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Application of World Ocean Atlas data for estimating the relative performance of a new construction of SWRO desalination plant

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ABSTRACT

Desalination offers one of the reasonable alternatives as a solution to water scarcity. Among the desalination technologies, seawater reverse osmosis (SWRO) process becomes increasingly attractive for freshwater supply with comparatively low energy consumption and cost-effective operation. In this study, a benchmark of operating Fujairah SWRO desalination plant in the United Arab Emirates is applied to assess the relative performance of a new and large plant construction in other sites. A process model was developed to simulate the performance of SWRO desalination process and to estimate its operating cost. The developed model was validated using one-year SWRO operation data obtained from Fujairah SWRO desalination plant. Temperature and salinity data were collected from World Ocean Atlas 2005, and then applied to the model to estimate the operating cost under the site-specific conditions of 9 different countries. The results of this study present that the performance of the SWRO desalination process was significantly influenced by feed water concentration (i.e., mainly salinity) and temperature, and that the total operating cost is significantly dependent of the local electricity costs. As a conclusion, World Ocean Atlas data and the benchmark provide a method of comparing the performance of various SWRO desalination systems among different countries. Furthermore the methodology is applicable to simulate the process model with site-specific water quality data and to estimate the operating cost before a new construction of SWRO desalination plant at a target area elsewhere.

Keywords: SWRO desalination; Cost estimation; Site-specific water quality data; World Ocean Atlas

1. Introduction

Even though desalination offers one of the reasonable alternatives as a solution to water scarcity, the increasing demand of fresh water in agriculture, industry, and society overwhelms the supply of limited fresh water resources [1,2]. Total production cost of seawater reverse osmosis (SWRO) desalination plant, which is closely related to plant design (i.e., capital cost) and operating efficiency of the process performance (i.e., operation and maintenance cost), depends on various site-specific conditions such as raw seawater quality and temperature, public water

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supply system, and its local power supply demand [3,4]. Therefore, it is essential to consider whether the site-specific conditions are sufficient to meet the prerequisites including seawater accessibility at a selected candidate site for a new construction of desalination plant.

To characterize and evaluate the performance of SWRO desalination process, a number of studies have reported in various ways: 1) deliverance of observed operating results from full-scale desalination plants [5–8], 2) characterization and comparison of several plants based on the data collected from existing desalination facilities [9], 3) classification of RO system based on site-specific feature [10,11], and 4) presentations of cost estimation methods based on the result of case studies in full-scale plant [12–14] as well as literature survey [4,15,16] and process modeling [17,18].

As far as operating data obtained from full-scale SWRO desalination plant and site-specific water quality data are acquired, it is possible to simulate the process performance and to estimate the energy consumption rate for the plant operation at a candidate site for a new plant construction according to the following aspects: 1) Feed water temperature and salinity are dominant factors to reflect the site-specific conditions, 2) If a fixed recovery rate (e.g., 43%) is applied to the simulation of operating the plant, then feed and permeate flux can be assumed to be constant, and 3) If an operating data set (e.g., data collected from Fujairah SWRO desalination plant in 2005) focuses on only an energy consumption of RO system without consideration of the membrane cleaning and replacement, then a developed process model can simply simulate the process performance [5].

In this study, a benchmarking associated with assessing the relative performance characteristics compared with running Fujairah SWRO desalination plant located in the United Arab Emirates (UAE), was applied for a new construction of a large scale plant in other sites. To this end, we attempted to develop a process model to simulate the performance of SWRO desalination plant and to verify the model with one-year operating data obtained from Fujairah SWRO desalination plant, UAE. Then, the site-specific water quality data extracted from World Ocean Atlas 2005 (WOA2005, NOAA) was applied to the developed model for estimating the specific operating cost which is defined as a cost unit per produced water unit (e.g., USD/m^3).

2. Data descriptions

2.1. Full-scale process operating data in Fujairah SWRO desalination plant

The Fujairah SWRO desalination plant located in UAE is one of the largest hybrid plants (i.e., thermal and SWRO desalinations) in the world. Independently, SWRO system in the hybrid system produces 170,500 m^3/d amount of drinking water via a two-pass membrane system. Data collected from this full-scale SWRO desalination plant provides the information of the operating conditions and performances for one train out of 17 trains in the first pass system. The data in the period of 2005 January to December was selected to validate the developed model and to simulate the plant performance because the SWRO plant has been stabilized to operate it with full production capacity since 2005. Cleaning-in-place (CIP) is not included from the operating cost estimation, because the SWRO system was operated without CIP during the period [5].

2.2. Site-specific seawater quality data from World Ocean Atlas 2005 (WOA2005)

In order to obtain a better understanding of the site-specific performance of SWRO desalination plant, it is required to build up data sets which can cover spatial and temporal scales for multiple water quality parameters. In previous studies [19,20], the global oceanic data, which has multidimensional data structure consisting of spatial, temporal, and water quality parameters as shown in Fig. 1, were usually utilized to explain the spatio-temporal patterns of the global climate changes.

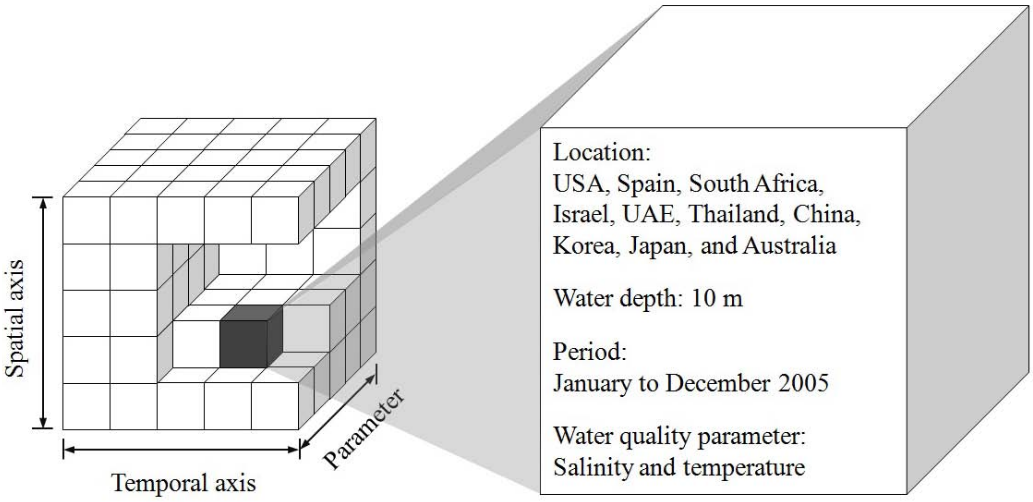
One of the popular global oceanic data set, WOA can provide the global information covering 1–5 degree resolution of longitude and latitude grids with 33 levels of vertical depth, in terms of temporal (i.e., monthly, seasonal, and annual) mean variables including temperature, salinity, dissolved oxygen, percent oxygen saturation, phosphate, silicate, and nitrate in their standard measurement units [21,22]. In this study, monthly mean seawater temperature and salinity data, which generally represent the site-specific seawater conditions, were extracted from WOA2005. The data at 10 m below the surface were selected and extracted since the depth reflects seawater intake location in Fujairah SWRO desalination plant. And then, the data were applied to simulate the relative performance of new plant construction in 9 different countries (i.e., China, Japan, Korea, South Africa, Thailand, Spain, USA, Australia, and Israel) as shown in Table 1. The data can be extended to more number of countries and shorelines. For convenience sake, the data in 10 representative countries related to desalination industry were depicted in Table 1 in terms of temperature and salinity.

2.3. Local electricity cost data

To estimate the operating cost associated with the electrical power demand, local electricity cost information for industrial clients was summarized in Table 1. The data were collected from several literature sources [23,24] for the 10 representative countries.

3. Cost estimation procedure

The total cost for a SWRO desalination plant consists



Spatial axis	Temporal axis	Parameter
Longitudinal, latitudinal , and vertical coordinates	Annual, seasonal, and monthly	Temperature, salinity, dissolved oxygen, Apparent Oxygen Utilization (AOU), percent oxygen saturation, phosphate, silicate, and nitrate

Fig. 1. Conceptual view of World Ocean Atlas data structure.

Table 1
Summary of site-specific seawater conditions (i.e., mean values of salinity and temperature ± standard deviation, n = 12) and cost estimation results (i.e., SEC[1], LEC[2], and SOC[3]). Values of SEC and SOC are limited to RO system itself in the first pass of SWRO desalination process

Location		Salinity (ppm)	Temperature (°C)	LEC (USD/kWh)	SEC (kWh/m^3)	SOC (USD/m^3)
Country	Area					
UAE	Fujairah	37,086 ± 366.02	28 ± 3.24	0.05	3.67 ± 0.10	0.18
China	Guang Zhou	33,841 ± 215.31	25 ± 2.90	0.05	4.04 ± 0.13	0.20
Japan	Hokkaido	33,371 ± 133.25	11 ± 5.67	0.12	4.34 ± 0.23	0.52
Korea	Ulungdo	33,909 ± 513.31	17 ± 5.03	0.07	3.91 ± 0.32	0.27
South Africa	Britannia Bay	35,131 ± 72.51	16 ± 0.72	0.02	4.07 ± 0.25	0.08
Thailand	Pattani	32,107 ± 483.29	29 ± 0.91	0.07	3.25 ± 0.11	0.23
Spain	Palma	37,258 ± 108.52	19 ± 3.89	0.09	4.04 ± 0.18	0.36
USA	California	33,490 ± 36.29	16 ± 1.57	0.06	3.90 ± 0.25	0.23
Australia	New Castle	35,503 ± 42.89	21 ± 2.05	0.06	3.83 ± 0.25	0.23
Israel	Israel	38,998 ± 175.69	22 ± 3.82	0.08	4.05 ± 0.13	0.32

[1]SEC: Specific energy consumption of reverse osmosis system in the first pass
[2]LEC: Local electricity cost for industrial uses in 2006 [28,29]
[3]SOC: Specific operating cost (defined as SEC×LEC) of reverse-osmosis system in the first pass

of capital cost and operation and maintenance (O&M) cost, which mainly depend on plant location, feed water quality, operating protocol, and local energy cost. Among these, only operating cost, which is directly related with energy consumption, is considered to estimate the specific operating cost (SOC) in this study. Fig. 2 shows two sequential procedures in the estimation of the site-specific operating cost: calibration of the membrane resistance using a model developed in our previous study [25] (Procedure I) and application of the calibrated model to estimate the operating cost of a potential SWRO plant at different locations (Procedure II).

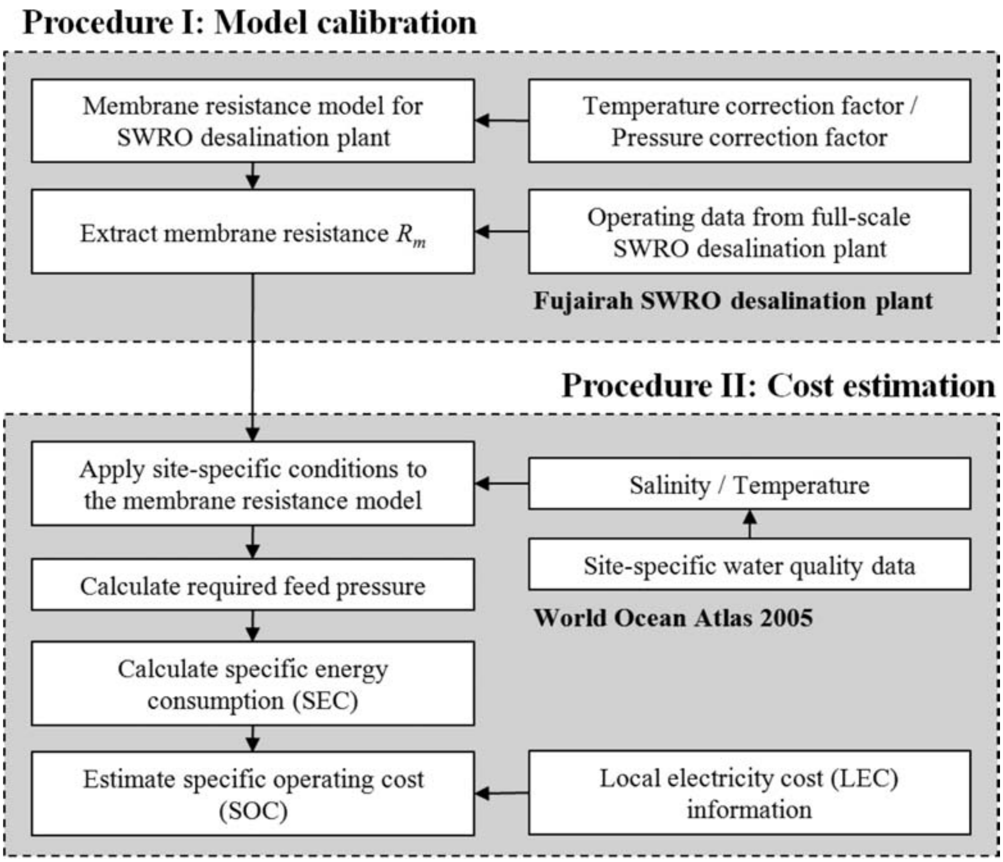


Fig. 2. Overall procedure used to estimate the specific operating cost for a SWRO desalination plant: Procedure I. Membrane resistance model calibration to simulate performance of the process, and Procedure II. World Ocean Atlas data application to estimate the specific operating cost (SOC) with the local electricity cost (LEC) information.

In Procedure I, a membrane resistance model was used to calculate monthly values of membrane resistance based on the operation data collected from the Fujairah SWRO desalination plant in 2005. The membrane resistance model [25] used in this study was a modification of the existing models [26–29] by using empirical factors reflecting variations of temperature and pressure (i.e., temperature and pressure correction factors). The calculated monthly values of membrane resistance (R_m) reflect the time varying performance of the membrane in relation to the fouling development within a year. In this study, it is assumed that monthly values of R_m calibrated from the operation data of the Fujairah SWRO desalination plant were identically applied to those in 9 candidate sites under the premise of a new SWRO desalination plant construction.

In Procedure II, site-specific data of seawater temperature and salinity for the 9 candidate sites obtained from WOA2005 were applied to the membrane resistance model with the values of R_m (n = 12) calibrated in Procedure I. Feed flow and recovery rate were treated as constant values in the simulations because a commercial SWRO plant generally aims to maintain constant permeate flux by varying feed pressure. From the simulation, the required feed pressure (i.e., P_{required}) at each site as well as each month, was calculated by aiming to produce a steady permeate flux (10,800 m^3/d) for a train in the first pass system with different site-specific conditions (i.e., seawater temperatures and salinities in different sites and months).

Subsequently, specific energy consumption (SEC in the unit of kWh/m^3) of the high pressure pump can be calculated by Eq. (1). In this equation, since recovery rates (i.e., R_{recovery}) were benchmarked with a value from Fujairah SWRO plants for all candidate sites, *SEC* can be considered as only a function of P_{required} in each site [30].

$$\text{SEC} = \frac{P_{\text{required}}}{R_{\text{recovery}}} \tag{1}$$

Finally, the specific operating cost (SOC in the unit of USD/m^3) is estimated from SEC multiplied by local electricity cost (LEC in the unit of USD/kWh) [28,29].

$$\text{SOC} = \text{SEC} \times \text{LEC} \tag{2}$$

4. Results and discussion

Each selected candidate site for new construction of a SWRO desalination plant was assumed having the same capacity of feed intake, recovery rate, and membrane characteristics with those of the Fujairah SWRO desalination plant. In order to maintain a constant permeate production rate, a higher feed pressure ($P_{required}$) is required to overcome an increased membrane resistance due to the membrane fouling with respect to the operating time [31]. The values of $P_{required}$ under different site-specific conditions of seawater temperature and salinity were used to compute the values of SEC, which are shown in Table 1.

In Table 1, when the simulation results for Korea and China are compared with each other, average values of salinity are equivalent, but feed water temperature in China causes greater permeate flux resulting in lower energy consumption as opposed to Korea [32]. Because of the same reason, the value of SEC in Thailand was the greatest due to the highest seawater temperature. However, it should be noted that this study did not consider the negative effect of membrane fouling on the permeate flux; high temperature of feed water can accelerate membrane bio-fouling, increasing the membrane resistance, and subsequently decreasing permeate flux [31]. On the other hand, when the values of SEC are compared between South Africa and USA, whose salinity values are almost identical, the SEC value in South Africa was greater than that in USA because of higher concentration of feed water salinity.

The results of SEC estimation in Table 1 show that how the RO process performance is affected by site-specific sea water conditions. The results of SOC estimation however demonstrate the importance of LEC as a crucial factor to determine the final water production cost. For example, although the value of SEC for Spain (4.04 kWh/m^3) is lower than that for South Africa (4.07 kWh/m^3), the value of SOC in Spain (0.36 USD/m^3) is four times higher than that of South Africa (0.08 USD/m^3) due to the higher value of LEC in Spain.

5. Conclusions

A total of 9 candidate sites were selected under the premise of a new construction of a SWRO desalination plant. Then, a model development with a benchmarking approach of Fujairah SWRO desalination plant operation in UAE was carried out to extract the required feed pressure values for each site. As critical input conditions for the model, site-specific seawater conditions (i.e., water temperature and salinity) in the 9 candidate sites were obtained from a global oceanic database, World Ocean Atlas. Finally, the specific operating costs (SOC in the unit of USD/m^3) were estimated and compared among the candidate sites. From the results, the relationship among the feed seawater characteristics, the specific energy consumption (SEC in the unit of kWh/m^3), and the local electricity cost (LEC in the unit of USD/KWh) could be summarized: 1) Higher temperature and lower salinity of feed water can result in the increase of the amount of final water production. 2) Even though the operating performance of a SWRO desalination plant is sensitive to changes in site-specific seawater characteristics (i.e., feed water temperature and salinity), LEC is another critical factor to be considered in determining the final water production cost. In conclusion, this study opened a new insight and methodology in the viewpoint of how the public accessible oceanic data can be used to predict the performance of a SWRO desalination plant and thereby to estimate the operating cost at a target area in the world.

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