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# The implementation of the preference selection index approach in ranking water desalination technologies

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**ABSTRACT**

A huge variation exists among countries in terms of freshwater availability. Water scarcity is considered a global problem that continues to grow with the fast increase in population and depleting sources of freshwater. Water desalination can be a professional solution for addressing such scarcity of water supply, but the selection of the suitable desalination method can be hard in some cases and depends on several criteria. Multi-criteria decision-making methods could be used to simplify the decision-making problem. In this paper, the preference selection index (PSI) will be used to rank seven desalination technologies; these include reverse osmosis, electrodialysis, multi-flash desalination, multi-effect desalination, mechanical vapor compression, nanofiltration and ion exchange. Twelve criteria were used in evaluating the desalination methods, including the capital cost, operating cost, the energy required, recovery ratio, product water quality, adaptability, lifetime, environmental impact, simplicity, reliability, maturity and applicability. The results of the PSI model showed that the ion exchange technology is the optimal desalination technology, followed by nanofiltration technology.

*Keywords:* Multi-criteria decision making; Desalination; Preference selection index; Water shortage; Secondary data

## 1. Introduction

According to a report in August 2015 by the World Resource Institute, it is expected that water scarcity will be the main issue for 33 countries around the world by 2040 [1]. This expectation is mainly due to a range of different reasons including, but not limited to, climate change, urbanization, population growth and economic development. Population explosion in some countries has increased the necessity to find novel solutions that use other sources to cover this huge deficiency in drinking water [2,3]. Some countries in arid and semi-arid regions are suffering from challenging water scarcity problems, especially with changes in weather due to global warming. This has forced these countries to start digging into the use of modern desalination technologies on brackish water.

Water scarcity is considered a global issue that affects many countries around the world, not only poor countries, and the establishment of a global consortium is vital for finding solutions to this problem [4]. One of the solutions to water scarcity is desalination, which has numerous socio-economic and environmental benefits. Desalination can be briefly described as the process of removing the salts and other chemicals or minerals that are dissolved in saltwater to reach a salinity amount permitted for drinkable water.

The installed desalination capacity is expected to grow as a result of the increasing demand for water [5] and has recently increased significantly around the world from about 35 million m$^3$ daily (MCM/d) in 2005 to approximately

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95 MCM/d in 2018 [6]. The energy consumption used for desalination is of concern in all desalination studies [7]. This forces many researchers to study the applicability of renewable sources of energy as the driver of desalination technologies.

Multiple water desalination technologies are currently being considered to enhance the supply of freshwater. These desalination technologies are divided into thermal-based, membrane-based and ion exchange-based technologies [8]. In thermal-based technologies, the water is initially transformed into vapor and then returned to the liquid state [9]. Several cost-effective technologies are currently used in thermal-based technologies, including vapor compression (VC), multi-stage flash distillation (MSF) and multi-effect desalination (MED) [10]. Many types of membranes can be used in membrane-based technology to separate the dissolved solids from water. Reverse osmosis (RO) and electrodialysis (ED) are the most commonly used in this respect. For ion exchange technology, an exchange of ions between the resin and the solution is achieved [11].

A large amount of research has been conducted in the last decade on different desalination technologies, to efficiently transform salty water into freshwater. The most important factor to consider when designing those desalination technologies is to have a cost-effective solution that can be commercialized by poor countries. Qasim et al. [12] developed a new zero-waste water reverse osmosis desalination system in Jordan, a semi-arid country. The researchers stated that if 500,000 reverse osmosis units of this system were implemented in homes in Jordan or similar countries, the expectation is to save around 18 million $m^3$ of supplied input water every year, with 100% water recovery [12].

The process of selecting the most suitable water desalination technology for a specific country is a complicated task [9]. This is because each water desalination technology has its advantages and disadvantages. Each technology has multiple constraints and objectives, which might contradict each other at some stages and should be optimized simultaneously. Furthermore, another problem is the shortage of sufficient data for selecting different techniques. This makes the process of selecting a suitable water desalination process a multi-criteria decision-making (MCDM) problem [8].

The preference selection index (PSI) decision approach requires simple calculations compared to the other MCDM approaches [13]. The PSI does not require the weighting of the considered attributes, and relies instead on statistical concepts [14]. The PSI methodology consists of defining the goal of the problem, formulating the decision matrix of criteria and alternatives, decision matrix normalization, calculating the preference variation value, specifying the overall preference value, determining the preference selection index, and then ranking alternatives in ascending or descending direction for results interpretation [15]. This study aims to identify the optimal desalination technology based on a PSI model using a secondary data collection method.

The rest of this paper is organized in the following manner. A literature review is reviewed in the next section. The overview of the preference selection index is shown in section 3. The methodology of the study is shown in section 4. Data collection and score allocation for the qualitative data are described in section 5. Results are shown in section 6. Discussion is provided in section 7. Lastly, the paper ends with the conclusions.

## 2. Literature review

MCDM methods have been proved suitable techniques for solving complicated decisions. Many MCDM methods have been successfully implemented for selecting suitable water desalination in many countries. Decision-making is an essential requirement of the average person's daily life. For some decisions, multiple criteria are the focus of the decision-making at the same time, while in other situations one criterion could be the focus of the decision-maker [16]. MCDM tools are used to evaluate candidate alternatives for ranking, choosing, or sorting based on many qualitative and/or quantitative criteria and are associated with different measurement units [17]. MCDM approaches are applied to many complex decisions. The MCDM approaches include, but are not limited to, the analytic hierarchy process (AHP), a technique for order of preference by similarity to ideal solution (TOPSIS), elimination and choice expressing reality (ELECTRE), grey theory, analytic network process (ANP) and the preference selection index (PSI).

In Jordan, an AHP model was used to select the most preferred desalination technology by comparing the multi-effect evaporation, multi-stage flash desalination, vapor compression and reverse osmosis technologies [18]. The criteria were based on environmental, economic and technical criteria. It was found that reverse osmosis was the best desalination technology to use in Jordan.

A two-stage AHP process was used to select the most appropriate water desalination technology for seawater [19]. Hajeeh and Al-Othman [19] compared five technologies that are commercially available in the Arabian Gulf region. The comparison was carried out between multi-stage flash distillation, reverse osmosis, multi-effect desalination, vapor compression and electrodialysis. Seven criteria were considered, including the quality of the produced water, recovery ratio, energy consumption, equipment efficiency, available technology, plant capacity and total cost. The results showed that the cost was the most dominant criterion, followed by the energy consumption rate and the recovery ratio, respectively. According to their study, reverse osmosis was the most suitable technology in the Gulf region, followed by multi-effect desalination.

In Kuwait, Hajeeh [20] conducted a study for choosing the best alternative among multi-stage flash distillation, multi-effect desalination and reverse osmosis according to the recovery ratio, energy requirement, pretreatment requirement, product water salinity, turnkey capital investment cost and corrosion potential. In this study, the AHP was based on a fuzzy set theory, to deal with the desalination problem, and a scale of triangular fuzzy numbers was used to conduct the pairwise comparison [20]. The results showed that the amount of energy required was the most important factor (37.8%) and reverse osmosis was the preferred desalination technology (40.1%), followed by multi-effect desalination.

Afify [10] developed a method to evaluate the best desalination technology based on the weighted summation method, for two different cases of brackish water and seawater in five zones in Egypt. The selection process was limited to five technologies, including reverse osmosis, multi-flash distillation, multi-effect desalination, vapor compression and electrodialysis. The selection criteria included the quality of the desalinated water, investment cost, operating and maintenance cost, environmental hazards and political preferences. The results showed that multi-effect desalination was the best technology, followed by multi-stage flash distillation and reverse osmosis considering proper plant size. It was concluded that, for brackish water, electrodialysis is the most suitable [10].

A two-step model based on the fuzzy AHP and TOPSIS was used to evaluate the optimum desalination of brackish groundwater in Iran [8]. The model considered technical, environmental and economic criteria. The technologies that were involved in this study were ion exchange, vapor compression, multi-stage flash distillation, multi-effect desalination and electrodialysis. The results showed that electrodialysis was the best technology with a closeness coefficient of 0.7547, meaning that electrodialysis was the most preferred desalination method among those being compared.

Eusebio et al. [1] designed a hybrid decision model based on the fuzzy AHP and grey rational analysis to compare five desalination technologies. The technologies compared were MSF, RO, electrodialysis, combined reverse osmosis and forward osmosis (RO-FO) and combined forward osmosis and membrane distillation (FO-MD). The criteria considered included the energy requirement, land footprint, system efficiency, economic viability and maturity of the technology. The system efficiency criterion was found to be the most important, with an important rate of 0.4079 when compared to the other criteria, and the FO-MED technology was the preferred technology, with a weight of 0.7805, while RO attained the lowest ranking [1].

Vivekh et al. [21] evaluated five different desalination technologies according to eleven criteria classified into technical, economic, social, energy and the environment as India is concerned. The technologies compared were electrodialysis, reverse osmosis, vapor compression, multi-effect distillation and multi-stage flash. TOPSIS and PROMETHEE-2 (preference ranking organization method for enrichment of evaluations) were used for comparison purposes separately. The results showed that electrodialysis was the most suitable alternative for the community. The other technologies were ranked in descending order of priority as reverse osmosis, vapor compression, multi-effect desalination and multi-flash distillation. In addition, the researchers found that TOPSIS is much faster than PROMETHEE-2 due to its ability to analyze all the data simultaneously. Thus, TOPSIS could be more useful when the majority of data is quantitative and available [21].

Derbali et al. [22] found that the best desalination process was electrodialysis, followed by reverse osmosis based on an AHP model. The other technologies considered were ranked in decreasing order of weights, including multi-effect desalination, multi-flash distillation and membrane distillation. The applicability for different types of water was the most important criterion, followed by the cost [22].

Marini et al. [23] proposed the use of renewable energy sources to overcome the cost of energy consumption. They conducted their research in Asinara Island, where the following combinations were evaluated: mechanical vapor compression with photovoltaic (PV) energy, mechanical vapor compression with wind energy, reverse osmosis with PV and reverse osmosis with the wind. Selection among these four combinations was a difficult issue and depended on many factors. A two-step AHP was used to solve the problem based on eight criteria, which were legislation, social characteristics, location characteristics, technical criteria, environmental impact, energy criteria, economic criteria and financial criteria. Each criterion has various sub-criteria. The results showed that the combination of reverse osmosis coupled with photovoltaic was the most efficient, followed by reverse osmosis combined with the wind [23].

Chamblás and Pradenas [24] used three MCDM approaches (AHP, ELECTRE and TOPSIS) to select the optimal desalination processes based on environmental, economic and technical criteria. These approaches are preferred MCDM tools that were used by researchers in several applications. The study compared the multi-stage distillation, multi-effect desalination, vapor compression, reverse osmosis, electrodialysis and nanofiltration desalination techniques. The results showed that reverse osmosis was the preferred technology based on all the MCDM techniques considered. The economic criterion considered was the main driver of their result [24].

Based on the literature review, no study has implemented the use of the PSI to evaluate the best desalination technology. In this study, the PSI will be used to select the best desalination technology. The main rationale behind this research is to compare all the most common desalination techniques based on 12 criteria, as previous researches did not compare all the techniques at once. Secondary data were used in this research and the PSI decision-making technique was considered for the evaluation.

## 3. Overview of the preference selection index

The PSI is a new decision technique that was proposed in Maniya and Bhatt [15]. This technique does not require the user to give importance to attributes, as required in most of the other MCDM tools. For each alternative, a PSI score is computed, where the best alternative is that of the highest score. The PSI is illustrated in the following steps based on [15]:

- *Step I*: Identifying the objective and determining all possible criteria and alternatives under consideration.
- *Step II*: Formulating the decision matrix. Let $C$ be a set of decision criteria where $C = \{C_j$ for $j = 1, 2, 3, \ldots, m\}$, $A$ is a set of alternatives, where $A = \{A_i$ for $I = 1, 2, 3, \ldots, n\}$, and $X_{ij}$ is the performance of alternative $A_i$ when it is studied with criterion $C_j$. As a result, a decision matrix is created as shown in Table 1.
- *Step III*: Data normalization, that is, the values in the decision matrix are transformed to the range 0–1. If the

case is 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 a negative expectancy (i.e., cost) the formula of normalization is:

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

where $X_{ij}$ are the attribute measures ($i$ = 1, 2, 3, ..., $n$ and $j$ = 1, 2, 3, ..., $m$) in the decision matrix.

- *Step IV*: Computing the preference variation value ($PV_j$), which is determined as:

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

where $\overline{R_j}$ is the mean of the normalized $j$ attribute value and computed as:

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

- *Step V*: Computing the deviation (Φ) of the preference value ($PV_j$) for every attribute as:

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

- *Step VI*: Computing the overall preference value (Ψ) for each attribute as follows:

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

The overall summation of the preference value of all attributes must give a value of one.

- *Step VII*: Computing the preference selection index ($I_i$) using:

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

- *Step VIII*: The alternatives are then ranked based on the $I_i$ value, where alternatives with the highest value are selected first.

Table 1
Decision matrix $X_{ij}$

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

## 4. Methodology

The methodology that was followed in this research started by defining the problem, followed by identifying the related criteria and available alternatives. The next step was the data collection, followed by the process of allocating scores for the qualitative data, and finally, the PSI calculations and results.

As clearly outlined, the problem goal, which is finding the best desalination, is firstly defined. The set of criteria and alternatives are then identified as shown in Tables 2 and 3, respectively. Based on the PSI steps, some of the criteria are maximized (beneficial) and some of them are

Table 2
The selected criteria, their definitions, and types

| Criteria | Definition | Abbreviation in the PSI model | Criteria type |
|---|---|---|---|
| Energy required | Electrical and thermal energy needed (kWh/m$^3$) | $C_1$ | Non-beneficial |
| Operating cost | Wages and the funds spent on the energy, the products, services and maintenance | $C_2$ | Non-beneficial |
| Recovery ratio | Product water relative to the input flow | $C_3$ | Beneficial |
| Produced water quality | Salinity of the produced water (TDS in ppm) | $C_4$ | Non-beneficial |
| Adaptability | Maximum input feed water salinity (TDS in ppm) | $C_5$ | Beneficial |
| Environmental impact | Amount of $CO_2$ emitted (kg/m$^3$) | $C_6$ | Non-beneficial |
| Lifetime | Lifetime of the technology until the major replacement | $C_7$ | Beneficial |
| Reliability | Robustness against failure | $C_8$ | Beneficial |
| Simplicity | Skills required for operation and the need for maintenance | $C_9$ | Beneficial |
| Maturity | Stage of development that the technology reached | $C_{10}$ | Beneficial |
| Applicability | Applicability to different types of feed water | $C_{11}$ | Beneficial |

minimized (non-beneficial) as shown in Table 2. Afterward, data were collected, and in this research, the secondary resources were considered, where some of the data were missing and some others were qualitative.

## 5. Data collection and score allocation for the qualitative data

One of the most vital aspects to preserve research integrity is to gain accurate data (e.g., quantitative or qualitative data), which is measured and gathered based on identified research questions. To perform this collection efficiently, the kind of data that is of research interest should be clearly stated, with samples of which are chosen from a certain population. Afterward, and finally, a suitable instrument is used to effectively get useful information out of these samples. As stated earlier, data are either qualitative or quantitative in type. The qualitative data are meant to be descriptive (non-numerical), while the quantitative data are expressed numerically.

Using the mixed methods approach is better than a single research design approach in collecting and assessing data in terms of validation and the reliability of the research. The mixed methods approaches merge quantitative and qualitative research data and gather them into a single research framework.

Data are classified as primary or secondary, based on the source of the data collection. In spite of the fact that results derived from the primary data type are more valid than those deduced from secondary data, which does not lessen the importance of the results inferred from the secondary data. This is because sometimes the primary data do not even exist, or are difficult to obtain, or are not easy to be exposed due to confidentiality issues or a lack of collaboration. This urges and forces the process of collecting and using secondary data instead. It is worth mentioning here that the primary data can be collected utilizing surveys, interviews, experiments and observations. On the other hand, secondary data are collected by digging into the records, data archives, internet articles, books, biographies, statistical data, newspapers, or research articles [25].

For this research, the secondary data collection methods were considered due to the lack of primary data and of experts in the field of desalination, who know all the different types of desalination techniques. In this research, the qualitative and quantitative data were collected mainly from research articles for the considered twelve criteria, including the capital cost, which was then eliminated due to many missing evaluations in desalination technologies. Intensive research was done for every criterion related to the considered desalination alternative. Some values and information related to capital cost, maturity, simplicity, reliability and lifetime were not found in the literature. For maturity, reliability, and lifetime, there was a single missing data related to only two desalination alternatives and for simplicity, there was missing information related to one desalination alternative.

The information related to qualitative data is transformed into numbers. The scoring system used in the PSI decision matrix of this research is presented in Tables 4 and 5. As shown in Table 5, for reliability, the multi-effect desalination technique is a very reliable process and it was awarded the maximum score for the reliability of five. Multi-flash distillation, electrodialysis and mechanical vapor compression proved their reliability and were therefore awarded a score of four, while reverse osmosis had a score of one because of its lack of reliability. Regarding simplicity, multi-flash distillation, multi-effect desalination and ion exchange were considered simple systems and required minimally skilled operators. Thus, all of these techniques were awarded a score of four. On the other hand, electrodialysis and mechanical vapor compression require highly skilled technicians, so a score of three was assigned. In addition, reverse osmosis is slightly complex to operate, so it was awarded a score of two. Regarding maturity, reverse osmosis is commonly used for industrial applications and was therefore awarded a score of five, while electrodialysis and multi-flash distillation were awarded a score of three, as they are still in the modification and improvement stage. Multi-effect desalination and mechanical vapor compression are well-established systems and as a result, were assigned a score of four.

Table 3
Technologies considered in the decision model

| Alternatives | Abbreviation in the PSI model |
|---|---|
| Reverse osmosis | $A_1$ |
| Electrodialysis | $A_2$ |
| Multi flash distillation | $A_3$ |
| Multi effect desalination | $A_4$ |
| Mechanical vapor compression | $A_5$ |
| Nanofiltration | $A_6$ |
| Ion exchange | $A_7$ |

Table 4
Scoring system used in the model

| Criteria | Score | | | | |
|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 |
| Reliability | Very low | Low | Medium | High | Very high |
| Simplicity | Very complex | Complex | Medium | Simple | Very simple |
| Maturity | Research stage | Development stage | System modification and improvement | Well established system | Commonly used for industrial application |

As the applicability of the technology is concerned, for which the desalination technology is excellent and applicable for different types of feed water, a score of five was awarded; however, for the technologies that are good and applicable only for one type of feed water the score was four.

## 6. Results

The PSI decision matrix for the desalination technologies and the specified criteria is shown in Table 6.

The data in Table 6 are normalized into the 0–1 range. The non-beneficial criteria ($C_1$, $C_2$, $C_4$, and $C_6$) 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. For the beneficial criteria ($C_3$, $C_5$, $C_7$, $C_8$, $C_9$, $C_{10}$, and $C_{11}$), each cell in these columns was divided by the maximum value in the corresponding column. Table 7 shows the normalized data for the case considered in this research. The mean of each attribute $\overline{R_j}$ is calculated as shown in Table 8.

Table 9 summarizes the following measures for each attribute: The preference variation value ($PV_j$), the deviation ($\Phi$) in the preference value ($PV_j$) and the overall preference value ($\Psi$).

Table 10 shows the last step in the PSI calculations, which is the preferred selection index ($I_i$) calculations for each alternative of the desalination techniques. In addition,

Table 5
Scoring assignments of the qualitative data

| | Reliability | Simplicity | Maturity | Applicability |
|---|---|---|---|---|
| Reverse osmosis | 1 | 2 | 5 | 5 |
| Electrodialysis | 4 | 3 | 3 | 4 |
| Multi flash distillation | 4 | 4 | 3 | 5 |
| Multi effect desalination | 5 | 4 | 4 | 4 |
| Mechanical vapor compression | 4 | 3 | 4 | 5 |
| Nanofiltration | Not found in the literature | Not found in the literature | Not found in the literature | 5 |
| Ion exchange | Not found in the literature | 4 | Not found in the literature | 5 |

Table 6
Decision matrix of the model

| Alternatives | Criteria | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ |
| $A_1$ | 6.91 | 1.12 | 0.56 | 10.00 | 45,000 | 3.8 | 20 | 1 | 2 | 5 | 5 |
| $A_2$ | 4.93 | 0.83 | 0.82 | 300.00 | 6,500 | 2.5 | 27 | 4 | 3 | 3 | 4 |
| $A_3$ | 24.75 | 1.40 | 0.50 | 30.00 | 60,000 | 6.9 | 35 | 4 | 4 | 3 | 5 |
| $A_4$ | 20.28 | 0.96 | 0.52 | 30.00 | 45,000 | 5.5 | 25 | 5 | 4 | 4 | 4 |
| $A_5$ | 10.53 | 0.92 | 0.50 | 10.00 | 42,000 | 5.1 | 30 | 4 | 3 | 4 | 5 |
| $A_6$ | 4.20 | 1.12 | 0.95 | 99.93 | 3,500 | 2.1 | 25 | 4 | 3 | 4 | 5 |
| $A_7$ | 1.10 | 1.05 | 0.99 | 13.00 | 1,500 | 0.5 | 27 | 4 | 4 | 4 | 5 |

Table 7
Normalized data of the model

| Alternatives | Criteria | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ |
| $A_1$ | 0.16 | 0.74 | 0.57 | 1.00 | 0.75 | 0.13 | 0.57 | 0.2 | 0.50 | 1.0 | 1.0 |
| $A_2$ | 0.22 | 1.00 | 0.83 | 0.03 | 0.11 | 0.20 | 0.77 | 0.8 | 0.75 | 0.6 | 0.8 |
| $A_3$ | 0.04 | 0.59 | 0.51 | 0.33 | 1.00 | 0.07 | 1.00 | 0.8 | 1.00 | 0.6 | 1.0 |
| $A_4$ | 0.05 | 0.86 | 0.52 | 0.33 | 0.75 | 0.09 | 0.71 | 1.0 | 1.00 | 0.8 | 0.8 |
| $A_5$ | 0.10 | 0.90 | 0.51 | 1.00 | 0.70 | 0.10 | 0.86 | 0.8 | 0.75 | 0.8 | 1.0 |
| $A_6$ | 0.26 | 0.74 | 0.96 | 0.10 | 0.06 | 0.24 | 0.71 | 0.8 | 0.75 | 0.8 | 1.0 |
| $A_7$ | 1.00 | 0.79 | 1.00 | 0.77 | 0.03 | 1.00 | 0.77 | 0.8 | 1.00 | 0.8 | 1.0 |

Fig. 1 shows the PSI values $I_i$ for the studied water desalination systems. Table 11 then shows the ranking of the desalination technologies where the value one in the ranking shows the preferred desalination technique. Based on the results, the highest PSI value was for the ion exchange desalination method (0.8895), followed by nanofiltration (NF), mechanical vapor compression (MVC), multi-effect desalination (MED), electrodialysis (ED), multi-flash distillation (MFD) and then reverse osmosis (RO).

Table 8
Mean of the normalized data $\overline{R_j}$

| | |
|---|---|
| $N_1$ | 0.264 |
| $N_2$ | 0.803 |
| $N_3$ | 0.698 |
| $N_4$ | 0.510 |
| $N_5$ | 0.485 |
| $N_6$ | 0.262 |
| $N_7$ | 0.771 |
| $N_8$ | 0.743 |
| $N_9$ | 0.821 |
| $N_{10}$ | 0.771 |
| $N_{11}$ | 0.943 |

## 7. Discussion

Ranking of the desalination technologies was accomplished by using the PSI method. As shown in Fig. 1, and based on the PSI method, ion exchange was the best desalination technology, with the highest preference selection index of 0.8895. With respect to membrane-based technologies, NF was ranked first with a PSI value of 0.76166. Among the thermal-based technologies, MVC was ranked first with a slight difference with the multi-flash distillation (MFS). However, this finding was based on many criteria as discussed previously.

After building the PSI model, a sensitivity analysis was performed using trial and error to eliminate criteria with small preference values ($I_i$) and to investigate their effect on the resulting rank. If the elimination of a selected criterion had a minor effect on changing the main rank, the PSI model was then updated by eliminating that criterion, then another iteration was performed to test another attribute. The iterations performed are described in Table 12,

Table 9
Calculating the $PV_j$, Φ and Ψ measures

| Measures | $C_1$ | $C_2$ | $C_3$ | $C_4$ | $C_5$ | $C_6$ | $C_7$ | $C_8$ | $C_9$ | $C_{10}$ | $C_{11}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $PV_j$ | 0.06 | 0.11 | 0.21 | 0.38 | 0.11 | 0.66 | 0.990 | 1.0100 | 0.30 | 0.11 | 0.67 |
| Φ | 0.94 | 0.89 | 0.79 | 0.62 | 0.89 | 0.34 | 0.010 | –0.0100 | 0.70 | 0.89 | 0.33 |
| $\psi_j$ | 0.14 | 0.14 | 0.12 | 0.10 | 0.14 | 0.05 | 0.002 | –0.0008 | 0.11 | 0.14 | 0.15 |

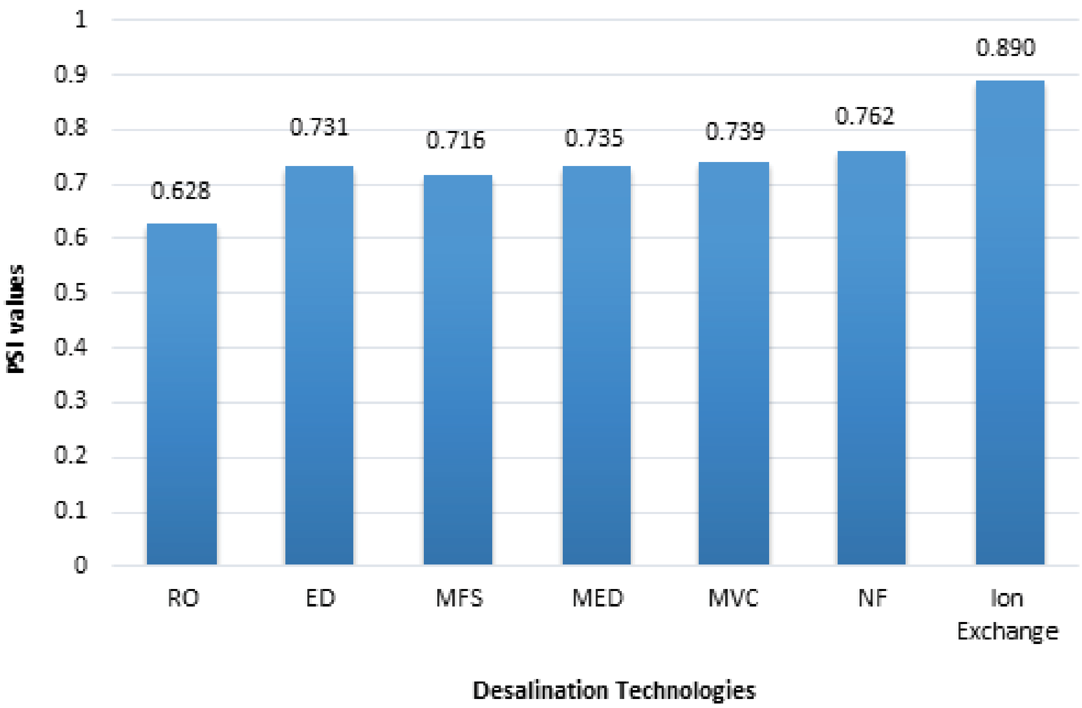


Fig. 1. The PSI values of the desalination technologies.

Table 10
Computing the PSI ($I_i$) for each desalination alternative

| | Energy required ($C_1$) | Operating cost ($C_2$) | Recovery ratio ($C_3$) | Produced water quality ($C_4$) | Adaptability ($C_5$) | Environmental impact ($C_6$) | Lifetime ($C_7$) | Reliability ($C_8$) | Simplicity ($C_9$) | Maturity ($C_{10}$) | Applicability ($C_{11}$) | $I_i$ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Reverse osmosis ($A_1$) | 0.147278 | 0.138352 | 0.061366 | 0.019459 | 0.079787 | 0.007026 | 0.001474 | –0.00079 | 0.061775 | 0.103578 | 0.008153 | 0.627455 |
| Electrodialysis ($A_2$) | 0.117823 | 0.083011 | 0.092049 | 0.077834 | 0.107713 | 0.01068 | 0.000213 | –2.6E-05 | 0.090731 | 0.139704 | 0.011431 | 0.731163 |
| Multi flash distillation ($A_3$) | 0.147278 | 0.083011 | 0.122732 | 0.077834 | 0.139628 | 0.003869 | 0.001965 | –0.00026 | 0.055156 | 0.082316 | 0.002277 | 0.715802 |
| Multi effect desalination ($A_4$) | 0.117823 | 0.110682 | 0.122732 | 0.097293 | 0.099734 | 0.004854 | 0.001474 | –0.00026 | 0.056811 | 0.12072 | 0.00278 | 0.734639 |
| Mechanical vapor compression ($A_5$) | 0.147278 | 0.110682 | 0.092049 | 0.077834 | 0.119681 | 0.005235 | 0.001375 | –0.00079 | 0.055156 | 0.125532 | 0.005352 | 0.739381 |
| Nanofiltration ($A_6$) | 0.147278 | 0.110682 | 0.092049 | 0.077834 | 0.099734 | 0.012714 | 0.000115 | –7.9E-05 | 0.104796 | 0.103115 | 0.013418 | 0.761656 |
| Ion exchange ($A_7$) | 0.147278 | 0.110682 | 0.122732 | 0.077834 | 0.107713 | 0.053399 | 0.000049 | –0.00061 | 0.109209 | 0.10999 | 0.051233 | 0.889509 |

and the alternative ranking obtained in each iteration is shown in Table 13.

According to Table 12, the reliability criterion showed a major change to the initial rank of desalination techniques. Details of this change can be seen in Table 13.

## 8. Conclusions

The preference selection index approach was implemented in this paper to compare seven water desalination technologies based on 11 criteria. The comparison was based on both qualitative and quantitative attributes. Data were collected using secondary data collection methods from different research articles and books. The use of secondary data has a positive value as well as the use of secondary data is significant for further development. Based on the model evaluation, it was concluded that the ion exchange desalination technology was the best, with a PSI value of 0.8895, followed by nanofiltration (NF) with a PSI value of 0.7617. RO attained the lowest PSI value of 0.6275.

In general, it was concluded that PSI is a direct method to solve MCDM problems. However, it has some limitations, including that there is no specific procedure to use for handling the qualitative attributes and the sensitivity analysis. In addition, the PSI assumes that the criteria are equally weighted. Another limitation of this paper is the lack of experts who are familiar with the different types of desalination technologies. This forced the use of secondary data collection methods.

Table 11
Rank of the PSI values of the desalination alternatives

| Alternatives | Rank |
|---|---|
| Reverse osmosis | 7 |
| Electrodialysis | 5 |
| Multi flash distillation | 6 |
| Multi effect desalination | 4 |
| Mechanical vapor compression | 3 |
| Nanofiltration | 2 |
| Ion exchange | 1 |

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Table 12
Elimination of attributes for sensitivity analysis purposes

| Iteration number | Eliminated criteria | Elimination effects on the main result |
|---|---|---|
| 1 | Operating cost ($C_2$) | Minor effect, the model was updated by eliminating $C_2$ |
| 2 | Recovery ratio ($C_3$) | Minor effect, the model was updated by eliminating $C_3$ |
| 3 | Applicability ($C_{11}$) | Minor effect, the model was updated by eliminating $C_{11}$ |
| 4 | Maturity ($C_{10}$) | Minor effect, the model was updated by eliminating $C_{10}$ |
| 5 | Lifetime ($C_7$) | Minor effect, the model was updated by eliminating $C_7$ |
| 6 | Simplicity ($C_8$) | Minor effect, the model was updated by eliminating $C_8$ |
| 7 | Reliability ($C_9$) | Major effect |

Table 13
Results of sensitivity analysis

| $A_i$ | Initial rank | Rank 1 | Rank 2 | Rank 3 | Rank 4 | Rank 5 | Rank 6 | Rank 7 |
|---|---|---|---|---|---|---|---|---|
| Reverse osmosis | 7 | 7 | 7 | 7 | 7 | 7 | 7 | 4 |
| Electrodialysis | 5 | 6 | 6 | 6 | 5 | 5 | 5 | 3 |
| Multi flash distillation | 6 | 3 | 2 | 3 | 2 | 3 | 3 | 7 |
| Multi effect desalination | 4 | 4 | 4 | 2 | 3 | 2 | 2 | 6 |
| Mechanical vapor compression | 3 | 5 | 3 | 4 | 4 | 6 | 6 | 5 |
| Nanofiltration | 2 | 2 | 5 | 5 | 6 | 4 | 4 | 2 |
| Ion exchange | 1 | 1 | 1 | 1 | 1 | 1 | 1 | 1 |

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