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Establishment of database on the physical, chemical, and biological characteristics of the seawater intake of Kuwaiti desalination plants

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ABSTRACT

The knowledge of the characteristics of seawater is important for designers and engineers to design and construct a desalination plant with low operational problems. Therefore, establishing a database for Kuwait's seawater characteristics is considered a crucial tool for researchers seeking to develop and improve desalination technologies for future applications. Because of this fact, this project was proposed to analyze the physical, chemical, and biological characteristics of Kuwait's seawater at Subiya, Doha, Shuwaikh, Shuaiba, and Az-Zour, and other two locations that belong to the Kuwait Institute for Scientific Research (KISR) as Doha Research Plants (DRP) used as the intake for desalination/distillation research activities. A database on Kuwait's seawater characteristics at the proposed locations was established. Then,the suitability of the proposed locations for future desalination activities was investigated depending on four fouling indices. The results obtained from the investigation of fouling indices were compared to the result obtained from experimental testing. This paper will summarize the results of the analysis and the experimental work and explore the best location for desalination activity in Kuwait and KISR.

Keywords: Seawater intake; Desalination plant; Physical, chemical, and biological characteristics

1. Introduction

Water characteristics are the key to understanding the chemical and the biological reactions associated with desalting processes. Changes in seawater characteristics over time could lead to performance deterioration, as increase in operating cost, corrosion and scaling problems, and finally the damaging of the expensive parts of the desalination plants. To avoid these problems, the designers of desalination plants should have the knowledge of possible changes in the feed water characteristics for a long term. The establishment of a database for seawater characteristics is very important and should be considered strongly before constructing any new desalination plant in Kuwait. It will help decision makers in the government and particularly of the Ministry of Electricity and Water (MEW), to select a suitable location for the future expansion of new desalination plants. Before constructing a desalination plant and spending a huge amount of money, the established data must be considered. Operational problems can be avoided,and the variation in the plant's performance can be minimized if the established data were considered. The characteristics of seawater have a direct effect on the design parameters of the desalination plant and can affect the operating equipment and the maintenance expenses. Furthermore, the established database is required to bridge the information gap in Kuwait's seawater characteristics, which is crucial for future research activities in seawater desalination.

Information on the characteristics of the feed water is necessary to control scaling and fouling problems and to select appropriate membrane and appropriate pretreatment and post-treatment methods [1–3]. Furthermore, this information is very important for successful desalination projectsin Kuwait. It is well known that the first factor affecting the performance of Kuwait's Multi-Stage Flash (MSF) desalination plant is the seawater characteristics of

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the feed water at the intake [4]. There are many parameters could affect the characteristics of Kuwait's sea water and result of temporary or long-term changes in these characteristics [5]. The high-temperature seasonal variations; global warming; and dumping a large quantity of brine water to the sea and contamination of seawater with oil are factors that could change the seawater quality [6–11]. Thus, each desalination plant must be designed based on the seawater characteristics at the intake location [12–14]. Therefore, establishing a database for Kuwait's seawater characteristics was considered a crucial tool for researchers seeking to develop, adapt, and improve desalination technologies for future applications. This knowledge is also very important for designers and engineers who are involved in the construction of desalination plants [15–18].

The most obvious example is the effect of high total suspended solids (TSS) on the Subiya Desalination Plant in Kuwait, where the high TSS in the feed water results in serious operating problems,the damage of equipment,and high consumption of antiscalant, anti-foams, and other chemical additives required for pretreatment. Moreover, the high TSS in feed water increases the operating expenses and reduces the productivity of the Subiya Desalination Plant. Thus, the database of the Gulf's seawater characteristics is essential to produce an exact design of the desalination plant and to control its operating parameters under the prevalent conditions in this region, and its availability to researchers, designers/manufacturers, and operators is the basis for the proper innovation, construction, and operation of new plants.

Therefore, this study considered as an attempt to explore the full characteristics of Kuwait's seawater, especially those necessary for designing desalting/distilled systems. The seawater characteristics were measured at the two locations that belong to KISR, and these two locations were distinguished as the source of seawater for all future research activity related to desalination in KISR. Furthermore, the characteristics of Kuwait's seawater at the intake of six Kuwaiti desalination plants were also considered, and a database was established on Kuwait's seawater characteristics using a geographic information system (GIS) for all researchers in the desalination field. Then, the suitability of the selected location for desalination activities was investigated.

1.1. The design characteristics for desalination activities:

The main chemical characteristics,which were required for the proper design of desalination/ distillation system, were pH, hardness, dissolved oxygen (DO), total dissolved solids (TDS), alkalinity, organic chemicals, inorganic ions (sodium, chloride, carbonate, sulfate, potassium, bromine, zinc, aluminum, iron, barium, boron, nickel, mercury, copper, silver, cobalt, and fluoride), or cations and anions in seawater. However turbidity, color, odor, silt density index (SDI), temperature, and TSS are related to the physical characteristics of seawater. The biological characteristics usually refer to aquatic life such as bacterial slimes, alga, living cell, plankton, and viruses found in water and organic matter. The indications mostly used for biological characteristics are total organic carbon (TOC), the biological oxygen demand (BOD), total bacterial count (TBC), fecal Coliform bacterial (FCB) and, chemical oxygen demand (COD). Table 1 summarizes the parameters, which were selected and included in the data base since they are essential for designing a desalination system and required for studying the suitability of the selected location for desalination/distillation activities.

Table 1
Chemical, physical, and biological characteristics of seawater samples

Parameters	
Chemical	Cl^-, SO_4^{--} HCO_3^-, NO_3^-,CO_3^{--}, Br, F^-, PO_4^{---} Na^+, Mg^{++}, Ba^{++} , K^+, Ca^{++} , Fe^{+++}, Mn^{++}, Al^{+++}, Sr^{++} Cu^{++}, Zn^{++}, Pb^+, Cd^+, Cr^+, Hg^+, total hardness (TH), silica (SiO_2), Ammonia (NH_4), and CO_2
Physical	TSS, TDS, conductivity, pH, temperature, and turbidity SDI_5/SDI_{15}
Biological	BOD, COD, TBC, FBC and, TOC

The SDI is an important operating parameter for all membrane desalination systems, and it helps the operator avoid colloidal fouling problems. In multi-stage flash (MSF) distillation plants, it is well known that the condenser temperature in the rejection section will increase if the temperature of feed water increases. That will also increase the temperature of the brine in the recovery section. Thus, the temperature is a design parameter in the thermal desalination plant [19,20]. Furthermore, the temperature of feed water is usually involved in the design calculations, because it affects the performance ratio, gain output ratio, operating cost, and heat exchanger area. The performance of membrane desalination processes such as nanofiltration (NF), micro filtration (MF), ultra filtration (UF) and reverse osmosis (RO), was a function of feed water temperature. As the temperature of feed water increased, the water viscosity decreased,membrane permeability increased, and the productivity increased. However, the productivity will be decreased if the temperature exceeds a critical temperature value [21]. The main advantage of the seawater beach well over the surface seawater intake is the steady feed water temperature produced on the beach well, while the surface seawater intake produces a varied surface seawater temperature [22].

The concentration of DO is a major indicator of water quality and plays an important role in the rate of corrosion of metals when they are exposed to seawater. In MSF plants, scavenger is added to reduce the DO and thereby reducing the risk of corrosion.

Organic matter refers to substances that contain carbon and hydrogen. The concentration of TOC used in seawater desalination plants as indication of organic matter in feed water, which is considered as an indication of fouling and clogging problems in membrane desalination. Although, the concentration of organic matter in seawater is usually very low (about 1–3 mg/l) [3], it must be considered before designing any desalination/ distillation system, since organic fouling is one of the major concerns in desalination industry. High fouling rate either increases the operating osmotic pressure to recover the decrease in flux rate or decreases the production of permeate, which consequently lead to a high operation cost, less productivity, membrane replacement,and high maintenance cost.

There are a lot of inorganic ions that are important to any desalination/distillation system such as sodium (Na^+); magnesium (Mg^{++}); barium (Ba^{++}); potassium (K^+); calcium (Ca^{++}); iron (Fe^{+++}); manganese (Mn^{++}); aluminum (Al^{+++}); strontium(Sr^{++}); copper (Cu^{++}); zinc (Zn^{++}); lead (Pb^+); cadmium (Cd^+); chromium (Cr^+); mercury (Hg^+); chloride (Cl^-), sulfate (SO_4^-,), silica (SiO_2), and fluoride (F). Although most of these inorganic ions exist in seawater in very low concentrations as barium, strontium and silicate, they play an important role in fouling and scaling problems in the desalination system [23,24].

The concentration of inorganic trace metal in the drinking water, recently, has gained special attention due to its adverse effect on human health and its lower percentage rejection by the RO system such as boron (B) and lead (Pb) [25]. The concentration of boron in the Arabian Gulf has been reported to range from 6.1 to 4.9 mg/l [26]. The World Health Organization (WHO) established a guideline for boron in drinking water to be less than 2.4 mg/l in 2017 [27]. The method of desalination can affect the boron concentration in the product water, where the water produced by thermal desalination is usually free of boron, while membrane desalination produces water with a high concentration of boron since most of the old modules of RO membranes have a very low rejection to boron (50 to 90%) [28]. Furthermore, at a high concentration of fluoride, calcium fluoride scaling is expected. The salinity level in seawater can be increased as the concentration of sodium, and chloride ions are increased in seawater, and the level of salinity will affect the percentage of rejection in membrane processes. Barium can form barium sulfate scaling when its concentration exceeds only 1 ppm in Kuwait's seawater [29], barium sulfate scaling can cause flux decline and potentially severe membrane damage [23]. Therefore, analyzing such ions is essential for predicting scaling indices and specifying operational parameters as well as proposing suitable treatment methods as scale inhibitors or an acid additional.

2. Methodology

This project analyzed all the physical, chemical, and biological parameters required for a proper design/operation of desalination/distillation system. The methodology consisted of collection the of samples followed by an analysis in accordance to the international standards for quality control/quality assurance (QA/QC), to obtain reliable data ensuring data accuracy, precision, representativeness, and completeness [30]. The use of written standard operating procedures (SOPs) for collection, preservation, transport, and storage of the samples; the calibration of the equipment; and the performance of each analysis are a part of the general QA/QC aspects followed during the sampling and the analysis [31].

The methodology for sample collection was explained below:

- Trace metals may adsorb onto the walls of glass containers or leach from the glass container,so polyethylene containers were used in the sampling processes for chemical and physical analysis. Whereas,three liters of surface seawater samples were collected from surface seawater in the in take of desalination plants at a constant time every week using two polyethylene containers and one glasses container, each container with 1-liter capacity. The polyethylene containers for chemical and physical while the glass container for biological analysis.
- A seawater composite samples were collected from the surface seawater at the intake of Shuwaikh, Shuaiba, Az-Zour, Doha East, Doha West, Subiya, and two further seawater samples were collected from the intake of Doha Research Plant's beach well (DRPBW) and KISR's Shuwaikh site. The surface seawater samples were collected from the surface at a low depth not exceeding 0.5 m from the middle of the flowing stream at the intake structure of desalination plants (Table 2). Whereas, a mixture of grape samples was collected from different locations of the intake structure and pooled together in one container to provide one sample since we concern about the average water quality of surface seawater at the intake structure.
- The sample bottles were cleaned one day before sampling process, with diluted acid then the sample bottles were soaked several times with deionized water but not sterilized, to minimize the effect of interferences especially for trace metal analysis.
- The glass container cleaned with diluted acid then baked in an oven at 150°C for 48 h to be sterilized before collecting sampling for biological analysis.

Table 2
The number, location, and frequency of water samples to be collected

Sample number	Location	Sampling frequency	Type of water sample
1	Intake of Subiya Power Station	Once a weak	Surface seawater
2	Intakes of Doha East Power Station	Once a weak	Surface seawater
3	Intakes of Doha West Power Station	Once a weak	Surface seawater
4	Intakes of Shuwaikh Power Station	Once a weak	Surface seawater
5	Intake of Az-Zour Power Station	Once a weak	Surface seawater
6	Intake of Shuaiba Power Station	Once a weak	Surface seawater
7	Doha Research Plant BW (DRPBW)	Once a weak	Beach well water
8	KISR Beach well Shuwaikh (SHBW)	Once a weak	Beach well water

DRP: Desalination Research Plant; KISR: Kuwait Institute for Scientific Research

- Before sampling, a label affixed to the sample containers; the label includes all information required as sample number, the name of collector, date, time and place of collection.
- All of the sampling bottles were rinsed two times with the water collected.
- The containers were filled completely for most required analysis, while for biological analysis space was left for aeration and mixing in the sampling containers. Then all the samples were mixed thoroughly to ensure homogeneity.
- The container, which aimed for trace metal analysis, was acidified with nitric acid to a pH below 2.0 to minimize precipitation and adsorption on container walls.
- The glass container for biological and bacteriological analysis was placed immediately in the dark and at a low temperature to retard any bacteriological activities
- Residual chlorine, pH, temperature, and turbidity were measured in the location immediately after sampling because these parameters will change during storage and transportation.
- Sampling was completed carefully to ensure that the analytical results represent the actual sample composition. After collecting water samples, all the samples were mixed thoroughly to ensure homogeneity
- The collected samples are immediately preserved in melting ice and submitted to the laboratory within three hours. All the required chemical, physical and bacteriological parameters were analyzed immediately after receiving the samples containers.
- The samples, which intended for chemical analysis was first, filtered to remove all the suspended matter and reduce the percentage of error to increase accuracy and precision.
- Duplicate samples, repeat measurements and blank samples from the deionized water were prepared independently and were analyzed randomly along with other samples, to assess the precision of the chemical analysis relative to the variation in sample preparation and sampling processes. The blank samples were acidified and handled in the same way as the normal samples.
- Water samples were collected in pretreated high-density polyethylene bottles;Then the collected samples were filtered through a Millipore filter of 0.45 µm pore diameter to remove all suspended contaminants.

Thus, more than forty seawater samples were collected from each representative site at the intake of the power plant. The collected samples were analyzed directly for biological parameters such as BOD, COD, TBC, FBC, and TOC, at the Water Research Center (WRC) laboratory, which belongs to KISR. A mobile SDI unit was fabricated to measure the SDI at the location directly as shown in Fig. 2.

Other physical and chemical characteristics were analyzed at the DRP laboratory. If these samples could not be analyzed directly, it was preserved by refrigeration or acid addition. The collected characteristics were managed and maintained in the database, and processed in tables and figures whenever needed. The collected database was used as a support tool for KISR's research activities related to desalination and to investigate the suitability of differ-

Fig. 1. The location of desalination power plants in Kuwait.

ent locations for constructing a desalination system. The suitability of the proposed location for future desalination research activities was investigated, using four fouling indices at each location as inorganic fouling, through calculating Stiff and Davis saturation index (S&DSI) and scaling potential of calcium sulfate ($CaSO_4$), barium sulfate ($BaSO_4$), strontium sulfate ($SrSO_4$), calcium fluoride (CaF), and silica (SiO_2). Other fouling indices were also investigated in this study as colloidal fouling, biofouling, and organic fouling. Thus, the potential of each location to fouling and biofouling problems were estimated using four fouling indicators. The result of the investigation was compared to the result obtained from the experimental test, which is fouling test using the water samples collected in this study (Fig. 1).

Fig. 2. The silt density index unit.

3. The experimental section

3.1. Fouling test

The degree of fouling was measured through experimental work using a fouling test unit (FTU).

The FTU used in this experimental work is shown in Fig. 3 and consists of two tanks, namely, feed tank and permeate tank, with a total working volume of 20 L. Feed water was stored in the feed tank and then enters the circulation loop using a diaphragm pump. The diaphragm pump will sustain the circulation of the flow rate in the circulation loop to the nanofiltration module. The nanofiltration module contains a new nanofiltration membrane at the beginning of each experiment. The circulation loop contains a pressure gauge to measure the pressure and a pressure valve to adjust the transmembrane pressure in the nanofiltration module. The flow of the permeate was measured using an electronic balance based on the operating hour as shown in equation one below.

$$J = \frac{\Delta V}{A \Delta t} \tag{1}$$

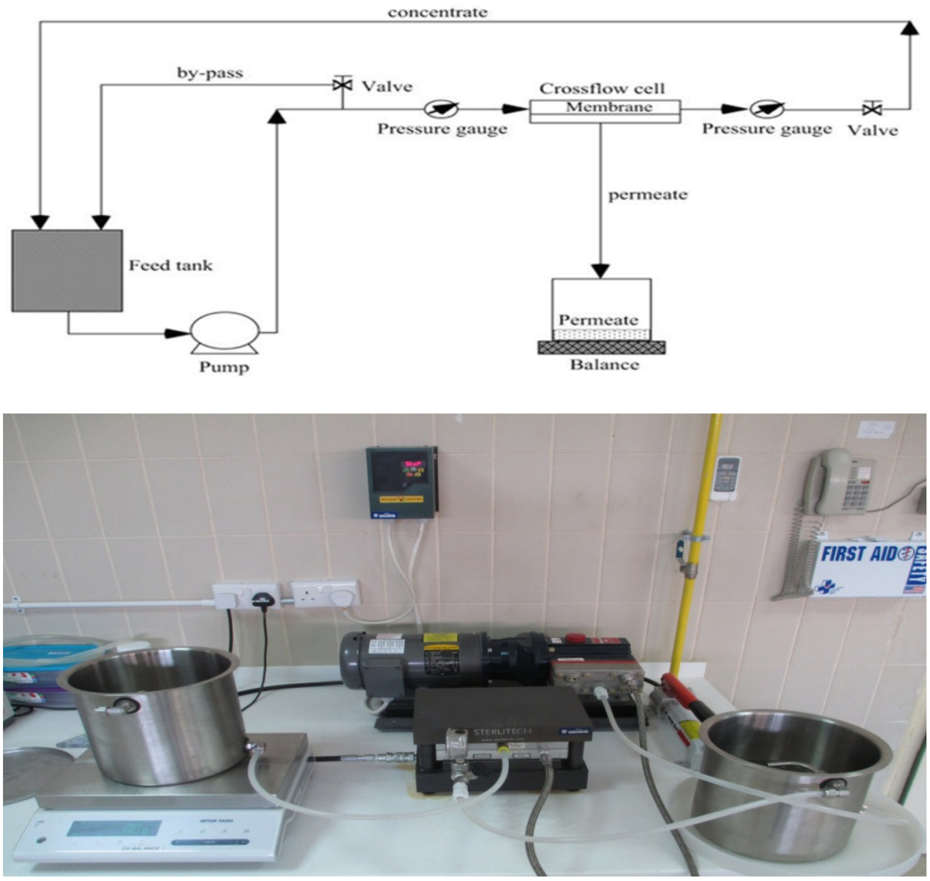

Fig. 3. Schematic figure of the fouling testing unit at DRP.

where A is the membrane area, which is equal to 0.0266 m^2 and ΔV is the volume of the permeate obtained from the relation between the density and the weight of the collected permeate.

As a baseline for the experimental work, the feed solution was distilled water (DI). Initially, the membrane was soaked with DI water for one hour, flux was measured at constant pressure, and the pressure depended on the type of the membrane used. Then, the permeate water was collected in the permeate tank for one operating hour. The initial membrane flux (J_{w1}) was calculated using Eq. (1) to be used as a base for water flowing without fouling.

Then, the feed solution was replaced with water samples from different desalination plants' intake such as Az-Zour, Doha East, DRP BW, Shuwaikh, and Subiya. The unit was operated for at least three operating hours to foul the membrane. After fouling the membrane, using the real seawater solutions for 3 h, the unit was operated with DI again to flush all of the precipitated salts on the membrane surfaces for one hour,and the final recovered flux was measured as (J_{w2}). Then the flux recovery ratio (FRR) was calculated using equation two below. FRR is measurements between the membrane flux after fouling to the membrane flux without fouling. Always higher FRR indicates an easy cleaning propensity of the membrane and low potential for fouling problem. So, FRR is an indication of low fouling characteristics.

$$FRR(\%) = \frac{J_{w2}}{J_{w1}} \times 100 \qquad (2)$$

4. Result and discussion

The suitability of the proposed sample locations for establishing desalting systems was investigated, based on the degree of the fouling potential expected at the selected locations. It is well known that fouling is the most persistent problem in desalination systems and the fouling potential is divided into four categories. The first type of fouling is the inorganic fouling or the precipitation of scaling compounds as $CaSO_4$, $BaSO_4$, $SrSO_4$, CaF, and SiO_2, which can be predicted based on the concentration of the scaling ions in the feed water using the ion product (IP), solubility product (KSP), and S&DSI.

The second type of fouling is the colloidal fouling, which is the accumulation of suspended particles (silicate, ferric oxide, and iron oxide) on the membrane surfaces and inside the membrane pores, forming a cake layer, clay, and flock. The main indicators, which are used to characterize the colloidal fouling in feed water are SDI, TSS, silica, turbidity, ferric oxide, iron oxide,and aluminum oxide colloidal. Biofouling is the third type of fouling and is noticed when there is a multiplication of microorganisms such as fungi, algae, yeast, and bacteria that will result of layers of biofilms accumulation and clog the membrane pores. TBC and fecal coliform are considered as good indicators for biofouling or microbial content. The fourth type of fouling is the organic fouling, which occurs due to the adsorption of natural organic compounds (NOC) on the membrane surfaces, causing gel formation. Folic acid, protein, polysaccharides, and polyacrylic polymer are examples of natural organic matters. TOC, BOD, nitrate, ammonia, phosphate, and COD measurements are the useful indicators of organic fouling. Therefore, the suitability of the selected locations for membrane desalination activities was investigated based on these four fouling categories. The average of chemical, physical, and biological characteristics of all selected locations shown in Table 3.

The chemical analysis of KISR's beach well at Shuwaikh (SHBW) shows that the water in this beach well is not of seawater quality, where it has a low conductivity less than 14000 mg/l, which is considered as of ground water quality and not as of seawater quality. Thus, it excluded from the comparison between the selected locations.

4.1. Inorganic fouling

The inorganic fouling is related to the precipitation of scaling compounds on membrane surfaces such as $CaSO_4$, $CaCO_3$, $BaSO_4$, $SrSO_4$, CaF_2, and SiO_2 scaling. The ion product (IP) of scaling compounds will be calculated in the brine stream at different concentrations and conversions,whereas IP will be compared to the KSP of each scale. The calculations will clarify the percentage of precipitation (i.e., the percentage of inhibition) expected for each scaling based on the seawater characteristics. The possibility of calcium carbonate precipitation will be predicted based on CO_2 and S & DSI. S & DSI is a seawater index used to predict the scaling tendencies of calcium carbonate [29]. The result of the study lists a variety of proposed conversions and calculates the expected inhibition for each scaling at a proposed conversion. The percentage inhibition was calculated as shown below in Eq. (3), where the KSP is a function of ionic strength and temperature.

$$\% \text{ inhibition} = (KSP_{(I,\,temp)} - IP_{(I)}/KSP_{(I,\,temp)})*100 \qquad (3)$$

4.1.1. Calcium sulfate scaling

The results of calculations related to calcium sulfate scaling at ambient temperature and differently proposed conversions for all of the proposed locations shown in Fig. 4.

From Fig. 4, it is clear that Shuiaba desalination plant has very low inhibition for $CaSO_4$ scaling even at ambient temperature followed by DRPBW, While there is four locations show similar good inhibition for $CaSO_4$ scaling,which are Shuwaikh, Doha West, Doha East, Subiya and Az-Zour desalination plants. The chemical composition of seawater at the intake of Shuaiba desalination plant show that the inhibition percentage for calcium sulfate precipitation was only 30% at 10% conversion and decreased as the conversion increased. So,calcium sulfate was expected to precipitate even though the conversion was only 5% and without increasing the temperature. Furthermore, the conversion in MSF desalination plant in the Arabian Gulf was not more than 10 to 15%. The scaling potential of seawater at DRPBW with regard to calcium sulfate is the next worst situation, whereas the calcium sulfate scaling is expected to precipitate immediately at an ambient temperature and conversion above 50%, while The inhibition for $CaSO_4$ scaling was 50% only at 10% conversion and decreased to 30% inhibition at

Table 3
The average analysis of all chemical and physical parameters of seawater at the intake of the selected desalination plants

	Subiya	Doha East	Doha West	Shuwaikh	DRPBW	Az-Zour	Shuaiba
Temperature (°C)	24.72	24.92	24.77	24.90	25.06	25.07	24.6
pH	8.06	8.13	7.96	8.05	7.27	8.08	8.1
Conductivity (mS/cm)	62.58	62.15	60.96	63.25	58.35	61.80	61.8
Turbidity (NTU)	6.26	2.90	1.87	2.88	1.03	2.05	1
TSS (mg/L)	3.24	2.00	1.20	1.70	0.75	2.05	1.7667
TDS (mg/L)	50024	43582	51370	57109	45534	47524	51106
Aluminum (mg/l)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Cadmium (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Chromium (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Copper (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Manganese (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Lead (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Zinc (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Potassium (mg/L)	415.32	465.71	470.63	493.32	343.26	449.77	870
Strontium (mg/L)	6.58	6.94	6.59	6.60	14.75	6.49	7.36
Iron (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Mercury (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Sodium (mg/L)	14535	14188	13757	14814	13978	14013	19238
Sulphate (mg/L)	3827.8	3740.8	3628.81	3551.1	3351.4	3623.2	5086
Fluoride (mg/L)	2.03	3.12	3.21	3.61	4.76	1.80	4.3
Silica (mg/L)	0.25	0.21	0.29	0.45	2.11	0.14	0.4
Barium (mg/L)	<1	<1	<1	<1	<1	<1	<1
Chloride (mg/L)	27815	27312	25453	27033	24972	25346	35050
Bicarbonate (mg/L)	132.47	135.20	131.00	147.07	128.55	141.21	141.5
Calcium (mg/L)	470.36	470.47	501.33	465.33	735.76	500.26	900
Magnesium (mg/L)	1641.74	1682.18	1633.55	1703.21	1281.76	1643.62	2496
Total hardness (mg/L)	8073.11	8178.43	8230.86	8471.10	6815.85	8042.30	12768
COD (mg/L)	82.31	84.77	82.92	90.52	89.71	81.97	89
BOD (mg/L)	<1	<1	<1	<1	<1	<1	<1
Total count (CFU/ml)	1.54E+4	3.75E+03	3.80E+03	5.15E+03	4.44E+03	4.71E+03	3.42E+03
Fecal coliforms (CFU/100 ml)	00	0.0	0.12	00	00	0.00	0

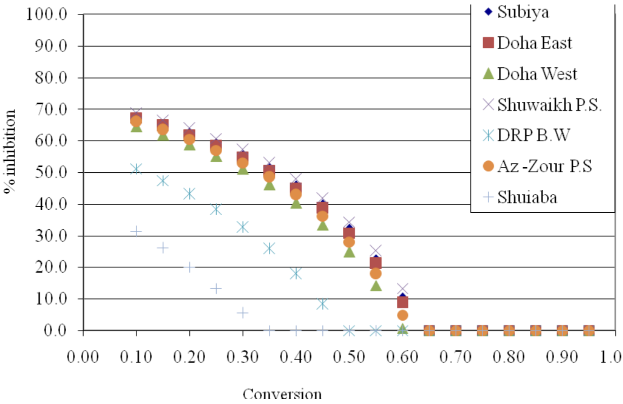

Fig. 4. The percentage inhibition of calcium sulfate at different conversions using different types of seawater from different intakes of desalination plants in Kuwait.

30% conversion and continued to decrease as the conversion increased. From Fig. 4, it can be seen that Shuwaikh, Doha West, Doha East, Subiya, and Az-Zour are the best with regard to $CaSO_4$ scaling where the percentage inhibition for calcium sulfate was 70% at 10% conversion and decreased to reach 55% inhibition at 30% conversion. Finally, it can be concluded that the scaling potentials for $CaSO_4$ at ambient temperature for seawater at Shuwaikh, Doha east, Doha West, Az-Zour, and Subiya were similar and close to each other. However, the worst location is Shuiaba Desalination Plant due to the high concentration of sulfate in Shuiaba (5086 mg/l) compared to its concentration at other locations such as DRPBW (3430 mg/l).

4.1.2. Strontium sulfate scaling

Fig. 5 shows the scaling potential of strontium sulfate at the selected locations at different conversions. The

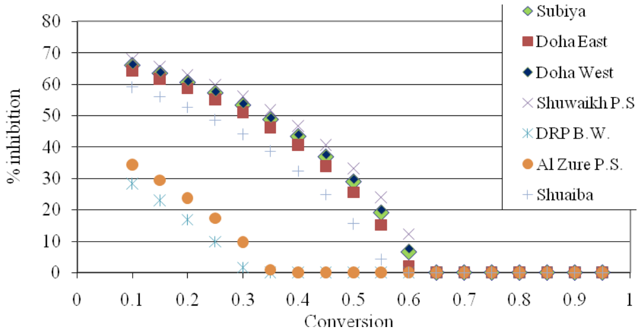

Fig. 5. The percentage inhibition of $SrSO_4$ at different conversion.

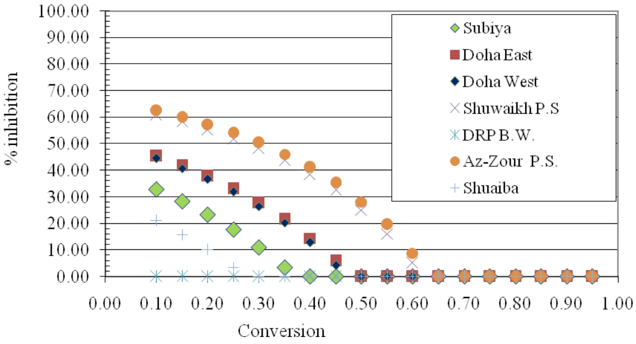

Fig. 6. The percentage inhibition of $BaSO_4$ at different conversion.

lowest potential for $SrSO_4$scaling was found in Shuwaikh seawater. Since the concentration of strontium was the lowest among the other locations, where the concentration of strontium at Shuwaikh was 6.58 mg/l, and the concentration at DRP BW was 14.61 mg/l, the high potential for the scaling of strontium sulfate was at DRP BW. Az-Zour showed a scaling potential similar to DRP BW where the percentage inhibition was only 30% at 10% conversion and decreased to zero inhibition (immediate precipitation) at only 35% conversion and ambient temperature. However, the Subiya, Doha East, Doha West, and Shuaiba have the similar and acceptable potential for strontium sulfate scaling, where the percentage inhibition was about 70% at 10% conversion and decreased to zero at 60% conversion.

4.1.3. Barium sulfate scaling

Fig. 6 shows the scaling potential of barium sulfate at different conversions at different locations. It is clear from Fig. 6 that all of the locations have a high potential for barium sulfate even though at very low conversion. Although the concentration of barium is very low when compared to the concentration of calcium or carbonate, its effect is very strong on scaling potential, whereas the concentration of barium does not exceed 0.05 mg/l (<1) in all of the locations. The highest concentration of barium recorded is 0.0166 mg/l at Shuiaba, and the lowest values were 0.0082 and 0.009 mg/l recorded at Shuwaikh and Az-Zour, respectively.

From Fig. 6 it is clear that the highest potential for barium sulfate scaling was expected at DRPBW, and the lowest potential for barium sulfate was found at Shuwaikh and Az-Zour desalination plant The percentage inhibitions at shuwaikh, and Az-Zour locations were similar, whereas the inhibition was 60% at 10% conversion and decreased to immediate precipitation at 60% conversion. However, the percentage of inhibition for barium sulfate is only 20% and decreased to zero inhibition at only 25% conversion for Shuiaba. While at DRPBW the inhibition was zero even though at ten percentage conversion. This implies Shuwaikh and Az-Zourare the best locations about barium sulfate scaling followed by Doha West and Doha East, especially at membrane desalination processes where the pressure is increased to 60 bar, and $BaSO_4$ scaling is expected even at low operating temperature.

4.1.4. Calcium fluoride scaling

The scaling potential of calcium fluoride is very low as shown in Fig. 7, whereas the percentage inhibition is greater than 90% even though at 90% conversion. Since the concentration of fluoride is very low in seawater at all of the investigated locations, So there is no danger from calcium fluoride at all selected locations. The maximum concentration of fluoride was recorded at DRP BW, which was 4.27 mg/l, and the lowest value was recorded at Az-Zour, which was 1.84 mg/l. Thus, all of the investigated locations are suitable with regards to calcium fluoride scaling, and no risk from this type of scaling is expected at room temperature desalination systems.

4.1.5. Calcium carbonate scaling

Calcium carbonate scaling is strongly related to the pH of feed water; the lower the pH, the lower the potential for calcium carbonate scaling, since the pH of seawater is a design and operating parameter in desalination plants, especially for an acid treatment system. The amount of carbonate (CO_3^-) or bicarbonate (HCO_3^-) present in seawater changes with the pH values. At lower pHs, there is greater alkalinity in the form of HCO_3^-, and at higher pHs, alkalinity is in the form of carbonate [20]. Many gases in the atmosphere were reported to affect the pH of seawater as carbon dioxide, and sulfur dioxide was emitted from power desalination plants [6]. The natural pH of seawater in the Arabian Gulf (8–8.3) was always adjusted to 5.5–6.5 [22,29,32] by the addition of acid in the pretreatment stages to avoid the scaling of calcium carbonate as in the reactions below.

$$HCO_3^- + H^+ \leftrightarrow H_2CO_3 \tag{4}$$

$$H_2CO_3 \leftrightarrow CO_3^{-2} + H_2O \tag{5}$$

Usually, surface seawaters have lower alkalinity than beach well water samples. High levels of alkalinity indicate the presence of strongly alkaline industrial waste. Also, alkalinity is significant in determining the suitability of water for desalination activities, whereas the alkalinity in seawater is used in the calculations of S & DSI as an indication of calcium carbonate scaling in the membrane and thermal desalination systems.

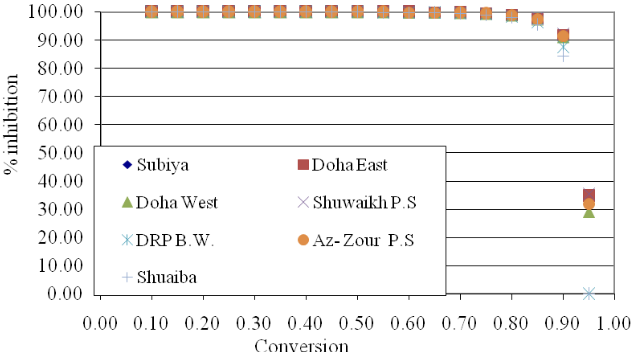

Fig. 7. The percentage inhibition of CaF_2 at different conversion.

Fig. 8 shows the scaling potential of calcium carbonate at different conversion and normal pH at different locations. It is clear from the figure that the potential for calcium carbonate is very high at all of the locations even at minimum conversion, which implies that pretreatment for calcium carbonate is required, whatever the desalination method used, even though at ambient temperature. DRP is the only location that shows low inhibition for $CaCO_3$, about 4% inhibitions at 10% conversion, decreased to immediate precipitation at 35% conversion. Thus, all the locations are expected to suffer from calcium carbonate scaling, and the reduction of pH by acid treatment is necessary, or anti scalant treatment is required.

About pH Table 3 shows that DRP has the lowest pH value, which implies that DRP will require the lowest quantity of acid treatment since it had the lowest normal pH followed by Doha West, Subiya, Al-Zour, Shuaiba, and Doha East desalination plants.

4.1.6. Silica scaling

Silica (SiO_2) content in seawater usually varies between 0.1 and 2.7 mg/l in Kuwait's seawater, but in some places, the concentration can reach up to 100 mg/l [33]. Silica has a direct relation to silica scaling in RO systems. The concentration of silica at DRPBW was the highest among other desalination plants (2.7 mg/l), and the concentration of silica increased to about 3.28 mg/l in the RO brine at DRPBW with 35% conversion. Silica level must be kept below 0.005 mg/l in very high-pressure applications as in boiler and turbine applications [34]. Fig. 9 shows a summary of all types of inorganic fouling at 10% conversion. Fig. 9 also shows the potential for silica scaling, and it is clear that all of the desalination plants in Kuwait showed a high inhibition for silica scaling, whereas almost all of the locations showed more than 95% inhibition for silica scaling. So no treatment is required for silica scaling in all the selected locations.

About inorganic fouling, DRPBW and Az-Zour desalination plant have a moderate potential for strontium sulfate precipitation, where the % inhibition for $SrSO_4$ is less than 35%. However, all of the other locations have a similar potential with regards to silica scaling, $CaSO_4$, and $CaCO_3$except Shuaiba, which has a high potential for $CaSO_4$ and $BaSO_4$ Although high inhibitions for $CaSO_4$ and $BaSO_4$ characterized the seawater at the intake of Az-Zour desalination plant, for $SrSO_4$ it had a moderate inhibition. So, Az-Zour can be considered suitable for thermal desalination more than membrane desalination. Shuwaikh has super inhibition for three type of scaling which is $CaSO_4$, $SrSO_4$,and $BaSO_4$, which implies that shuwaikh is Suitable for both thermal desalination and RO desalination regarding inorganic fouling. Doha West, Doha east and Subiya have a high inhibition (greater than 60%) for $CaSO_4$ and $SrSO_4$ and a moderate inhibition of $BaSO_4$ (greater than 30% inhibition). Thus, the best locations with regards to inorganic fouling are Shuwaikh followed by Doha West, Doha East, Az-Zour, and Subiya. However, the worst condition with regards to inorganic fouling is at DRPBW, where it could result in the severe scaling of $CaSO_4$, $BaSO_4$,and $SrSO_4$

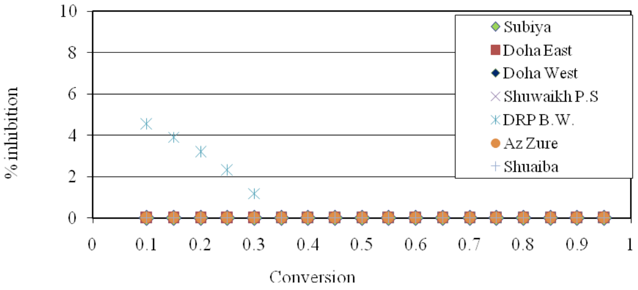

Fig. 8. The percentage inhibition of $CaCO_3$ at different conversion.

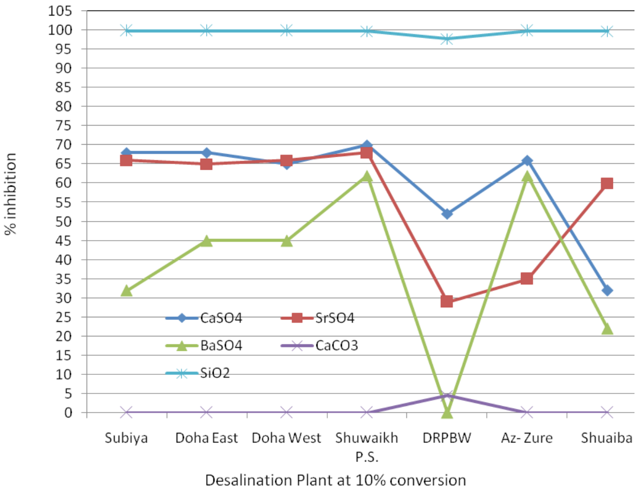

Fig. 9. Summary of inorganic fouling at 10% conversion.

4.2. Colloidal fouling

All particles in feed water, such as fine, coarse, sand, gravel, algae, silt, clay, silica, aluminum oxide, ferric oxide, aluminum hydroxide, and any non-dissolved organic and inorganic particles, could result in colloidal fouling. These particles can be suspended in the bulk solution or precipitated on the surface of the desalinated equipment forming a cake layer. The precipitated particles will clog the pore of any membrane system and reduce productivity [35,36].

The colloidal fouling depends on the type of feed water, whereas the fouling in wastewater is usually due to organic matter and residual iron colloids [37]. Groundwater commonly rich in iron, and lake and river water typically have a high content of silica [38]. Seawater usually has a high fouling potential due to the suspended clay, silica, sand, silt, and inorganic scaling [39].

The colloidal fouling in the RO system is usually precipitated on the membrane surfaces, while in the forward osmosis (FO) systems; the precipitation of colloidal fouling is reported to precipitate in the feed channel. The main factors, which could control the colloidal fouling in membrane processes, are the size of the foulant; the aggregation of foulant; the adhesion of foulant to membrane surfaces; the roughness of the membrane surface, and the membrane hydrophobicity [40–42].

The precipitation of suspended particles will result in different adverse effects on the desalination system's performance such as reducing the productivity of RO system, reducing the performance of thermal desalination systems,increasing the chemical consumption, increasing the pitting corrosion, increasing the silicate scaling, and then increasing the operational cost in any desalination system [43].

The main sensitive tools used to predict the potential for colloidal fouling are TSS, SDI, turbidity, silicate, iron, aluminum concentration, and feed inlet pressure. However, reducing the pH of feed water, applying a hydraulic cleaning and increasing the cross flow rate to eliminate the effect of a cake layer, and reducing the pH of feed water were proposed as solutions for colloidal fouling [44]. Moreover, these indices often fail to predict the extent of colloidal fouling in real seawater membrane systems, due to the differences in the pH of feed water, membrane pore size, and the applied pressure; type of the precipitated colloid; and the complex of fouling mechanisms [45]. Thus, new indices were emerged recently in desalination to estimate the potential for colloidal fouling such as surface hydrophilicity, water contact angle, total surface tension, Lifshitz-Van der Waals (LW) surface tension, and zeta potential [40].

4.2.1 SDI

SDI is an old operating parameter for all desalination systems and gains a high priority in the RO system to minimize the risk of colloidal fouling (Fig. 10) [46]. Most manufacturers proposed that feed water with SDI less than five could result in low fouling problems [47]. While feed water with an SDI higher than five will force the operators of the desalination plant to apply extra expensive pretreatment methods such as sand filtration, coagulation, and flocculation, which result in higher operating expenses [21,48]. A modify fouling index (MFI) a new emerged test recently modified from the old SDI testing (Fig 10) The MFI index was proposed to predict the potential for colloidal fouling accurately. MFI was calculated from the gradient of the filtrate volume over filtration time. Moreover, this index was corrected to standard reference conditions using a 0.45-μm filter paper membrane [49]. Boerlage in 2004 proposed another two new indices, which are MFI-UF and MFI-NF. The main difference between these two indices and the old one is using a UF membrane and an NF membrane in the filtration process [50]. Ju et al., in 2014, tested the efficiency of these two indices in predicting the colloidal fouling using different colloidal sizes and found that MFI-UF is the best test, which can be used to predict the colloidal fouling even though the colloidal size is very low [51]. A new more accurate index was proposed by Jeong et al. in 2015, which is the MFI-UF10 test. This test combines the blocking index test and the assimilable organic carbon (AOC) analysis.

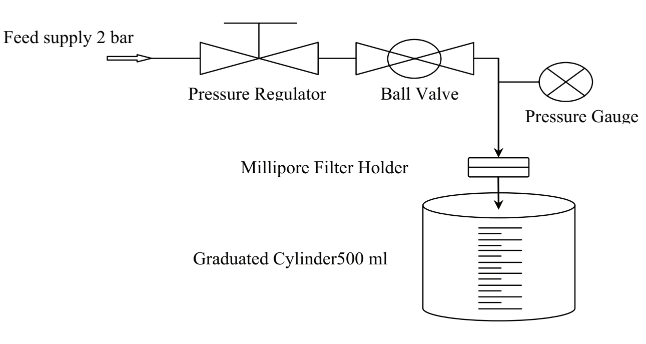

Fig. 10. Schematic diagram of the old SDI unit.

However, the collected seawater samples at all of the selected locations were very turbid, which resulted in a non-measurable SDI; only the seawater at DRPBW has a measurable SDI. Thus, investigation of the colloidal fouling potential will mainly depend on the turbidity, TSS, and silica measurements as shown in Figs. 11, 12, and 13.

4.2.2. Turbidity

The turbidity of the water is a measurement of the degree of cloudiness or clearance of water. The turbidity of seawater is usually affected by both dissolved and the suspended particles that can scatter light. Organic and inorganic particles,such as phytoplankton, zoo plankton, clay particles, sand, silt, fine, organic matter, algae, and microscopic organisms, are the main reason for seawater turbidity. Turbidity can be used to evaluate the efficiency of the desalination system and considered as a key for water quality, especially in drinking water system. Turbidity is usually used in desalination systems if the measurements of SDI or TSS are difficult or the quantities of the suspended particles are very high as in Subiya location in special and Arabian Gulf in general, whereas the high turbidity of the Arabian Gulf usually represents a significant challenge for the reverse osmosis (RO)system designer. Fig. 11 shows the turbidity of seawater at the intake of selected different desalination plants in Kuwait.

Fig. 11 shows that the turbidity measurements at DRPBW are the most stable and the lowest among other desalination plants. That's because DRPBW samples were collected from beach well at Doha Research Plant.

Furthermore, Fig. 11, also show that Az-Zour and Doha West have the lowest turbidity of surface seawater intake of desalination Plant after excluding DRPBW since it is a beach well and not open surface intake. The clearance of beach well seawater samples and the stability of turbidity values over different seasons was referred to the natural filtration associated with beach well water. And it well is known that all the beach well samples always have low and stable turbidity, SDI, and low TSS when compared to open surface intake samples.

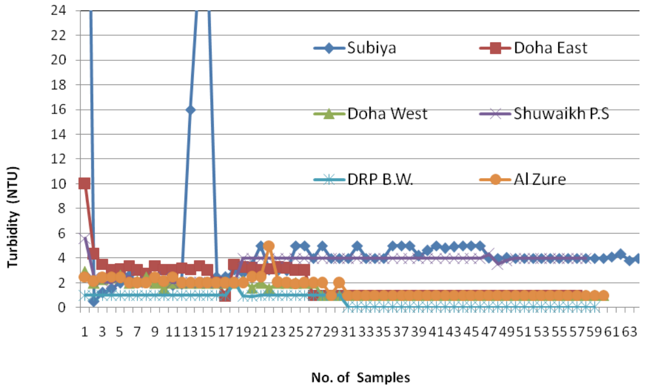

Fig. 11. The turbidity of seawater at the intake of different desalination plants in Kuwait.

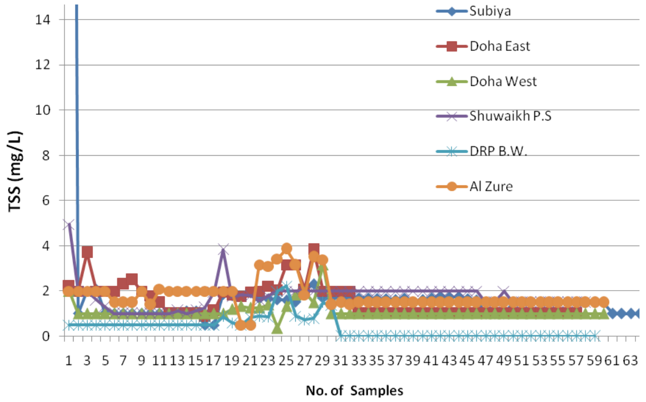

Fig. 12. TSS of seawater at the intake of different desalination plants in Kuwait.

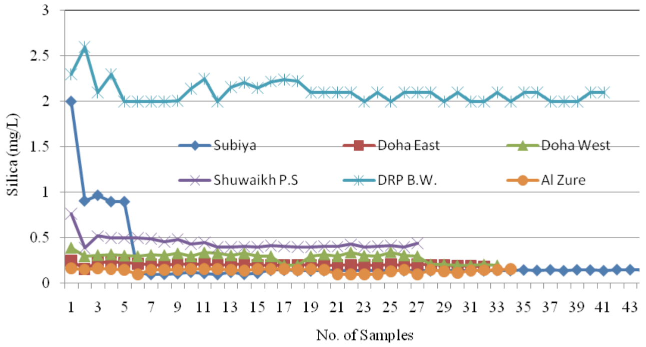

Fig. 13. The concentration of silica at the intake of different desalination plants in Kuwait.

Moreover, it is reported that the main source of turbid particles of the Kuwait Bay,including Sulaibikhat Bay, El-Esheirij Industrial Area, intake of Doha Power Plants, and Shuwaikh area, is Shatt Al-Arab discharges, whereas Shatt Al-Arabisthe only source for many organic and inorganic particles dissolved or suspended in the Kuwait Bay [52]. That is why the turbidity, salinity, silica, and dissolved organic matter of Kuwait's seawater at Az-Zour and Al-Shuaiba is usually lower than that of the seawater located at the intake of desalination plants in the Kuwait Bay or the north western side of the Arabian Gulf such as Shuwaikh and Doha Power Station.

The turbidity of seawater at the intake of Doha West was very low when compared to the turbidity of seawater at other locations in the Kuwait Bay. Al-Ghadban et al., in 2005, refer to the good mixing of seawater at Doha West intake, which results from the northwestern counter-clockwise water circulation of the Arabian Gulf and the coastal currents in the Kuwait Bay [53]. The result obtained in this investigation agrees with the study that conducted by Al-Shammari et al., in 2013 [54]. Where they investigated the characteristics of the surface sediment in Sulaibikhat Bay, Kuwait, and found that, the south side of the Sulaibikhat Bay, which is close to Shuwaikh Port and Al-Ghazali outfall,is characterized with high TOC, high concentration of hydrogen sulfide, and usually associated with the decomposition of organic matter and high variation of turbidity. As it was shown in Fig. 11, there is a big variation of turbidity at the intake of Subiya Desalination Plant.

The variation may be due to the location of Subiya Desalination Plant at the outfall of Shatt Al-Arab. This variation in water quality was the result of big operational problems in Subiya Desalination Plant. The variation in the water turbidity can cause failure and force the operator to apply expensive and costly pretreatment methods to avoid such variations and keep the feed water quality stable. Although the beach well will provide a reliable and better quantity and quality of water, it cannot be considered an economical choice for large capacity desalination plant due to its limitation in productivity. Beach well can be considered as an optimal choice for small capacity desalination plant only. Thus, the best location with regards to turbidity for between the desalination plants which have open surface intake structure is Doha West,Az-Zour Desalination Plant followed by Doha East Desalination Plant.

4.2.3. TSS

TSS is a measurement for all settable and non settable particles that are larger than 2 microns in size. However, any particle that has a size less than 2 microns considered as dissolved particles. Most TSS is composed of inorganic materials such as sand, gravel, silt, clay, bacteria, and algae. TSS provides an empirical estimation of water quality in different water treatment systems such as membrane bioreactor (MBR); RO; UF; MF; bipolar membrane (BPM); pressure retarded osmosis (PRO); and FO. TSS is used in water treatment systems to calculate the efficiency of the filtration, coagulation, and flocculation processes. The high TSS can reduce the effectiveness of the chlorination process in a thermal desalination plant. Furthermore, TSS can limit the penetration of sunlight to the deep layers of the ocean and therefore affect the rate of the photo synthetic process. Fig. 12 shows the TSS of seawater samples at the intake of the selected locations of different desalination plants in Kuwait. From Fig. 12, it is clear that the lowest TSS value measured at DRPBW is 0.75 mg/l, and the highest TSS values are found at Subiya seawater. However, the TSS for all of the other locations was below 4.0 mg/l. The best location with regard to TSS is DRPBW followed by Doha West then Doha East then Az-Zour and. A high value of TSS experienced at shuwaikh seawater, which may be due to the discharge from industrial areas of Shuwikh and El-Esheirij, which increases the turbidity and the pollutants at the Shuwaikh site, in addition to the discharge at Shuwaikh outfall.

High TSS was reported to induce the alkalinity of seawater or result in an increase in the precipitation of $CaCO_3$ scaling [55]. TSS also affects the adsorption of oil in seawater [56]. Coagulation-flocculation is usually applied to separate the suspended solids or the colloidal fouling by adding a coagulant aid such as aluminum chloride, ferric chloro-sulfate, or ferric chloride. Recently, a polymeric coagulant was used in coagulation instead of a chemical coagulant aid, where a small concentration of polymeric coagulants,such as 0.2 mg/l, can complete the coagulation process instead of using a high concentration of chemical coagulant aids such as 30 mg/l. Sedimentation and filtration also remove the suspended solids, through gravity filtration using silica sand, crushed coal, and garnet media.

4.2.4. Silica

The lowest concentration of silica was recorded at the intake Az-Zour, Doha East, Doha West then Shuwiakh Desalination Plant, whereas the average concentration of silica at Az-Zour was 0.14 mg/l. The concentration of silica in the seawater at the intake of Doha West and Doha East was very low with stable values when compared to the variation of silica concentration at Subiya (Fig. 13). The highest concentration of silica was recorded at DRPBW (2–2.5 mg/l), followed by Shuwaikh seawater, which has an average silica concentration between 0.7 to 0.48 mg/l.

Even though the TSS and the turbidity are very low at DRPBW, the potential for silica scaling is expected to be higher than that of other locations due to the high concentration of silica. That implies that the beach well is not always better than the surface seawater with regard to colloidal fouling. Silica plays a major role in membrane fouling especially when RO is used for treating wastewater [57]. A high concentration of silica in seawater feed water contributes to silica scaling. However, silica scaling in groundwater desalination is a significant issue, where high silica concentration will limit the recovery of the RO system,whereas to reduce the risk of silica-scaling, pH will be increased, which will increase the risk of calcium carbonate and magnesium hydroxide scaling [33]. Finally, it is clear that, with regards to colloidal fouling that, Az-Zour, Doha West, and Doha East are the lowest locations in the potential for colloidal fouling. A high potential for colloidal fouling is expected at the intake of Shuwaikh and Subiya Desalination Plants.

4.3. Biofouling

The main reason for biofouling is the gradual accumulation of waterborne organisms on the membrane surfaces such as bacteria(e.g., cholera, typhoid, and coliform organisms), viruses (e.g., hepatitis A and poliomyelitis), algae, colonies, protozoa(e.g., Cryptosporidium, amebae, and giardia), microorganisms, microbes, and animals. These organisms were reported to survive under high operating temperatures up to 110°C and a pH values between 0.5 and 13 [58]. That is why different types of desalinated systems are suffering from biofouling problems. The accumulation of these organisms on the membrane surface will form a harmful biofilm, which is considered as the second big problem in the RO systems. Biofouling has many adverse effects on the RO membrane systems Biofouling is result of blocking the pore of the membrane surface by biological slims which declining the permeate flux and forming a cake layer at the membrane surfaces. The cake layer and the biological slims will degrade the membrane materials, increase the roughness of the membrane surfaces, required implying more chemical cleaning and reduce the life of RO membranes. That will result in increasing the operating cost and lowering the quality of produced water. Many serious biofouling problems were reported in the Middle East regions, due to the high potential for microorganism growth. Biofouling is usually a common problem in all membrane filtration systems such as RO, UF, MF, NF, forward osmosis (FO), membrane distillation (MD),MBR; however, thermal desalination plants such as ME, MSF, and thermal vapor compression (TVC) are always exposed to less biofouling problems. Vrouwenvelder et al., in 2000 and 1998 [59,60], observed that membrane biofouling is the major operational problem in 12 out of 13 NF and RO membrane systems, which imply that biofouling problem dominated all membrane systems and it is very difficult to be controlled.

Thermal desalination plants are also prone to biofouling problems, where biofouling was observed inside the condenser tubes, which will cause a reduction in the heat transfer, and thereby plant efficiency. Plant designee compensates for this decrease by enlarging surface areas, which mean more capital cost (winters, 1995). Thus, monitoring or characterizing the feed water using more advanced organic indices is required to reduce biofouling problems. Recently, many indices were linked to biofouling such as TBC, fecal coliform bacteria (FCB), TOC, AOC, particular organic carbon (POC),and the dissolved organic carbon (DOC) [61–63]. These measurements were considered as useful tools for estimating the potential for fouling and biofouling in the desalinated system since it can measure the level of a nutrient in the feed water [62]. TBC and FCB usually represent the bacteriological population in different membrane systems and are used as indicators for monitoring fouling intensity in many membrane systems such as MF, UF, and submerged membrane bioreactor [63,64].

AOC is a sensitive tool to predict the biofouling problems, where a concentration of only 80 µg/l of AOC of feed water in desalinated systems will result in high amounts of biofilm, high bacteria population, and severe biofouling problems. So, a concentration of AOC below ten µg/l was recommended to prevent biological fouling [65–66]. Moreover, the normal concentration of TOC in the surface seawater is usually less than 10 mg/l, and in groundwater, it is less than 2 mg/l. The membrane manufacturer recommended considering a pretreatment when the concentration of TOC exceeds only 3 mg/l in the feed water to the desalination system. However, other researchers recommended a more restricted concentration, below 0.5 mg/l TOC, to avoid fouling and biofouling problems [61]. Baig and Kutbi (1998) proved that an average concentration of 3.5 mg/l TOC in the feed water of the RO plant in Al-Jubail, Saudi Arabia, resulted in severe fouling and biofouling problems and reported that TOC is related to both organic fouling and biofouling. TOC measurements are related to both DOC and POC in water samples, where as the only difference in the measurements of DOC and POC is filtering the water samples through a filter paper of 0.4 and 0.7 µm pore diameter separately. However, DOC is used as an indication of fouling and biofouling in thermal desalination plants, since DOC material usually absorbs and adheres to the interior surfaces of heat exchanger tubes, which are considered as suitable surfaces for the biofouling microorganism population in thermal desalination plants. Adenosine triphosphate (ATP) is another new emerging indicator used to estimate the microbiological population and consequently the potential for biofouling in desalinated systems [62,67]. At DRPBW, the available indicators are TBC, TOC, and FCB, which are used to estimate the potential for the biofouling of different seawater samples at the intake of different desalination plants in Kuwait including beach well at DRP.

Table 3 shows that the result of FCB at all the of selected locations is zero, which implies that FCB will be excluded from the analysis of biofouling potential. Therefore, the potential for biofouling will depend on the result of TOC and TBC.

4.3.1 TBC

Usually, TBC is used in evaluating the efficiency of various treatment processes and for checking the quality of finished water in a desalination system. Fig. 14 shows that Subiya has the highest potential for biofouling since the TBC was in the range of 10^4 CFU/ml, while the other locations had similar potential for biofouling as the TBC for all of them were in the range of 10^3. Shuwaikh seawater also shows a higher potential for biofouling than the other locations. Seawater at the intake of Doha West, Doha East, Shuaiba, and Az-Zour desalination plants show the lowest potential for biofouling. The chlorination of seawater is the most common method used to control RO membrane biofouling, with a concentration of 0.5–1.0 mg/l of free chlorine maintained in the entire pretreatment line. New innovative membranes emerged recently in desalination, which has a high resistance to biofouling and was introduced by many authors, as the zwitterionic polymer membrane and the silver nanoparticles impregnated polyether sulfone (PES) membrane [68,69].

4.3.2. TOC

TOC measurements are very important parameters used to investigate the suitability of any location for desalination activity, whether it is membrane desalination or thermal desalination since it is strongly related to the organic matter content, which is responsible for fouling and biofouling problems in desalination systems.

Furthermore, it is well known that during the disinfection processes, and when the feed water contains a high content of TOC or organic matter, the chlorine will react with the organic content and form chlorinated organic compounds, which are cancer-causing compounds and named as disinfection by-products. To reduce the chance for disinfection by-products formation, the TOC content in feed water must be controlled. Table 4 shows the TOC analysis at the intake of selected desalination plants in Kuwait.

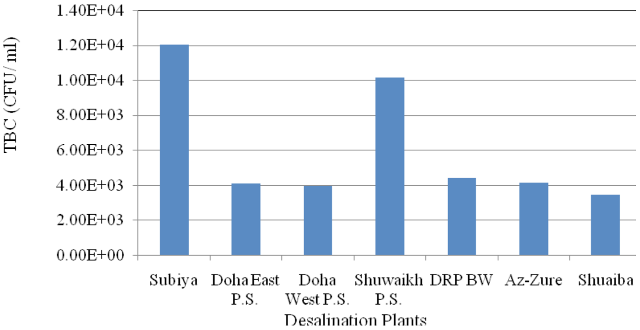

Fig. 14. The average TBC of seawater samples at the intake of different desalination plants in Kuwait.

The highest value analyzed for TOC is in the seawater at the intake of Shuwaikh Desalination Plant, which is 2.12 mg/l. That because the Shuwaikh Desalination Plant is located close to the Shuwaikh harbor that discharges raw water and treated water from the sewage treatment plant as well as the sewage from the pumping station [70]. Furthermore, petrochemical industries in the Shuwaikh Industrial Area are considered as a source of organic material such as oils. In addition to Al- Ghazali, the sewage discharges and the storm water outfalls of Sulaibikh at Sports Club, hospital, and Kuwait University are heavily loaded with nutrients and sanitary wastes, which result in increasing the TOC of seawater at the intake of the Shuwikh Desalination Plant. The lowest TOC values were experienced in Az-Zour (1.31 mg/l), followed by the seawater at the intake of Doha West (1.627 mg/l) and Doha East (1.8915 mg/l).

Thus, based on TBC and TOC analysis, it was found that Az-Zuor, followed by Doha West and Doha East are the best locations with regards to biofouling, where as Subiya and Shuwaikh are the worst cases with regards to the potential for biofouling.

5. Organic fouling

The main reason for the organic fouling is the presence of OM in feed water such as carbohydrates, protein, polysaccharides, amino acids, lipids, fatty acids, phenolics, polyhydroxyaromatics, polyhydroxylbutyrates, natural macromolecules, and colloids, sewage and industrial particulates, soil organic matter, living phytoplankton and other plant materials. Although the content of OM in seawater is usually very low when compared to the content of inorganic compounds, the organic fouling is harder to control than inorganic fouling. OM is classified into two types of organic matters, namely, biodegradable organic matter (BDOM) and a non biodegradable organic matter (NBDOM). It is well known that microorganisms in feed water can only oxidize the BDOM and release energy, which is used for the growth and reproduction of microorganisms. So, both TOC and BDOM can be used to estimate the potential for fouling in desalination systems [71]. The amount of oxygen consumed during the oxidization of BDOM is called the BOD. BOD is another indicator, which can be used to evaluate the potential for fouling in desalination systems. COD is similar to the BOD indicator; the only difference is that COD includes oxidization of all BDOMs as

Table 4
TOC Concentration at the intake of different desalination plants in Kuwait

TOC (mg/l)	6/11/2016	2/11/2016	14/11/2016	21/11/2016	Average
Subiya	3.58	1.48	1.701	1.557	2.0795
Az-Zour	1.281	1.13	1.464	1.404	1.31975
Al-Shuwaikh	2.26		2.096	2.005	2.12033
Doha West	1.701	1.554			1.6275
Doha East			1.829	1.954	1.8915

well as NBDOM organic materials using a strong chemical oxidizing agent. Both COD and BOD are indicators used to characterize the organic content in feed water in desalination and wastewater treatment plants [72]. COD value is recommended to be below 10 mg/l of feed water to RO or NF system to prevent fouling problems [73].

Recently, COD and BOD are used to evaluate the performance of the process of electrochemical oxidation electrodes, which is the treatment process for high salinity brine water [74]. Although both BOD and COD are good indicators to estimate the potential for organic fouling in desalination systems, new indices emerged in desalination, because of the long incubation time required for the measurements of BOD and COD indicators. DOC, POC, natural organic matter (NOM), and dissolved organic matter (DOM) all are new indicators used to estimate the fouling potential in desalination systems.

POC is a measurement of carbon content in feed water and usually refers to both living and nonliving organisms in seawater, which retain from filtration using a 0.45-µm filter, whereas DOC is a measurement of carbon content in DOM and usually expresses, the non-living organisms, which can pass through a 0.45-µm filter [75]. POC value usually represents 10% of the TOC [76,77].

Monitoring POC in desalination systems proves to reduce the biofouling on MF by 50%. A concentration of 1 to 20 mg/l DOC indicates feed water with a low fouling potential [62].

Furthermore, it was recommended to measure the DOC on a routine basis to control the performance of the coagulation-flocculation process, backwash system, ozonation, cleaning with a chemical reagent, and activated carbon filtration in desalination systems [39,78–83]. Recently, a new innovative indicator is introduced in seawater desalination to characterize the fouling potential, which is the membrane surface elasticity. The elasticity can measure or express the adhesion forces between organisms and the membrane surfaces, which is a good indicator to predict the organisms' population [84]. TOC, COD and BOD, ammonia, phosphate and nitrateare all biological indices and are selected to evaluate the different seawater samples with regards to organic fouling. Table 3 shows that the BOD values for all of the selected locations are less than one (Table 3); so, BOD indicator is excluded from the evaluation processes.

5.1. COD

Fig. 15 shows the COD for seawater samples at the selected locations. From Fig. 15, it is clear that the seawater at the intake of Az-Zour (81.97 mg/l) is the lowest in COD values followed by Subiya (82.31 mg/l), and then Doha West (82.92 mg/l), Doha East (84 mg/l), Shuiaba (89.0 mg/l), DRP BW (89.7 mg/l), and finally Shuwaikh seawater (90.52 mg/l). That implies that the highest content of organic matter is expected at Shuwaikh seawater intake and the highest potential for biofouling is expected at Shuwaikh. The best location related to organic fouling is Az-Zour site.

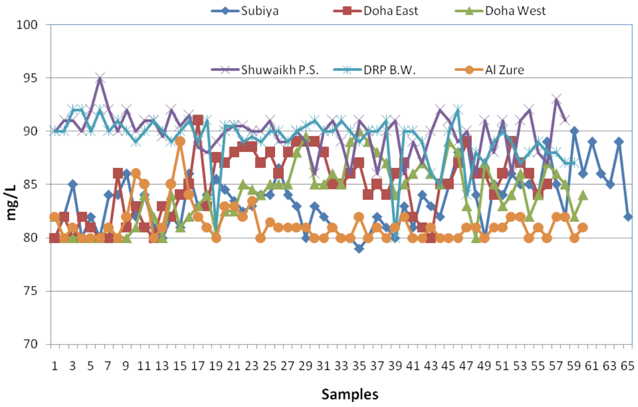

Fig. 15. The COD analysis of seawater at the selected locations of desalination plants.

5.2. Nitrate, phosphate, and ammonia

Nitrate, phosphate, and ammonia in seawater are considered as nutrients and are present as a result of the large population of algae in seawater, which is the main reason for clogging desalination equipment, especially the screen mesh and the pumping station. Furthermore, the growth of algae in the feed water will result in the deterioration of the water quality and an increase in the TSS and turbidity of water. The algae growth will increase the content of TOC and membrane biofouling rate.

Ammonia (NH_4) in water is an indicator of possible bacterial population, algae multiplications,and sewage contamination. So, NH_4 is an important parameter to detect the algae blooms in the feed water to desalinated systems and to maintain a constant production in membrane water systems. The natural levels of NH_4 in ground water and surface seawater are usually below 0.2 mg/L [85–86].

It is well known that the levels of nitrate (NO_3); nitrogen (N); phosphate(PO_4^{3-}); trace metal as cobalt (CO^{2+}), iron (Fe^{3+}), and molybdenum (Mo^{2+}); Fe^{2+} (iron); and manganese (Mn^{2+}) concentrations are the limiting factors for algae growth in seawater [87–89]. From Table 5 it is clear that the

Table 5
The analysis of ammonia, nitrate, and phosphate at the intake of the selected locations

	Subiya	Doha East P.S.	Doha West P.S.	Shuwaikh P.S.	DRP BW	Az-Zour	Shuaiba
Nitrate (mg/L)	4.84	1.26	2.09	3.58	4.20	3.26	4.83
Ammonia (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Phosphate (mg/L)	0.293	0.129	0.091	0.124	0.201	0.100	0.090

Table 6
The DO, temperature, pH, and TDS of selected desalination plants in Kuwait

	Subiya	Doha East	Doha West	Shuwaikh	DRP BW	Az-Zour	Shuaiba
DO	4.93	4.03	4.50	4.51	5.23	3.81	–
Temperature (°C)	24.72	24.92	24.77	24.90	25.06	25.07	24.6
pH	8.06	8.13	7.96	8.05	7.27	8.08	8.1
TDS (mg/L)	50024	43582	51370	57109	45534	47524	51106

concentration of ammonia is very low at the intake of all selected desalination plants, and the locations are considered clean from any wastewater pollution. Doha East has the lower concentration with regard to nitrate followed by Doha West and Az-Zour Desalination Plant. Subiya, Shuaiba, and DRPBW show the highest concentration of nitrate, which are 4.84, 4.83, and 4.20 mg/l.

The concentration of ammonia is very low at all of the desalination plants and lower than 0.01 mg/l. However, the concentration of phosphate is very low in Doha West, Shuiaba, and Az-Zour desalination plant. Higher values were found at Subiya, DRP BW, and Shuwaikh Desalination Plant. From the previous results of COD, TOC, nitrate, phosphate, and ammonia, it is clear that Doha West is the best with regards to organic fouling, followed by Doha East and Az-Zour. Shuwaikh Desalination Plant can be considered as the worst with regard to organic fouling.

6. DO and TDS

DO is usually measured at the inlet and the outlet of the deaerator in thermal desalination plants for checking its efficiency. DO is also measured at the condensate pump for checking any leakage. The concentration of DO in the seawater depends on the salinity and temperature and varies with the depth of the seawater. DO is a useful tool in material selection during the design stages. It is well known that as the concentration of DO increases, the potential for corrosion problems increases. DO is an essential parameter for calculating the required dosing of anti-corrosion chemicals in thermal desalination plants. Furthermore, it is an indication of the biological activities in seawater and used in the measurements of BOD and COD.

From Table 6 it is clear that the lowest value with regards to DO is at Az-Zour, which implies that a lower rate of corrosion is expected at this desalination plant and the lowest biological activities are also expected at Az-Zour Power Station, followed by Doha East, Doha West, Shuwaikh, Subiya, and finally DRP BW.

TDS is a measure of the combined content of all dissolved inorganic and organic substances in the water. TDS for sea water differs from one location to another. The Arabian Gulf sea water is characterized by the highest salinity based on the highest values of TDS. TDS plays an important role in increasing the operating pressure required to overcome the natural RO in a desalination system. The osmotic pressure required for desalinating seawater at a TDS of 35,000 mg/l is about 2700 kJ, while the osmotic pressure required for a TDS of 3000 mg/l is only about 230 kJ. TDS is also considered as a monitoring parameter in the membrane systems. The highest TDS at the intake of a selected desalination plant was at Shuwaikh Desalination Plant, followed by Doha West, Shuaiba, Subiya, and Az-Zour. DRP PW has the lowest TDS values among the selected desalination plants. Thus, DRP BW is the best location with regard to TDS and has the lowest osmotic pressure required for desalinating seawater using the membrane desalination method.

Table 7
The FRR of different water samples using the fouling testing unit

Intake	*Jw1*	*Jw2*	FRR (%)
Al-Zour	18.8	16.9	89.9
Doha West	18.8	15.9	84.57
Doha East	22.5	16.5	73.3
DRPBW	26.3	18.8	71.4
Shuwaikh Power Station	22.5	15.4	68.4
Subiya Power Station	18.8	12.4	65.9

7. The result of fouling test

The degree of fouling was measured through experimental work and the result obtained was compared to the result obtained from analyzing different fouling indices. Table 7 shows the FRR of the different water samples at the selected locations.

From Table 7, it is clear that Az-Zour is the best location followed by Doha West,Doha East followed by DRPBW.

Shuwaikh and Subiya are the worst locations with regards to fouling indices.

8. Conclusion

The selected locations were investigated based on many parameters, and the result of all indices showed that Az-Zour is the best location followed by Doha West, Doha East, and then Shuaiba Desalination Plant with regards to organic fouling, colloidal fouling, and biofouling. However,with regards to inorganic fouling, Shuwaikh is the best followed by Doha West, Doha East, then Az-Zour and Subiya. However, the worst condition with regards to inorganic fouling is at DRPBW. Since organic fouling, colloidal fouling, and biofouling are very difficult to control. While inorganic fouling can be controlled more easily by antiscalant and acid treatment, Thus, it is recommended to install a new desalination plant at Az-Zour desalination power plant followed by Doha West then Doha East desalination power plant and finally Shuaiba desalination power plant. Furthermore,it is recommended to keep away from Subiyah and Shuwaikh location., Since they are the worst locations with regards to biofouling and organic fouling because they are close to the Shatt Al-Arab outfall, shuwaikh industrial area and Al-Ghazali outfall which increases the organic content in the seawater and could result of fouling and biofouling problems.

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