Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27176

224 (2021) 12–20
June

Optimization modeling for the use of antiscalants in the brackish RO desalination plants

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Received 1 July 2019; Accepted 24 February 2021

ABSTRACT

Reverse osmosis (RO) technologies present a solution for water scarcity in many parts of the world where brackish water exists. Antiscalants act as a pre-treatment water additive for the RO plants in order to protect the membranes from scaling. This paper presents field and experimental lab works to examine the effects of antiscalants on the small and medium-scale brackish RO desalination plants under real operation conations. To assess the impact of the different antiscalants, a sample of 50 RO desalination plants has been selected along the Gaza Strip, Palestine. The evaluation process was based on three steps: (i) RO plant's operational questionnaire, (ii) water samples collection and chemical water quality analysis and (iii) built a generalised linear model for operational process optimisation based on the antiscalants' type, dilution and dose. According to the optimization model to maximize the pollutants' removal, the results show that in order to reach the maximum salts rejection (98%) the first type of antiscalant (polyphosphates) should be used, at 1 ppm concentration with a dilution of 2 L of antiscalant to 250 L of water. However, using the second type of antiscalant (phosphonates) with the same dose and concentration would lead to a 92% salts rejection.

Keywords: Antiscalant; Reverse osmosis; Desalination; Optimization

1. Introduction

Desalination contains a wide range of processes that are utilized to reduce the dissolved salts in water. Desalination can provide a reliable unconventional source for water supply worldwide, especially where there is water scarcity. The desalination process has been applied for many decades with precise technical and economic feasibility [1,2]. There are several conventional methods of desalination, such as multi-stage flash, multi-effect distillation, and reverse osmosis (RO). RO has been developed to be a robust technique for sustainable water [3–6]. Many groundwater sources would have moderate-to-high dissolved salts, due to many reasons such as seawater intrusion phenomena in the coastal aquifers [7–9] or the direct contact with rocks and formations that would increase the salt concentrations in the groundwater in particular in the areas that characterized with low rainfall, which leads to less recharge to the groundwater aquifer [10,11]. Brackish water forms as a result of the high dissolved salts and are not suitable for drinking and irrigation purposes, and

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that leads to the use of different desalination processes to produce good quality water [12,13]. Groundwater aquifer is considered the primary water supply source in the Gaza Strip (domestic, industrial and agricultural purposes) [14,15]. However, groundwater has declined in both quality and quantity because of low rainfall rates, the increase in the urban areas which led to a decrease in the recharge volume of the aquifer, also the increase in the population and the seawater intrusion phenomena [16,17]. The major crisis associated with groundwater for future sustainability is the increase in salinity due to seawater intrusion.

Reverse osmosis is extensively used as the preferred technology for brackish water desalination plants in the Gaza Strip. Distilled water serves as an alternative water resource for supplying drinking water for the communities in Gaza Strip through small to medium scale brackish water RO private desalination plants [18,19]. Mainly, reverse osmosis is used because of the simplicity of the process, the high-end product quality, and it can handle the salinity of the available feedwater [20]. However, the majority of desalination RO plants have problems with fouling caused by inorganic scales and the scaling influenced by the precipitation of salts onto the membrane surface, which results in reducing the permeate flow [21].

Surface water and groundwater contain ions such as calcium, sulphate and bicarbonate which lead to the deposition of salt minerals on the RO membranes' surfaces, which is commonly known as scaling [22]. Depending on the feed water source, the scale deposits may consist of salts such as $CaCO_3$, $CaSO_4$ and SiO_2 [23]. Scales fall under the categories of alkaline, non-alkaline, and silica-based, with non-alkaline scales more challenging to remove than alkaline scales [24]. The most common non-alkaline scale is calcium sulphate and is typically prevented by maintaining unsaturated conditions. Another typical scaling is calcium phosphate, which is most effectively treated by acidification of the feed water. Silica scale can be prevented by either pretreatment or acidification [25]. In general, scale formation leads to operational and maintenance problems and loss of efficiency. In the RO systems, scaling of membranes results in decreasing the plant efficiency and that leads to higher power consumption because of the need for higher pumping pressures. The cost due to scaling may be equivalent to about 10% of the capital cost of the plant [26]. To tackle membrane scaling, there are many techniques for scaling removal, as mentioned before. However, the most used techniques are the addition of acid or antiscalants materials [27,28]. Antiscalant is typically polyelectrolytes with various functional groups to target different scaling problems. The choice of the type and dosage of antiscalant is highly dependent on the source water characteristics [29].

This research paper assesses the effects of different commercially available antiscalants on the efficiency and productivity of small to medium scale brackish RO desalination plants utilizing field, and experimental lab works to examine the effects of antiscalants under real operation conations. The evaluation process was based on three steps (i) RO plant's operational questionnaire, (ii) water sampling collection and chemical water quality analysis and (iii) built a generalised linear model for operational process optimisation.

2. Materials and methods

To assess the impact of antiscalant on RO desalination plants in the Gaza Strip and study their effect on the quality of desalinated water, the flowchart shows the research methodology as shown in Fig. 1.

The continuous dramatic increase in salinity of the groundwater source in the Gaza Strip that feeds into the small-scale desalination plants is a unique situation that causes an overload on those plants. Due to this uniqueness, this paper aims to investigate the relationship and the possibility of determining the effectiveness of inhibitors in terms of salt retention degree and other operational parameters. This is a fundamental investigation in the optimization of the maximum removal of salts in relation to the type of antiscalant and how that would affect the overall RO efficiency.

A survey for private and public brackish desalination plants in the Gaza Strip was conducted to gather the operational conditions data. All workable RO desalination plants in the Gaza Strip were 159 plants distributed from North to South of the Gaza Strip. The target group of RO desalination plants for this study was statistically calculated using a sample size equation to have a represented sample. The statistical sample size was 50 plants distributed along the Gaza Strip, as shown in Fig. 2 and Table 1. For this study, the sampled RO desalination plants are evaluated based on three steps (i) operational conditions questionnaire, (ii) water samples collection and analysis and (iii) built a generalised linear model for optimising the operational conditions.

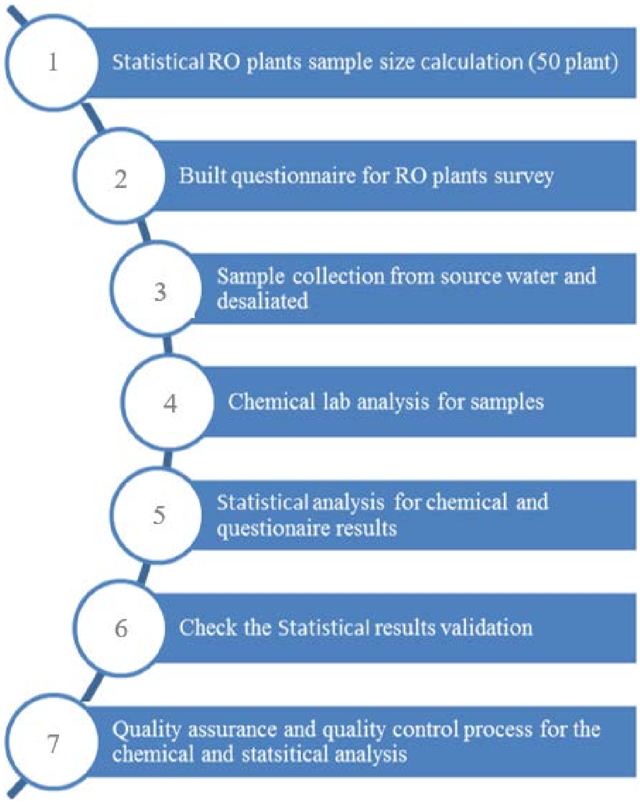

Fig. 1. Research methodology flowchart.

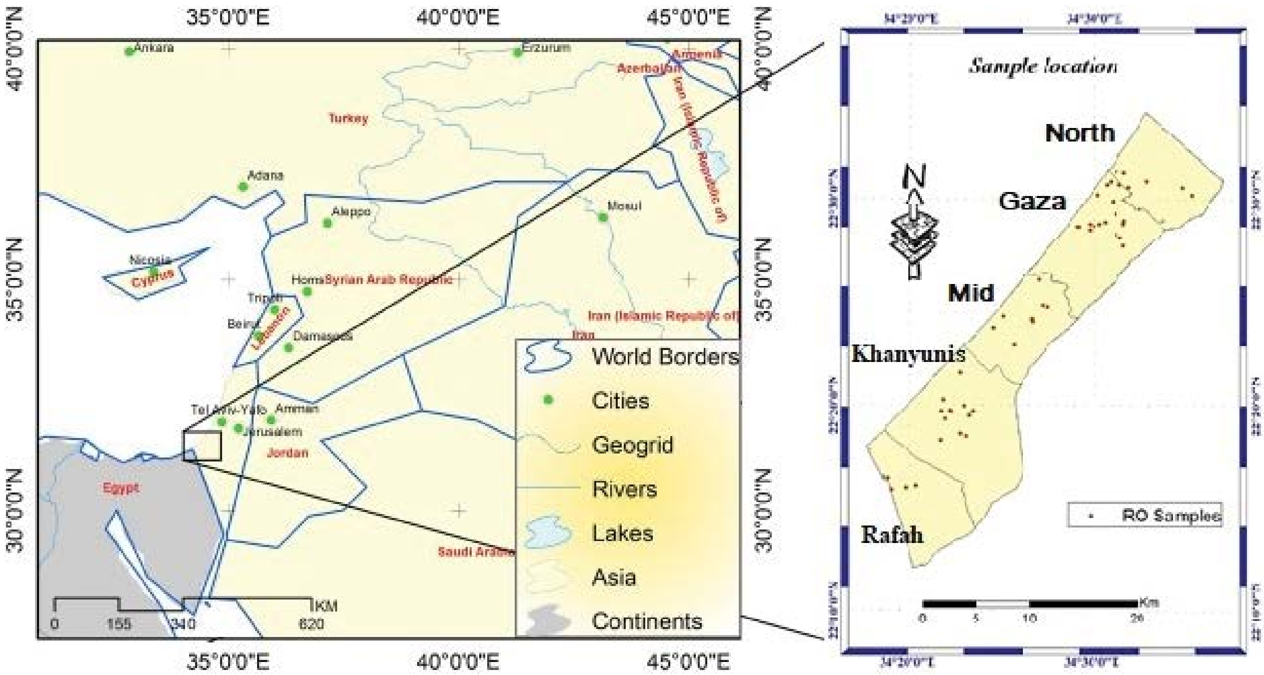

Fig. 2. RO sampling location map.

Table 1
Numbers of selected RO plants by governorate

Governorate	No. of RO plants	%	No. of selected plants
North	22	14%	7
Gaza	55	36%	18
Mid	28	18%	9
Khan Yunis	36	23%	12
Rafah	13	8%	4
Total	154	100%	50

Water sampling and analysis have been performed according to the standard methods for the examination of water and wastewater [30]. Two sizes of samples were collected from each RO plant, a 500 mL and a 2 L polyethylene. The 2 L samples were used for physical and chemical analysis of the desalinated water. The desalinated water samples were collected immediately after the membrane stage and before any post-treatments were applied, the RO plants membranes types were not taken into account through this study. The 500 mL samples were collected from the feedwater to the RO plants. All the collected water samples were analyzed immediately after collection. During the sampling and in order to prepare a statistical representative sample from each desalination plant, one input and one output sample from the 50 desalination plants, were collected twice every day for one week for both the desalinated water and the feed water. The samples were cumulatively collected at the starting time and the end of the working day on one container for both desalinated water and feed water. After then, these samples were mixed to have 50 samples for desalinated water and 50 samples for feed water and analyzed. For each desalination plant and every day for one week, the following physical parameters were measured: pressure, water flow rate which refers to the efficiency of RO membrane, power consumption, number of working people and the antiscalants' type, dilution and dose. Also, for each sample from each desalination plant (for both the desalinated and the input water), the following chemical analysis was performed: total dissolved solids, pH, electrical conductivity and concentration of chlorides, calcium, magnesium, sodium, sulphates and nitrates. A sample of the used antiscalant at each desalination plant was collected and analyzed using IR spectroscopy and pH meter to determine the antiscalants' chemical composition and sort the local antiscalant type according to it. All the chemical analyses were carried out in the Laboratories of Al-Azhar University, Facility of Science, Chemistry Department (The Research Lab).

The data was compiled, statistically analyzed, modelled and presented using R-Studio. Mainly the descriptive statistical analysis was performed for the collected dataset to describe the main features of the data and to study the bivariate relationships among the variables.

Generalized linear models are extensions of traditional regression models that allow the mean to depend on the explanatory variables through a link function, and the response variable to be any member of a set of distributions called the exponential family (e.g., Normal, Poisson, and Binomial). R-Studio data-driven generalized linear optimization model was trained to test the statistical significance of the different parameters and to optimize the real operational conditions to maximize the pollutant removals in the RO desalination plants. The trained optimization model was based on optimizing the real operation conditions of the antiscalants' type, dilution and dose.

3. Results and discussions

3.1. Antiscalants analysis

The antiscalants' samples taken from the desalination plants were imported from 2 companies and they distributed for all workable RO desalination plants, these samples of antiscalants have been analyzed using IR spectroscopy and pH meter in order to classify them into their types. In order to categories, the antiscalants' groups, the chemical composition of each sample analyzed using IR spectroscopy, which is typically used to determine the functional groups in molecules. In general, all the samples can be categorized into two types of antiscalants with various functional groups to target different scaling problems. Both antiscalants are strong acidic materials, which can save RO membranes from the precipitation of salts. The antiscalants types were found as follows:

- Antiscalant (1): polyphosphates with pH equals to 4, Fig. 3.
- Antiscalant (2): phosphonates with pH equals to 4.5, Fig. 4.

By comparing the studied antiscalant composition results with other studies which give similar chemical composition and acidic pH behavior. Amjad [31] studied the impact of antiscalants on the calcium sulfate dihydrate crystallization forms at 25°C, polyphosphates, phosphonates, polystyrene sulfonate, polyacrylamide, polyacrylate antiscalants which were applied in this study. And Rosenberg et al. [32] studied the effect of using phosphonate antiscalant at acidic pH on the gypsum scale ($CaSO_4·2H_2O$) scale deposition which caused a reduction in the pH at reject-brine when a strong acidic effluent has added.

3.2. Statistical analysis for water quality samples

Water quality samples were collected as described. In the previous section from desalination plants as 50 samples from feed water and 50 samples from desalinated water. The samples were analyzed for the water quality evaluation purposes concerning permeate including pH, electrical conductivity, chlorides, nitrate, magnesium, calcium, sodium and sulphates. Tomaszewska et al. [33] illustrated that numerical modelling has a high level of assurance for estimating precipitation phenomena because it depends on the process factors like pressure and temperature, and a related to the physicochemical properties of feedwater. The modelling of phenomena related to the forecast of membrane scaling should also depend on water type and the dose of antiscalants. Antiscalants activated with chemical reactions on the membrane surface produce new, varies mineral forms causing a drop in membrane efficiency. Table 2 shows the results of the descriptive statistical analysis for the chemical analysis for the feed water, which indicates that the feed water was in general, a weak base with average pH (7.8). This pH level is considered as a common trend for the RO desalination plants' water wells, and it meets the WHO standards for water quality (pH (6.5–8.5)) [34]. The majority of the feed water samples' electrical conductivity has a high level of EC, more than 2,500 ms/cm. The feed water of all plants was found to have a high concentration of chlorides, nitrates, calcium, magnesium, sodium and sulphates, which all exceed the standards levels of the WHO.

Fig. 5 shows the Piper diagram for all the feed water samples categorized by the different governorates; the Piper diagram is used to understand the sources of the dissolved constituents in the water.

However, Table 3 presents the results of chemical analysis for permeate. The average pH equals 6.5, which is considered to be a common trend for the RO desalination process. The electrical conductivity for the permeate water of all the plants was less than 2,500 ms/cm, which meets the WHO standards for drinking water. This indicates the high RO efficiency with high salt rejections. The majority of the permeate water samples from the RO desalination plants had low concentrations of chlorides, nitrates, calcium, magnesium, sodium and sulphates well below the WHO standards for drinking water. The minimum, maximum, mean, standard deviation and standard error values of all parameters generated data are given in Table 2. The results presented in this section related to the permeate water well agree with the work of [35,36].

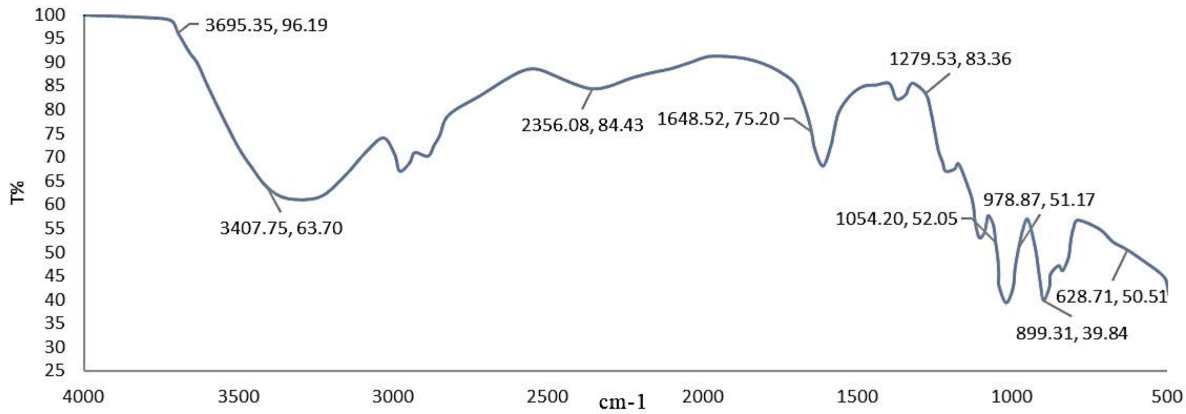

Fig. 3. Fourier-transform infrared spectroscopy of antiscalant for the antiscalant (1).

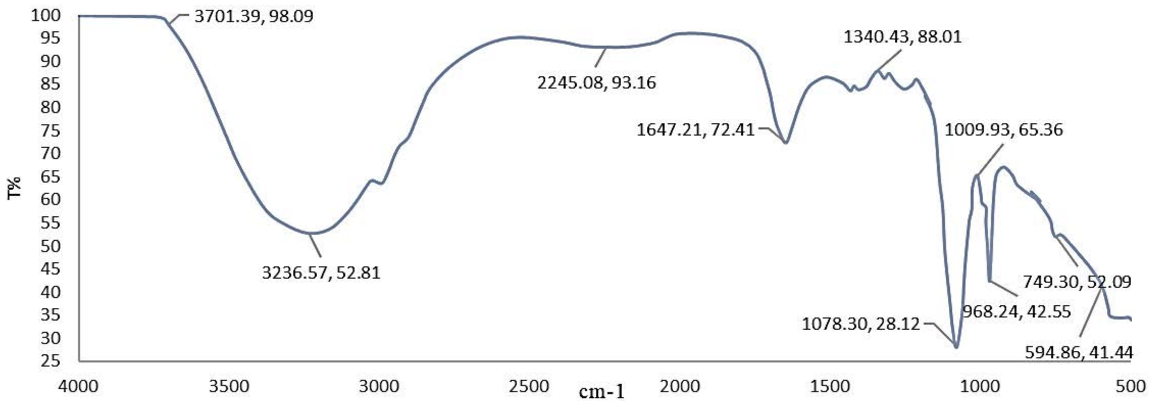

Fig. 4. Fourier-transform infrared spectroscopy of antiscalant for the antiscalant (2).

Table 2
Descriptive statistics for the chemical analysis of the feed water

Parameter	*N*	Mean	WHO standards	Standard error (SE) mean	Standard deviation	Minimum	Median	Maximum
pH	50	7.8	6.5–8.5	0.07	0.52	6.5	7.9	8.5
EC (ms/cm)	50	3.08	2.5	0.19	1.32	0.69	3.29	6.9
Cl^- (mg/L)	50	350	250	21	149	72	376	750
NO_3^- (mg/L)	50	134	50	12.3	86.7	20	119	443
Ca^{+2} (mg/L)	50	20	100	3.57	25	4	16.5	180
Mg^{+2} (mg/L)	50	7.26	60	1	7.1	0	4.33	40
Na^+ (mg/L)	50	61.1	200	5.2	36.8	10	50	200
SO_4^{-2} (mg/L)	50	15.3	250	2.9	20.3	0	8.35	95.8

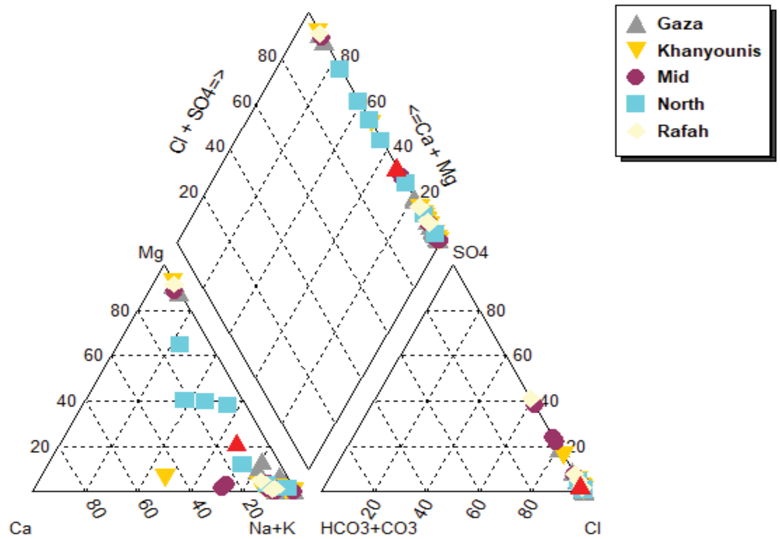

Fig. 5. Piper diagram for the feed water quality.

Table 4 shows the calculated average removal pollutants and salts removal. The results presented in Table 4 indicate the high desalination efficiency of the RO membranes along the Gaza Strip.

The overall average removal percentage has been calculated for each sampled RO desalination plant involving all the chemically analysed parameters before and after the RO. Fig. 6 shows the factors which affect the efficacy of the RO membrane and one can indicate that the RO membrane efficiency increases by increasing one or more of the following parameters: the number of operating staff, production capacity and average working hours. Also,

Table 3
Descriptive statistics for the chemical analysis of the permeate water

Parameter	*N*	Mean	WHO standard	SE mean	Standard deviation	Minimum	Median	Maximum
pH	50	6.5	6.5–8.5	0.1	0.76	5.09	6.54	7.9
EC (ms/cm)	50	0.26	2.5	0.04	0.29	0.03	0.18	1.9
Cl^- (mg/L)	50	26.9	250	3.5	24.7	5	18	122
NO_3^- (mg/L)	50	13.9	50	2.6	18.44	0	7.5	93
Ca^{+2} (mg/L)	50	1.6	100	0.35	2.45	0.2	1	13
Mg^{+2} (mg/L)	50	3.9	60	0.41	2.92	0	3	12
Na^+ (mg/L)	50	26	200	2.5	17.7	0	23.5	80
SO_4^{-2} (mg/L)	50	5.79	250	0.9	6.18	0	3.92	34.6

Table 4
Descriptive statistics for the pollutants' removal (%)

Parameter	*N*	Mean	SE mean	Standard deviation	Minimum	Median	Maximum
Cl^- (%)	50	90	1	10	51	95	95
NO_3^- (%)	50	86	3	21	23	96	95
Ca^{+2} (%)	50	90	2	13	13	93	98
Mg^{+2} (%)	50	43	2	13	21	44	98
Na^+ (%)	50	26	2.5	17.7	0	23.5	80
SO_4^{-2} (%)	50	56	3	24	20	50	98

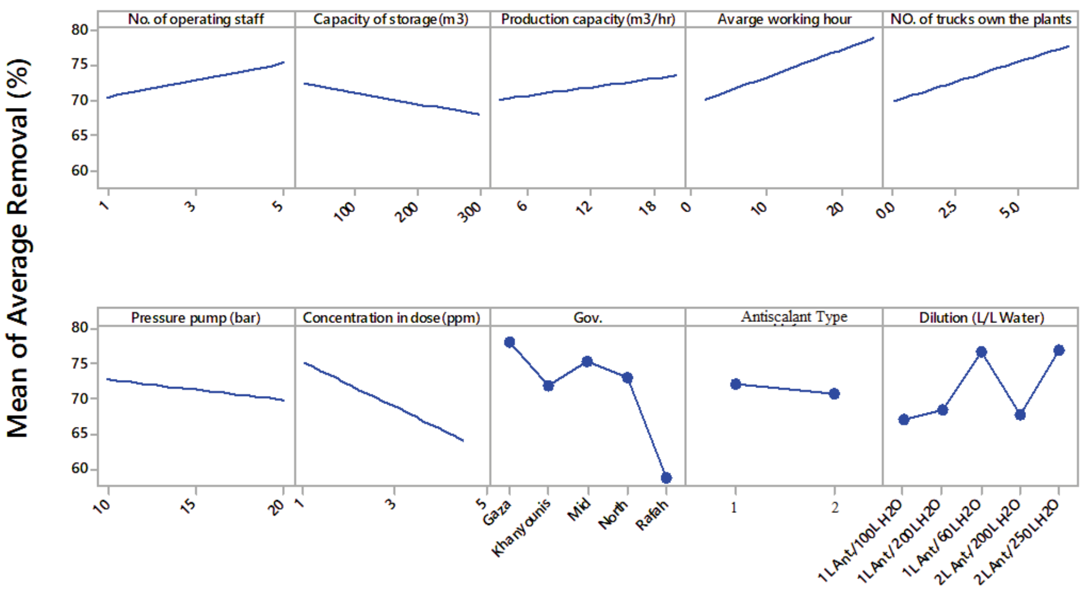

Fig. 6. Main effect plots for average total removal (%).

one can observe that the efficiency of the RO membrane decreases by increasing any of the following: the storage capacity, the capacity of the high-pressure pump and dose concentration of the antiscalant.

Also, Fig. 6 presents a fundamental investigation in the optimization of the maximum removal of salts in relation to the unique operational protocols for the small-scale RO plants in the Gaza Strip which go under the continuous dramatic increase of the input water salinity. Fig. 5 represents the interaction between operation characteristics that are concluded from the surveying questionnaires on the operational protocols of the RO plants. However, it shows there is a significant high removal percentage associated with Mid governorate whenever the first antiscalant is used at a dose of 1 L of antiscalant to 100 L of water to save the efficacy of RO membrane. Also, Fig. 7 shows that the lowest removal percentage is in Rafah governorate associated with the use of the second antiscalant which unsuitable

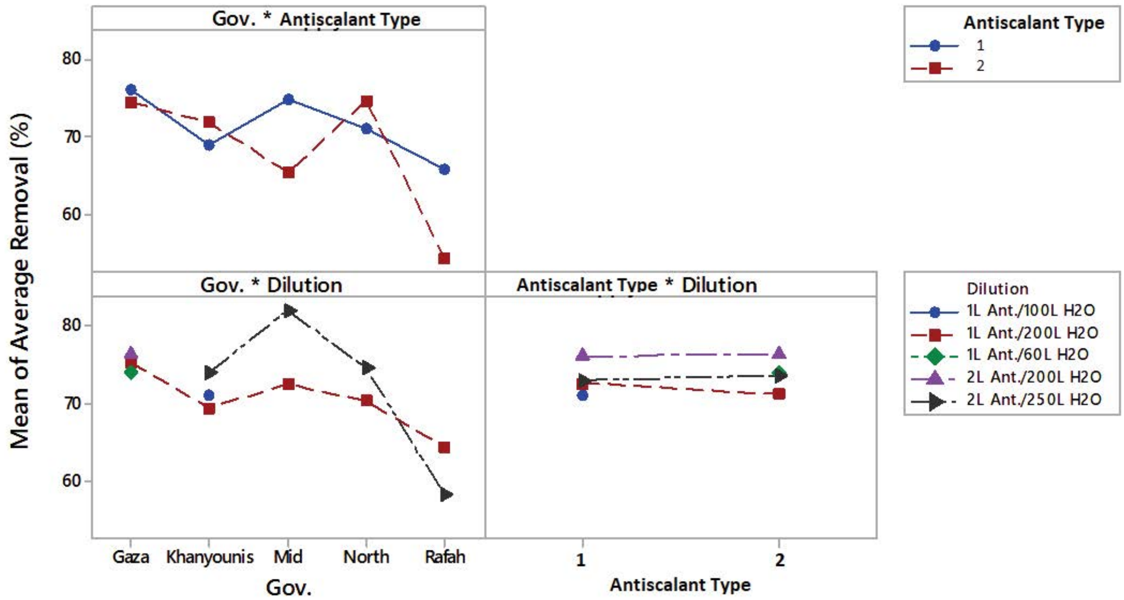

Fig. 7. Interaction plot for average total removal (%) with governorate, dilution and suppliers.

for RO membrane in this area. In general, one can notice that the first antiscalant type performs significantly better than the second antiscalant type on RO membrane.

3.3. Optimization modelling results

A general linear model was trained using all the collected data in the previous two steps in order to optimise the ideal working conditions for maximum average removal of all the pollutants. The trained optimization model was based on optimizing the real operation conditions of the antiscalants' type, dilution and dose. The R-square was 0.83, and the root mean square error was 3.8. The model was targeted to maximize the average overall removal as a response parameter. The model had the following parameters as inputs: pressure, water flow rate, which refers to the efficiency of RO, power consumption, number of working people and the antiscalants' type, dilution and dose. All the input parameters had weight equals to 1 and importance equals to 1 as well, and that was mainly because all parameters had a significant effect on the functionality of the RO membrane.

The results of the optimization model indicate that to reach the maximum removal in the Gaza governorate RO desalination plants (98% salts rejection) the first type of antiscalant should be used with 1 ppm antiscalant concentration and a dilution rate of 2 L of antiscalant to 250 L of water. However, to get only 92% salts rejection at Rafah governorate RO desalination plants, the second type of antiscalant should be used with 1 ppm concentration and the dilution rate of 2 L of antiscalant to 250 L of water. Although, in the North governorate to reach the 98% salts rejection in the RO desalination plants the first type of antiscalant should be used with 1.04 ppm concentration and dilution rate of 2 L of antiscalant to 250 L of water. For the Middle governorate in order to get the 98% salts rejection, the first type of antiscalant should be used with 1 ppm concentration and dilution rate of 2 L of antiscalant to 250 L of water. Finally, to reach the 98% salts rejection at Khan Yunis governorate RO desalination plants, the first type of antiscalant should be used with 1ppm concentration and dilution rate of 2 L of antiscalant to 250 L of water.

Fig. 8 shows the optimization plots with the optimized conditions for the maximum removal of all the parameters including salts, sulfates, sodium, magnesium, calcium, chlorides and nitrates. The red line corresponding to each input parameter indicates the optimized condition to get the maximum removal percentage in modelled RO desalination plants.

4. Conclusions

This research presents field and experimental lab works to examine the effects of antiscalants on the small and medium scale brackish RO desalination plants under real operation conations. A total number of 100 samples were collected from 50 RO desalination facilities along the Gaza Strip, Palestine. Several 50 samples were collected from the feedwater, and the other 50 samples were collected from permeate. The samples were analysed and evaluated for pH, total dissolved solids, electrical conductivity, chlorides, nitrates, magnesium, sodium, sulphates and calcium. From a water quality point of view, electrical conductivity, sodium, chlorides, calcium, sulphates and nitrates concentration levels for the permeate were found to be within the WHO guidelines for drinking water quality. All the sampled RO desalination plants were found to use one of two types of antiscalants; both were strong acidic materials. The antiscalant types were categorized as antiscalant (1): Polyphosphates with pH equals to 4 and antiscalant (2): phosphonates with pH equals to 4.5. A general linear model was trained using all the collected data in order to optimise the ideal working conditions for the maximum average removal of all the pollutants. The

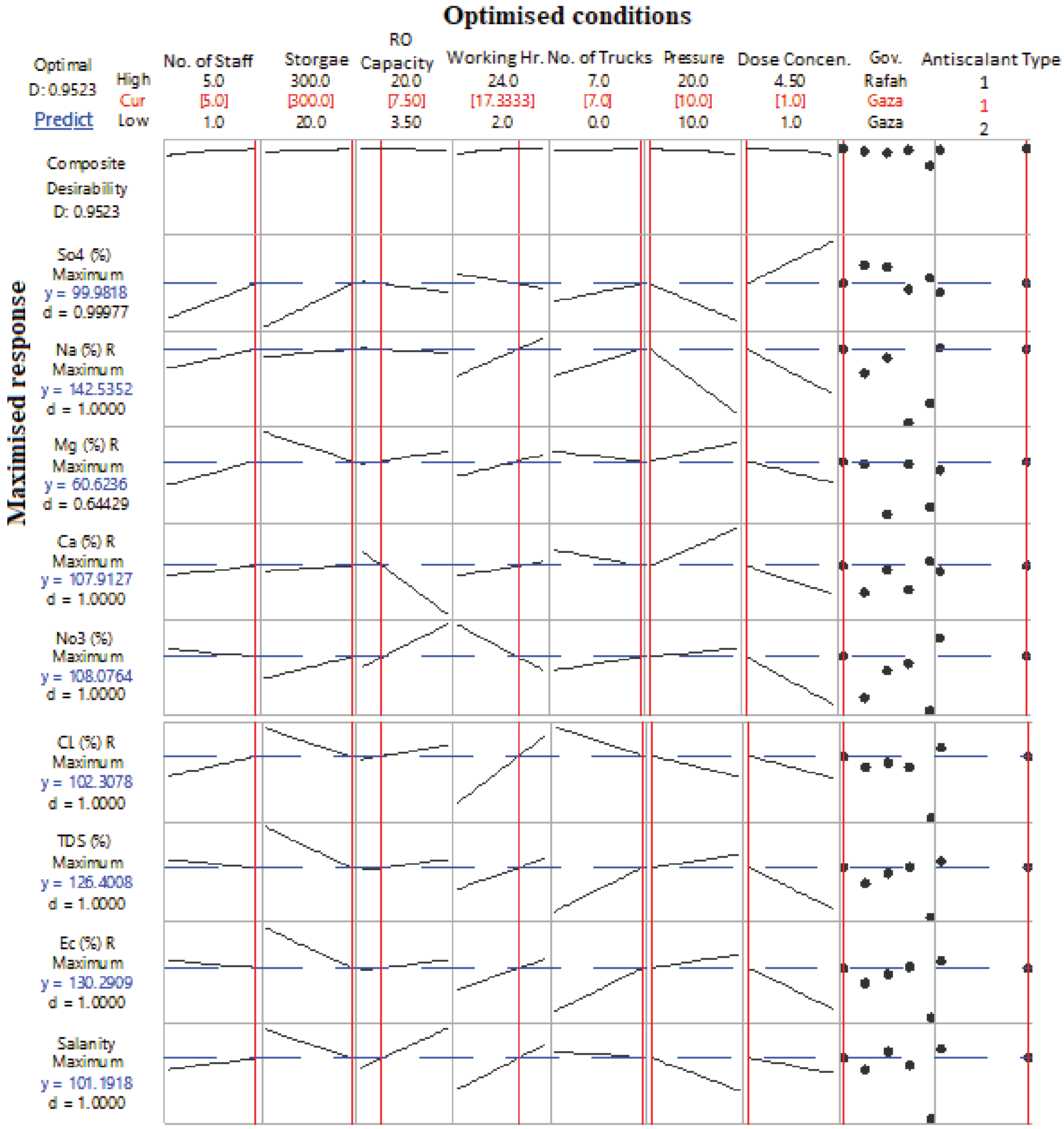

Fig. 8. Optimisation plots with the optimised conditions (highlighted in red) for the maximum removal of the different parameters.

trained optimization model was based on optimizing the real operation conditions of the antiscalants' type, dilution and dose. The two types of antiscalants were found to be effective in reducing salts precipitation and crystallization on the surface of the membrane to save the efficacy of the membrane. However, the results show that in order to reach the maximum salts rejection (98%) the first type of antiscalant (polyphosphates with pH equals to 4) should be used, at 1 ppm concentration with a dilution of 2 L of antiscalant to 250 L of water. However, using the second type of antiscalant (phosphonates with pH equals to 4.5) with the same dose and concentration would lead to a 92% salts rejection and finally, the choice of antiscalant is depending on the chemical properties of feed water analysis to determine the water type and suitable type of antiscalant.

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