

Efficiency and reliability of membrane processes in a water reclamation plant

Mohamed F. Hamoda, Meshari AL-Harbi and Hasan AL-Ajmi

ABSTRACT

Performance of a water reclamation plant using ultrafiltration (UF) and reverse osmosis (RO) treating 280,000 m³/d of wastewater was evaluated over 1 year. Statistical analyses were performed on flow rate, temperature, pH, total suspended solids (TSS), total dissolved solids (TDS), biochemical oxygen demand (BOD₅) and total coliforms. Variations in flow rates coincided with those in temperature, both being seasonal, but plant performance was not highly influenced by such variations. The RO system recovered 85% of water flow. Data on process variables conform to a normal probability distribution and reveal the high process efficiency and reliability of UF and RO systems. Plant efficiencies were >99% for TSS, TDS, BOD₅ and total coliforms. Efficiencies were the highest for TSS and total coliforms in the UF system, while they were the highest for TDS and BOD₅ in the RO system. Cumulative frequency distribution analyses indicate that RO plays an important role in maintaining a stable plant performance and high quality reclaimed water. The UF system proved essential for complimenting successful performance of the RO system. Reclaimed water satisfies, at 99% frequency, the quality standards for potable water concerning TSS, TDS, BOD₅ and total coliforms even though membranes have been operating continuously for 6 consecutive years.

Key words | process efficiency, reliability, reverse osmosis, ultrafiltration, water reuse

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INTRODUCTION

Water reclamation is expected to increase in future years, mainly due to a steady increase of the world's population and water use contrasted with a decrease in the availability of freshwater supply and in the affordability of meeting such an increase (Angelakis *et al.* 2003; Asano *et al.* 2007). This will require a coordinated effort involving water management and purification, water conservation and water reuse (Goosen & Shayya 1999). Reclamation of treated wastewater from municipalities and industries has been considered a supplementary source of water supply in many parts of the world, particularly in some areas where water resources are scarce and population and economic growth is rapid (Hamoda 2004).

Membrane processes have been considered a promising technology for wastewater recycling and reuse. Numerous membrane technologies based on micro-filtration, ultrafiltration (UF), nanofiltration and reverse osmosis (RO) have

been used downstream of biological treatment units to act as selective barriers that permit separation and removal of contaminants in a fluid by a combination of sieving and sorption diffusion mechanisms (Asano *et al.* 2007; Chang *et al.* 2007; Lazarova *et al.* 2013).

RO is a membrane-based process that employs semi-permeable membranes under high pressure differentials to separate and remove dissolved solids, organics, submicron colloidal matter, color, nitrate, phosphorus and bacteria from wastewater (Asano *et al.* 2007). The RO process has been used extensively in reclamation of wastewater and in desalination of brackish/sea water. Removal of organic contaminants by RO was first demonstrated by Hamoda *et al.* (1973), and was followed by numerous studies investigating the use of RO for the removal of individual organics from domestic and industrial wastewaters (Peng *et al.* 2004; Bodalo-Santoyo

et al. 2004; Arsuaga *et al.* 2006; Nataraj *et al.* 2006; Dolar *et al.* 2013).

UF membrane processes use a wide range of pore size and an operating pressure range of 3–10 bar (Cheryan 1986). The separation mechanism in UF is selective sieving through the membrane pores. Dissolved salts and small organic molecules pass through the semi-permeable membrane in the liquid phase while larger molecules and solids are rejected and concentrated in the retentate (Tansel *et al.* 1995). UF is often used as a pre-treatment process for RO to reduce the adverse effects on downstream RO. In a previous study, Glueckstern *et al.* (2000) used two-stage media filtration and UF as pre-treatment for RO to treat contaminated brackish fish-pond effluents and showed that UF was more effective than multi-media filtration in improving water quality. In another study, a significant reduction in total solids concentration and chemical oxygen demand (COD) was achieved by the UF system treating poultry processing wastewater (Lo *et al.* 2005). Furthermore, Nelson (2006) reported that UF reduced organic and microbial pollutants from poultry processing wastewater while Avula *et al.* (2009) found that UF improved the quality of recycled poultry wastewater and provided a solution to water resources limitations.

Combinations of UF and RO technologies have also been investigated. In one study (Fababuj-Roger *et al.* 2007), tannery wastewater was reclaimed by UF and RO after a conventional physical–chemical treatment. The results showed that a simple combination of physical–chemical treatment and UF was not sufficient to remove the soluble COD from wastewater, leaving a concentration more than 2,000 mg/L in the permeates from all tested UF membranes. Conversely, more than 98% rejection of both salts and COD were achieved when RO treatment was included. Their study clearly demonstrates the capability of RO systems, especially when the effluent contains high organic matter content. In another study (Tomaszewska *et al.* 2005), oily wastewater and bilge water were treated using a combination of UF and RO systems operating via two-stage treatment, with UF being used in the first stage and RO in the second stage. It was found that permeate from the first stage had oil content below 10 ppm, was free of suspended solids and almost all turbidities were removed. In the second stage, total organic carbon (TOC) removal was

more than 70% while 90% of all cations examined (Na^+ , K^+ , Mg^{2+} , Ca^{2+} , Zn^{2+} , Mn^{2+} , Al^{3+} , Li^+), P_2O_5 and sulfate were removed. In addition, Murthy & Choudhari (2009) investigated the application of UF and RO membranes in a pilot plant treating wastewater for removal of color and contaminants. The results showed that the rejection efficiencies of UF and RO membranes for total dissolved solids (TDS), COD, biochemical oxygen demand (BOD_5), sulfate and potassium were 97.9%, 96.8%, 97.9%, 99.7% and 94.65%, respectively. Similar results were reported in other studies (Shi & Benjamin 2009; Huang *et al.* 2011).

Previous studies on UF and RO, as reported in the literature, have been conducted mostly on laboratory or pilot-scale systems but not on full-scale operations. Therefore, this study was carried out to evaluate the performances of UF and RO systems at full-scale operation, to give a clearer understanding of the performance at a large scale. The Sulaibiya wastewater reclamation plant in the State of Kuwait, being the largest UF/RO plant in the world, was investigated in this study to determine the process efficiency and performance reliability of the UF and RO membrane systems.

MATERIALS AND METHODS

Plant description

The Sulaibiya wastewater treatment plant (WWTP) is located at Sulaibiya near Kuwait City. It was commissioned in the year 2005, with a design capacity of 375,000 m³/day which was increased to 425,000 m³/day, as the world's largest membrane-based water reclamation facility utilizing UF and RO systems. The reclaimed water from this facility is used for several non-potable uses. The water reclamation facility (Figure 1) receives secondary-treated municipal wastewater, which is pre-filtered with disk filters and then fed to the UF system. The UF permeate feeds the RO plant, and UF retentate is recycled to the WWTP. The system receives almost 100% of the effluent from the biological treatment plant since UF retentate is recycled. RO is placed just after UF and therefore, the inlet feed of RO is also 375,000 m³/day. The RO system is constructed for 85% water recovery and thus, the production rate is

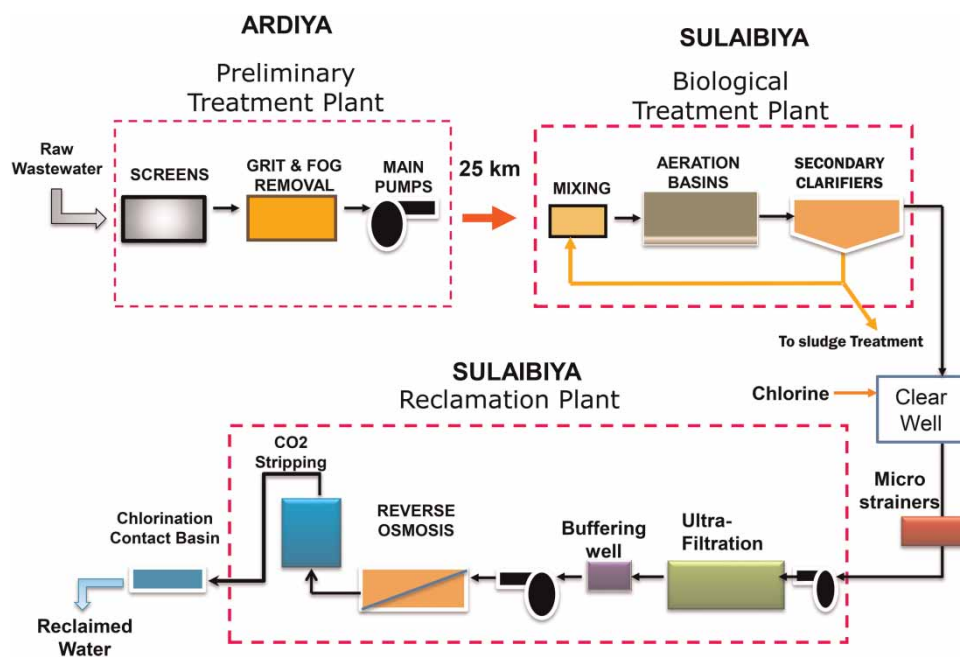


Figure 1 | Flow diagram of treatment processes at Sulaibiya WWTP.

expected to be 318,750 m³/day. The WWTP is designed to produce an effluent with an average monthly value of less than 20 mg/L BOD₅ and 20 mg/L total suspended solids (TSS). It should be noted that the effluent TDS from this plant has to be <100 mg/L (the influent contains 1,280 mg/L), which is apparently better than World Health Organization (WHO 2008) potable water guidelines of <1,000 mg/L. As shown in Figure 1, the preliminary treatment at Ardiya consists of particulate and grit removal, as well as fat, oil and grease removal. The wastewater is then pumped for about 25 km to Sulaibiya for secondary and advanced (reclamation) treatment stages. To enhance biological removal of nitrogen and phosphorus in the WWTP, anoxic and aerobic systems are used in the secondary treatment stage in addition to secondary clarifiers. To minimize variation in flow, buffer volume was taken into account in the design of the facilities at Ardiya, and the aeration basins and the clarifiers at Sulaibiya. For sludge treatment, both aerobic digesters and drying beds are used, which are suitable under warm to hot climatic conditions prevailing in Kuwait. According to the regulatory agencies in the State of Kuwait, the digested sludge could be used as organic fertilizer or soil conditioner. The reclaimed water could be

used for non-potable uses such as irrigation and for groundwater recharge.

UF system

Since RO systems require pre-treatment as to protect RO membranes from fouling, UF was selected to provide appropriate pre-treatment of the secondary-treated municipal effluent before being fed to the RO. The UF technology is robust, has favorable life cycle costs and provides better quality water to the RO membranes. The characteristics of the UF system used in this plant are presented in Table 1. Each UF unit can be operated individually. These units are regularly backwashed to ensure removal of suspended matter retained on the membranes. The backwash water is pumped back upstream of the WWTP to receive appropriate treatment and accomplish the maximum total water recovery for the plant. The influent to the UF first passes through a disk filter and subsequently, a small amount of coagulant (ferric chloride at 1–2 mg/L) is added to coagulate fine particulates and possibly allow some TOC removal to facilitate the operation of the plant. The silt density index of the UF product is consistently below 2, which is

Table 1 | Characteristics of membrane systems employed at Sulaibiya water reclamation plant

Membrane system	Membrane type (manufacturer; catalogue no.)	Membrane configuration	Membrane arrangement	Membrane area
UF	Polyvinylidene fluoride; (Norit X-Flow, The Netherlands; XIGA SXL-225)	Capillary hydrophilic hollow fibers	Membranes are packed in 20 × 152 cm membrane elements (35 m ² /element), 4 membrane elements are placed inside a membrane housing. There are 68 skids, each with 32 membrane housings for a total of 8,704 membrane elements (4 × 32 × 68)	8,704 × 35 m ² = 304,640 m ²
RO	Polyamide composite (Toray, USA; TML 20-400)	Spiral wound	Membrane modules of 42 identical skids in a 4:2:1 array of modules. Each module contains about 504 RO elements (72 pressure vessels × 7 RO element/vessel) for a total of 21,168 membrane elements (7 × 72 × 42)	21,168 × 37 m ² = 783,216 m ²

the key standard for the RO plant performance (Gagne 2002).

RO system

The characteristics of the RO system adopted in the Sulaibiya plant are shown in Table 1. This system is used to desalinate the wastewater effluent to 100 mg/L TDS and to provide an additional barrier to bacteria and viruses. The salinity of the secondary-treated effluent has an average monthly value of 1,280 mg/L TDS, with a maximum value of 3,014 mg/L. The RO system modules are arranged in a 4:2:1 array, forming three stages of RO treatment. The first stage recovers 50%, the second stage recovers 50% and the third stage recovers 40% of the flow. Recovery of water by the RO system is limited to 85% by calcium phosphate precipitation, which can be often a limiting factor for recovery of water in the membrane desalination systems in municipal wastewater (Gagne 2002). RO effluent passes through the stripper unit to remove the CO₂ to adjust the pH with a minimum of caustic soda prior to distribution, then the product is chlorinated before leaving the plant. The system's brine is disposed of into the waters of the Arabian Gulf. The WANDA Control module is used extensively to verify and optimize the normal operating procedures, such as backwash operations and pump switches. To minimize fouling, the membranes are regularly cleaned in place using surfactants, sulfuric acid, biocide and sodium hydroxide.

Plant operation

The treatment steps have been selected to minimize the use of power and chemicals, and are simple to operate and maintain. A high degree of standby equipment and redundancy was incorporated into the design to ensure reliable operation. A key to the successful operation of this facility is to employ highly trained and motivated staff. Operating personnel include a number of managers, chemists and engineers, as well as qualified technicians and laborers. Training to the appropriate level was provided at the manufacturers' premises and on-site during commissioning and testing.

The plant receives primarily domestic wastewater with only slight variations in influent concentration levels. Moreover, the plant has several storage tanks to balance water flows of different treatment steps. This contributes to steady operation of the plant and low time variability. The characteristics of the raw wastewater are typical of those of high-strength sewage. A unique feature is the high TDS of the raw wastewater mainly due to the infiltration of saline water into the sewerage collection system as a result of seawater intrusion and subsurface water rise.

METHODOLOGY

This study used 12 months of complete daily measurements of quantitative data from Sulaibiya WWTP for the period 1 September 2010 to 31 August 2011 to build a database.

Although the study is based on real data collected daily, the database suffers from some missing values over some weekends which can be compensated for by taking averages. In the studied WWTP, it is common to make daily analytical measurements of process variables on samples collected from influent and effluent of each treatment stage in general and each treatment process in the reclamation plant such as UF and RO in particular. The process variables considered for the database are flow rate and temperature whereas quantitative water quality data includes solids (measured as TSS and TDS), organic matter (measured as BOD₅, and coliform bacteria (measured as total coliforms). Flow rate and temperature are recorded from on-line signals coming from sensors whereas the water quality parameters were determined according to *Standard Methods* (APHA 2005).

The final data set covers a homogeneous representative period of 320 consecutive days, excluding some weekends, where each day is considered as a new sample. Monthly averages for a period of 12 months were determined based on the daily sets of data. The data were subjected to statistical analysis, including basic statistical descriptors of the parameters included in the database, the normal probability distribution plots and the cumulative frequency distributions of the influent and effluent concentrations of the UF and RO systems. Such statistical methods for data analysis have become common tools for plant data (Asano *et al.* 2007; Mujeriego & Peters 2008). In this study, the main objective of data analysis was to statistically quantify the process efficiency and the performance reliability of both UF and RO membrane systems of the water reclamation plant.

RESULTS AND DISCUSSION

In the following section, plant performance will be analysed through: (1) percentage reduction efficiency and a comparison of the effluent concentrations with the water quality standards for reuse; and (2) cumulative frequency distributions of the influent and effluent concentrations. The statistical analysis was performed on the variables pH, TDS, TSS, BOD and total coliforms. Each of these five variables was monitored in both the influent and the effluent to the UF and the RO systems. Both the daily records and the monthly averages were used in the analysis.

Operating parameters

The performance of a treatment system is usually influenced by two important 'input' variables, namely the influent flow rate and temperature. The effluent variables considered in this study are pH, TSS, TDS, BOD and total coliforms. These five parameters were presented in 15 groups of data values, namely five groups for UF influent, five groups for UF effluent/RO influent and five groups for RO effluent. The first step in the statistical analyses conducted on plant performance data attempted to examine the statistical distribution of each variable. To apply the statistical tests associated with normal distribution, one of the variables (TDS) was examined. The normal probability plots for TDS in influent and effluent of RO are shown in Figure 2, confirming that data follow a normal distribution pattern. The regression lines obtained showed high correlation coefficients of 0.9182 and 0.9659 for influent and effluent TDS,

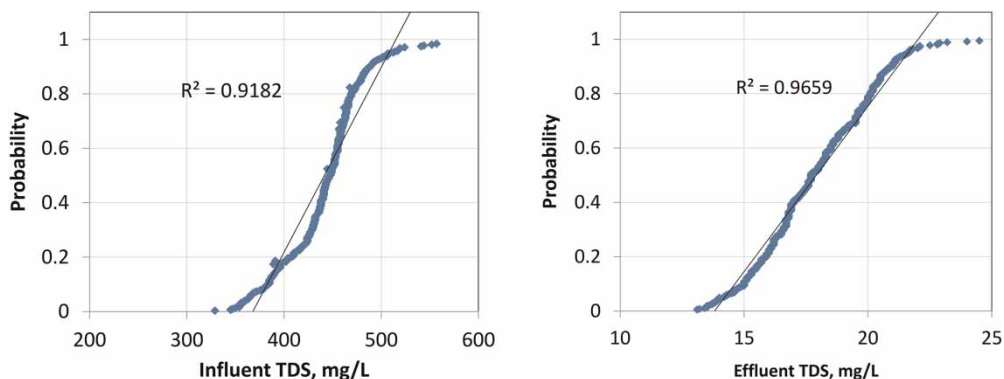


Figure 2 | Normal probability plots of TDS for the RO system.

respectively. Similarly, other variables inspected were normally distributed. Thus all the 15 groups of data conform to a normal probability distribution (regression lines). Such features make characterization of plant performance much simpler.

Figure 3 illustrates the daily variations in each of the flow rate and temperature over a period of 1 year. The water reclamation plant is currently operated under its design flow, with average influent flow rate of $280,000 \pm 14,800 \text{ m}^3/\text{d}$, as compared to the design flow of $425,000 \text{ m}^3/\text{d}$. Seasonal variations in flow rate were minor ($\pm 5\%$), with highest flow rates being recorded in the summer months when water consumption is high, hence wastewater generated increases. In general, the plant is operated under pseudo steady-state conditions. It should also be mentioned that flow recovery by the RO system is 85%, therefore, the plant effluent flow rate is approximately $238,000 \pm 10,600 \text{ m}^3/\text{d}$. The average influent temperature is $32 \pm 3.5 \text{ }^\circ\text{C}$. Variations in temperatures were appreciable with two distinct seasons, summer and winter which reflects the climatic conditions prevailing in the state of Kuwait. It is also noted that the daily variations in flow rates coincide with those in temperature, with both being of a seasonal nature. The observed patterns of behavior are very coherent. Meanwhile, it has been observed that the effluent flow rate from the RO unit varied with temperature which is due principally to the change in viscosity of the water with change in temperature.

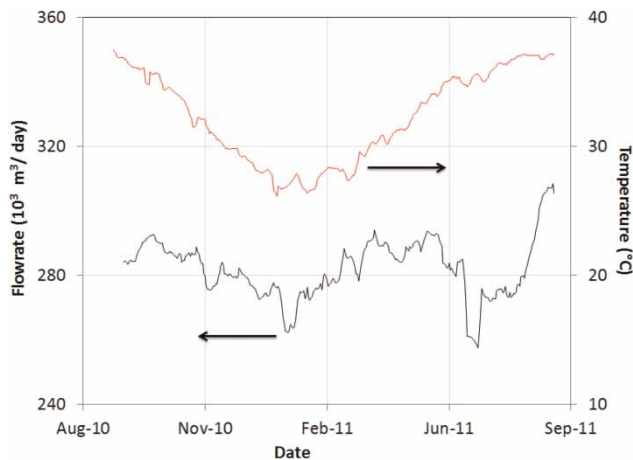


Figure 3 | Variations in influent flow rate and temperature during the period 1 September 2010–31 August 2011.

The pressure applied to the UF system is 3 bar whereas the pressure exerted on the RO system is in the range of 7–11 bar, 11–14 bar and 14–16 bar for the first stage, the second stage and the third stage of RO module's trains, respectively. The energy consumption across the RO unit in terms of water produced ranged from 1.4 to 1.7 kWh/m³. The RO membranes employed in this plant are low-pressure type membranes with the highest pressure applied being 16 bar (about 230 lb/inch²). It is noteworthy to mention that membranes used have been operated for almost 6 years with a replacement rate of only 10%. Biofouling of membranes was properly controlled as chloramine was dosed to the RO feed water to control the rate of biofouling.

System performance

The operation of the water reclamation plant (Figure 1) indicates that the influent to the UF system is the biologically treated wastewater after chlorination and micro-straining while the effluent of the UF system enters as influent to the RO system that produces the reclaimed water. Figure 4 displays three sets of data (UF system's influent, UF effluent/RO influent and RO effluent) for each performance parameter. The performance data for each parameter were monitored over a period of 1 year. Monthly average data were calculated for each parameter and plotted in Figure 4 along with their standard deviation values calculated in each case.

The pH of influent to the UF system (Figure 4(a)) did not vary much over the 1-year period, being in the range of 6.9–7.1. It is important to stress that the UF effluent passes through a buffering well (Figure 1) so as to adjust the pH value to meet the RO system requirements. Therefore, the pH values as recorded directly prior to entering the RO system (6.6–6.8) were slightly lower than that of UF effluent. Meanwhile, the pH values of RO effluent increased again (7.1–7.3) as it passed through a stripper for removal of CO₂ to adjust pH with a minimum amount of caustic before the distribution system. Ultimately, the effluent from RO system is chlorinated to be ready for water reuse.

The monthly average TSS values of UF influent were variable and ranged from 5 to 14 mg/L. The UF effluent TSS concentration levels decreased to a stable value of <1 mg/L and remained at this level in the RO system

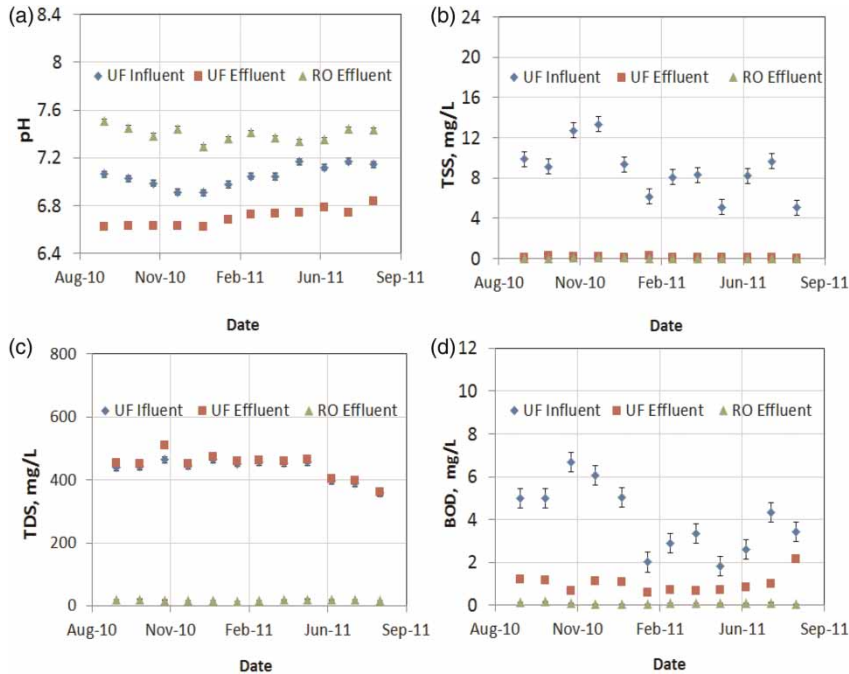


Figure 4 | Influent and effluent daily performance data: (a) pH, (b) TSS, (c) TDS and (d) BOD.

effluent (Figure 4(b)). This demonstrated that UF system is unique and efficient in removing TSS, thus preventing it from entering RO system and fouling the RO membranes (Peng *et al.* 2004). In contrast, the monthly average TDS values were more stable in the UF influent at 400–500 mg/L and remained almost unchanged in the UF effluent. Subsequently, the TDS values were greatly reduced to <10 mg/L and remained consistently at this level over the 1-year period (Figure 4(c)). For BOD₅, the monthly average varied between 2 and 7 mg/L and decreased consistently to 1 mg/L in the UF system and further to <1 mg/L in the RO system effluent (Figure 4(d)).

The plots displayed in Figure 4 highlight the process efficiency by greatly reducing the concentration of each quality parameter and its standard deviation, as well as the process reliability by lowering the time variability of each parameter in the course of treatment. It should be noted that the relevance of dissolved organic matter and specifically trace or priority organics are the primary concern when using advanced processes for water reclamation. Such organics are better expressed as COD or TOC of water quality parameters. However, the data obtained from the studied plant do not include such parameters and are limited to

BOD since the standards to be satisfied by the reclaimed water are expressed in terms of BOD as a measure for biodegradable organic matter. The TDS levels, conversely, account for such dissolved organic matter and their very low concentrations detected in the RO effluent reflect their retention by RO membranes.

The total coliforms (Figure 5) were highly variable in the UF system influent ranging between 0.2×10^6 and 10×10^6

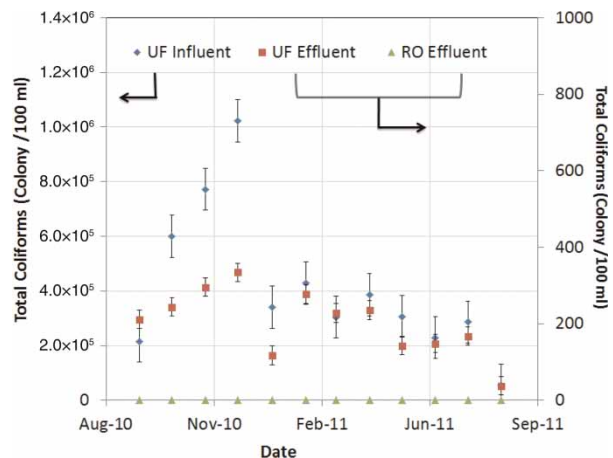


Figure 5 | Influent and effluent daily performance data for total coliforms.

colony-forming units (cfu)/100 mL and decreased to a range of 0.05×10^6 and 0.47×10^6 cfu/100 mL in the UF system effluent. It was further decreased substantially to a constant value of <1 cfu/100 mL (i.e. not detectable) in the RO system effluent. It is to be noted that reduction in total coliforms was expressed in percentages rather than in log units based on the data obtained from the plant. For instance, a bacterial removal of 3.0 log units (say from 10^5 to 10^2) designates a 99.9% removal.

For the UF system, the concentration-based removal efficiencies of TSS, TDS, BOD and total coliforms are $85 \pm 7\%$, $10 \pm 5\%$, $72 \pm 13\%$ and $85 \pm 10\%$, respectively. Conversely, for the RO system, the corresponding removal efficiencies for each parameter are $>95\%$. The overall removal efficiencies for the water reclamation plant combining UF and RO systems are $>99\%$ and the reclaimed water consistently complies with the quality standards as clearly demonstrated by the data in Figures 4 and 5, and as compared to various standards adopted in Kuwait as presented in Table 2. The quality of reclaimed water (Table 2) is comparable to that of desalinated water (drinking water) but at a much lower

(one-third) treatment cost. The results obtained in this study agree very well with those reported by other researchers (Franks et al. 2004; Bartels et al. 2010; Stover 2013).

It should be mentioned that water quality parameters such as BOD and TSS are commonly measured by WWTPs since plant laboratories have cost-effective techniques for conducting such measurements, even at the very low concentrations found in the RO-treated effluents. Other parameters such as TOC, although more accurate to monitor removal of organics at low concentrations, require more costly equipment such as the carbon analyser which is not available in most treatment plant laboratories to be used on routine basis. Moreover, water quality standards often use parameters such as BOD, COD and TSS to determine suitability of treated wastewater effluents for reuse.

Frequency analysis

Cumulative frequency distributions of the influent and effluent concentrations for the parameters pH, TSS, TDS and BOD are shown in Figure 6. The 50% cumulative frequency is

Table 2 | Characteristics of wastewater and reclaimed water compared to Kuwait's standards

Parameter	Unit	Inflow to WWTP	Inflow to water reclamation plant	RO effluent for reuse	Irrigation water standards	Drinking water standards
pH	–	6.5–8	6.5–7.5	6–8	6.5–8	6.8–7.5
Conductivity	µs/cm	1,200–3,000	1,100–2,200	–	1,500	515
TSS	mg/L	100–500	<10	<1	15	–
VSS	mg/L	70–350	<7.0	<1	–	–
COD	mg/L	250–750	<40	15	100	–
BOD ₅	mg/L	100–400	<10	<1	20	–
Grease and oil	mg/L	10–50	NIL	< 0.05	5	–
TDS	mg/L	700–1,800	800–1,500	< 100	–	400
Chloride	mg/L	200–400	200–400	–	–	103
Ammonia	mg/L	15–50	1–5	<1	15	–
Nitrite	mg/L	0.04–0.7	0.1–1.5	<1	–	–
Heterotrophic plate counts	cfu/100mL	2.40×10^9	10^5	0	–	0
Total coliforms	cfu/100 mL	3.20×10^8	400	0	400	0
Faecal coliforms	cfu/100 mL	4.10×10^7	0–10	0	20	0
<i>Salmonella</i>	cfu/100 mL	4.50×10^6	0	0	–	0
Streptococci	cfu/100 mL	1.40×10^7	0	0	–	0
Fungi	cfu/100 mL	2.10×10^5	2–100	0	–	0

VSS, volatile suspended solids.

particularly important to express the variability of each parameter between 0.1 and 99.9% frequencies. For the pH, Figure 6(a) indicates that the pH of the UF influent was, for 50% of the time, ≤ 7.0 but decreased to a value of 6.8 in the UF effluent/RO influent and then increased to a value of 7.2 in the RO effluent. It is to be noted that the cumulative frequency plots are steep, indicating low variability in this parameter with time. In contrast, parameters such as TSS, TDS and BOD are removed as they pass through the membranes. For instance, TSS was ≤ 9 mg/L for 50% of time and decreased significantly to < 1 mg/L in the UF effluent to protect the RO membranes, and remained at this level in the RO effluent (Figure 6(b)). This was also true for TDS which was ≤ 410 mg/L for 50% of time and remained almost unchanged in the UF effluent/RO influent where it was greatly reduced to only 1 mg/L in the RO effluent (Figure 6(c)). The BOD was ≤ 3.5 mg/L for 50% of time but was reduced down to 1.5 mg/L by UF and further to < 1 mg/L in the RO effluent (Figure 6(d)).

Figure 7 shows that total coliform count was $\leq 3 \times 10^5$ cfu/100 mL for 50% of the time but was $\leq 1.3 \times 10^5$ cfu/100 mL for 99% of the time indicating high variability in this parameter. It is also decreased significantly to < 1 cfu/100 mL in the UF effluent and remained so in the RO effluent with no variability. Figures 4 and 5 reveal that the UF system is effective in reducing the concentration level and

variability of TSS and total coliforms, whereas the RO system is very effective in reducing the concentration level and variability of the TDS and BOD parameters. Together, the UF and RO systems complement each other in achieving almost complete removal of TSS, TDS, BOD and total coliforms in the water reclamation plant.

Frequency distribution plots obtained for all parameters studied (Figure 6) clearly highlight the performance reliability of the UF and RO systems. These plots, in addition to those displayed in Figure 4 for time variability of concentrations of the same parameters serve to verify the degree of conformity to the normal probability distribution and visualize the high process efficiency and performance reliability of the UF and RO systems used for water reclamation.

CONCLUSIONS

Based on the results obtained from statistical analyses of operating data it is possible to conclude that the performance of the water reclamation plant over a period of 1 year was not significantly influenced by variations in the wastewater flow rate and/or temperature. The data on process variables conform to a normal probability distribution. The study demonstrates that the overall removal efficiencies for the water reclamation plant combining UF and RO systems are

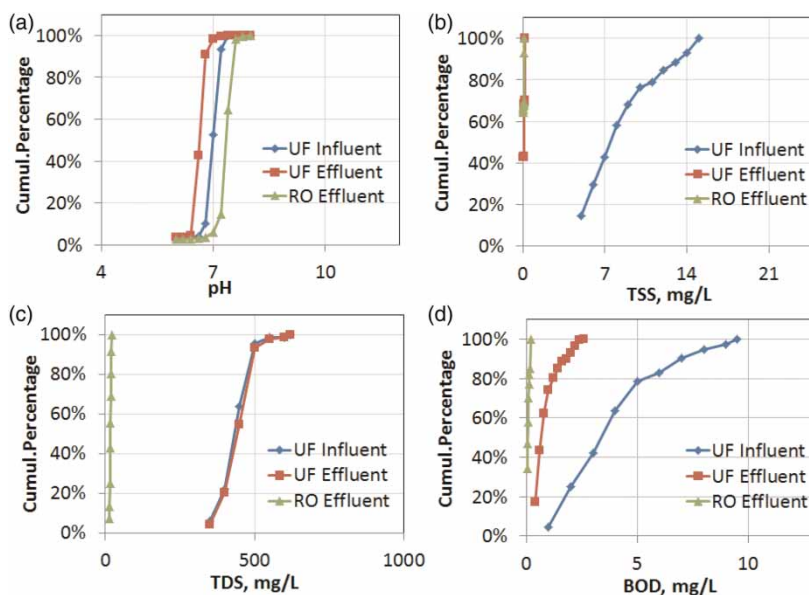


Figure 6 | Cumulative frequency distributions of the influent and effluent daily performance data: (a) pH, (b) TSS, (c) TDS and (d) BOD.

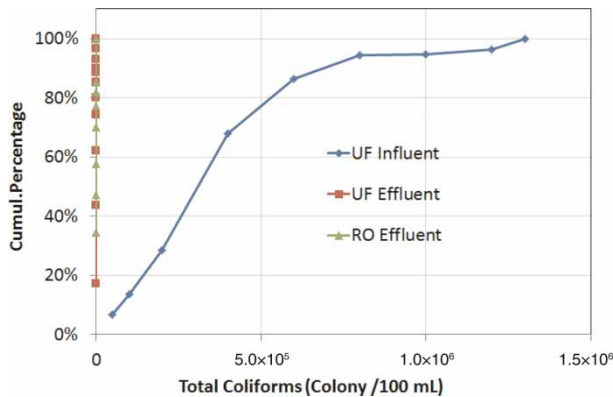


Figure 7 | Cumulative frequency distributions of the influent and effluent daily performance data for total coliforms.

>99% for TSS, TDS, BOD and total coliforms. Average removal efficiencies are the highest for TSS and total coliforms in the UF system, while they are the highest for TDS and BOD in the RO system. Cumulative frequency distribution analysis highlights process reliability indicating that UF and RO systems play an important role in consistently maintaining a stable plant performance and a high quality reclaimed water. The UF system proved essential for complementing successful performance of the RO system. The reclaimed water satisfies, at 99% frequency, the quality standards for potable water concerning TSS, TDS, BOD and total coliforms. The statistical analysis of performance data produces homogeneous groups of variables and signals the greater importance of cumulative frequency distribution in interpreting performance data.

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