Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2017.20659

78 (2017) 1–11
June

Economic analysis on environmentally sound brine disposal with RO and RO-hybrid processes

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Received 6 October 2016; Accepted 16 December 2016

A B S T R A C T

The critical environmental impact of brine solution has been pointed out as an important issue in desalination technology, which should be resolved urgently. In this study, an economic analysis with respect to environmentally sound brine disposal was conducted along with the open outfall system and seawater reverse osmosis (SWRO) basis processes (stand-alone SWRO, SWRO-pressure retarded osmosis (PRO) hybrid, and SWRO-membrane distillation (MD)-PRO hybrid processes). The parameters of an open outfall system were controlled to mitigate the environmental impacts, and the capital cost of the open outfall system was estimated with WTCostII software. The estimated capital cost data were treated with statistical techniques for cost factor analysis, and variations of the capital cost were observed according to the key parameters of desalination processes. Results shown found that the diameter of pipeline is a dominant cost factor and the total capital cost of an open outfall system can be approximately estimated only with the length and diameter of the brine discharge pipe. In addition, this study also confirmed the fact that the trade-off between the two variables made the capital cost fluctuate. Among the desalination configurations, the capital cost of the open outfall in the stand-alone SWRO process changed most since the brine flow rate from other processes kept increasing regardless of the RO recovery rate. Based on the results, further research for the cost analysis on brine disposal system is required to optimize an environmentally sound open outfall system.

Keywords: Seawater reverse osmosis; Hybrid desalination process; Brine disposal; Open outfall; Economic analysis

1. Introduction

Desalination processes have emerged as an effective solution to relieve the water stress around the world [1,2]. Especially, seawater reverse osmosis (SWRO) has been developed most among desalination processes, and it is almost dominating the global desalination market [3]. Despite excellences of SWRO, some technical problems are still left unresolved and undermining the value of SWRO process.

Brine, which indicates the residual solution from the filtration step of the SWRO, is one of those problems related to the SWRO process. Since the brine is a highly concentrated solution, inappropriate disposal of the brine can have harmful impacts on the ecosystem [4]. According to the previous study, the concentrated brine, which is discharged to the seawater body directly, can be critical to the benthic organisms living in the sea bottom. Furthermore, the negative impacts of the concentrated brine are not only confined to the boundary of organisms but also valid for the environmental surroundings such as soils [5]. Therefore, all of the possible

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critical impacts should be taken into account when designing the brine disposal system.

Expenditure is another reason why the design of the brine disposal system is important for the desalination process. Since the design of the brine disposal system is highly reliant on the site of the plant, the cost model of the system cannot be generalized easily. Consequently, the designs of the brine disposal systems have become different from site to site and method to method, and it caused dramatic differences in the brine disposal costs. One study stated that a ratio of the brine disposal cost to the total desalination cost ranges from 5% to 33% for different plants [6]. In other words, the brine disposal costs only have been estimated according to the complexions of the specific plant without generalized models, especially for the open outfall method [7].

Moreover, there has been no trial yet, as far as we investigated, to incorporate the environmental impacts and economics of the brine disposal system simultaneously although none of them can be ignored. In order to advance the technological level of the SWRO process further, it is essential to conduct a research regarding the brine disposal considering the environmental and economic aspects at the same time.

Therefore, the objective of the current study is in analyzing the cost variation trends of the environmentally sound brine disposal system by utilizing statistical methods and cost estimation software. The open outfall system was selected in this study among a variety of brine disposal systems, and several different types of SWRO-basis processes were introduced to compare the effects of the concentration and flow rate of the brine on the seawater ecosystem.

2. Materials and methods

2.1. Brine disposal methodology

2.1.1. Comparison of brine discharge methods

In real fields, ways to dispose of the brines from desalination plants can differ in accordance with the desalination plant sites, climates, and various other complexions. Among the methods, open outfall is the most primitive method to dispose of the brines. Namely open outfall is a method to discharge the brines onto (or into) the seawater directly without additional treatments. This method is less expensive and more convenient for plants compared with other methods, but it can have negative impacts on ecosystem if the discharged brines are highly concentrated [5,6]. Due to the harmful effects of the brines on the ecosystem, many countries and environmental agencies around the world are trying to regulate the open outfall method by having the plants not discharge highly concentrated brines into the seawater and to construct the facility farther from the shore as much as possible [6]. However, the regulations authorized so far are valid only for a few areas, such as Arabian Gulf, and many of regulations are just suggesting a sort of recommendations rather than mandatory compliances [8]. Definitively, that makes the situations worse since the desalination plants don't have duties to discharge the brines with taking an account of the negative impacts on the ecosystem for now.

There are several more brine disposal methods utilized in the desalination fields. Deep well injection is a method originally used in the oil industry to bury the residuals resulted from the crude oil refinery process [9]. As the desalination industry grew up, some of the desalination plants started disposing of the brines by using the deep well injection. Even though this method has some advantages such as low energy consumptions, it is not being utilized as frequently as the open outfall method since it is too site-specific and much more expensive than the open outfall [10,11].

Spray irrigation is a way to utilize the brines as agriculture waters. It is beneficial in that the brines can be re-used for another industry. However, the points that it cannot be applied to the desalination plants of large capacity make spray irrigation hard to be utilized widely. The reason why it cannot be applied to the large capacity plant is because the amount of water that vegetation and soil can ingest at one time is limited. Additionally, it is another obstacle for the method that the vegetation species, which can be raised by the salty water, is fewer [12].

Evaporation pond is a way to dispose of the brines by evaporating all the solvents of brines. Left solutes after the evaporation like NaCl could be sold or thrown away [13]. This method doesn't require complex management and isn't dependent on the plant site. Just like spray irrigation, however, it can be only applied to the small-scale plant. Moreover, it needs a large-sized premise to maximize the surface of brine exposed to the sun and that is directly linked to the land fee [14]. Table 1 shortly represents the advantages and drawbacks of each brine disposal method used for desalination.

In this study, the open outfall was selected as the brine disposal method since other methods are basically utilized for the brackish water reverse osmosis (BWRO) process, not for the SWRO process. Furthermore, the cost estimation model of the open outfall system has not been suggested in contrast to other methods due to its difficulty of generalizing [7]. With a bunch of assumptions, the current study tried to build up the cost estimation model for the open outfall system and to observe the comprehensive trends of its capital cost.

Table 1
Advantages and drawbacks of each brine disposal method

Disposal methods	Advantages	Drawbacks
Open outfall	• Low disposal cost • Free from the plant scales	• Impacts on ecosystems • Complicated legitimate approval
Deep well injection	• Appropriate for inland plants • Low energy consumption	• Site-specific • Impacts on aquifers
Spray irrigation	• Easy to be applied	• Limited to the small-scale plants • Impacts on soil and aquifers
Evaporation ponds	• Easy to manage and be applied • Free from plant sites • Low energy consumption	• Need for large premises • Limited to the small-scale plants • Influenced by the climates

2.1.2. Design of open outfall

As mentioned before, open outfall is more economical and convenient one beside other disposal methods and that is what makes open outfall preferred by the industry. However, it is important to consider the environmental impacts of open outfall since brines are still being discharged in undesirable ways [4].

Controlling the discharge angle of pipe θ_d is one way to mitigate the environmental impacts of the open outfall [15]. If concentrated brine is discharged to the sea body horizontally, the discharged solutions just sink down to the bottom of the sea body without additional mixing process due to higher solution density of the brine than the seawater. The sunken solutions could influence on the benthic organisms harmfully. Therefore, varying θ_d is a strategy to prolong the mixing duration of brine, and the mixed brines could have less harmful impacts on the ecosystem. As the brines get more concentrated, θ_d should become more slanted because the mixing duration required for the brines gets longer as well. Bulk dilution factor (S_i) is a measurement to judge whether the discharged brine was diluted enough when it reaches the sea body bottom, which is called as impingement point (x_i), after the mixing process [15]. Bulk dilution factor is defined as follows:

$$S_i = \frac{C_d}{C_i} \tag{1}$$

where C_d is a concentration of chemicals other than salts in initial brine effluent, and C_i is a concentration of the chemicals in diluted brine at the impingement point. A higher value of S_i implies that the discharged brine was mixed with the sea body better, and it also indicates that the determined θ_d is effective. It is possible to assort the meaning of S_i values as follows:

$$S_i = \begin{cases} \text{Low dilution rate}\,(0 < S_i \le 10) \\ \text{Medium dilution rate}\,(10 < S_i \le 20) \\ \text{High dilution rate}\,(20 < S_i) \end{cases} \tag{2}$$

Eq. (2) was determined based on the general concentration of chlorides added to the raw seawater in the pre-treatment step (0.5–1.5 ppm) and its residual concentration in the brine (200–500 μg/L) [16]. Even though the amount of the chlorines left in the brine is not that much, it was already said that even small amounts of chlorine can have critical impacts on the ecosystem since the totally accumulated amounts of chlorine are so massive [17]. Moreover, the concentration of the residual chlorine will increase as the recovery rate of the desalination process increases for sure. That is, it is important to dilute C_d as much as possible by increasing θ_d. Once the proper value of S_i (where $20 < S_i$) is observed, then it can be said that θ_d was slanted enough for the desalination plant.

However, what is directly related to the capital cost of open outfall is not θ_d though. To estimate the capital cost of the open outfall, the terrain of the shoreline should be considered additionally. There are two parameters that we have to consider regarding the terrain of the shoreline in designing open outfall system: one is a slope of the shoreline (θ_s), and the other is the local water depth (Z). These two parameters are important for they are controlled in order to avoid the interference of the brine with the seawater surface. If the brine interfered with the seawater surface, then the interference would cause slower dilution and wider dispersion of the brine [4]. Therefore, θ_s and Z should be taken into consideration when designing the environmentally sound open outfall system. The allowance range of Z for the environmentally sound open outfall system was suggested in the previous study as follows [15]:

$$Z_m \le 0.75Z \tag{3}$$

where Z_m is the maximum height of brine effluents. When we look into Eq. (3), we can find that the maximum height of brine effluents should be less than or equal to three-fourth of local water depth to discharge the brines environmentally friendly. Given that the brine should not meet with the seawater surface, it is not hard for us to know that Z_m is dominated by the discharge velocity (U_d) and θ_d. Thus, both U_d and θ_d should be controlled within the appropriate allowance ranges. The allowance range of U_d for Eq. (3) was suggested as 4–6 m/s and that of θ_d for stand-alone RO was suggested as 30°–45° [15].

By combining θ_d and Z together, we can obtain an exact relation for the length of the pipe (L), θ_s, and Z, and Fig. 1 is depicting their relations. If we denote the offshore location of the pipe as x, the x can be defined as follows by putting all the facts written above together:

$$\tan\theta_s = \frac{z}{x} \tag{4}$$

$$\therefore x = \frac{z}{\tan\theta_s} \tag{5}$$

Assuming that the length of both pipe ends and the trenched depth are negligibly short, L can be described as follows:

$$L = \frac{1}{\cos\theta_s} x \tag{6}$$

that is:

$$L = \frac{z}{\sin\theta_s} \tag{7}$$

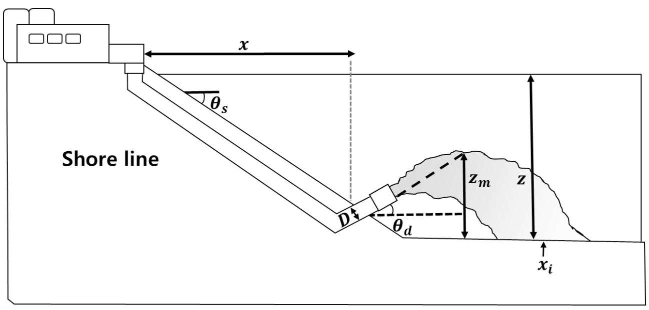

Fig. 1. A schematic overview of the open outfall system.

By incorporating Eqs. (3) and (7) together, we can obtain the following relation:

$$\frac{4}{3}\frac{Z_m}{\sin\theta_s} \le L \tag{8}$$

Eq. (7) states that L increases as θ_s decreases and Z increases. Also, Eq. (8) is suggesting the effects of θ_d on L because Z_m is dominated by θ_d.

Since the terrain of shoreline differs extremely according to the plant sites and areas change, θ_s should be determined by administrators for their own. In this study, the value of θ_s was fixed as 10° arbitrarily.

Volume rate of the brines (Q_d) is another crucial component to determine the capital cost of open outfall system since it is related to the diameter of pipe (D). When designing the open outfall system, the diameter can be determined as follows:

$$D = \frac{U_d^2}{|g_d|\mathrm{Fr}^2} = \left(\frac{4Q_d}{\pi \mathrm{Fr}|g_d|^{\frac{1}{2}}}\right)^{\frac{2}{5}} \tag{9}$$

where g_d and Fr are the buoyant gravitational acceleration of brines, which is calculated according to the density of brine and Froude number, respectively. Froude number is a dimensionless number representing a ratio of discharge velocity of brine to the resistance that prevents the brines from being discharged straight. That is, the mixing process of the discharged brine won't be conducted well unless the Froude number is large enough owing to the high resistance that hinders the straight discharge of brines [15]. Therefore, Froude number should be large enough (Fr ≥ 10) to ensure the sufficient mixing process of brines with the sea body. Once the value of the Froude number is sufficiently large for the brine discharge, then D can be calculated. In this study, the lowest value of Froude number for modeling was fixed as 15, to make sure that the Froude number is large enough for discharge, and the highest value of Froude number for modeling was fixed as 40. The limitation to the highest value of the Froude number is attributed to the probability of the overload on the discharge pump, which can cause the unnecessarily excessive velocity of U_d.

In this study, the values of L were determined with Eq. (8), and each value of L was rounded up in units digit. On the other hand, the values of D were determined with Eq. (9), and each value of D was rounded up in the second decimal point.

2.2. Desalination processes

2.2.1. Desalination process configurations

In order to compare the capital costs of open outfall system according to changes of C_d and Q_d, three different desalination processes were introduced in this study, which are stand-alone RO process, RO-pressure retarded osmosis (PRO) hybrid process, and RO-membrane distillation (MD)-PRO hybrid process (Fig. 2). PRO process usually not only generates the energy with salinity differences but also plays a role to dilute the brine solution from the previous process as a result. Therefore, the PRO sub-system added onto each hybrid process will help find effects of C_d on the open outfall capital cost. In contrast to PRO, MD sub-system in the RO-MD-PRO process serves to decrease Q_d and increase C_d, and it makes the RO-MD-PRO process comparable with another process.

The recovery rate of RO sub-system (Rec) within each process ranged from 40% to 60% with an increment of 5%, and recovery rate of MD sub-system within RO-MD-PRO process and dilution rate of PRO sub-system within each hybrid process were fixed as 20% and 50%, respectively. Therefore, C_d changed along with the variations of Rec. The temperature change of the brines from RO-MD-PRO process was neglected for a convenience.

As a result, the brines from stand-alone RO process retained the highest C_d and the lowest Q_d, since there was no additional blending process for the stand-alone RO process. In contrast, RO-PRO process discharged brines retaining the lowest C_d and the highest Q_d. Brines from RO-MD-PRO process retained intermediate values in both aspects. Also, θ_d changed along with the individual variations of C_d and Q_d of each desalination process for proper mixing process of the discharged brines. Table 2 is tabulating the features of each process written above.

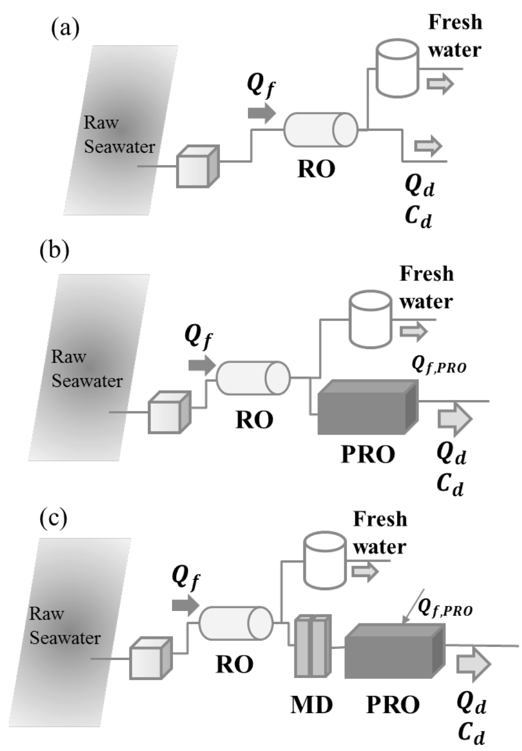

Fig. 2. Schematic figures on the desalination process configurations simulated in the current study, which are (a) stand-alone SWRO, (b) SWRO-PRO hybrid, and (c) SWRO-MD-PRO hybrid processes. All of the hybrid processes in this study were configured as a "multistage type", i.e., the brine solution of the prior sub-system is conveyed to the subsequent sub-system, not thrown away.

2.2.2. Seawater intake and pre-treatment step

The concentration of the raw seawater utilized for the simulation was fixed as 35,000 ppm, and the volume rate of feed inlet (Q_f) ranged from 50,000 to 100,000 m^3/d. Also, it was assumed that raw seawater was pre-treated after the intake step. In the pre-treatment step, a popular oxidant (chlorine) and other incidental additives (e.g., anti-scalants) were added to the raw seawater, and the residual additives in brines were used to measure S_i. In this study, C_d of stand-alone RO process with Rec = 60% was assumed as 500 μg/L, and it was designated to the reference value. C_d of other processes with different Rec were calculated based on the reference value.

Treated wastewater effluent was utilized for the feed solution for PRO sub-system. The feed solution was assumed to retain 1,000 ppm of concentration, and its flow rate varied along with the changes of Q_d and C_d.

2.3. Cost factor analysis

The capital cost estimations of open outfall system for each desalination process were conducted with the software called as WTCostII. Even though WTCostII is offering functions to estimate the capital cost of various brine disposal methods, the estimated capital costs are only dependent on Q_d, not on C_d, and L and D are selectable as a user wants [18]. Additionally, the information offered by the software is veiled so that it is almost impossible to grasp the exact relation between the open outfall capital cost and the variables directly [19]. Thus, the cost factor analysis was conducted, after the capital cost estimation, to confirm the contributions of each variable to the open outfall capital cost. In this study, the cost factor analysis was conducted based on the statistical techniques: principal component analysis (PCA), varimax, and multiple linear regression (MLR).

2.3.1. Principal component analysis and varimax

PCA is the process of finding a suitable lower-dimensional space in which to represent the original data [20]. This process reduces the dimensionality of the data set and creates new sets of coordinates (principal components, PC), which consist of the original variables.

The first step for PCA is to calculate the covariance matrix. The covariance matrix (S) is computed as follows:

$$S = \frac{1}{n-1} X_C^T X_C \tag{10}$$

where X_C is a matrix transformed from the original data matrix X, which has the zero mean. n is the number of row of the matrix X, and the subscript T indicates the transpose of the matrix. After S is computed, the eigenvectors and eigenvalues (λ_j, where j = 1, ..., d) of S can be found by solving the following equation for each λ_j:

$$\left|S - \lambda I\right| = 0 \tag{11}$$

where I is an identity matrix. Once the eigenvalues are determined, the eigenvectors emerge by solving following equation:

$$\left(S - \lambda_j \mathrm{I}\right) a_j = 0 \tag{12}$$

At the moment, the set of eigenvectors has to be orthonormal. The λ_j of covariance matrix is derived by calculating the diagonal matrix (L) as follows:

$$L = A^T S A \tag{13}$$

where A is a matrix that consists of eigenvector a_j, which resulted from Eq. (11). Now, the elements of L except zeros represent λ_j if we calculated Eq. (12). Finally, the eigenvectors of S can be used to obtain newly transformed variables, PCs. The jth PC is given by:

$$\mathrm{z_j} = a_j^T (\mathrm{X} - \overline{\mathrm{X}}) \tag{14}$$

The calculated PCs are linear combinations of the original variables where the elements of a_j are providing the coefficients. The data would be transformed to the PC coordinate system subsequently when using the following matrix multiplication:

$$\mathrm{Y} = \mathrm{X_c A} \tag{15}$$

Table 2
Features of each desalination process and seawater intake

Process types	Seawater conditions	Brine characteristics
Stand-alone SWRO	• Volume of feed inlet (Q_f): 50,000–100,000 t/d • TDS of feed inlet (C_f): 35,000 ppm • RO process recovery (Rec): 40%–60%	• Q_d: 20,000–60,000 m^3/d • TDS: 57,800–87,500 ppm • C_d: 333–500 μg/L
SWRO-PRO hybrid	• MD recovery: 20% • PRO dilution rate: 50% • Slope of shoreline (θ_s): 10°	• Q_d: 28,500–90,000 m^3/d • TDS: 38,800–41,010 ppm • C_d: 223–240 μg/L
SWRO-MD-PRO hybrid		• Q_d: 25,000–72,000 m^3/d • TDS: 45,000–49,000 ppm • C_d: 260–280 μg/L

where Y is the matrix containing the PC scores, and we can find that the PC scores of each variable.

Even though PCA is an effective statistical method to find the PC sets, the variables can be categorized absurdly if a multicollinearity among the variables is too high. Therefore, the PCs should be treated additionally with another statistical method called as varimax. Varimax is an orthogonal rotation method that minimizes the number of variables, which have high loadings on each factor. This method simplifies the interpretation of the factors so that clarifies the relations among variables. All of PCs in the current study had treated with the varimax, and the final interpretations on the data were made based on results of varimax.

2.3.2. Multiple linear regression

PCA and varimax were utilized to check the correlations among the variables and to determine the representative component sets with the least number of independent variables. Based on the results of PCA and varimax, the MLR was conducted to generalize the cost model of open outfall system. The derived MLR model was used to predict the capital cost of open outfall with the least number of variables, and the predicted capital costs were compared with the open outfall capital cost data from the WTCostII to demonstrate the credibility of the developed MLR model.

2.4. Modeling procedure

First of all, a desalination process that would be simulated was selected out of three different types. Second, the parameters such as θ_d were controlled to minimize unwanted effects using Eqs. (1)–(9). Based on results of the parameters, D and L were calculated. Third, the values of D and L were put into the WTCostII software, and the total capital cost of open outfall system was calculated. Finally, the cost factor analysis was conducted using Eqs. (10)–(15) and varimax method. The variables linked to the open outfall capital cost directly were selected to build up the MLR model.

3. Results and discussion

3.1. Cost factor analysis

Accumulated open outfall capital cost data were treated with Eqs. (10)–(15) and varimax method as mentioned in section 2.3. The results are shown in Tables 3 and 4. Table 3 represents fractions of explained total variances. When the data were treated only with PCA, PC1 and PC2 accounted for 60.7% and 23.6% of explained total variance, respectively. However, the fractions of explained total variances changed into 44.7% for PC1 and 39.6% for PC2 if the data were treated additionally with the varimax. This indicates that the variable composition for each PC changed as the varimax method is applied to the PC sets. Table 4 represents how each PC comprises variables or parameters and their fractions in terms of loading and score coefficient. The variables related most to the PC1 are L, θ_d, and C_d, and their loadings are, respectively, 0.965, 0.944, and 0.910 as given in the Table 4. In other words, all the three variables are related deeply to the PC1 rather than other variables or parameters. In addition to it, Fig. 3 is depicting the correlations among the three variables. Points

Table 4
The rotated loading and score coefficients of each variable

	Rotated loading		Score coefficient	
	PCs		PCs	
	1	2	1	2
Recovery	0.372	–0.406	0.073	–0.112
Diameter	0.431	0.878	–0.010	0.150
Length	0.965	–0.059	0.370	0.150
Flow rate	–0.378	0.890	0.013	0.327
Angle	0.944	–0.240	0.328	0.066
Concentration	0.910	–0.274	0.309	0.044
CAPEX	0.117	0.965	0.221	0.447

Note: Both rotated loading and score coefficient show that discharge angle, pipe length and brine concentration are related to each other in the PC1 and brine flow rate and pipe diameter are related to each other in PC2.

Table 3
Fractions of explained total variance for each principal component (PC)

PCs	Default eigenvalues			Cumulative squared sum			Cumulative rotational squared sum		
	Sum	Variance (%)	Accumulated (%)	Sum	Variance (%)	Accumulated (%)	Sum	Variance (%)	Accumulated (%)
1	4.253	60.752	60.752	4.253	60.752	60.752	3.131	44.728	44.728
2	1.656	23.657	84.409	1.656	23.657	84.409	2.778	39.681	84.409
3	0.772	11.035	95.443						
4	0.151	2.151	97.594						
5	0.125	1.789	99.383						
6	0.028	0.393	99.776						
7	0.016	0.224	100.000						

Note: Left – fractions of total variances for each PC resulted from a pure principal component analysis (PCA) method. Middle – 84.4% of total variances could be accounted for by PC1 and PC2. The rest of PCs were excluded from considerations for convenience. Right – resulting fractions of total variances for each PC from the varimax method. The quantity of accumulated total variances with PC1 and PC2 unchanged, but each fraction of PC1 and PC2 varied.

of the three variables on the coordinate plane of rotational space are located very close to each other, which implies that the variables are collinearly connected [20].

Similar conclusions could be made for PC2 in the same way. PC2 mainly consists of D, Q_d, and CAPEX, and points of the variables are as close as three main factors of PC1 on the coordinate plane. One thing different from the result of PC1 is that the outfall capital cost, which is a dependent variable of the MLR model, is in the colinear relations with Q_d and D. This indicates that Q_d and D are related closely to the capital cost of open outfall system rather than any other variables. However, the results of PCA and varimax methods cannot account for how further each variable affects the open outfall capital cost. It is because all that we could find from the results of PCA and varimax was not a quantified relation between variables and open outfall capital cost, but a fact that D and Q_d would dominantly influence on the total capital cost. Therefore, it is needed to generalize and quantify the relation between variables and the open outfall capital cost via MLR.

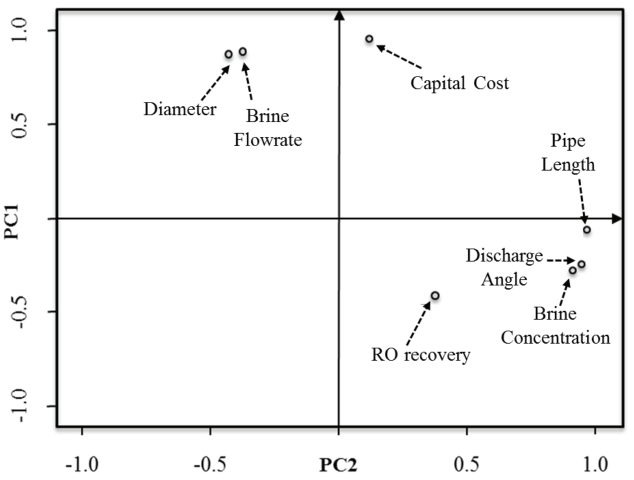

Fig. 3. Resulting correlation diagram of the coordinate plane of rotational space from the varimax method.

A preliminary step, which is to select the least number of variables, is required to conduct the MLR subsequently. It is because of the multicollinearity among the variables as shown in the results of PCA and varimax. If the MLR were conducted without considerations on the collinearity, the MLR model would be too complicated to interpret the model, and it can reduce the credibility of the developed model [21]. Fortunately, we could find that D and L were mainly affected by Q_0 and C_d, respectively, and it became possible to select those two variables as independent variables of the MLR model, X_1 and X_2.

Table 5 and Fig. 4 are, respectively, representing the summary of the developed MLR model and a plot comparing the predicted open outfall capital cost with the data of WTCostII, which all the other variables including θ_d and Q_0 are taken account of the capital cost estimation. In Table 4, R^2_{adj} values are shown as 0.612 ($p < 0.05$) for a case when $X_1 = D$ and 0.872 ($p < 0.05$) for a case when $X_1 = D$ and $X_2 = L$. This

Table 5
Model 1 is a one-variable regression model where X_1 is designated as D, and model 2 is a two-variable regression model, the one being referred to as the developed MLR model in the current study

MLR model summary

Models	R	R^2	R^2_{adj}	Standard error	df1	df2	p value of F-text
1	0.785[a]	0.617	0.612	21,446.48	1	79	0.000
2	0.935[b]	0.875	0.872	12,323.77	1	78	0.000

Coefficients

Models		Unstandardized coefficient		Standardized coefficient	p value	Collinearity statistics	
		B	Standard error	Beta		Tolerance	VIF
1	(Const.)	–36,259.214	10,062.623		0.001		
	D	273,820.748	24,291.051	785	0.000	1.000	1.000
2	(Const.)	–129,209.204	9,328.140		0.000		
	D	375,246.193	16,082.018	1.076	0.000	0.753	1.327
	L	21.620	21.620	0.586	0.000	0.753	1.327

ANOVA

Models		df	F value	p value
1	Regression model	1	127.069	0.000[a]
2	Regression model	2	273.038	0.000[b]

[a]Predicted value: (Const.), diameter.
[b]Predicted value: (Const.), diameter, and length.
[c]Independent variable: CAPEX.
Note: As L takes account of the capital cost estimation, the goodness of the fitting (R^2_{adj}) also increased by about 0.26, i.e. the MLR model could be more generalized by combining D and L together.

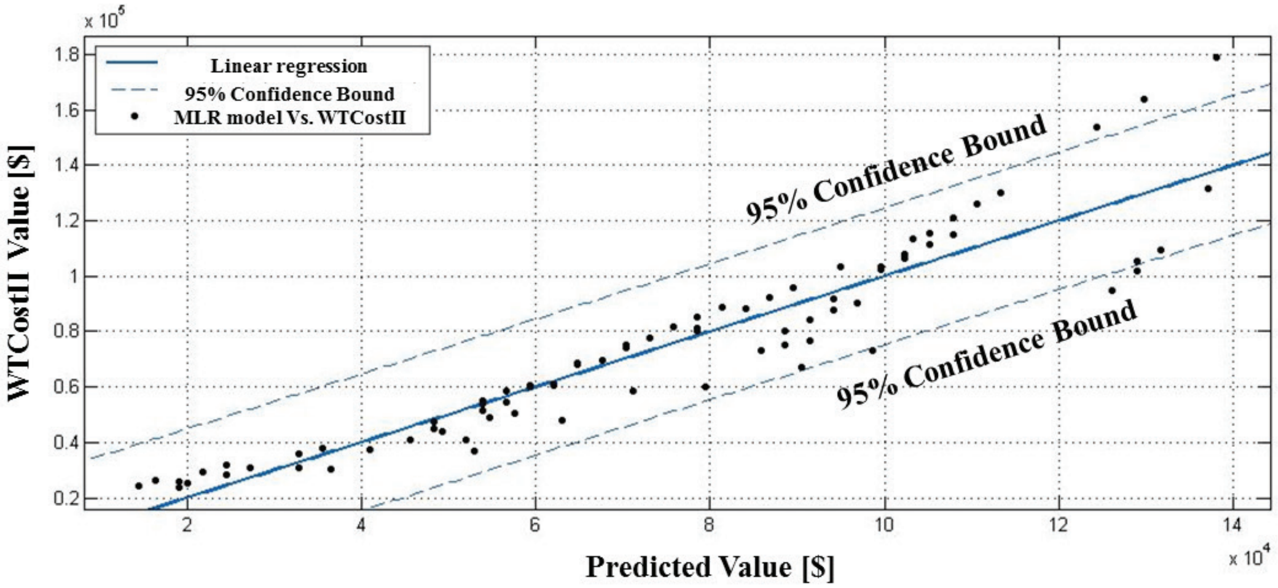

Fig. 4. A comparison between the multiple linear regression (MLR) model and the WTCostII software data.
Note: The black dots on the coordinate plane indicate the individually compared data. The blue linear line is a regression plot depicting the general relations between the predicted values (MLR model values) and WTCostII data values. Most of the black dots are placed within the 95% confidence bound (blue dashed lines) except for some deviations.

implies that the overall tendency of the MLR model can be acquired by the X_1, and the goodness of the fitting can be improved if the X_2 is considered additionally. Another important result that we can obtain from the R^2_{adj} value is that the credibility of the developed model is significantly high, i.e., the multicollinearity of the independent variables is low. A way to check the level of the multicollinearity in MLR model is to confirm the value of variance inflation factors (VIF) [20], and the VIF is given by:

$$\text{VIF} = \frac{1}{1 - R^2_{\text{adj}}} \tag{16}$$

Based on the results in Table 5, the VIF value of the developed two-variable MLR model is calculated as 1.37. That is, the multicollinearity of the developed model would be low enough if considering a common rule that the multicollinearity is thought as high when VIF > 5 [22].

Fig. 3 shows that the relations between the developed MLR model and the data from the WTCostII software are in a linear trend. In other words, Fig. 3 shows that the capital cost of open outfall system can be approximately estimated only with D and L. This result can be interpreted in two distinct ways. First, D and L can be good delegates to replace other variables such as Q_d and θ_d, which were considered in the WTCostII data. Second, the fluctuations of the points around the MLR linear line imply that there is the trade-off between D and L when estimating the capital cost. It is because of the general reciprocal relations of D and L in the desalination processes. That is, Q_d increases as Rec decreases, but C_d decreases as Rec decreases and vice versa. Since Q_d is related to D and C_d is related to L, Rec can be an indirect cost factor contributing to the capital cost estimation.

3.2. Effect of feed inlet volume on capital cost

Fig. 5 represents plots of estimated open outfall capital cost according to the variations of Q_f. The two linear dashed lines located on the top and bottom side of the figures are investigated upper and lower bound of the brine disposal costs in USA, respectively [23]. Fig. 5 shows us that the total capital cost of open outfall increases regardless of the desalination process types as Q_f increases, and this result coincides with the result of 3.1. When it comes to the trends of the plots, it may be easy to find that there are a couple of cost-leaping sections like the open outfall capital cost variations of stand-alone RO process between 60,000 and 80,000 m^3/d of Q_f in Fig. 5(a). It is due to the changes of D resulted from the increase of Q_d. One fixed D can bear the increased Q_d to some extent, but the value of D should be recalculated if Q_d had been increased passing through a critical point of the pipe.

Interestingly, we can find that the open outfall capital cost of the stand-alone RO process topped when Rec = 40%, but became the lowest one when Rec = 60% beside other processes of the same Rec. This resulted from the fact that the critical point of the pipe doesn't change for one fixed value of D. Let us assume, for example, that the critical point of Q_d regarding 0.3 m diameter pipe was determined as 37,000 m^3/d. Then, the value of D should be increased at 61,600 m^3/d of Q_f when Rec = 40%. However, the value of D need not be changed until 92,500 m^3/d of Q_f when Rec = 60%. In other words, the cost-leaping section gets sparse as Rec increases and even may not appear. Although the capital cost still increases gradually even with one fixed value of D due to effects of other cost factors, their contributions to the capital cost are not so critical as the variations of D.

In contrast, cases of RO-PRO and RO-MD-PRO are different from that of stand-alone RO. Since the brine from the RO or RO-MD sub-systems got blended continuously with the PRO feed solutions, the final Q_f of RO-PRO and RO-MD-PRO processes are always higher than that of stand-alone RO and that makes the processes showing cost-leaping sections in every case. In spite of the cost-leaping sections of RO-PRO and RO-MD-PRO processes, the open outfall capital cost of stand-alone RO was higher than other processes when Rec = 40%. This might be because the amount of PRO feed solutions for the brine dilution at lower Rec is relatively smaller than other cases. Since brine concentration of RO process increases as Rec increases, the amount of PRO feed solution should be naturally increased for further dilution, i.e., the lower brine concentration from RO sub-system is, the smaller amount of PRO feed solution is. Moreover, the brine solution from the RO process, which is the draw solution of PRO process, will draw an even larger amount of the feed solution as it gets concentrated. Definitively, because the brine concentration of stand-alone RO process is higher than that of other processes, *L* should be lengthened more in order for an environmentally friendly brine disposal. Simply, *L* played a primal role to determine the capital cost of open outfall at Rec = 40%. As a result, the open outfall of stand-alone RO process at 40% of Rec resulted in higher capital cost beside other processes even though the process produced the smallest amount of brines.

3.3. Effect of RO recovery rate on capital cost

Fig. 6 shows how the open outfall capital cost of stand-alone RO process varies along with the changes of Rec. Noticeably, stand-alone RO process in Figs. 6(a) and (b), where Q_f are, respectively, 50,000 and 75,000 m^3/d, shows extreme fluctuations of the open outfall capital cost. This result implies that there are cost-leaping sections between 40% and 50% of Rec if Q_f is 50,000 and 75,000 m^3/d. Increasing cost between 50% and 60% of Rec in Figs. 6(a) and (b) can be attributed to the increased value of *L*. Since C_d increases as Rec increases, the value of *L* should be controlled according to the increased C_d. However, such a tendency isn't observed in Fig. 6(c), and this is might be due to the result of section 3.1 that the overall trend of the capital cost is determined by *D* although the total open outfall capital cost is approximately estimated by both *D* and *L*, i.e., *D* is more predominant cost factor over *L* in designing open outfall system. It can be also applied to the analysis of Figs. 6(a) and (b) in that the capital cost increasing gaps, resulted from the increase of *L*, in the figures are relatively smaller than the capital cost dropping gaps, resulted from the decrease of *D*.

On the other hand, the open outfall capital costs of RO-PRO and RO-MD-PRO processes keep increasing without falls along with the increase of Rec, and these results coincide with the results of sections 3.1. and 3.2. That is, the

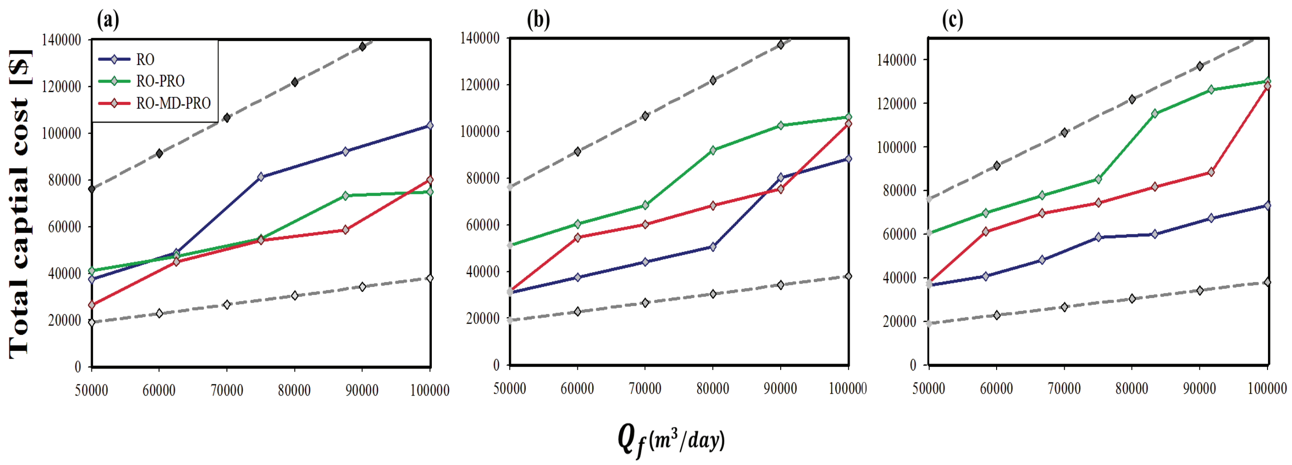

Fig. 5. Plots representing the open outfall capital cost according to Q_f when (a) Rec = 40%, (b) Rec = 50%, and (c) Rec = 60%.
Note: The dashed linear lines located on the top and bottom indicate the upper and lower boundary of brine disposal costs in the USA, respectively.

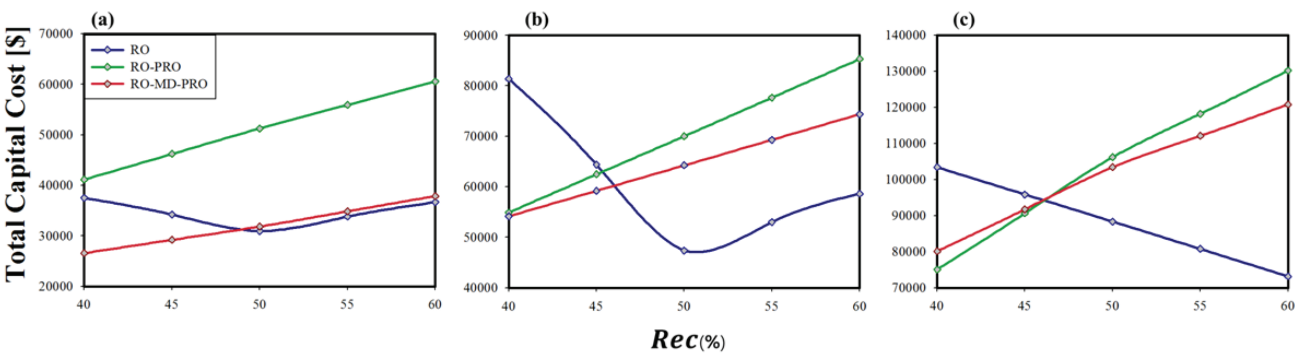

Fig. 6. Plots representing the open outfall capital cost according to Rec when (a) Q_f = 50,000 m^3/d, (b) Q_f = 75,000 m^3/d, and (c) Q_f = 100,000 m^3/d.

higher Rec is, the more PRO feed solution will be added in order to dilute the brines from the previous sub-system.

We can also find that the open outfall capital cost of RO-MD-PRO process is generally equal to or lower than that of RO-PRO process. This is due to a role of the MD sub-system in the RO-MD-PRO process. The brine solution from RO sub-system is filtrated once more throughout the MD sub-system before it is injected into the PRO sub-system as the draw solution. As a result, the MD sub-system rejects 80% amounts of brine to the PRO sub-system while the brine solution from the RO sub-system in the RO-PRO hybrid process turns into the draw solutions of PRO sub-system utterly. Although the PRO sub-system in the RO-MD-PRO process requires even more amounts of feed solution than RO-PRO process in order to dilute the MD brine, it seems like that the effects of the additional amount of feed solutions don't surpass the effects of the MD sub-system on the open outfall capital costs.

4. Conclusions

In this study, an economic analysis on the environmentally sound open outfall system of three-different SWRO-basis desalination processes (stand-alone SWRO, SWRO-PRO hybrid process, and SWRO-MD-PRO hybrid process) was conducted based on controlled parameters and statistics techniques. For the construction of the environmentally sound open outfall system, the variables or parameters of the open outfall system were constrained, and the total capital cost of the open outfall system was estimated by utilizing the cost estimation software, WTCostII.

The data of the open outfall capital cost were analyzed via statistical techniques, which were PCA, varimax, and multiple linear regression, to confirm the relations among variables and the effects of the variables on the capital cost. Results demonstrated that the diameter of the pipe and the flow rate of the discharged brine are closely related and the concentration of the brine and the length of the pipe are closely related as well. Also, we found that the diameter of the pipe and the length of the pipe, the diameter of the pipe in particular, can be primary cost factors for the open outfall system in accordance with the results of the varimax and MLR.

In addition to the capital cost data of the open outfall system, we could draw four other conclusions. First, the capital cost of the open outfall system increases as the amount of RO feed solution increases regardless of the process types and RO recovery rate. Second, the total capital cost of a stand-alone RO process is overtaken by that of other processes as the RO recovery rate increases since the flow rate of the brine decreases. Third, although the total capital cost of the open outfall can be approximately estimated with the diameter and length of the pipe, the overall trend of the capital cost is determined by the diameter of the pipe rather than the length of the pipe. Finally, since a higher RO recovery rate causes a decreased flow rate of the brine and higher concentration of the brine simultaneously, total open outfall capital cost plots cannot form linear shapes, which results in the complicated distribution of the open outfall capital cost, as given in Figs. 5 and 6.

The results of the current study imply that the variables and parameters should be carefully determined when designing an environmentally friendly open outfall system, because of its extremely sensitive cost factor. Therefore, further research on the open outfall system is required to optimize the system and make it more economical.

Symbols

x	—	Offshore location, m
x_i	—	Impingement point, m
Z	—	Local water depth, m
z_m	—	Maximum height of effluent, m
D	—	Diameter of pipe, m
L	—	Length of pipe, m
θ_s	—	Shore slope angle, °
θ_d	—	Discharge port angle, °
g_d	—	Buoyant gravitational acceleration, m/s^2
U_d	—	Discharged brine velocity, m/s
C_i	—	Concentration of brine at impingement point, ppm
C_d	—	Initial concentration of discharged brine, ppm
S_i	—	Bulk dilution factor (= C_d/C_i)
Rec	—	RO sub-system recovery

Subscripts

i	—	Impingement point
m	—	Maximum height
s	—	Shoreline
d	—	Discharged brine

Acknowledgments

This research was supported by a grant (code 16IFIP-B065893-04) from Industrial Facilities and Infrastructure Research Program funded by Ministry of Land, Infrastructure and Transport of Korean government.

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