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Post-treatment of desalinated water and water quality characteristics in Yanbu Industrial City

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ABSTRACT

Yanbu Industrial City (YIC) in Saudi Arabia depends on seawater desalination for its entire fresh water supply. The fresh water is supplied by a desalination plant that consists of nine multi-stage flash (MSF) distillation units and seven reverse osmosis (RO) desalination trains. The product water from the MSF and RO desalination processes requires post-treatment to prepare it for potable use. The distillate from the MSF units is remineralized by adding hydrated lime and carbon dioxide, chlorinated by the injection of chlorine gas, and aerated with compressed air. The remineralization steps result in raising pH, alkalinity, and hardness of the water, thereby stabilizing the water. For the permeate from the RO trains, hydrated lime and sodium hypochlorite are added. This paper presents the potable water quality data for the last 6 years from 2006 to 2011 and the water characteristics in YIC, along with the post-treatment processes of the desalinated water. YIC's potable water produced by seawater desalination is of high quality and prevents bacteriological growth without any microbiological contamination. The water is healthy and suitable for human consumption and use on the basis of the water quality monitoring data with respect to its physical, chemical, and biological characteristics.

Keywords: Seawater desalination; Multi-stage flash distillation; Seawater reverse osmosis desalination; Post-treatment; Remineralization; Water quality; Trihalomethanes; Boron

1. Introduction

In some parts of the arid regions of the world, where fresh water resources are limited, desalination of seawater and brackish water plays a pivotal role in meeting fresh water requirements. In particular, in the Middle East, seawater desalination has become a vital and dependable fresh water resource and has emerged as an important water supply source. In the Kingdom of Saudi Arabia, a world leader in seawater desalination, the government has placed great emphasis on the desalination of seawater to satisfy the growing demand for potable water. Saudi's installed capacity of desalination plants was nearly 10 million m^3/day in 2009 [1]. Seawater accounted for 79% of the desalination feedwater and 84% of the desalinated water was used for municipal purposes in 2006 [2]. The largest seawater desalination plant in the Kingdom has a production capacity of 880,000 m^3/day (233 million gal/day) [3].

Yanbu Industrial City (YIC), located on the Red Sea coast about 350 km northwest of Jeddah, has been

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developed by the Royal Commission for Jubail and Yanbu (RC). The site has been transformed from a mere desert to a complete, full service, modern city. In existence for more than three decades, Yanbu is presently host to over 85 primary, secondary, and light manufacturing industries. Yanbu is a very dynamic industrial center, a cornerstone of Saudi Arabia's manufacturing economy, and a catalyst for stimulating the Kingdom's economy. At present, YIC has an on-site population of 91,479 residents. Another 49,360 people (employees working in the industrial city, plus their dependents) are supported by the Yanbu economy.

YIC depends upon seawater desalination for its entire fresh water supply and the desalinated water is the only source of both municipal and industrial water supply. Yanbu's fresh water is supplied by the integrated power, desalination, and seawater cooling (PD&SC) complex that is located in the industrial area. The complex was built and operated by the Royal Commission and was transferred to Marafiq Company in 2003. The seawater desalination plant consists of nine multi-stage flash (MSF) distillation units and seven reverse osmosis (RO) trains with a combined installed plant capacity of 154,560 m^3/day. The desalination plant produces potable water for domestic purposes and process water for industrial uses. Yanbu's total water demand is close to 104,000 m^3/day. The potable water is supplied to the city through the piped water system.

Since the mineral content of the desalinated water is low with poor buffering capacity, the water requires post-treatment to prepare it for potable use. Following treatment, the water quality complies with the World Health Organization's guidelines for drinking water quality and the Royal Commission drinking water quality standards. The Royal Commission monitors potable water quality for the city on a weekly basis. This paper presents the water quality data obtained for the last 6 years (2006–2011) and potable water characteristics in YIC, along with the post-treatment process of the desalinated water. The effects of the post-treatment on the various water quality parameters are discussed. The parameters include pH, alkalinity, hardness, dissolved solids, turbidity, residual chlorine, trihalomethanes (THMs), trace elements, and other water quality data.

2. Desalination of seawater

Yanbu's desalinated water is produced by the PD&SC complex shown in Fig. 1. The desalination plant consists of nine MSF distillation units with a capacity of 95,760 m^3/day and seven RO trains with a capacity of 58,800 m^3/day. Currently, Marafiq Company is expanding the desalination plant by constructing two 27,500 m^3/day multiple-effect distillation seawater desalination units.

Fig. 1. PD&SC complex with the seawater intake channel in the foreground.

2.1. Seawater supply

Raw seawater is drawn from the seawater open intake channel as shown in Fig. 1. The intake system supplies seawater to the seawater desalination plant and the steam turbine power plant, and Yanbu industries for cooling purposes. The seawater flows into the pumphouse through trash racks and traveling screens to remove debris. The seawater is then treated by injecting sodium hypochlorite to prevent the growth of algae, bacteria, and microorganisms.

Sodium hypochlorite is generated on site by electrolysis. Residual chlorine after the injection of sodium hypochlorite varies from 0.5 to 0.7 ppm. Seasonal variations of the seawater temperature ranging from 22 to 33°C occur at the site. The typical salinity of the seawater is about 45,500 ppm of dissolved salts and its pH varies from 8.1 to 8.3. The typical seawater characteristics are presented in Table 1.

2.2. MSF distillation

The MSF distillation plant consists of three 570 m^3/h and six 380 m^3/h units. Each unit is designed for a top brine temperature of 121°C by employing a decarbonation method with a performance ratio of 19 kg of distillate per 1,000 kcal heat input, with a seawater supply temperature of 32°C. The MSF units are of brine recirculation type and each rectangular MSF evaporator has 25 heat recovery stages and 3 heat rejection stages (Fig. 2). Sulfuric acid

Table 1
Major seawater components

TDSs, mg/l	41,300–46,400
Conductivity @ 25°C, umhos/cm	57,000–64,000
Temperature, °C	22–33
pH	8.1–8.3
Total suspended solids (TSS), ppm	1
Turbidity, NTU	0.5–1
Total alkalinity as $CaCO_3$, ppm	120–130
Bicarbonate alkalinity as $CaCO_3$, ppm	85–95
Chloride as Cl^-, ppm	21,600–23,500
Sulfate as SO_4^{2-}, ppm	3,000
Sodium as Na^+, ppm	11,700–12,500
Potassium as K^+, ppm	425–650
Calcium as Ca^{++}, ppm	490–560
Magnesium as Mg^{++}, ppm	1,500–1,600
Total dissolved oxygen as O_2, ppm	3.5–5
Residual chlorine at desalination plant intake as Cl_2, ppm	0.1–0.25

Fig. 2. MSF units.

is used to control alkaline scale formation in the units. Distillate product water contains normally 2–10 ppm of dissolved solids. The product water is stabilized by the injection of a mild caustic solution for process water supplied to Yanbu industries and for potable water prior to remineralization and disinfection.

The primary energy source of the MSF units comes from the adjacent gas turbine generators (GTGs) power plant coupled to the non-fired heat recovery steam generators (HRSGs). The HRSGs recover heat from the GTG exhaust flue gas and produce saturated steam required for the MSF unit brine heaters. Condensate from the brine heaters is returned to the HRSG deaerators to form boiler feedwater for the HRSGs.

2.3. RO desalination

The seawater RO plant is made up of seven trains, each with a capacity 8,400 m^3/day. The plant consists of five basic components: a seawater supply system, a feedwater pretreatment system, high pressure pumping, RO modules, and a permeate post-treatment system. The plant is equipped with a distributed control system using state-of-the-art computerized technology (Fig. 3).

The raw seawater is passed through dual media filters (DMF) which remove suspended solids. The filter media are sand and anthracite. The chlorinated and flocculated feedwater is filtered to obtain a silt density index (SDI) value of <4 after passing through the gravity DMF. From the DMF, feedwater flows to the micron cartridge filters that remove particles larger than 10 μm. Various chemicals added to the seawater are: (1) sodium hypochlorite for the prevention of microorganism growth, (2) ferric chloride as a flocculant, (3) sulfuric acid for the adjustment of pH and the control of hydrolysis and scale formation, and (4) sodium bisulfite to dechlorinate.

Filtered seawater provides protection to the high pressure pumps and the RO membranes of the plant. High pressure stainless steel pumps raise the pretreated feedwater to a pressure appropriate to the RO membranes so that water can pass through them and the salts can be rejected. Salt rejection by semipermeable cellulose triacetate membranes using the hollow fine fiber configuration is approximately 99.4%. The pressure ranges from 64 to 76 kg/cm^2 g for seawater, depending on the operating temperatures and the age of membranes, etc. The concentrated brine returns to the energy recovery turbines and then is discharged into the sea for disposal.

Recently, three second-stage RO trains, each with a capacity of 8,400 m^3/day were added to produce process water which is supplied to Yanbu industries. The first-stage permeate is repressurized and passed through a second-stage RO modules to reduce the total dissolved solid (TDS) of the permeate from the first stage. The second stage employs brackish water membranes that operate at a lower pressure and higher flux and recovery than those of the first stage.

The typical permeate recovery ratio of the first-stage RO units is designed for 38.5%. The permeate produced by the first-stage RO trains has a typical TDS in the range 200–450 ppm. The permeate TDS tends to increase and the flux tends to decrease as the membranefouling occurs over an extended operating time prior to recovery after chemical cleaning of the membranes.

Fig. 3. Overview of the RO plant with the water storage tanks in the background.

3. Post-treatment of product water

3.1. MSF distillate

Desalinated water produced from the MSF plant is of high purity with a very small amount of dissolved salts and minerals. Therefore, the water is aggressive, unstable and corrosive to the materials such as metals and concrete commonly used in water storage, transmission and distribution systems, and in household plumbing and pipes systems. In order to overcome problems with aggressiveness and the relatively poor taste of the distillate, a post-treatment method—the potabilization process—is employed.

The potabilization process is shown schematically in Fig. 4. The process for treating the MSF distillate consists of four unit operations: carbonation, liming, chlorination, and aeration. The carbonation and liming, based on the use of carbon dioxide gas and hydrated lime, result in an increase in hardness and alkalinity of the water to a desirable level so that the water becomes well buffered and non-aggressive while maintaining a slightly positive Langelier saturation index (LSI).

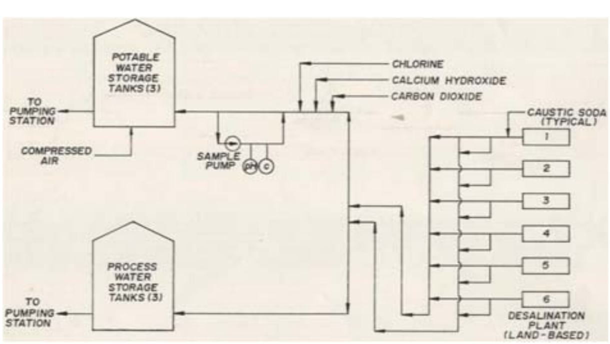

Fig. 4. Post-treatment system for MSF distillate.

The lack of carbonate alkalinity makes the desalinated water unstable and aggressive and prone to wide variations in pH due to the low buffering capacity. The basic principle involved in the remineralization steps is the chemical reaction between carbon dioxide and calcium hydroxide to form water-soluble calcium bicarbonate and simultaneous adjustment of pH. Such treatment method aids in establishing the calcium carbonate equilibrium and forming corrosion-inhibiting protective layers of calcium carbonate. The chlorination is conducted by injecting chlorine gas to disinfect the water and to eliminate bacterial growth. The aeration is undertaken to replace oxygen driven out by the MSF distillation process, thereby improving the taste of the water.

The lime preparation and dosing system shown in Fig. 5 include the storage stacks, a belt conveyor for transfer and feed, a chute, a bucket elevator loading hopper, and lime dissolving tanks. Approximately 5% lime slurry is prepared in the tanks and injected by a metering pump. The slurry from the pump discharge is further diluted down to a concentration of 1% by the addition of potable water to minimize clogging of the pipelines, and injected into the potable water header connected to the water storage tanks. The average lime feed rate into the MSF distillate is about 34 mg/l of calcium hydroxide (or 0.034 kg/m^3 water).

Carbonation is conducted by injecting gaseous carbon dioxide that is generated by the CO_2 plant on site by combusting light fuel oil (LFO), and recovering CO_2 gas from flue gas and purifying it (Fig. 6). The carbon dioxide generation plant with a capacity of 150 kg/h CO_2 includes an LFO storage tank, a

Fig. 5. Lime dosing system.

Fig. 6. On-site carbon dioxide generation plant.

reboiler, gas purification trains, an SO_2 scrubber, compressors, dryers, liquefaction units, and two bulk CO_2 storage tanks. Also included are the ancillaries system such as a CO_2 cylinder filling unit, interconnection with the potable water, pilot gas storage cylinder, a recirculating cooling water system, an integrated control panel. The carbon dioxide injection system consists of vaporizers, vapor storage tanks, flow meters, and carbonators. An alternative method for recarbonation of the distillate is to recover CO_2 released from the MSF evaporating brines [4–6].

The carbon dioxide production efficiency is about 3 kg CO_2 per 1 kg of LFO. A 15–18% monoethanolamine solution is used to absorb the CO_2 gas and stripped for reuse in a closed circuit. The gas purification system consists of three separate units packaged as the potassium permanganate gas scrubber, the water wash gas scrubber, and the activated carbon deodorizer. The compressed gas is fed into a dryer to a dew point of −40℃ where moisture is removed. The dryer is supplied with an activated alumina desiccant. The gas (with a minimum purity of 99.5% on a dry basis) is liquified at 17 kg/cm^2 and −23℃ by the refrigeration system. The vaporizer uses electrical power to transform CO_2 from the liquid phase to the gaseous phase. The vaporized gas is first dissolved in a potable water carrier stream. Then the carbonated water is injected into the potable water main header connected to the water storage tanks. The average feed rate of CO_2 is about 0.037 kg/m^3 of water.

Remineralization using lime and carbon dioxide is based on the principle of corrosion control through calcium carbonate deposition by maintaining a slightly positive LSI. The index is dependent on various parameters such as temperature, pH, TDS concentration, calcium concentration, and total alkalinity as they relate to the solubility of calcium carbonate. It is standard practice to maintain the index at +0.1 to +0.3 or to make water slightly oversaturated in the range of 4–10 mg/l as $CaCO_3$. The parameters of pH, calcium, and alkalinity are controlled by adjusting the amount of lime and carbon dioxide.

Chlorine is injected for disinfection of the product water. The chlorination system consists of a chlorine handling and an injector building. The injector building houses injector water booster pumps which supply the injector water for solution mixing. Chlorine is received in one-ton containers and is handled by a motorized hoist and monorail trolley. Three chlorination systems are provided: continuous chlorination of the upstream of the water distribution pumping station, continuous chlorination of the water supply to the water storage tanks, and a spare system for either of the two, that may also be used to shock-treat the storage tanks one at a time.

The chlorine dosage at the desalination plant has been established at about 1.2 mg/l to maintain a residual chlorine concentration at about 0.2 mg/l at the tap. The chlorine dosage rates are 0.7 mg/l to the water supply system and 0.5 mg/l to the water distribution system. The chlorine demand for city water has been established at about 1 mg/l. Shock treatment of the entire contents of one 40,000 m^3 water storage tanks is achieved over a 24-h period to a chlorine residual concentration of 5 mg/l.

The dissolved oxygen content of distillate is negligible because oxygen is driven out by the MSF process for corrosion control. The water is aerated to replace oxygen, which improves the taste of the water. The system uses ceramic dome diffusers in the potable water storage tanks on a grid pattern to provide uniform dispersion of air. The storage tanks have screened, mushroom-type roof vents. Since the lime slurry and carbonated water are injected into the main header to the storage tanks, the aeration provides a means of mixing the remineralization chemicals for efficient reaction in the tanks. The oxygen content of potable water is in a saturation state as a result of aeration in the tanks. The aeration system includes oil-free reciprocating air compressors, a complete closed-loop, air-cooled water cooling system, necessary controls, vacuum relief valves, an air receiver for unloading and control purposes, and an air inlet filter-silencer, plus the air piping to and inside the tanks and the ceramic diffusers.

Table 2 presents the typical water quality analysis data of the samples collected from the potable water storage tanks located in the power, desalination and seawater cooling (PDSC) complex.

3.2. RO permeate

The RO process reduces the dissolved solids content of permeate, but does not reduce it to the low levels achieved by the MSF process. The permeate contains salts upto approximately 500 mg/l depending upon the membrane operating time and other operating conditions. The water quality of the typical permeate is shown in Table 3. Permeate contains certain amounts of CO_2 and alkalinity. The addition of sulfuric acid (for pretreatment of feed seawater to control calcium carbonate scale) results in the conversion of bicarbonate into carbonic acid (Fig. 7) which maintains alkalinity and passes through the RO membrane. Bicarbonate alkalinity is then recovered when pH is increased by the addition of lime. Bicarbonates make water stable and prevent variations in pH [8]. However, calcium is removed through the membranes and therefore, calcium is added in the post-treatment step.

Table 2
Typical water quality analyses on post-treated water from the MSF plant [7]

Parameter	Value
Temperature, ℃	25–32
pH at 25℃	8–8.5
Residual chlorine, mg/l	1
TDSs, ppm	30
Total alkalinity, mg/l as $CaCO_3$	40
Phenolphthalein alkalinity, mg/l as $CaCO_3$	1
Carbonate alkalinity, mg/l as $CaCO_3$	2
Bicarbonate alkalinity, mg/l as $CaCO_3$	38
Carbonate hardness, mg/l as $CaCO_3$	40
Calcium hardness, mg/l as $CaCO_3$	40
Dissolved oxygen, mg/l	7
Turbidity, NTU	0.5
Langelier saturation index	+0.1 to +0.3

The lack of carbonate alkalinity makes permeate unstable and prone to wide variations in pH due to the low buffering capacity. For permeate produced from the RO plant, post-treatment includes pH adjustment, addition of lime, and disinfection using sodium hypochlorite. The permeate is passivated by the addition of lime and this increases hardness and alkalinity, raises pH, reduces the tendency of the water to leach calcium from any concrete, and minimizes corrosion of materials used in the water transmission and distribution system. The pH of the permeate is adjusted to such a level that a slightly positive LSI is obtained.

The lime handling system consists of a lime silo, a transfer conveyor, and a slurry preparation and dosing system (Fig. 8). The product water (treated permeate) is stored in the product water storage tanks. The product water is then pumped to the pump station for distribution. The typical pH, TDS, and chloride concentration of the permeate obtained from RO plant operations in August 2007, when membranes were relatively new, are presented in Table 4.

Table 3
Permeate quality

Composition	Concentration (ppm)
TDS	<500
Cl^-	<250
SO_4^{2-}	15
HCO_3^-	3
Na^+	135
K^+	6
Ca^{++}	3
Mg^{++}	6
pH	5

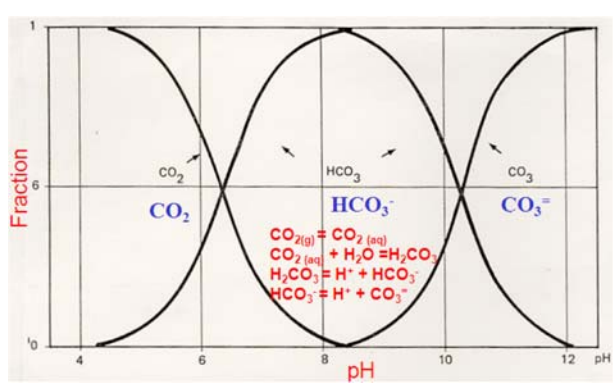

Fig. 7. Distribution of carbonate species as a function of pH.

Fig. 8. Lime dosing system for RO permeate.

Table 4
SWRO permeate analyses with relatively new membranes

Train	Date	pH	TDS (ppm)	Chloride (ppm)
D	8/11/2007	4.90	144	76
	8/12/2007	4.83	132	70
	8/13/2007	4.87	172	69
	8/14/2007	4.86	129	69
	8/15/2007	4.92	130	71
	8/16/2007	4.89	127	70
	8/17/2007	4.60	129	70
E	8/11/2007	4.90	139	74
	8/12/2007	5.30	135	72
	8/13/2007	4.92	189	76
	8/14/2007	4.86	142	75
	8/15/2007	4.88	142	79
	8/16/2007	4.90	140	78
	8/17/2007	4.63	140	80
F	8/11/2007	4.88	146	77
	8/12/2007	4.78	146	77
	8/13/2007	4.82	175	70
	8/14/2007	4.85	143	76
	8/15/2007	4.80	143	80
	8/16/2007	4.90	140	78
	8/17/2007	4.60	140	75

4. Potable water quality

For the potable water, blending of the treated MSF distillate with the treated RO permeate is done at the PDSC complex. No blending of desalinated water with either seawater or brackish water is practiced for Yanbu's potable water. Water storage facilities for 280,000 m^3 of potable water exist in several locations, as indicated in Fig. 9 which shows the original YIC, Yanbu 1. Yanbu 1 occupies 187 km^2 of land, approximately 26 km long and 8 km wide. More industrial and community facilities are currently under construction or in various stages of development and planning. The city is being expanded by adding 420 km^2 of additional land forming Yanbu 2. The potable water storage tanks include three 40,000 m^3 epoxy-coated steel tanks at the desalination plant site and eight 20,000 m^3 concrete tanks in the city buffer zone. Three pumping stations and over 600 km of potable water pipelines are in place to distribute potable water throughout the city. Yanbu's current potable water demand is approximately 50,000 m^3/day.

4.1. Sampling, measurement, and chemical analysis

For sampling potable waters throughout the city (Figs. 10 and 11), the city is divided into four sections and 10 locations from each section and water samples are collected weekly. Therefore, 40 water samples are gathered and analyzed for physicochemical parameters. Trace elements are analyzed once every two months. In the desalination plant, various water samples are collected and analyzed every 8 h.

For chemical analyses of the water samples, the APHA and AWWA standard methods [9] are used. The water quality parameters analyzed include: calcium, chloride, color, conductivity, fluoride, hardness, magnesium, nitrate, odor, pH, potassium, residual chlorine, sodium, sulfate, taste, TDS, turbidity, total and fecal coliforms, and trace elements (Ag, Al, As, Be, Bi, Cd, Co, Cr, Cu, Fe, Mn, Mo, Ni, Se, Sn, Ti, V, Zn).

Bacteriological quality of the water samples is determined by using the membrane filter method which is a standard method for enumeration of total and fecal coliforms in the water and wastewater. Water samples of 100 ml each are collected in sterilized bags containing sodium thiosulfate tablets to neutralize residual chlorine and are filtered through sterilized filters and incubated at 35℃ for total coliforms and at 45℃ for fecal coliforms. After 24 h incubation colonies with greenish gold metallic sheen for total coliforms and blue sheen for fecal coliforms are counted under a $10 \times 15\times$ microscope.

For the analyses of THMs, all the water samples are collected in Pyrex glass bottles. The bottles are filled to overflow in such a manner that no air bubbles are trapped in the samples. Sodium thiosulfate in 10 mg/40 ml sufficient for up to 5 ppm chlorine is added to neutralize residual chlorine. The bottles are

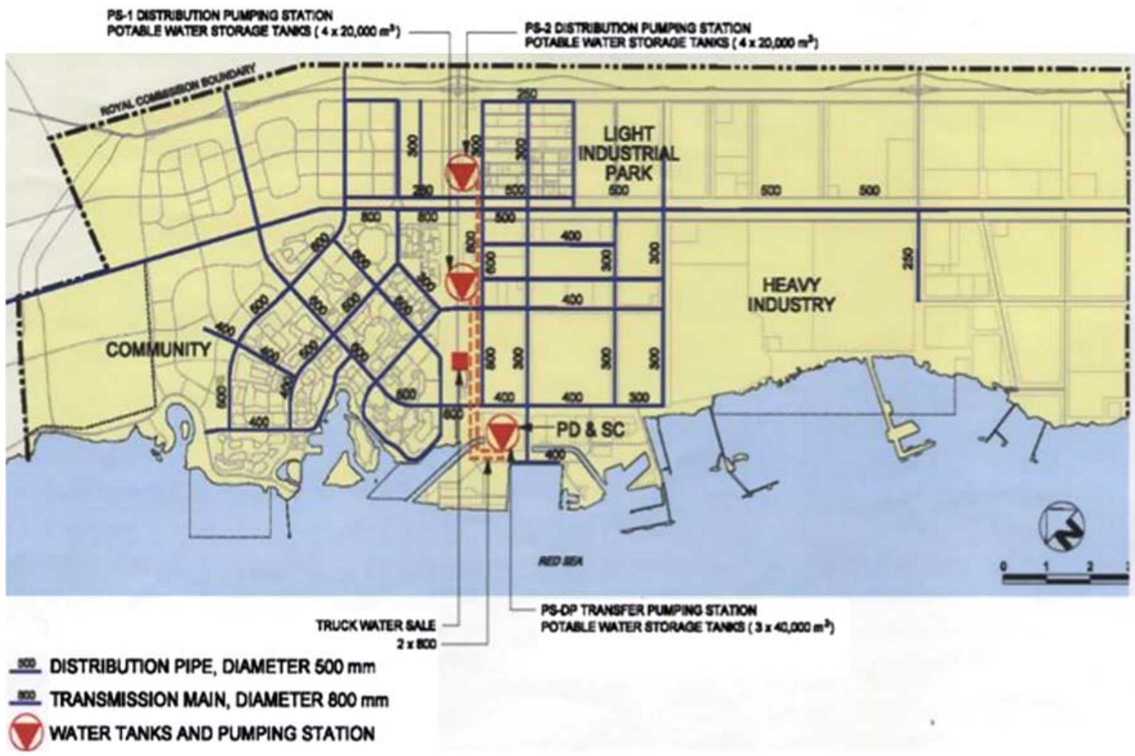

Fig. 9. Water distribution system for Yanbu Industrial City.

Fig. 10. Yanbu Industrial City community.

Fig. 11. Yanbu industries.

sealed and shaken vigorously for one minute to neutralize residual chlorine. Field test kits are used to measure chlorine. The water samples are analyzed within two hours after the samples are collected. The US EPA method 524.2 with some modification is employed for purge and trap extraction of THMs and analysis by GC–MS [10].

4.2. Physicochemical

The important physicochemical parameters of the potable water such as pH, residual chlorine, turbidity, alkalinity, hardness, TDS, chloride, nitrate, sulfate, and nitrite, are measured. Fig. 12 shows that on the basis of monthly average values, the pH of water varies from 7.5 to 8.5, with an average value of about 8.2. pH is an important indicator of water which changes chemically. The maximum monthly average pH measured in the six-year period is 8.5. The pHs of the

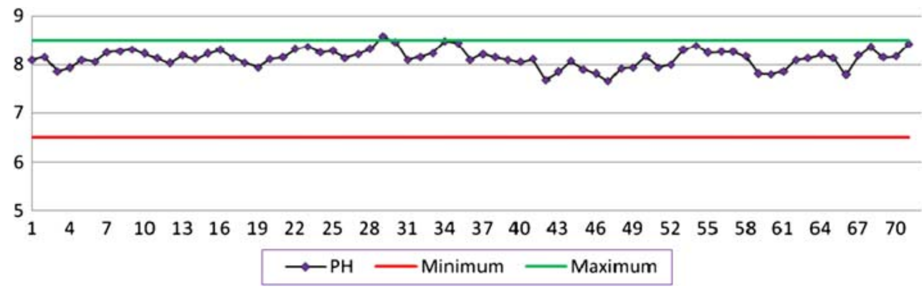

Fig. 12. Monthly average pHs for 6 years (2006–2011).

water are kept on weak alkaline levels to make the LSI slightly positive in order to minimize corrosion of the water distribution system.

TDSs are an important parameter in evaluating the quality of drinking water and determine the suitability of water for domestic and industrial uses. The TDS values indicate the quantity of salts present in potable water. The average TDS concentrations in the water exceed 200 mg/l after operation of the RO trains (Fig. 13), which is well above the minimum limit set forth in the Royal Commission potable water standards. The TDS levels are affected by the blending ratios of the MSF distillate and the RO permeate since the MSF distillate contains a small amount of salts. The targeted TDS concentrations for Yanbu are in the range 100–500 mg/l. The major constituents of the TDSs are chloride, sodium, calcium, sulfate, potassium and magnesium. The salt passages through the RO membranes are different for different ions. Passages of monovalent ions are greater than that of divalent and trivalent ions.

Turbidity is another important indicator of water quality. High turbidity indicates the presence of particulate matter which is suspended in the water. The measurements show that the turbidity of the water is always less than 0.6 resulting in the water of sufficient clarity. The maximum monthly value observed in the six-year period is 0.7, with an average value of about 0.3 nephelometric turbidity unit (NTU) (Fig. 14). It should be noted that virtually no substances such as clay, silt, finely divided organic and inorganic matter, and microscopic organisms are present in the water because of the closed pipe system.

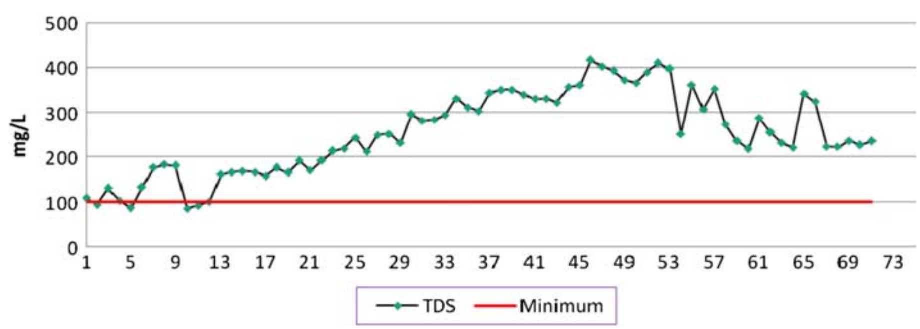

Fig. 13. Monthly average TDS for 6 years (2006–2011).

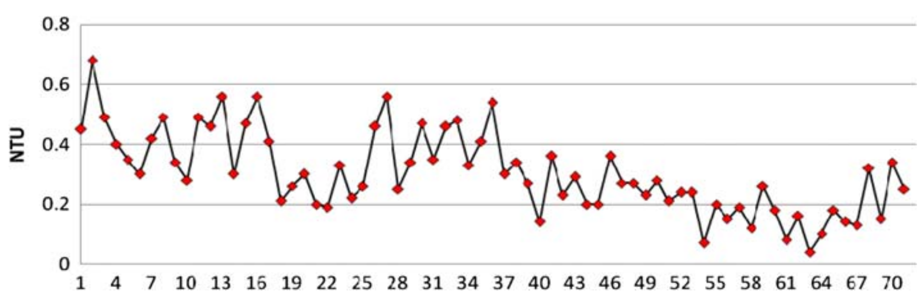

Fig. 14. Monthly average turbidities for 6 years (2006–2011).

Parameters such as sodium, chloride, potassium and sulfate are within the WHO drinking water guidelines [11] and the RC drinking water quality standards [12] (Table 5). The concentrations of fluoride, nitrate, nitrite, phosphate and bromide in the water samples were negligible. The RO plant has improved the quality of the potable water as certain mineral concentrations have been increased since the commissioning of the RO trains.

In the case of the MSF product water whose TDS is very low, one of the criteria for potabilization is to maintain at least an alkalinity level and calcium hardness level of 40 mg/l as $CaCO_3$ and a slightly positive LSI (preferably +0.1 to +0.3). In general, the hardness and alkalinity of the treated MSF distillate fall in the range 40–45 mg/l as $CaCO_3$. The magnesium content is virtually nil and the total hardness is derived entirely from calcium hardness, resulting from the addition of hydrated lime. The majority of the MSF water alkalinity is obtained from bicarbonate alkalinity by reacting carbon dioxide with calcium hydroxide.

For the MSF product water, pH is determined by the balance of carbonic acid from carbon dioxide and alkaline calcium hydroxide. In the potable water pH range, the predominant ionic species is present as bicarbonate, as predicted from the chemical equilibrium of carbon dioxide in an aqueous solution. As the carbonic acid is in excess, the pH of the water decreases, whereas the pH increases by increasing the lime dosing. The pH is adjusted to such a level that a slightly positive LSI can be obtained.

When water is referred to as "hard," it contains more minerals than ordinary water, particularly calcium and magnesium. The amount of dissolved calcium and magnesium in water determines its "hardness." The hardness is expressed in terms of calcium carbonate ($CaCO_3$). Water with less than 75 mg/l as $CaCO_3$ is considered to be "soft," 76–150 mg/l "moderately hard," and above 150 mg/l "hard" water. Calcium and magnesium are essential nutrients for the human body. The concentrations of calcium are presented in Fig. 15. The minimum calcium levels are maintained at 20 mg/l. As shown in Fig. 16, Yanbu's potable water is "soft," and the hardness level is

Table 5
Limits of some water quality parameters for Yanbu Industrial City

Parameter	Unit	Minimum	Maximum
TDSs	mg/l	100	500
Turbidity	NTU	–	1
pH	unit	6.5	8.5
Total hardness	mg/l as $CaCO_3$	75	500
Total alkalinity	mg/l as $CaCO_3$	40	–
CO_2 (free)	mg/l	–	Nil
Dissolved oxygen	mg/l	1.0	–
Calcium	mg/l	30	–
Magnesium	mg/l	5	–
Chloride	mg/l	–	250
Sodium	mg/l	–	20–30
Sulfate	mg/l	–	250
Potassium	mg/l	–	10
Nitrate	mg/l as NO_3	–	50
Residual chlorine	mg/l	0.2	0.5
Aluminum	mg/l	–	0.1
Ammonia	mg/l total as N	–	0.5
Antimony	mg/l	–	0.02
Arsenic	mg/l	–	0.01
Barium	mg/l	–	0.7
Boron	mg/l	–	0.5
Bromate	mg/l	–	0.01
Cadmium	mg/l	–	0.003
Copper	mg/l	–	2
Fluoride	mg/l	–	1.5
Iron	mg/l	–	0.3
Lead	mg/l	–	0.01
Mercury (inorganic)	mg/l	–	0.006

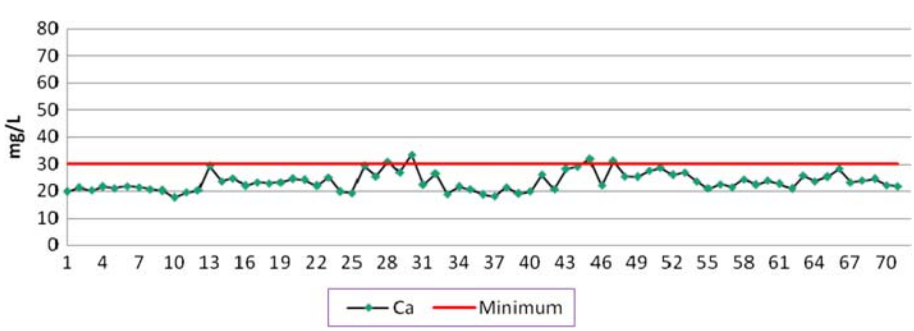

Fig. 15. Monthly average calcium concentrations for 6 years (2006–2011).

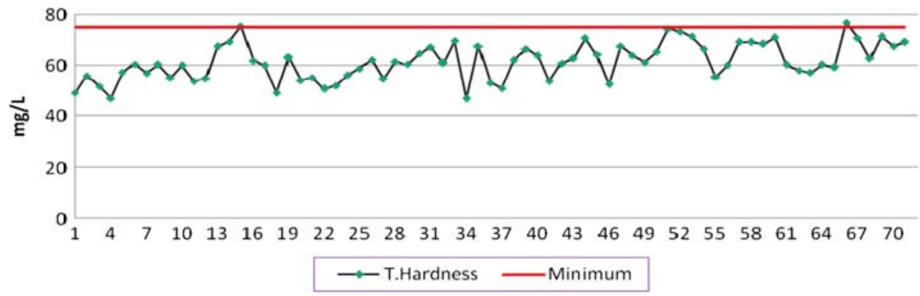

Fig. 16. Monthly average total hardness as mg/l $CaCO_3$ for 6 years (2006–2011).

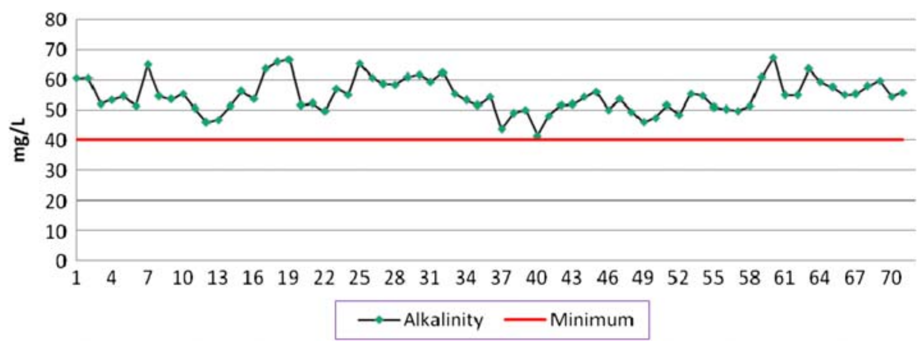

Fig. 17. Monthly average alkalinities as mg/l $CaCO_3$ for 6 years (2006–2011).

Table 6
Trace metal concentrations in mg/l

Element	Al	As	Ba	Cd	Co	Cr	Cu	Fe		Mn
Concentration mg/l	0.003	BDL	BDL	BDL	0.001	0.001	0.007	0.007		0.001
Element	Mo	Ni	Pb	Se	Sr	Zn	Ag	Ti	V	Hg
Concentration mg/l	BDL	0.003	BDL	BDL	0.014	BDL	BDL	BDL	BDL	BDL

targeted to be above 75 mg/l as $CaCO_3$. The alkalinity levels of the potable water are shown in Fig. 17 and they are satisfactory.

4.3. Trace elements

The concentrations of the important metals were analyzed and are presented in Table 6. The results show that concentrations of almost all metals were found to be in traces. Trace elements may cause different health effects. Even some essential minerals required for human health were deficient in the water. Minerals are often present in water as free ions, so they are more readily absorbed from water as compared to food. Concentrations of the trace metals fall within the WHO guidelines and the Royal Commission standards.

Table 7
Average boron concentrations of daily water samples

	Water sample	Boron (mg/l)
Desalination Plant (i)	Seawater (desalination plant feed)	5.20
	First stage RO permeate	2.54
	Second stage RO permeate	1.50
	MSF product water	0.21
	Potable water storage tank (blending of MSF and RO product waters)	0.75
Community (ii)	Location A	0.73
	Location B	0.75
	Location C	0.79

Notes: (i) Daily water samples for 18–24 December 2011. (ii) Daily water samples for 23–29 January 2012.

Boron is one of the trace elements possessing some health effects. The WHO sets a limit of 2.4 mg/l for boron in drinking water as a guideline value [11]. The efficiency of reduction of boron from the MSF plant was over 95% whereas the RO plant removed about 50%, as shown in Table 7. The seawater contained 5.2 mg/l boron. The average boron content in the city water samples was 0.76 mg/l which is well below the WHO guideline value. Boron speciation in water is strongly influenced by pH and temperature $[B(OH)_{3(aq)} + H_2O = H^+ + B(OH)_4^-]$. In general, boric acid is poorly rejected by RO membranes because of small size and lack of charge whereas borate ion rejection is higher by RO membranes because of bigger size and presence of charge. The boron rejection in the RO process is influenced by the parameters such as feedwater pH, temperature, operating pressure, type of membranes, the boron concentration in the feedwater, recovery ratio, etc. [13–19].

4.4. *Trihalomethanes*

Chlorination is the most widely used disinfection technique for the desalinated water and it generates organohalogen disinfection by-products (DBPs) [17]. However, there is little likelihood that the use of chlorine will be discontinued because it is the most economically acceptable chemical for bacterial control for desalinated water. The most widely prevalent species among THMs is a group of four halogenated hydrocarbon compounds, namely chloroform ($CHCl_3$), bromodichloromethane ($CHCl_2Br$), dibromochloromethane ($CHClBr_2$), and bromoform ($CHBr_3$). The WHO health-based guideline values for THMs in drinking water are presented in Table 8 [11].

The THM analysis results are summarized in Table 9 and Fig. 18. These results are the average of replicates of five samples from each location collected at different times. It is evident that all four THMs are present in the potable water due to the chlorination of desalinated water. The presence of brominated THMs are mainly due to the reaction of bromide with sodium hypochlorite or chlorine, which further reacts with organic matter to form brominated products [20]. The data show that the average THM concentration was 8.6 μg/l, which is far lower than the WHO guideline values. The concentrations of THMs gradually increase from chloroform to bromoform. As the number of substituted bromine atoms increases, THM concentration increases (Fig. 18). It is indicated that 63% of the total THMs were of bromoform type and 21% dibromochloromethane, and bromoform is dominant and present more than the other three THMs.

The formation of THMs depends on many factors, such as the nature and concentration of dissolved organic precursors present in raw water, pH, chlorine dose, post-reaction temperature, contact time, concentrations of bromide ions, and residual chlorine [20–24]. The MSF process is known to be very effective in removing organics and THMs formed from chlorinated seawater even though there is minor carryover of traces of THMs into the distillate from the flashing brine. But chlorination of the product distillate results in the formation of traces of THMs as DBPs.

Table 8
WHO guideline values for THMs

Chemical	Guideline value (μg/l)
Bromodichloromethane, $CHCl_2Br$	60
Bromoform, $CHBr_3$	100
Chloroform, $CHCl_3$	300
Dibromochloromethane, $CHClBr_2$	100

Table 9
Average THM concentrations

Sampling locations	THM (μg/l)				
	$CHCl_3$	$CHCl_2Br$	$CHClBr_2$	$CHBr_3$	Total
L-1	0.26	0.95	1.21	4.25	6.67
L-2	0.16	0.72	1.40	5.56	7.85
L-3	0.54	1.41	2.33	6.11	10.39
L-4	0.48	1.33	1.80	4.74	8.35
L-5	0.26	0.96	1.55	6.28	9.05
L-6	0.26	1.24	2.16	6.69	10.34
L-7	0.27	1.46	2.25	4.86	8.82
L-8	0.16	0.78	1.44	6.00	8.38
L-9	0.24	0.80	1.96	4.29	7.29
L-10	0.26	1.06	2.25	5.56	9.13
Average	0.29	1.07	1.83	5.43	8.62

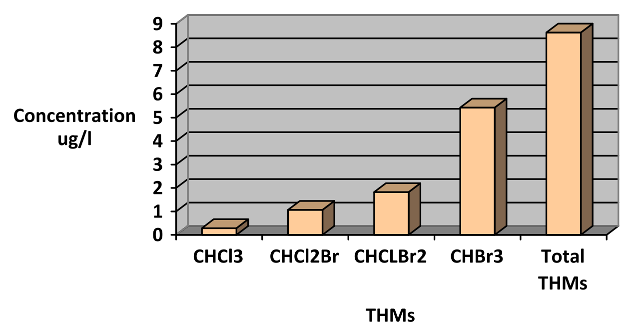

Fig. 18. Average THM concentrations.

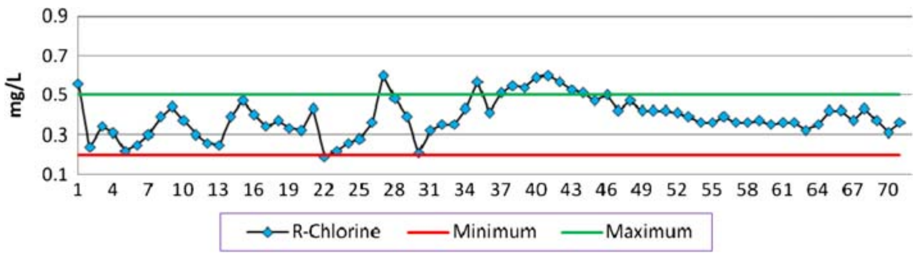

Fig. 19. Monthly average residual chlorine concentrations for 6 years (2006–2011).

4.5. Bacteriological

The presence of coliform bacteria in aquatic environments indicates that the water has been contaminated with the fecal material of humans or animals. At the time of occurrence, the source water may have been contaminated by pathogens or disease-producing bacteria or viruses which can also exist in fecal material. The presence of fecal contamination is an indicator that a potential health risk exists for individuals exposed to this water. The six-year data show that the total and fecal coliform tests were found to be negative. The analyses of the water samples show that not even a single sample during the whole period was found to be contaminated with coliforms. To date, no coliforms have ever been found in the water samples taken from the city. This implies that tap water supplied to the city is free from bacteriological contamination. Fig. 19 reveals that certain levels of residual chlorine were maintained at all times within the intended limits so that no microorganisms could grow. Generally, the residual chlorine levels of the city tap water varied from 0.2 to 0.4 mg/l (Fig. 19).

5. Concluding remarks

The post-treatment processes for the MSF distillate and the RO permeate employed at Marafiq's seawater desalination plant in YIC are effective for their conversion to potable water. YIC's potable water produced by seawater desalination is of high quality and prevents bacteriological growth without any microbiological contamination. The water is healthy and suitable for human consumption and use on the basis of the water quality monitoring data with respect to its physical, chemical, and biological characteristics. Overall, the potable water complies with the WHO guidelines for drinking water quality and the Royal Commission standards for potable water.

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