Ranking of Water Desalination Technologies Based on the Preference Selection Index

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Abstract

Water is a vital part for all creatures, however, huge variation exists between countries in terms of clean water availability. Most countries suffer from extreme shortage in water resources along with fast increase in population. This resulted in even more complicated problem that has a direct impact on the economical and development aspects of countries. This paper employs the Preference Selection Index (PSI) in selecting the most suitable water desalination process for different types of feed water. Seven water desalination technologies were compared: The electrodialysis, reverse osmosis, multi flash distillation, multi effect desalination, vapor compression, ion exchange and nanofiltration. A total of 12 criteria were considered in evaluating the selected desalination methods, these were related to the technology cost, lifespan, simplicity, reliability, quality and environmental impact. Results showed that the ion exchange is the most suitable desalination technology.

Keywords

Multi criteria decision making, Water desalination, Water shortage and Clean water

1. Introduction

A wide variation exists between countries in terms of the availability of clean water (Hajeeh & Al-Othman, 2005). Several water desalination processes are currently used to treat saltwater and enhance the limited freshwater supply. These technologies are categorized into the Membrane-based, thermal based technologies and ion exchange (Ghassemi & Danesh, 2013). In membrane-based technology, many types of membranes could be used to separate dissolved solids from water. The two most commonly used technologies in this type are the reverse osmosis (RO) and electrodialysis (ED). In the thermal based processes, water is transformed initially into vapor and then returned into the liquid state. A variety of cost efficient technologies are currently used in the thermal based processes such as multi stage flash distillation (MSF), multi effect distillation (MED) and vapor compression (VC) (Afify, 2010). In the ion exchange technology, an exchange of ions between the solution and resin is accomplished (Galama, 2015).

Every water desalination technology has its advantages and disadvantages, which make the process of selecting an optimum and most suitable water desalination for a specific location a complicated task. This is because of having multiple objectives and constraints, which might contradict with each other at some levels and should be optimized simultaneously. In addition, the lack of sufficient data to select between different techniques is another problem. This kind of decisions, selecting water desalination process, is considered one of the Multi Criteria Decision Making (MCDM) methods, where many choices are compared and ranked (Ghassemi & Danesh, 2013).

Decision-making and judgments are essential requirement of the average person's daily life. Human judgment received considerable attention in and out of the psychology science (Anderson, 1970), (Dawes, 1971), (Louviere, 1974). For some decisions, one criterion can be the focus of the decision maker, while other decisions rely on multi-criteria, simultaneously. MCDM tools are used to evaluate candidate alternatives for the purpose of ranking, choosing or sorting based on a number of qualitative and/or quantitative criteria and is associated with different measuring units

(Özcan, et al., 2011). Multi-criteria decision analysis could be applied to many complex decisions. The Analytic Hierarchy Process (AHP) is considered one of the primary MCDM approaches that helps decision maker reach the optimal decision. Other MCDM approaches include Analytic Network Process (ANP), Elimination and Choice Expressing Reality (ELECTRE), Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS), Grey Theory and the Preference Selection Index (PSI).

The PSI method is a direct decision making method that requires simple and less calculations as compared to the other multi-criteria decision making approaches (Maniya & Bhatt, 2011). The PSI method relies on the statistical concepts without the necessity of weighting the considered attributes (Attri & Grover, 2015). The methodology of the PSI method consists of defining the problem goal, formulating the decision matrix of alternatives and criteria, normalizing the decision matrix, computing the preference variation value, determining the overall preference value, obtaining the preference selection index and ranking alternatives according to ascending or descending order to facilitate results interpretation (Maniya & Bhatt, 2010).

Many researchers used multiple criteria decision-making techniques to evaluate desalination technologies in different areas. (Hajeeh & Al-Othman, 2005) used a two-stage AHP process to select the most appropriate alternative. Seven criteria were selected to identify the most appropriate desalination technology. (Mohsen & Al-Jayyousi, 1999) used a five-step AHP model to evaluate different desalination technologies. (Vivekh, et al., 2016) used TOPSIS and PROMETHEE-2 methods to select the most appropriate desalination technology based on eleven criteria. (Eusebio, et al., 2016) used fuzzy AHP and grey rational analysis to select the optimal desalination technology with respect to five criteria. (Ghassemi & Danesh, 2013) applied two step model based on fuzzy AHP and TOPSIS to select the most appropriate ground water technology for treatment of brackish groundwater in Iran. (Derbali, et al., 2016) used AHP by implementing a simplified weight system for selecting the best desalination process. It was concluded that electrodialysis is the most preferable technology. (Hajeeh, 2010) evaluated three desalination technologies according to recovery ratio, energy requirement, pretreatment requirement, product water salinity, turnkey capital investment cost and corrosion potential by using fuzzy AHP. It was concluded from this study that RO is the best technology.

To our knowledge, no research was found that used the PSI method in comparing desalination technologies for both seawater and brackish water. In this paper, the PSI decision-making approach is used to select the most appropriate desalination technology by comparing seven desalination technologies based on 12 criteria.

2. Preference Selection Index (PSI)

PSI method is a new approach (Maniya & Bhatt, 2010). In this technique, it is not required to give an importance between attributes. For each alternative, a PSI value is calculated, in which the best alternative is that of the higher PSI value. PSI method is explained in the next steps based on (Maniya & Bhatt, 2010).

1) Identifying the objective, determining all possible criteria, its measures and alternatives.
2) Formulating the decision matrix. Let A be a set of alternatives, where A= {Ai for i= 1, 2, 3, . . ., n}, C be a set of decision criteria where C={C_j for j = 1, 2, 3, . . . , m} and X_{ij} is the performance of alternative A_i when it is studied with criteria C_j. Table 1 illustrates an example of the decision matrix.

Table 1. The decision matrix Xij

Alternatives (A_i)	Criteria (C_j)				
	C_1	C_2	C_3	…	C_m
A_1	X_{11}	X_{12}	X_{13}	…	X_{1m}
A_2	X_{21}	X_{22}	X_{23}	…	X_{2m}
A_3	X_{31}	X_{32}	X_{33}	…	X_{3m}
…	…	…	…	…	…
A_n	X_{n1}	X_{n2}	X_{n3}	…	X_{nm}

3) Normalizing data. In this step, data of the decision matrix are transformed into values in 0-1 range. In the case of a positive expectancy (i.e. profit), the normalization formula is:

$$R_{ij} = \frac{X_{ij}}{X_j^{max}} \quad (1)$$

While in the case of the negative expectancy (i.e. cost), the normalizing formula is:

$$R_{ij} = \frac{X_j^{min}}{X_{ij}} \quad (2)$$

Where X_{ij} is the attribute measures (i = 1, 2, 3, ..., N and j = 1, 2, 3, . . . , M) in the decision matrix.
4) Calculating the preference variation value (PVj) based on the Equation:

$$PV_j = \sum_{i=1}^{N} [R_{ij} - \overline{R_j}]^2 \quad (3)$$

Where $\overline{R_j}$ is the mean of the normalized values of attribute j and its equation as follows:

$$\overline{R_j} = \frac{1}{N} \sum_{i=1}^{N} R_{ij} \quad (4)$$

5) For each attribute, the deviation (Φ) in preference value (PV_j) is computed based on the Equation:

$$\Phi = 1 - PV_j \quad (5)$$

6) The overall preference value (Ψ) is computed for each attribute by using the Equation:

$$\Psi_j = \frac{\Phi_j}{\sum_{j=1}^{M} \Phi_j} \quad (6)$$

The overall summation of the preference value of all attributes must add to one.
7) The preference selection index (Ii) is then calculated based on the Equation:

$$I_i = \sum_{j=1}^{M} (R_{ij} \times \Psi_j) \quad (7)$$

8) Finally, alternatives are ranked according to Ii value, those of the highest I_i value are selected first.

3. Methodology

For the purpose of this paper, secondary data collection methods were used due to the lack of primary data. The qualitative and quantitative data were collected mainly from published research articles for twelve criteria in desalination technologies. An intensive search was made for every related criterion for each alternative in the literature.

A total of seven water desalination methods were considered. These are the electrodialysis (ED), reverse osmosis (RO), multi flash distillation (MFD), multi effect desalination (MED), vapor compression (VC), ion exchange and nanofiltration (NF). These technologies were compared based on 12 criteria. These include the energy required (C1), capital cost (C2), operational and maintenance cost (C3), recovery ratio (C4), product water quality (C5), adaptability (C6), environmental impact (C7), lifetime (C8), system's reliability (C9), operational simplicity (C10), maturity of technology (C11) and system's applicability (C12).

4. Data

The PSI decision matrix is basically determined from literature as shown in Table 2. Numbers in Table 2 show the mean among all sources found in the literature for the same point. Some data were missing in the literature, to solve this problem, the mean of all available data was considered to overcome this missing.

Table 2. The PSI decision matrix

Alternative	Criteria											
	C1 (kwh/m^3)	C2 ($\$/m^3$.day)	C3 ($\$/m^3$.day)	C4	C5 (ppm)	C6 (ppm)	C7 (kg/m^3)	C8 (Year)	C9	C10	C11	C12
RO	6.21	1750	1.04	0.54	10	45,000	3.8	20	2	3	5	5
ED	4.75	1824.25	0.38	0.81	300	6,333	2.5	27	4	3	3	1
MFD	25.78	2250	1.38	0.37	30	63,333	6.9	35	4	4	3	5
MED	20.78	1975	0.97	0.41	30	45,000	5.5	25	5	4	4	1
VC	11.02	1322	0.92	0.5	13.33	42,000	5.1	30	4	3	4	5
NF	4.01	1824.25	1.12	0.82	96.96	3,500	2.1	25	4	4	4	5

Ion exchange	1.1	1824.25	1.05	0.99	13	1500	0.5	27	4	3	4	5

5. Results and Discussion

The decision matrix shown in Table 2 was normalized as shown in Table 3. In the normalization step, cells of the energy required (C1), capital cost (C2), operational and maintenance cost (C3), product water quality (C5) and environmental impact (C7) were normalized by dividing the minimum value in each column in the decision matrix by the value in each cell of the decision matrix at the corresponding column. This was not the case for the data normalization in the remaining columns of the decision matrix, where each cell in these columns was divided by the maximum value in the corresponding column. The mean of each attribute ($\overline{R_j}$) is calculate as shown in Table 3.

Table 3. The normalized data

Alternative	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
RO	0.1771	0.3654	0.7554	0.5455	1.0000	0.7105	0.1316	0.5714	0.40	0.75	1.00	1.00
ED	0.2316	1.0000	0.7247	0.8182	0.0333	0.1000	0.2000	0.7714	0.80	0.75	0.60	0.20
MFD	0.0427	0.2754	0.5876	0.3737	0.3333	1.0000	0.0725	1.0000	0.80	1.00	0.60	1.00
MED	0.0529	0.3918	0.6694	0.4141	0.3333	0.7105	0.0909	0.7143	1.00	1.00	0.80	0.20
VC	0.0998	0.4130	1.0000	0.5051	0.7502	0.6632	0.0980	0.8571	0.80	0.75	0.80	1.00
NF	0.2743	0.3393	0.7247	0.8283	0.1031	0.0553	0.2381	0.7143	0.80	1.00	0.80	1.00
Ion exchange	1.0000	0.3619	0.7247	1.0000	0.7692	0.0237	1.0000	0.7714	0.80	0.75	0.80	1.00
$\overline{R_j}$	0.1464	0.4641	0.7436	0.5808	0.4256	0.5399	0.1385	0.7714	0.76	0.88	0.77	0.73

Table 4 summarizes the following measures for each attribute: the preference variation value (PVj), the deviation (Φ) in preference value (PVj) and the overall preference value (Ψ).

Table 4. Attributes' PVj, Φ and Ψ

Measures	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12
PVj	0.67	0.36	0.10	0.35	0.81	0.94	0.66	0.11	0.19	0.11	0.11	0.91
Φ	0.33	0.64	0.90	0.65	0.19	0.06	0.34	0.89	0.81	0.89	0.89	0.09
Ψ_j	0.07	0.13	0.19	0.14	0.04	0.01	0.07	0.19	0.17	0.19	0.18	0.02

Table 5 shows the last step in PSI calculations, which is the preference selection index (Ii) calculations for each alternative. As shown in Table 5, the highest Ii value was for Ion exchange water desalination method (1.072), followed by the vapor compression (VC), then by nanofiltration (NF), electrodialysis (ED), multi effect desalination (MED), multi flash distillation (MFD) and then by reverse osmosis (RO).

Table 5. Computing the PSI (Ii) for each alternative

Alternative	C1	C2	C3	C4	C5	C6	C7	C8	C9	C10	C11	C12	Ii
RO	0.012	0.048	0.142	0.074	0.039	0.009	0.009	0.106	0.1	0.1	0.2	0	0.849
ED	0.016	0.132	0.136	0.111	0.001	0.001	0.014	0.143	0.1	0.1	0.1	0	0.943
MFD	0.003	0.036	0.11	0.051	0.013	0.012	0.005	0.186	0.1	0.2	0.1	0	0.865
MED	0.004	0.052	0.126	0.056	0.013	0.009	0.006	0.133	0.2	0.2	0.1	0	0.903
VC	0.007	0.055	0.188	0.069	0.029	0.008	0.007	0.159	0.1	0.1	0.1	0	0.961

NF	0.019	0.045	0.136	0.113	0.004	7E-04	0.017	0.133	0.1	0.2	0.1	0	0.952
Ion exchange	0.069	0.048	0.136	0.136	0.03	3E-04	0.071	0.143	0.1	0.1	0.1	0	1.072

6. Conclusions

In this paper, seven water desalination technologies were compared based on 12 criteria. The PSI multi criteria decision making technique was considered as a novel tool to judge between water desalination technologies. Published literature was the main source for data collection. The PSI concluded that the most favorable water desalination methods was Ion exchange, followed by vapor compression, nanofiltration, electrodialysis, multi effect desalination, multi flash distillation and then by reverse osmosis.

As a future study, the seven water desalination technologies that have been studied could be compared using different multi criteria decision making tools to validate the PSI results.

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