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Performance evaluation of a wastewater reclamation plant using ultrafiltration and reverse osmosis

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ABSTRACT

Water reuse is receiving increasing attention worldwide as a means of sustainable water management. The Sulaibiya Wastewater Treatment and Reclamation Plant in Kuwait was established with a design capacity of 425,000 m^3/d to be the world's largest membrane-based water reclamation facility. These plants use ultrafiltration (UF) and reverse osmosis (RO) for reclamation of secondary-treated wastewater. Statistical analysis of plant data during 2012 revealed that the UF/RO was capable of producing effluents that satisfy water quality requirements for various reuse applications. It showed high stability and minimal response to seasonal variations in water temperature and to about 13% increase in inflow over its design capacity. The plant achieved almost 99% removal of common pollutants along the treatment stages by removing traces of residual pollutants such as BOD, TSS, nitrogen, phosphorus, and coliforms in the reclamation stage. Also, RO lowered the total dissolved solids of plant effluent considerably and maintained stability in effluent quality as raw wastewater composition changed. The effluent quality parameters were within the required potable water quality range and its variability was minimal as indicated by the coefficient of variation of each parameter. Water quality index of the treated effluent has improved substantially by the addition of the UF/RO reclamation stage.

Keywords: Wastewater reclamation; Ultrafiltration; Reverse osmosis; Plant performance

1. Introduction

Wastewater reclamation is the treatment or processing of wastewater to make it reusable with definable treatment reliability and to meet the required effluent water quality criteria. Over the last 40 years, the concept of promoting wastewater reclamation for water reuse to provide a water resource supplement has grown worldwide [1]. Moreover, Mantovani et al. [2], Anderson [3], and Hamilton et al. [4], among others, studied the environmental benefits of water recycling and reuse. They concluded that wastewater reclamation and reuse leads to reduced discharge of wastewater into the environment, particularly to receiving water bodies. Tong et al. [5] reported that using the reclaimed water for higher value applications results in a larger environmental credit.

The Middle East and North Africa (MENA) countries are considered to be the highest water-scarce

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countries in the world. Hamoda [6] reported that 6.3% of the world's population are living in the MENA, sharing only 1.4% of the world's renewable fresh water. The MENA countries use more of its renewable water resources than other countries and more water than it receives each year [7]. Currently, nearly 75% of the water resources in the MENA countries are allocated to agriculture, 22% to domestic use, and 3% to industries [8]. By the year 2050, it is expected that the demand for fresh water in the MENA region will increase by 50% and two-thirds of MENA countries could have less than 200 m^3 of renewable water resources per capita per year [7,9].

In the Arabian Gulf region, the Food and Agriculture Organization of the United Nations [10] confirms that the Gulf Cooperation Council (GCC) countries, with the exception of Oman, are using in excess of 100% of their available freshwater resources. In addition, the next 10 years will show an increase in water demand, as the GCC's expanding middle class takes over an increasingly water-intensive lifestyle, such as golf course areas, public and private swimming pools, and gardens. As a result, the GCC countries will face potential water shortages and will be among the world's highest per capita users of water.

The degree of treatment provided to domestic wastewater will largely be based on the required treated effluent standards set by the regulatory agencies when the effluent is to be discharged into a watercourse or land, or to be reused for different purposes [11]. In the GCC countries, all municipal wastewater treatment plants are required to treat wastewater to the tertiary stage. In addition, some treatment plants provide the tertiary-treated effluent with quaternary (advanced) treatment using membrane processes to render an effluent suitable for all water reuse purposes.

Membrane technology utilizes a semipermeable membrane for the separation of suspended and dissolved solids from water. It has been applied for many years in desalination of brackish and sea waters and was adopted recently in the wastewater treatment field. Membrane technologies are receiving special recognition as alternatives to conventional wastewater treatment and as a means of polishing treated wastewater effluent for reuse applications [12,13]. There has been a rapid growth in the use of reverse osmosis (RO) in the reclamation of wastewater. Relative to other technologies, the main drivers for this include the low energy consumption of RO and the high rate of contaminant removal [14]. Meanwhile, the most important target for the design of an RO-based wastewater reclamation system is to minimize membrane fouling through selection of an efficient pretreatment method such as ultrafiltration (UF) [15].

Nowadays, membrane technologies such as micro, ultra, nanofiltration, and RO play an increasingly important role in wastewater reclamation in large-scale municipal wastewater treatment plants. Table 1 shows the capacity of some large plants in operation worldwide: The Sulaibiya plant in Kuwait is the largest worldwide plant using the RO process for domestic wastewater reclamation.

Reclaimed water quality evaluation is required to determine conformity with applicable criteria and standards. Statistical methods for data analysis have become the common standard for assessing process efficiency and performance reliability [16,17]. Therefore, this study was initiated to evaluate the performance of the Sulaibiya plant. Such an evaluation is required to assess the existing effluent quality, determine plant efficiency, and generate additional data which can be used in the improvement of plant operation to cope with increasing loading conditions.

2. Plant description

The State of Kuwait, represented by the Ministry of Public Work embarked on its first build-operate-and-transfer (BOT) project—Pretreatment plant and pumping station at Ardiya and a reclamation plant at Sulaibiya to respond to the increasing demand for new fresh water resources. This wastewater treatment and reclamation plant (WWTRP) is a pioneer project, not only in the MENA countries where it is the first infrastructure facility of its size to be executed as BOT but also worldwide being the largest membrane-based water reclamation facility. The plant was commissioned officially in March 2005 after trials started on 4 November 2004.

2.1. Ardiya pretreatment plant and pumping station

As shown in Fig. 1, the raw wastewater entering the Ardiya pretreatment plant is conveyed via pressurized pipelines from the pumping stations in

Table 1
Common wastewater reclamation plants using membrane technologies worldwide

No.	Plant, country	Capacity m^3/d
1	Bedok, Singapore	32,000
2	Kranji, Singapore	40,000
3	West Basin, California, USA	50,000
4	Ulu Pandan, Singapore	170,000
5	Orange County, California, USA	270,000
6	Sulaibiya, Kuwait	425,000

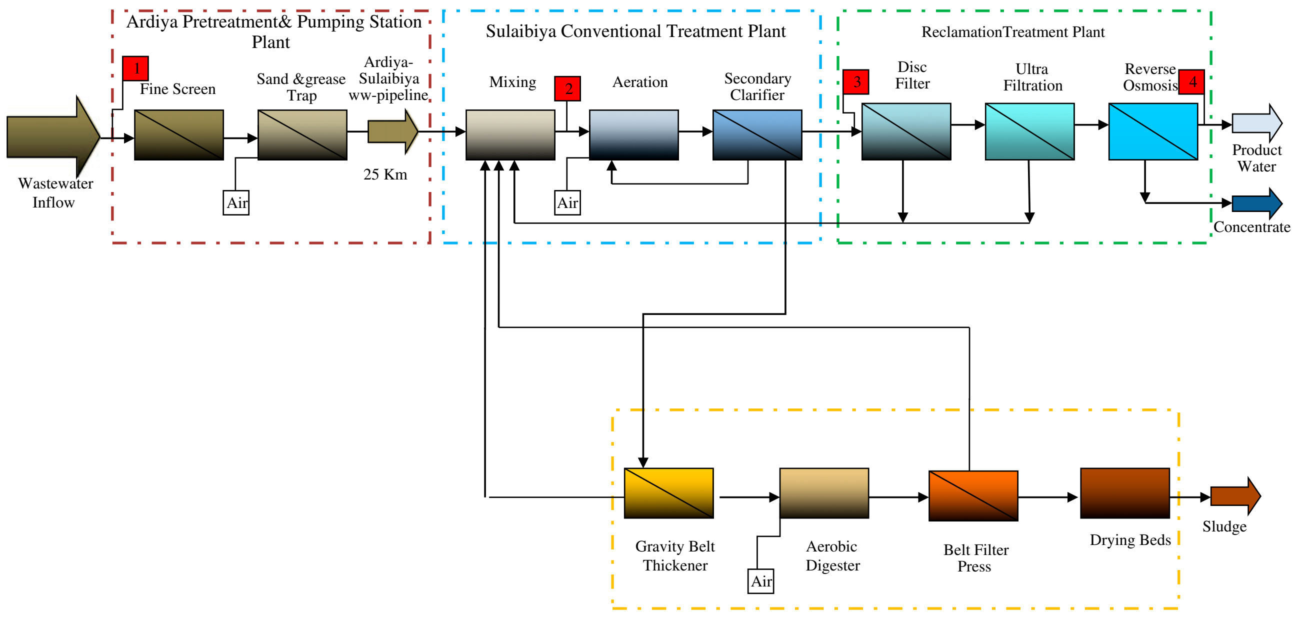

Fig. 1. Flow description of Ardiya—Sulaibiya WWTRP.

Kuwait city in a closed system to prevent contact with the atmosphere. Raw wastewater is screened through a fine screen (6 mm) to remove suspended material. The flow is then passed through aerated grit chamber to remove sand with a particle size above 0.2 mm and to grease traps. The flow is balancing in a buffer tank before pumping from the Ardiya site to the Sulaibiya site through three parallel pipelines with a length of approximately 25 km.

2.2. Secondary wastewater treatment stage

The inflow to Sulaibiya, backwash from disk filters, backwash from UF, filtrate from belt filter press, and filtrate from gravity belt are congregated in a distribution chamber before being introduced into aeration tanks for activated sludge treatment. The aeration tanks comprise of aerobic, anoxic, and anaerobic zones to provide nitrification, dentrification, and biological phosphorous removal. The secondary effluent is conveyed to circular secondary clarifiers to perform the separation of treated effluent and then return the activated sludge.

2.3. Reclamation plant

The secondary effluent is conveyed to the reclamation treatment stage to improve water quality by removing both undissolved and dissolved matters. The reclamation plant consists of disk filters, UF System, and RO system. The secondary effluent is first passed through mechanical disk filters having a mesh opening of 60 μ. The filters are suitable to fully remove all the suspended solids harmful to the UF system, and partially remove the fines, thus result in a reduced load to the UF and therefore in improved performance of the whole system even during possible upsets of the biological plant. The total flow is fed to the inside of the hollow fibers of the UF which are an effective barrier to solids, most colloids, bacteria, and viruses. The water pressure forces the water through the membrane pores (35 nm) into the permeate stream. UF system consists of five trains fed by six pumps via one common header, and one standby pump. Three trains consist of 14 skids each and two trains consist of 13 skids each. The filtrate from the UF system is conveyed by a pumping station to the RO plant. The RO plant, in-turn, consists of six trains, with each train having three stages. Pressure forces the water through a semi permeable membrane which freely passes water and rejects most of the dissolved materials including ions as well as bacteria or viruses in the feed water. The first stage consists of four pumps feeding four RO-skids from the same reservoir. Downstream of the skids, the permeate flow (50% of the feed flow) is conveyed to the permeate header; whereas, the reject flow (also 50% of the feed flow) is introduced to the second stage. The second stage consists of two pumps feeding two RO-skids. Here also, 50% of the feed is permeate flow, which is conveyed to the permeate header and 50% of the feed is rejected.

Table 2
Characteristics of membrane systems employed at Sulaibiya water reclamation plant

Membrane system	Membrane type	Membrane configuration	Membrane arrangement	Membrane area
Ultrafiltration (UF)	Norit's X flow cross-flow, The Netherland (Model XIGA SXL-225) Polyvinyldene fluoride	Capillary hydrophilic hollow fibers	Membranes 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
Reverse osmosis (RO)	Toray of America (Model TML 20-400) polyamide composite	Spiral wound	Membrane modules of 42 identical skids in a 4:2:1 array (train) 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 reject flow is introduced to the third stage which consists of a pump feeding one skid. Here, 40% of the feed is permeating, while 60% of the feed is rejected. A valve downstream of the third stage skid maintains a constant flow rate.

The reclamation system is equipped with clean-in-place systems for both the UF and RO membranes and chemical injection systems for required chemical dosing. Product from the RO system flows to the CO_2 stripping tower and then to the permeate basin. The product water is conveyed to storage tanks for reuse while the concentrate is discharged into the Gulf waters.

2.4. Design parameters

The design parameters of the treatment and reclamation plant are as follows: the total design inflow is 425,000 m^3/d and the nominal production of the plant is 361,250 m^3/d based on the RO product recovery of 85%. Characteristics of each of the UF and RO membranes are summarized in Table 2.

3. Methodology

A one-year operating and performance data on various parameters were collected daily during the year 2012 (January–December) and were subjected to statistical analysis. The objective was to statistically determine the final effluent quality, the reclamation process efficiency, and the plant performance reliability. The effluent quality was compared with the Kuwait's EPA [18] Regulations and Standards, and WHO criteria for potable water [19].

The water samples were collected from four locations along the plant as shown in Fig. 1. The sampling points specified represent different stages as:

- Stage (1) the raw wastewater influent to Ardiya pretreatment and pumping station plant.
- Stage (2) the wastewater received at Sulaibiya after primary treatment in Ardiya (before secondary biological treatment).
- Stage (3) the treated wastewater after secondary clarifier (after biological treatment).
- Stage (4) the final product water after UF/RO treatment (after reclamation).

These samples were analyzed, according to standard methods [20], in the laboratory of the Sulaibiya plant which is equipped with advanced analytical instruments of high degree of precision. Several physical, chemical, and biological parameters were determined in the influent (raw wastewater), the primary-treated effluent, the secondary-treated effluent, and the final reclaimed effluent (product water). In the case of biological (bacteriological) parameters, both total coliforms and fecal coliforms were determined in CFU/100 ml and MPN/100 ml units.

4. Results and discussion

Statistical analysis of Sulaibiya plant data was conducted to assess the performance of UF/RO reclamation process. Such analysis has become a common tool to evaluate process performance and process reliability. Monthly averages of different parameters at various treatment stages were determined and compared.

4.1. Variations in plant operation and performance parameters

Figs. 2 and 3 show the monthly variations in operating parameters (flow rate and temperature, respectively) while Figs. 4 and 5 present the performance parameters such as effluent quality concentrations (i.e. TSS, total dissolved solids (TDS), BOD, etc.) along the treatment stages. Fig. 2 displays the seasonal increase in flow rates during the period July–December when compared to those recorded during the period January–June. In addition, it shows that the average recovered water flow from RO was about 80% of influent water. In December, the reclamation plant was under maintenance for 2 weeks, which explains the drop in plant capacity by almost 40% during the maintenance period.

Currently the plant treats around 60% of Kuwait's total domestic wastewater. With an initial daily capacity of up to 375,000 m^3/d when formally dedicated in March 2005 and a design capacity of 425,000 m^3/d—the Sulaibiya plant received up to 480,000 m^3/d of wastewater during the year 2012 (Fig. 2) which represents about 13% increase in flow over its design capacity. Plans are underway to extend the plant capacity to 600,000 m^3/d through new expansion of facilities. The facility contributes about 25% of Kuwait's overall fresh water demand for non-potable uses. The current use of product (reclaimed) water is limited to agricultural and industrial applications and possibly in a variety of house usages. In order to maintain water sustainability, it is strongly believed that the reclaimed water be recharged to the groundwater aquifers to become strategic water storage and replenish the over use of groundwater in agriculture which has led to problems of increased salinity of groundwater. Moreover, the RO reject concentrate can be valuable for makeup of heavy oil field development.

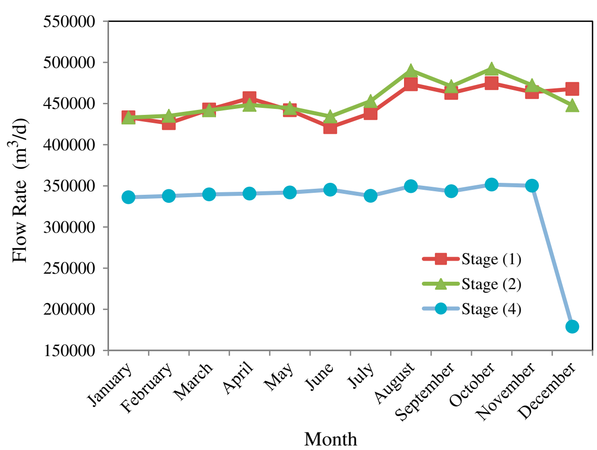

Fig. 2. Variations in influent flow to primary and secondary treatment stages when compared to the final recovered effluent from the quaternary stage.

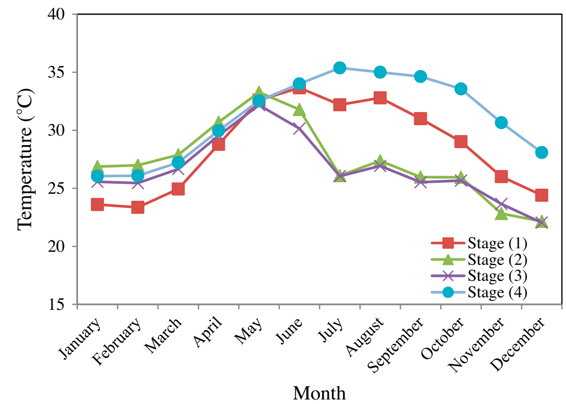

Fig. 3. Monthly variations in water temperature along the treatment stages.

For water temperature variations, Fig. 3 displays two distinct periods where the months from July to December showed higher temperature than those of the months from January to June. This trend is somewhat similar to that observed for flow variations and reflects the increase in water consumption and the corresponding increase in wastewater flow at higher ambient temperatures and the resulting increase in water temperatures. Such variations in plant operating parameters were reflected, but to a lesser extent, in plant performance parameters shown in Figs. 4 and 5. Unlike stages 1–3, the water reclamation stage (designated as 4 in all figures) showed minimal variations in response to variations in inflow (up to 13% increase beyond design capacity) and in seasonal temperatures indicating high stability of UF/RO process performance.

For operating pressures, the feed pressures to the RO modules arranged in three stages (4:2:1 modules array) were 11 bar to the stage 1 modules, 13 bar to the stage 2 modules, and 15 bar to the stage 3 modules. The transmembrane pressure data were stable and the RO membranes showed high resistance to fouling since the pretreatment was effective and the automatic-controlled membrane washing system was efficient.

4.2. Effectiveness of treatment stages

Figs. 6–8 display the general trend in the reduction of different pollution parameters along the treatment stages. In each case, the minimum, average, and maximum concentrations were calculated and presented in bar graphs. Based on average values shown, the

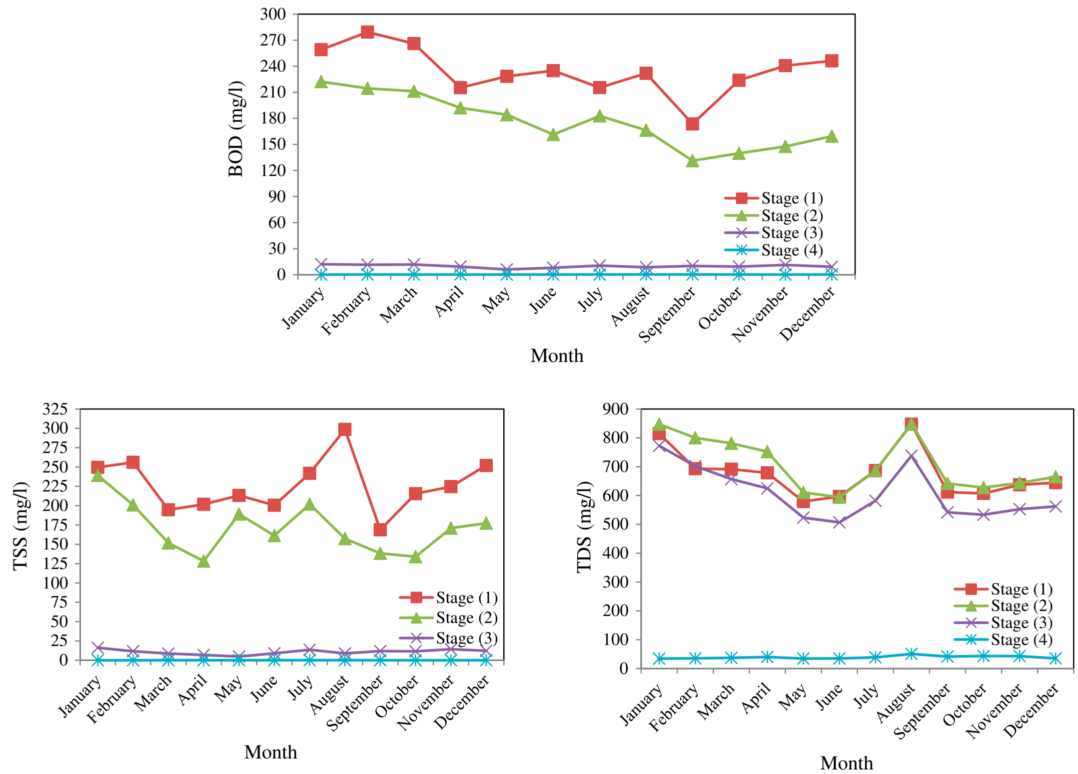

Fig. 4. Monthly variations in effluent BOD, TSS, and TDS along the treatment stages.

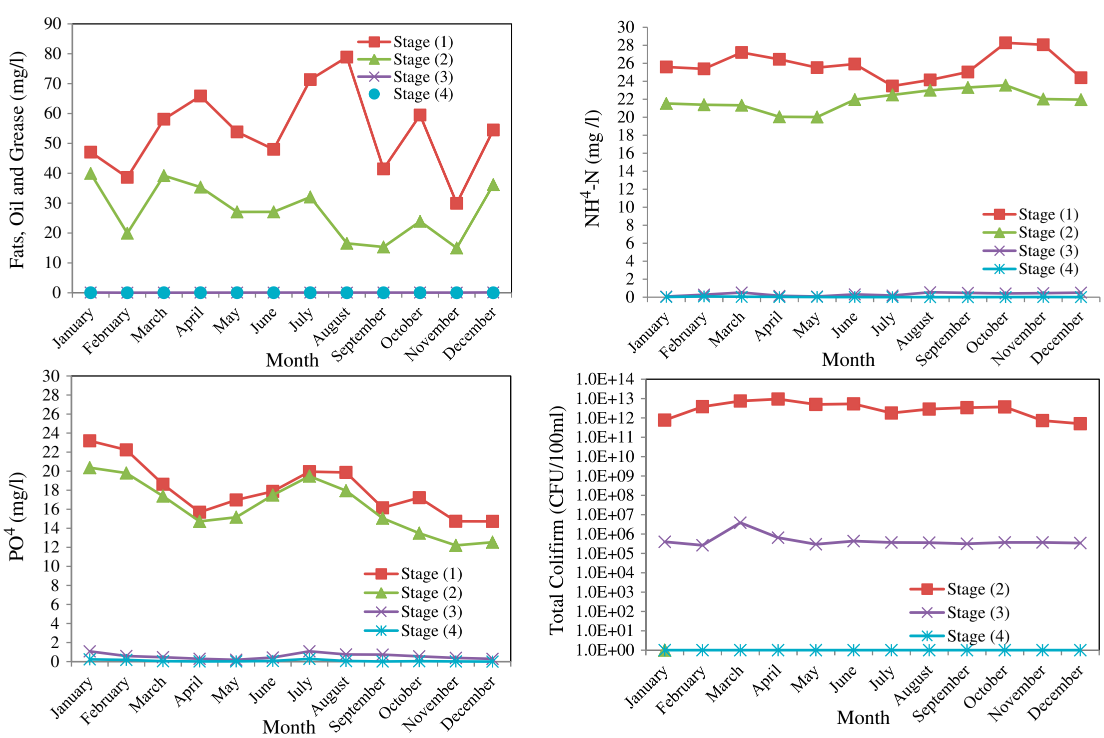

Fig. 5. Monthly variations in total fats, ammonia, phosphate, and coliforms along the treatment stages.

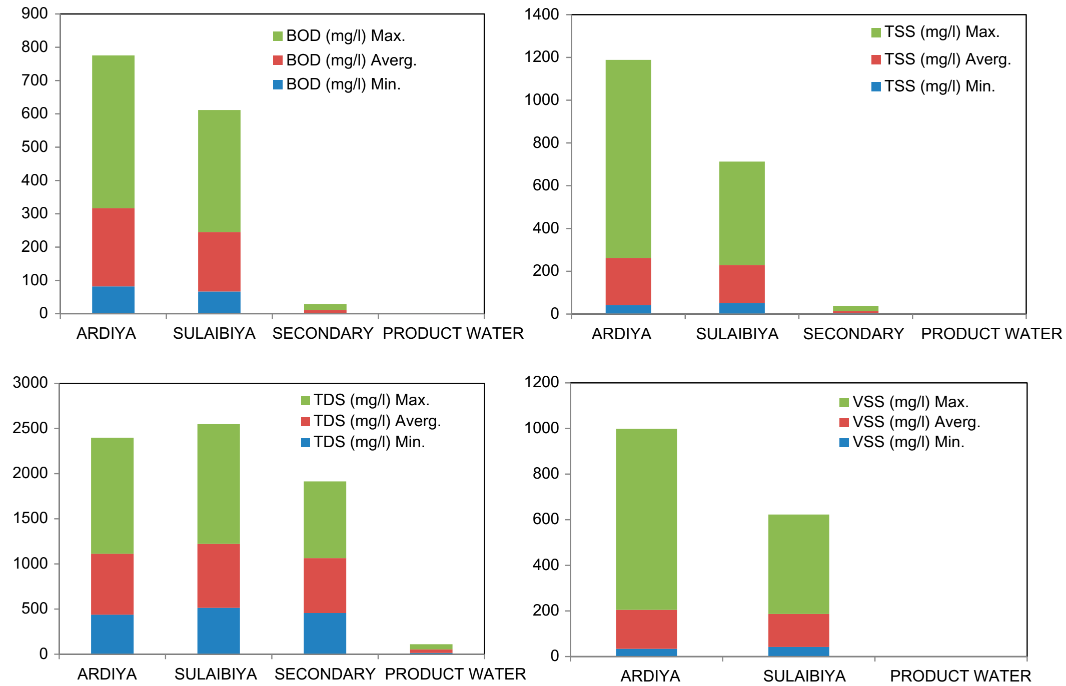

Fig. 6. Statistical variations in BOD, TSS, TDS, and VSS concentrations along treatment stages.

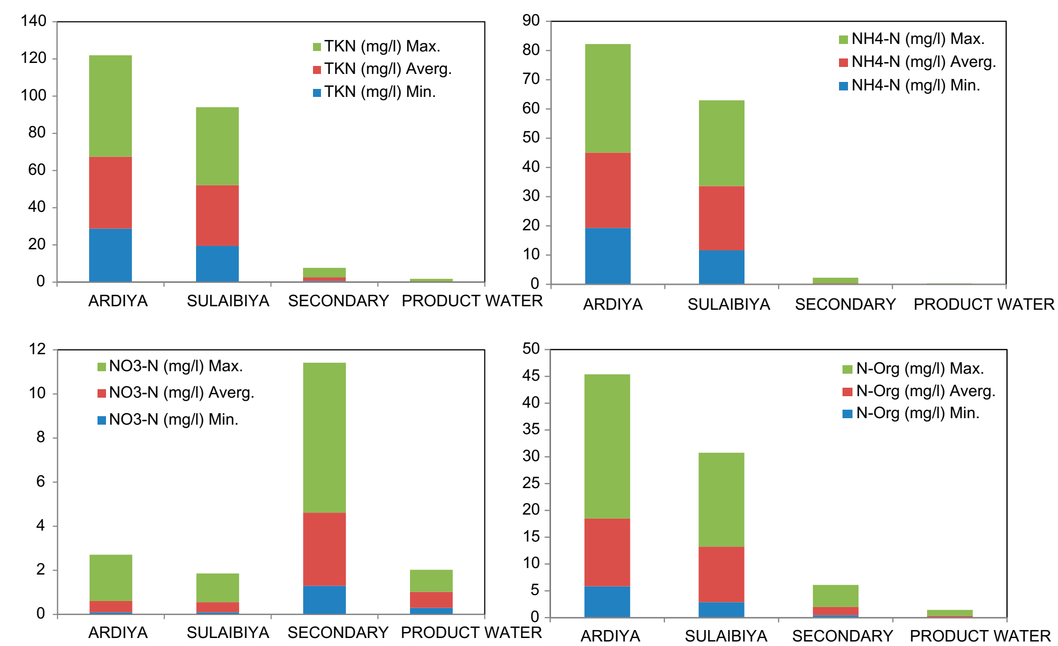

Fig. 7. Statistical variations in TKN, ammonia, nitrates, and organic nitrogen concentrations along treatment stages.

overall removal efficiencies achieved after the reclamation stage were consistently greater than 95% for all parameters based on the average concentration values obtained in each case. Such removal efficiencies reached up to 99% for BOD, TSS, PO_4, and coliforms. Although the secondary treatment stage was quite effective in removing some pollution parameters, the reclamation stage played a complimentary or

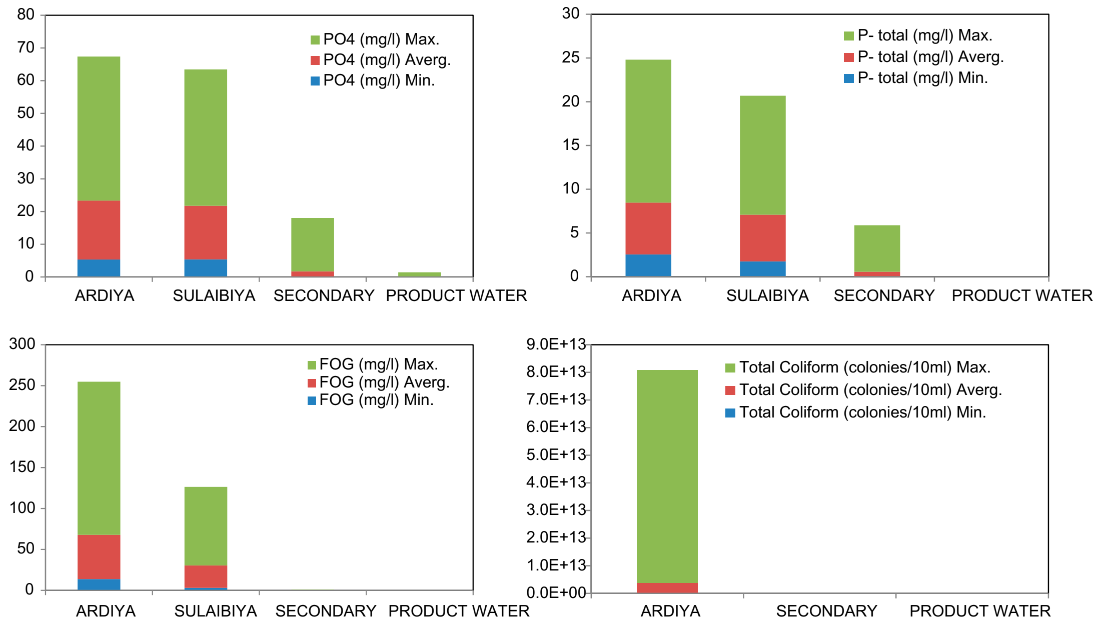

Fig. 8. Variations in total phosphates, phosphorus, fats, and coliform concentrations along treatment stages.

Table 3
Effluent quality of secondary-treated and reclaimed product water when compared to water quality criteria

Parameter	Unit	Secondary effluent	Reclaimed product water	Kuwait standard for irrigation water (Max.)	Kuwait standard for unbottled potable water (Max.)	WHO allowable limits for drinking water (Max.)
pH	–	7.3	7.3	6.5–8.5	6.5–8.5	6.5–8.5
BOD	mg/L	11	0.23	20	–	–
TSS	mg/L	7	0.024	15	–	–
TDS	mg/L	580	39.3	1,500	1,000	1,200
NH_3-N	mg/L	0.53	0.025	15	1.5	1.5
NO_3-N	mg/L	1.1	0.73	35	–	10
PO_4	mg/L	1.2	0.04	30	–	–
Sulfide	mg/L	2	0.013	0.1	0.05	0.1
Chlorine	mg/L	0.25	0.11	0.5–1.0	0.2–0.5	–
Fats, oil, and grease	mg/L	4.9	0.015	5	0.01	0.01
Turbidity	NTU	30	1		–	–
Hardness as $CaCO_3$	mg/L	360.8	2.9	500	500	500
Total coliform	MPN /100 mL	300	1	400	Free	1
Fecal coliform	MPN /100 mL	15	0	20	Free	Free

major role in removing the last traces of each parameter. In fact, RO was primarily responsible for reductions in TDS concentrations which remained almost unchanged, or even increased due to chemical additions, in the course of prior treatment stages. This was also true for UF in the case of TSS concentrations.

4.3. Effluent quality

For the reclamation plant effluent data (Table 3), it is noted that the specifications of the reclaimed water produced from the Sulaibiya plant not only satisfied the irrigation water quality criteria, but also the WHO guidelines for potable water quality and Kuwait's EPA standards for Unbottled Potable water, 2001. The plant produced the highest water reuse quality of reclaimed water that is suitable for potable water supply and for groundwater recharges [21]. Moreover, heavy metal concentrations were all much lower than the maximum allowable limits for both irrigation waters and potable waters.

If the concentrations of water quality parameters, especially the nutrients, exceed the standard limits, the reclaimed water can be problematic to agriculture and the environment. The hydraulic conductivity of the soil can be reduced if reclaimed water contains high C:N ratio which can promote excessive growth of the soil microfauna and cause clogging in the soil pores. Presence of fats, oil, and grease (FOG) also adversely affect water reuse applications. Moreover, the TDS as well as coliforms of the treated effluent are critical parameters for water reuse in irrigation. It is also necessary to examine the variability in water quality parameters to determine compliance with applicable criteria and standards.

Table 4 presents the statistical parameters of plant performance data and effluent quality parameters. Product water quality showed minimal changes as raw wastewater composition changed but values were within the required water quality range. Moreover, the variability in product water quality was minimal as indicated by the coefficient of variation (CV) of each performance parameter which is calculated as follows:

$$\text{Coefficient of Variation (CV)} = \text{Standard Deviation/Mean}$$

The low CV (≤0.2), obtained in numerous cases, for a series of product water data in Table 4 clearly shows

Table 4
Statistical values of water quality parameters for streams along the Ardiya–Sulaibiya wastewater plant

	Raw influent			Primary effluent			Secondary effluent			Product water		
Parameters	Mean	SD[a]	CV[b]	Mean	SD	CV	Mean	SD	CV	Mean	SD	CV
Temp (°C)	24.40	3.97	0.162	27.32	3.94	0.141	30.4	3.21	0.122	31.2	3.54	0.111
pH	6.89	0.12	0.017	7.21	0.11	0.017	7.31	0.12	0.017	7.31	0.11	0.015
BOD (mg/L)	246.2	69.94	0.284	178.5	51.62	0.289	11.09	2.706	0.244	0.23	0.02	0.087
TSS (mg/L)	251.94	98.80	0.392	177	57.49	0.324	7.02	2.04	0.291	0.024	0.0059	0.246
TDS (mg/L)	644.87	159.51	0.247	708.3	138.83	0.196	580.2	105.0	0.181	39.3	6.73	0.171
Turbidity (NTU)	ND[d]	ND	ND	ND	ND	ND	30	6	0.200	1	0	0
Alkalinity[c] (mg/L)	165.21	16.71	0.10	185.11	15.62	0.08	4.68	0.48	0.103	0.808	0.074	0.091
FOG (mg/L)	54.49	26.87	0.491	27.39	12.89	0.472	4.91	2,018	0.411	0.015	0.006	0.389
NH_4-N (mg/L)	24.39	3.15	0.130	21.98	2.23	0.131	0.53	0.059	0.111	0.025	0.003	0.110
N-Org (mg/L)	14.12	3.46	0.241	10.35	2.31	0.222	3.05	0.641	0.211	0.053	0.010	0.180
NO_3-N (mg/L)	0.48	0.21	0.43	0.46	0.16	0.34	1.10	0.319	0.29	0.73	0.12	0.164
P-total (mg/L)	4.80	1.88	0.392	5.33	1.47	0.275	0.41	0.099	0.241	0.013	0.003	0.238
PO_4 (mg/L)	14.72	5.57	0.38	16.38	4.51	0.28	1.21	0.328	0.271	0.041	0.010	0.251
Chlorine (mg/L)	ND	ND	ND	ND	ND	ND	0.25	0.105	0.421	0.11	0.043	0.388
Chloride (mg/L)	164.48	77.86	0.47	ND	ND	ND	120.23	49.29	0.410	22.11	5.373	0.243
SO_4 (mg/L)	122.61	23.89	0.19	ND	ND	ND	ND	ND	ND	22.13	2.434	0.111
Sulfide (mg/L)	ND	ND	ND	ND	ND	ND	2.1	0.989	0.471	0.013	0.006	0.462
TKN (mg/L)	39.57	4.55	0.11	32.64	2.69	0.08	4.68	1.273	0.261	0.808	0.133	0.165
Hardness[c] (mg/L)	ND	ND	ND	ND	ND	ND	360.8	137.46	0.381	2.9	0.45	0.155
Total coliform (MPN/100 mL)	ND	ND	ND	ND	ND	ND	300	129	0.433	1.0	0.0	0.0
Fecal coliform (MPN/100 mL)	ND	ND	ND	ND	ND	ND	15	6	0.400	0.0	0.0	0.0

[a]SD: standard deviation.
[b]CV: coefficient of variation.
[c]Expressed as $CaCO_3$.
[d]ND: not determined.

that the group of data is less variable and it is more stable (or more uniform). This clearly indicates the reliability of the UF/RO process performance.

4.4. Water quality index

The water quality index (WQI) is a tool to provide consistent procedures for concerned jurisdictions to report water quality information to both management and the public. Indices are communication and education tools that summarize a number of water quality variables into a single measure of overall water quality. Calculations of indices are best performed by scientific specialists with expertise in environmental water quality. For simplicity, an online calculator for determining a WQI of surface waters developed by the National Sanitation Foundation, as posted on website [22], was used in this study to compare the quality of four water streams generated along the stages of the Sulaibiya treatment plant. The WQI used is a 100-point scale that summarizes results from a total of eight different parameters, namely pH, dissolved oxygen (% saturation), turbidity (NTU), BOD (mg/L), total solids (mg/L), total phosphates (mg/L), nitrates (mg/L), and fecal coliforms (MPN/100 mL). The 100-point index can be divided into several ranges corresponding to the general descriptive terms as "Excellent" (90–100), "Good" (70–89), "Medium" (50–69), "Bad" (25–49), and "Very Bad" (0–24). The WQI was thus calculated in this study based on average values for each of the eight parameters at each of the four sampling points of the water streams along the treatment stages. The results are presented in Fig. 9, indicating that the WQI has improved from being "very bad" (23 points) for the raw wastewater to "Good" (72 points) for the secondary-treated effluent and was upgraded to "Excellent" (97 points) after the UF/RO reclamation stage. This clearly indicates the role of the reclamation stage in improving the effluent quality substantially, thus making the reclaimed effluent suitable not only for discharge into water streams but also for utilization in a variety of water reuse applications.

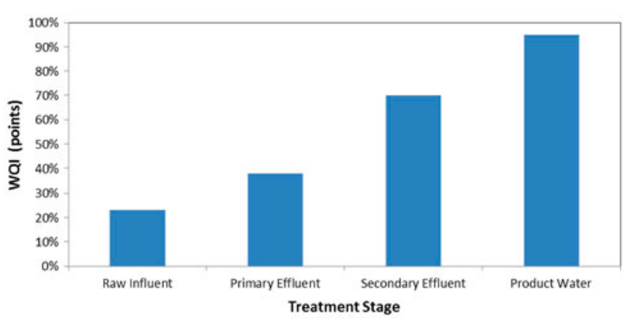

Fig. 9. Water quality index of various streams along the treatment stages.

5. Conclusions

Evaluation of plant performance and quality of reclaimed water by statistical analysis serves to verify the time variability of the plant results. Estimated values for the mean and the standard deviation were used to evaluate process performance and reliability of different treatment stages over a one-year operation period. The water reclamation stage at Sulaibiya plant showed high stability and minimal response to seasonal variations in water temperature and to up to 13% increase in inflow over its design capacity. The reclamation plant achieved almost 99% removal of pollutants along the treatment stages by removing traces of residual pollutants and lowering the TDS of the plant effluent considerably. It produced the highest water reuse quality of reclaimed water that is suitable not only for irrigation but also for potable water supply and for groundwater recharge. The UF/RO system provided stability in overall plant performance. Product water quality showed minimal changes as raw wastewater composition changed and values were within the required potable water quality range and achieved an excellent water quality index. Moreover, the variability in product water quality was minimal as indicated by the CV of each performance parameter. The plant performance data presented in this study provide basic references for establishing consistent regulatory water quality limits, determining regulatory compliance, controlling water reclamation processes and facilities, and evaluating process performance and reliability.

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