modeled. The changes in membrane permeability to water and to salts, including imperfect cleaning and membrane replacement, have also been modeled. In this model, the cleaning effectiveness decays linearly with time [22]. The effectiveness of system flushing and chemical cleaning has been experimentally determined.

Fractional factorial design has been used to characterize and optimize membrane physical and chemical cleaning for RO membranes treating effluent [23]. This work found that time between system flushes and the duration of the system flushes have significant effects on the efficacy of the system flush. It also found that chemical cleaning efficacy was highly dependent on the temperature and the concentration of the alkaline cleaning solution used. Following the chemical cleaning procedure with a system flush was able to restore the permeate water flow rate to about 97% of its pre-fouled value.

The cleaning efficacy of alkaline solutions, acid solutions, surfactants, and detergents on seawater RO membranes fouled with calcium sulfate (90%) and calcium phosphate have been studied [24]. It was found that alkaline cleaners combined with a chelating agent and a surfactant can remove most of the calcium sulfate, and restore the clean water flux to its pre-fouled flow rate. It was also found that higher concentration of cleaning chemicals, longer duration of cleaning, and higher temperatures increase the effectiveness of foulant removal.

#### 2.3.2. Current maintenance practices

The state of the art in RO system maintenance is to use a fixed periodic maintenance schedule based on guidelines provided by the RO membrane manufacturer [25]. The type of chemicals used for cleaning will depend on the feed water chemistry. Predetermined, fixed maintenance schedules work well for systems operating under quasi-constant conditions. However, when operating conditions change, such as experienced by a small PVRO system, the prescheduled maintenance will not maximize the amount of water produced over time. For example, rainfall runoff may change the surface water chemistry feeding into a brackish groundwater source, potentially changing the fouling mechanisms and fouling rates. The objective of this work is to develop algorithms to permit non-expert operators to adapt maintenance protocols to adapt to such changes.

Condition-based maintenance (CBM) for conventional RO systems has been proposed [17]. CBM is a reactive maintenance procedure. In CBM for RO systems, operational parameters, such as fresh water flow rate or the pressure drop from the feed entrance to the brine exit, would be monitored. When the measurements reach predetermined thresholds, maintenance actions would be performed. Experienced operators have suggested that for large, grid-powered RO systems, maintenance should be performed when the normalized product water flow rate drops by 10% or when the normalized pressure drop increases by 15% [17,20]. While effective for such conventional systems operating under largely static conditions, CBM is not likely to meet the needs of small PVRO systems. In the results presented in this paper, CBM is used for comparison with the model-based approach presented here.

## 3. Analysis

Mathematical models to capture the underlying behavior of the desalination, fouling, and remediation processes are presented in this section. These models describe the water production of a PVRO system over time, subject to both fouling and remediation. The equations are then used in a numerical optimization to find the frequencies of maintenance actions that maximize the water production for a given PVRO system, provided that all parameters and operating conditions are known or measured.

### 3.1. PVRO process models

For a PVRO system, the model of the conversion of solar energy to hydraulic pressure is a complex function that depends on the hardware configuration of the PVRO system [6,26]. This model is briefly described here.

The power $P_{elec}$ (W) produced by a solar panel is given by [26]:

$$P_{elec} = \eta I A_{sp} \tag{1}$$

where $\eta$ is the solar to electrical conversion efficiency of the panel, $I$ is the incident solar radiation (W/m$^2$), and $A_{sp}$ is the area of the solar panel (m$^2$).

The conversion from solar panel electrical power to hydraulic pressure of the feed water after exiting the high-pressure pump depends on the PVRO power management system and the physical characteristics of the motor and pump units. PVRO power management may include power-optimizing Peak Power Tracking and computer-controlled variable brine energy recovery [5].

The fresh water flow through an RO membrane, $q_p(t)$, is a function of the hydraulic pressure and membrane permeability, and is given by [27]:

$$q_p(t) = A_m K(t)\left[\bar{P}(t) - \bar{\pi}(t)\right] \tag{2}$$

where $\bar{P}(t)$ is the average hydraulic pressure (bar), $\bar{\pi}(t)$ is the average osmotic pressure (bar), $K(t)$ is the membrane permeability to water (cm/bar/s), and $A_m$ is the area of the membrane (cm$^2$).

The water produced by the RO system over a period of time is given by integrating Eq. (2):

$$Q_p = \int_{t_S}^{t_F} q_p(t)dt = A_m \int_{t_S}^{t_F} K(t)\left[\bar{P}(t) - \bar{\pi}(t)\right]dt \tag{3}$$

Eq. (3) can be solved numerically if the permeability and pressures are known functions of time.

### 3.2. Fouling model

The literature's temporal–spatial fouling models are generally based on physical interactions combined with empirically determined parameters that are functions of the fouling potential of the feed water, the rate of deposition of colloids, the friction coefficients, etc. A similar approach is taken here, however a result that describes the average decrease in membrane permeability is generated, rather than one that describes the local velocity and cake layer growth as a function of membrane area and time that is often calculated. This average result is sufficient for maintenance protocol analysis.

In membrane fouling, colloidal particles and minerals are transported to the membrane surface by the water passing through the membrane and the permeate. Some of these particles and minerals are also swept away from the membrane by the brine left behind, see Fig. 3. Under steady operation, there is a net rate of particle deposition on the membrane surface that forms the fouling layer [28]. The accumulation of particles on the membrane surface will change the membrane permeability to water over time, and is given by:

$$\frac{dK(t)}{dt} = -\gamma v = -\gamma \frac{q_p}{A_m} \tag{4}$$

where $\gamma$ is a parameter that describes the change in permeability due to particle deposition and is dependent on the water chemistry, temperature, and axial flow (1/bar/s), and $v$ is the permeate velocity through the membrane (cm/s). Substituting Eq. (1) into Eq. (4) yields the following:

$$\frac{dK(t)}{dt} = -\gamma K(t)\left[\bar{P}(t) - \bar{\pi}(t)\right] \quad (5)$$

Eq. (5) is valid for particle deposition, but not for the microbial attachment, growth, and detachment associated with biofouling. Biofouling is not considered here, since the UV disinfection used in a small PVRO system not only sterilizes the input water but also greatly reduces the likelihood of biofouling. The use of the UV lamps is practical in a PV-driven system since their added PV power demand cost is negligible.

### 3.3. Remediation models

The remediation models in the literature for system flushing calculate the concentration of salts on the feed and permeate sides for the RO membrane as functions of pressure and system flushing time, and require knowledge of the diffusion coefficients for water and salts. The models for chemical cleaning remediation calculate the RO membrane permeability after cleaning procedures have occurred, and are functions of time. Here, models that provide the changes in membrane permeability as function of system flushing and chemical cleaning are central to optimizing maintenance protocols.

#### 3.3.1. System flushing

Manufacturers provide recommendations for suitable system flushing flow rates that depend on membrane type. The change in membrane permeability during system flushing can be described as a constant $C_{bf}$ (cm/bar/s$^2$) that depends on the system flushing flow rate:

$$\left.\frac{dK(t)}{dt}\right|_{t=t_{bf}} = c_{bf} q_{bf} = C_{bf} \quad (6)$$

where $c_{bf}$ is the increase in membrane permeability that will depend on the composition of the fouling (1/bar/cm$^2$/s) and $q_{bf}$ is the system flush volumetric flow rate (L/s). Noting that if the system flush duration is short (on the order of minutes) when compared with the rate of fouling (on the order of days to months), the system flushing process can be approximated using a delta function [29]:

$$\frac{dK(t)}{dt} = C_{bf}\delta\left(t - t_{bf}\right) \quad (7)$$

#### 3.3.2. Chemical cleaning

Chemical cleaning the membranes within an RO pressure vessel can take anywhere from a few hours to a day. However, when compared with the operational lifetime, which is on the order of months to years, the duration of the chemical cleaning is short. As with the system flushing, the change in membrane permeability can also be described using a delta function:

$$\frac{dK(t)}{dt} = C_{cc}\delta(t - t_{cc}) \quad (8)$$

where the value of the increase in permeability $C_{cc}$ (cm/bar/s$^2$) will depend on the ability of the chemical cleaning process to remove the foulant. Note that no cleaning process can increase the membrane permeability to be greater than its initial value.

### 3.4. Representative degradation and remediation example

Eqs. (2), (5), (7), and (8) can be used to calculate RO permeate flow rate as a function of time under constant conditions. For example, assume a representative small-scale RO system uses a single, brackish water, 4-inch diameter, 40-inch long membrane, and desalinates feed water at 25˚C with a salinity of 20,000 ppm using a pressure of 18 bar.

The initial membrane permeability is $4.62 \times 10^{-7}$ (cm/bar/s). Clean water is calculated for four cases: no remediation, daily system flushing, monthly chemical cleaning, and both daily system flushing and monthly chemical cleaning. The system flushing is done for 5 min at 0.57 L/s, and increases the membrane permeability by $1 \times 10^{-9}$ (cm/bar/s). Note that if the membrane permeability has not decreased by this much from its initial permeability, system flushing is assumed to restore RO membrane permeability to its initial value.

Chemical cleaning takes 4 h and requires approximately 7,000 L of permeate water. This increases the membrane permeability by $4.0 \times 10^{-8}$ (cm/bar/s). As with system flushing, chemical cleaning cannot increase RO membrane permeability beyond its initial value. The increases in membrane permeability for the different cleaning processes are calculated based on experimental results in [23].

Fig. 5 shows the clean water production with and without daily system flushing for 11 d of operation. The small increases in flow rate after system flushing are visible. It is evident that system flushing slows the decline in permeate flow rate.

Fig. 6 shows the permeate flow rate with and without system flushing over a longer operating period. For this representative case, the permeate flow rate drops to 30% of its initial value after 200 d of operation without any system flushing. With daily system flushing, permeate production drops to 60% of its initial value after 200 d.

Fig. 7 compares long-term permeate flow rate with and without chemical cleaning. In this example, the permeate flow rate drops to about 70% of its initial value after 200 operating days when chemical cleaning is performed monthly.

As shown in Fig. 8, combining chemical cleaning and daily system flushing provides greater benefits than using either one by itself. In the first 200 d, the permeate production drops to 80%. After a year, it drops to 75% of its initial value with maintenance. Without maintenance, permeate flow drops to 15%.

Fig. 8 shows the effectiveness of cleaning over three years. It is known that repeated chemical cleaning can cause damage to the membrane surface, and that as the membrane ages, chemical cleaning becomes less effective [22]. Here, no membrane damage is considered.

### 3.5. Total water production

The example presented above illustrates the effects of cleaning on the clean water production. However, both the system flushing and chemical cleaning

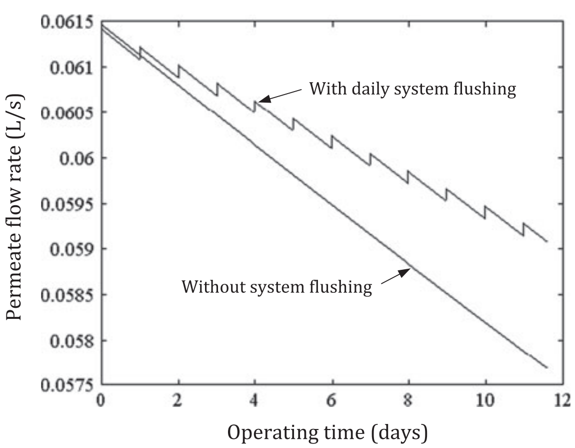


Fig. 5. Short-term permeate flow rate with and without system flushing.

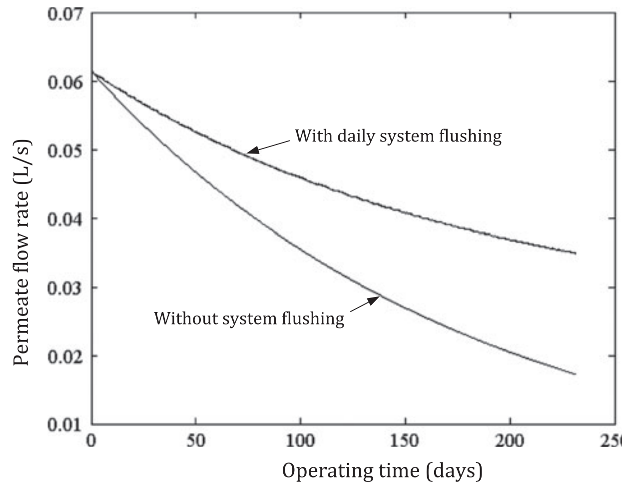


Fig. 6. Long-term permeate flow rate with and without system flushing.

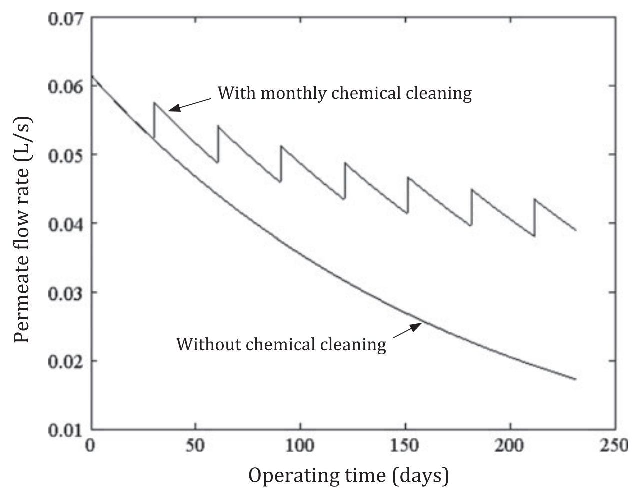


Fig. 7. Long-term permeate flow rate decline with and without chemical cleaning.

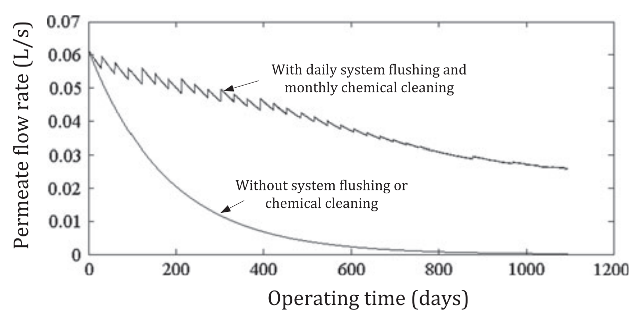


Fig. 8. Permeate flow rate decline with and without maintenance.

processes require the use of some of the product water. The water produced over a period of interest (i.e. between cleaning processes, when the RO system is on) is described by Eq. (3). The net water produced by the system including the water used for cleaning and the time the system is shut off is calculated using:

$$Q_{net} = \sum_{k=1}^{K} [A_m \int_{t_{S,k}}^{t_{F,k}} K(t)\left[\bar{P}(t) - \bar{\pi}(t)\right]dt] - NQ_{bf} - MQ_{cc} \quad (9)$$

where $K$ is the number of time periods the RO system produces water between maintenance procedures of any type, $t_{S,k}$ is the time the RO system is turned on during the $k$th interval between cleaning events, $t_{F,k}$ is the time the RO system is turned off during the $k$th interval between cleaning events, $N$ is the number of system flushes during the period of interest, $Q_{bf}$ is the volume of permeate water used during a system flush (L), $M$ is the number of chemical cleanings during the period of interest, and $Q_{cc}$ is the volume of permeate water required during a chemical cleaning (L).

Eq. (9) is able to account for the loss of productivity during cleaning and system flushing since it adds the water production only when the RO system is operating.

## 4. Optimization example

Eq. (9) can be used to optimize the maintenance routine over a given period of time if the operating conditions, fouling rate, and effectiveness of remediation processes are assumed known. An example is used to demonstrate the method.

### 4.1. Representative system and assumptions

Here, an optimal maintenance protocol for a small-scale PVRO system operating in the Yucatan Peninsula, Mexico, can be determined under known conditions, as shown in Table 1. This calculation accounts for the seasonal changes in the available solar power. The PVRO system is assumed to have UV disinfection pre- and post-treatment to eliminate biofouling on the membrane and in the product water tank. It is sized to produce 1,000 L of fresh water per day from brackish groundwater over 6 h. The relevant system and operating parameters are presented in Table 1.

The incident sunlight on the solar panels is calculated using the clear sky model from [6,30]. The calculations account for the seasonal variations in solar radiation. Using Eq. (1) and the following empirically derived relationship, the RO pressure can be calculated as:

$$\bar{P}(t) = -\left(5.09 \times 10^{-5}\right)P_{elec}^2 + 0.056P_{elec} - 0.2197 \quad (10)$$

This relationship was derived from operating data from a small-scale experimental seawater PVRO system and scaled appropriately for a brackish water system [5].

Eqs. (5), (7), and (8) are used to calculate the change in membrane permeability. In this example, system flushing takes place for 3 min at a flow rate of 0.57 L/s. Chemical cleaning is assumed to consist of an acid cleaning to remove the calcium carbonate scale, followed by an alkaline cleaning. Table 2 lists the values of the cleaning parameters. As in the constant pressure degradation example, the increase in permeability after system flushing is limited such that the post-system flush permeability is no greater than the initial “clean membrane” permeability. The increase in membrane permeability after chemical cleaning is limited to 97% of its original permeability. Chemical cleaning effectiveness is limited since it does partially damage the RO membrane.

To determine the optimal pre-scheduled maintenance, Eq. (9) is solved using exhaustive search. This method is applicable due to the small number of combinations of system flushing and chemical cleaning frequencies considered. The number of days between chemical cleanings ranges from 365 to 3 in single day increments. The time between system flushes ranges

Table 1
Representative 1,000 L/d brackish water PVRO parameters

| Parameter | Value |
|---|---|
| Latitude | 18.5056˚N |
| Longitude | 89.3972˚W |
| Feed water osmotic pressure | 1.1721 bar |
| Feed water temperature | 20˚C |
| Number of RO membranes | 1 |
| Membrane diameter | 0.1016 m |
| Membrane length | 1.016 m |
| Initial membrane permeability | $4.62 \times 10^{-7}$ cm/bar/s |
| Number of PV panels | 2 |
| Solar panel summer tilt | Horizontal (0˚) |
| Solar panel winter tilt | 18.5˚ |
| Solar panel area $A_{sp}$ | 1.244 $m^2$ |
| Solar panel conversion efficiency $\eta$ | 17.9% |
| Fouling parameter $\gamma$ | $3.4614 \times 10^{-9}$ 1/bar/s |
| Operating period | 3 years |

Table 2
Remediation parameters

| Parameter | Value |
|---|---|
| System flushing permeability increase $C_{bf}$ | $5.0 \times 10^{-10}$ (cm/bar/s) |
| Permeate water used during system flush $Q_{bf}$ | 85.5 L |
| System flush duration | 3 min |
| Chemical cleaning permeability increase $C_{cc}$ | $4.009 \times 10^{-8}$ (cm/bar/s) |
| Permeate water used for chemical cleaning $Q_{cc}$ | 5,000 L |
| Chemical cleaning duration | 4 h |

from 3 h to once per day, and then from one day to seven days in single-day increments. Water production for cases with only system flushing, with only chemical cleaning and with no maintenance are also calculated. Operation for all cases starts on 1 January.

### 4.2. Results for the system with known fouling parameters and conditions

The optimal system flushing frequency was once per day, at the end of the day, when there was no chemical cleaning as part of the maintenance protocol. System flushing is done at the end of the day, when there is low solar energy and low water production so the loss of water production penalty is small.

The optimal chemical cleaning frequency, when system flushing is not part of the cleaning protocol, is once every 54 d. The chemical cleaning takes several hours and is assumed to be at the beginning of the day.

The optimal combination of system flushing and chemical cleanings is found to be daily system flushing with chemical cleaning every 301 d.

Fig. 9 compares the average daily water production for the system for the following cases: (1) no cleaning, (2) daily system flushing only, and (3) daily system flushing with chemical cleaning every 301 d. Case 3 was found to maximize water production.

When the system is not maintained, water production meets the desired level of 1,000 L/d for the first 275 operating days, but after a year, it is only able to meet 80% of the demand. The figure shows that the water production increases with increasing daylight hours, as expected. The seasonal cyclic variation in water production is apparent. With daily system flushing alone, the system meets its 1,000 L/d water demand. Improvement in water production when chemical cleaning is added to the maintenance protocol becomes apparent as operation time increases. After three years of operation, the system can produce approximately 100 more liters of fresh water per day when it is chemically cleaned and system flushed, compared to when it is only system flushed. This implies chemical cleaning may extend the useful life of the RO membrane.

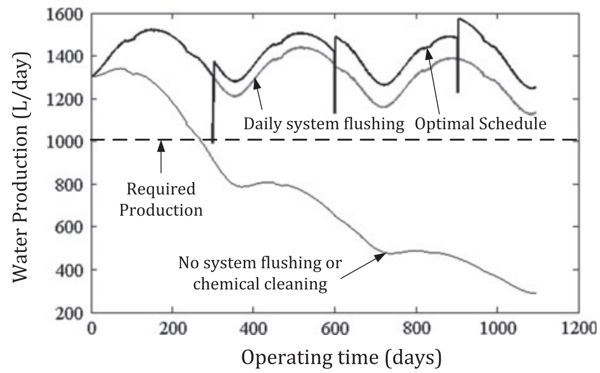


Fig. 9. Comparison of daily water production with three cleaning protocols.

### 4.3. Results for the system with uncertain fouling parameters and conditions

The optimal scheduled maintenance protocols calculated above are shown here to be no longer optimal if the operating conditions and fouling parameters vary, as would be expected in practice. The parameters used to calculate the fouling rates are not easy to estimate since they depend on many complex factors, such as hydrodynamics within the feed channel of the RO membrane, changes in water chemistry of the feed water, variation in water production rates, etc. In this study, a sensitivity analysis of the optimal maintenance protocol to the fouling parameter was conducted. Simulations of the system's performance over three years with a 20% overestimation and 20% underestimation of the fouling parameter values are done, using the maintenance protocol determined with the nominal fouling parameters.

Fig. 10 shows system water production when the fouling parameter is overestimated by 20%. Results show that adding chemical cleaning to the maintenance protocol does not provide any additional benefit to the system production. This suggests that at low fouling rates, system flushing alone is suitable.

Fig. 11 shows system water production when the fouling parameter is underestimated by 20%. As expected, the frequency of chemical cleanings should increase to maximize water production. The new optimal chemical cleaning frequency for this case is every 147 d.

#### 4.3.1. Comparison with CBM

In this section, a comparison of the proposed model-based method with reactive, CBM is discussed. In the CBM applied to RO systems, some measured parameter of the system performance is monitored and compared with some ideal value. When the ratio of these values reaches some predetermined threshold, remediation is performed. Clearly, part of the "art" of applying CBM is the selection of the variables to be measured, the ideal values, and the "trigger" ratios. Driving pressure, solar panel power, and permeate flow rate are measureable in the example PVRO system considered in this study.

An example of a performance metric that can be used for CBM of RO systems is the normalized permeate flow rate, $q_n$, defined in [17]. The conventional definition is not suitable for PVRO systems because it is calculated using static, steady operating conditions. The following definition of normalized permeate flow rate for PVRO systems is proposed, which is a ratio of RO permeate flow to electrical power:

$$q_n = \frac{q_p}{P_{elec}} \tag{11}$$

The ideal (reference) value of the normalized permeate flow is defined as the normalized permeate flow at the

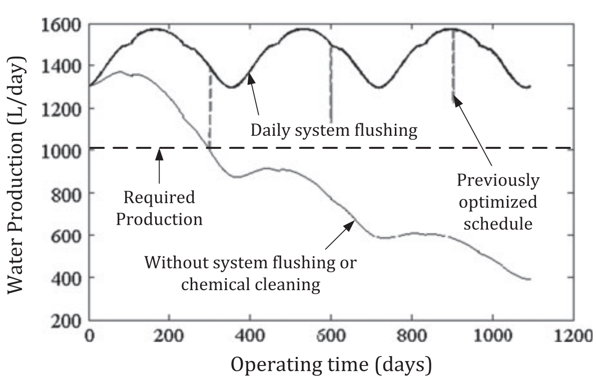


Fig. 10. Comparison of daily water production over time, low fouling parameter.

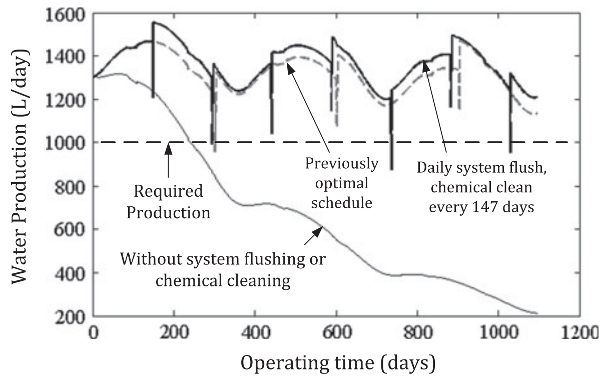


Fig. 11. Comparison of daily water production over time, high fouling parameter.

time of highest electrical power produced by the PV panels during a sunny, summer day (hence the highest solar radiation) using a new, clean RO membrane. As an example, the solar radiation, electrical power generated by the solar panels, and RO permeate flow rate through a clean, new membrane over the course of 15 July for the example PVRO system are calculated. The highest electrical power produced by the solar panels is 459 W, and the permeate flow rate at that power level is $4.62 \times 10^{-3}$ L/s. The normalized flow rate is $1.006 \times 10^{-4}$ L/s/W.

For large systems using constant power from the grid, experts recommend chemical cleaning when the normalized permeate flow rate drops by 10% [17,20]. For small-scale PVRO systems, performing chemical cleaning at such a ratio may not be best. Normalized permeate flow, as defined in Eq. (11), may not be a suitable metric either.

Detailed simulations using the models developed in this study show that, for the system considered, one could perform exhaustive searches to determine which variables, ideal values, and ratios could be used to design a CBM and achieve results that approach the results shown by the model-based approach. However, this open-loop methodology relies on a number of choices of variables, ratios, and extensive trial and error studies that are beyond the capabilities of non-experts who would be operating these systems in the field. In comparison, the model-based approach relies on only a few parameters that are ideally a function of the water chemistry, average water being produced, and the cleaning effectiveness. While some of these parameters may not be well known, it can be shown that they can be identified by simple online algorithms. A detailed discussion of such algorithms and methods is beyond the scope of this paper.

## 5. Summary and conclusions

In this paper, simple models of water production, RO membrane fouling, and remediation in small-scale PVRO plants for remote communities operated by non-experts are presented. They permit the calculation of water produced by a small-scale PVRO system as a function of time under deterministic field conditions. They are also shown here to be appropriate in a model-based maintenance approach to determine frequencies of system flushing and chemical cleaning that maximize water production of a system under deterministic operating conditions.

The sensitivity study shows that the optimal prescheduled maintenance strategy is not robust to large changes in the fouling rate parameter. The fouling rate parameter is not easily determined from water chemistry, since it also depends on hydrodynamics within the feed channel. Furthermore, feed water chemistry may change due to rainwater runoff, seasonal variations, etc.

The application of conventional CBM is also considered here. The models presented can be used to optimize a CMB protocol for a small-scale PVRO system operating under deterministic conditions. However, such optimization requires exhaustive search methods and extensive trial and error, which is beyond the scope of non-expert operators.

The results of the study also suggest the robustness of the proposed model-based maintenance strategy to key fouling rate parameters. It is suggested that these parameters can be identified by simple online algorithms. In conclusion, this work shows that using model-based methods have the potential to permit non-experts to operate a PVRO system under uncertain, changing conditions, and still meet the community water demand.

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