*Desalination and Water Treatment*
www.deswater.com
doi: 10.1080/19443994.2016.1148640

57 (2016) 24742–24749
November

Taylor & Francis
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# Long-term assessment of the product water of sulaibiya wastewater treatment and reclamation plant, Kuwait

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Received 22 November 2015; Accepted 25 January 2016

ABSTRACT

This paper presents a long-term assessment of the quality of the final product water of Sulaibiya Wastewater and Reclamation Plant (SWTRP), which is the world's largest reverse osmosis (RO) wastewater plant. The assessment was based on 10 years of the plant's monthly records of the effluent quality. The results obtained indicated that the final product water had met targeted design values all the times without a single incidence of violation. However, statistical analyses have shown that some of the parameters have seasonal patterns, and most of them are characterized by high variability. Further, the distributions of the effluent data were found to be highly skewed. In general, the distributions of the effluent data were found to neither follow normal nor log normal distributions. Knowledge of effluent distribution is of fundamental importance in assessing the reliability of existing wastewater treatment plants. It is also basic for design of new plants.

*Keywords:* Wastewater; Reuse; Membrane; Reverse osmosis; Modeling; Control

## 1. Introduction

Although wastewater reuse has many more economical and environmental benefits, the main driving forces for the worldwide rise in reuse of wastewater are the water scarcity and the increasing demand for food and fibers [1,2]. In fact, wastewater reuse has become the most attractive option to alleviate pressure on the scarce water resources. It is now common practice, especially arid and semiarid regions [3].

Kuwait is situated in a harsh environment characterized by little rainfall (130 mm/yr) and high evaporation rates (400 mm/yr), and it has no natural freshwater resources other than very limited amounts of brackish groundwater, which is overexploited. For long time, thus, Kuwait has depended on the expensive desalination of seawater to satisfy all its water demands. To maintain sustainable development, the country has recently pursued an ambitious program to reuse treated municipal wastewater as mainly irrigation water. Towards that goal, Kuwait has built the world's largest reverse osmosis (RO) wastewater treatment plant, Sulaibiya Wastewater Treatment and Reclamation Plant (SWTRP) (Fig. 1). The use of RO in wastewater treatment plants has started in 1970s in USA [4].

SWTRP was built for treating on average 375,000 $m^3$/d (maximum: 425,000 $m^3$/d) of mainly domestic wastewater, with the possibility of future expansion of up to 600,000 $m^3$/d [5]. SWTRP, which was officially commissioned in 2005, treats at present more than 425,000 $m^3$ per day [6].

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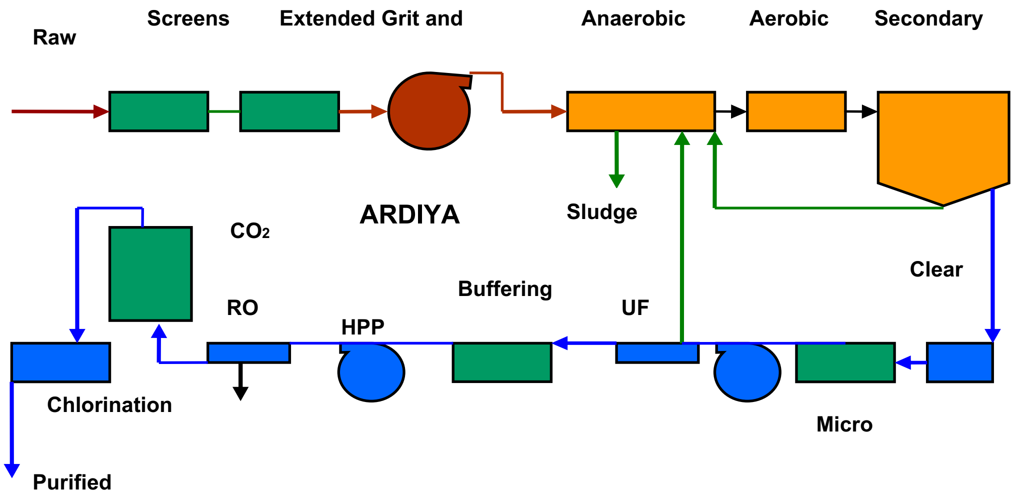


Fig. 1. Layout of Sulaibiya wastewater treatment and reclamation plant [7].

SWTRP consists of two parts: Ardiaya and Sulaibiya parts. Ardiya part is located about 25 km from the main treatment and reclamation units in Sulaibiya. At Ardiaya only preliminary treatments take place (removal of particulate matter, grit, oil, and grease), while both secondary and advanced treatments are provided at Suliabiya. The secondary treatment units consist of advanced biological nutrient removal (BNR) tanks and secondary settling tanks. The BNR tanks are designed with anaerobic, anoxic, and aerobic zones for enhanced biological removal of nitrogen and phosphorus. The main advanced treatment (the reclamation) units at Sulaibiya are the disk filtration units, the ultra filtration (UF) units and the RO units. The RO permeates pass carbon dioxide ($CO_2$) stripping and then undergo chlorine disinfection before leaving the plant as final product water. The RO reject (brine) water is discharged to the Gulf after dilution. More information about the plant's design can be found in, e.g. Gagne [7] and Hamoda et al. [6].

UF + RO treatment processes are usually used to remove residual pollutant, dissolved solids and pathogens [8]. Reclamation using RO usually results in high-quality final product water that exceeds the World Health Organization (WHO) standards for potable water. Such advanced treatment often deprives the water of nutrients and other elements essential for plant growth, and thus, makes it unsuitable for agricultural uses [9]. At present, however, SWTRP product water is used mainly for agricultural and landscape irrigations. The main objective of this paper is to assess the long-term quality of SWTRP final product water.

## 2. Materials and methods

### 2.1. Data used in the study

Data used in this study are the monthly records of the performance of SWTRP since its commission in 2005–2014. This data contain measured quality and quantity of the various wastewater streams. Wastewater quality parameters were determined in SWTRP's laboratories according to the American Public Health Association [10] standard methods for examination of water and wastewater [6].

### 2.2. Statistical analysis

Matlab software was used in the statistical analyses. First, descriptive statistics (mean, maximums, minimums, standard deviations, and coefficient of variations) were determined. As normality is a basic assumption of the descriptive statistics, the data were then tested whether they are approximately normally or log-normally distribution, using graphical technique (normal and log-normal plots). Normally distributed data usually form approximately straight lines when they are plotted in a log-scale against a theoretical normally distributed data. Log-normally distributed data will also appear as a straight line when they are plotted on a log–log scale. Significant departure from a straight line is often taken as a sign of not following normal or log-normal distribution. The departures from normal distribution (e.g. skewness, long, and/or short tails) were then confirmed from histograms. Box plots were mainly used to assess the existence of seasonal variability in the data.

## 3. Results and discussion

Table 1 presents the statistical summary of the measured quality parameters of SWTRP's final product water. Table 2, which compares the measured values to targeted values, clearly shows that the targeted values were met at all times. In general, most of the measured values were far below the targets. For example, TDS was only 30.5 mg/l, while it is desired to be just below 100 mg/l. In fact, the quality of the final product water was even better than potable water quality. However, the high values of the coefficient of variation (CV), given in the last column of Table 1, indicate that most of the quality parameters are characterized by high variability. Variability of TSS and VSS were around 200%, while that of $H_2S$ and total coliform were around 400% or more. This is not in agreement with the finding of Hamoda et al. [6], who studied only the records of year 2012. Table 2 also shows that the standard deviation is higher than the average value for most of the parameters. This indicates that values of the parameters were spreading widely. It also points to the existence of a significant number of outliers in the data.

Fig. 2 shows clearly that all the quality parameters do not form straight lines when they were plotted in log papers. It is apparent that obtained plots depart highly from the theoretical straight lines, particularly at the lower ends. This indicates that the distributions are not normally distributed, but they are highly skewed to the right. Because some measured data contained zero values, we were able to create log–log plots only for pH, TDS, $NO_3$-N, and $CaCo_3$ hardness data (Fig. 3). In comparison to Figs. 2 and 3 shows a slight improvement in the fit to the theoretical straight. However, there still significant departure from the straight line at the lower ends. Therefore, it can be concluded that the distributions of the quality parameters do not follow normal or log-normal distributions.

To give more of an idea about the shape of the distributions, measured values of the parameters were plotted as histograms (Fig. 4). These histogram shows clearly that the distributions are highly skewed and none of them follows a normal distribution. It is also apparent that the distributions of TSS, VSS, TDS, $NH_4$-N, $PO_4$, $CaCo_3$ hardness, $H_2S$, and total coliform are highly skewed to right, while the distributions of pH and $NO_3$-N are skewed to left. Thus, the basic assumption that the data are normally distributed is violated. In such a case, the use of the statistics given in Table 1 can lead to incorrect conclusions [11,12].

Fig. 5 presents the box plots of the measured quality values of the product water. Box plot is a convenient way of graphically depicting numerical data through their quartiles, through box and whiskers. The box boundaries represent the first and third quartiles, respectively. Depending on the data, the median (shown here as a dot in a circle) is often shown inside the box. The spacing between the whiskers indicates the spread of the data and the presence of skewness and outliers, if any, in the data. Outliers are usually are symbolized by cross signs. Fig. 5 shows that TSS, VSS, TDS, $NH_4$-N, and $CaCO_3$ hardness are highly skewed to right. It also shows that TSS, VSS, $PO_4$-P, and $BOD_5$ have significant numbers of outliers at the higher values, while pH has outliers at the lower values. These findings confirm that the data are not normally distributed nor log-normally distributed. High spread nature of the data and presence of outliers

Table 1
Characteristics of SWTRP's final product water

| Parameter | Average | Max. | Min. | Standard deviation | CV (%) |
|---|---|---|---|---|---|
| pH (–) | 7.21 | 7.72 | 5.92 | 0.29 | 3.96 |
| TSS (mg/l) | 0.07 | 0.50 | 0 | 0.12 | 177.52 |
| VSS (mg/l) | 0.07 | 0.50 | 0 | 0.12 | 178.58 |
| TDS (mg/l) | 30.53 | 60.30 | 14.60 | 13.03 | 42.69 |
| O & G (mg/l) | 0 | 0 | 0 | 0 | 0 |
| $NH_4$-N (mg/l) | 0.14 | 0.50 | 0 | 0.13 | 95.72 |
| $NO_3$-N (mg/l) | 0.67 | 0.90 | 0.40 | 0.14 | 21.47 |
| $PO_4$-P (mg/l) | 0.09 | 0.60 | 0 | 0.12 | 133.89 |
| $H_2S$ (mg/l) | 0.00 | 0.00 | 0 | 0.00 | 375.73 |
| $CaCO_3$ Hardness (mg/l) | 1.82 | 3.90 | 0.58 | 1.12 | 61.66 |
| Total coliform | 2.48 | 93.00 | 0 | 11.84 | 476.75 |
| $BOD_5$ (mg/l) | 0.18 | 0.80 | 0 | 0.13 | 74.01 |
| Water recovery rate (%) | 74.85 | 86.22 | 27.21 | 11.30 | 15.09 |

Table 2
Targeted vs. measured characteristics of the final product water [7]

| Parameter | Targeted monthly average | Measured monthly average |
|---|---|---|
| pH | 6–9 | 7.21 |
| TDS (mg/l) | <100 | 30.53 |
| TSS (mg/l) | <1 | 0.07 |
| $BOD_5$ (mg/l) | <1 | 0.18 |
| $NH_4$-N (mg/l) | <1 | 0.14 |
| $NO_3$-N (mg/l) | <1 | 0.67 |
| $PO_4$-P (mg/l) | <2 | 0.09 |
| O & G (mg/l) | <0.05 | 0 |
| TOC (mg/l) | <2 | – |
| Hardness as $CaCO_3$ (mg/l) | <10 | 1.82 |
| Enteric viruses | 5 MPNIU/10 l | – |
| Total coliform | <2.2 colonies/100 ml | 2.48 |

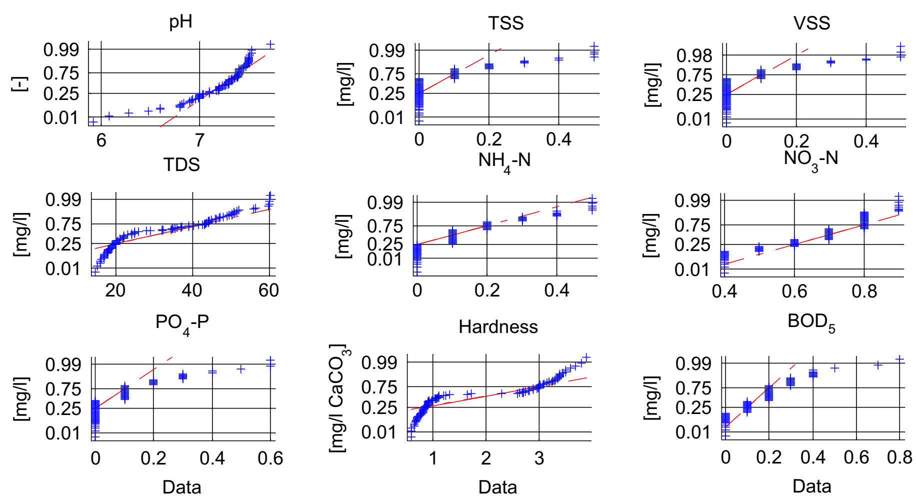


Fig. 2. Normal plots of the final product water quality parameters.

explains why the standard deviation of some parameters was found to be higher than the mean value (Table 1).

Box plots were mainly used to detect any seasonal variability that may exist in the data. For that purpose the whole data-set was sorted by the month of the year, and then a box plot was created to compare the recorded values for the quality parameters during the 12 months of the year. Apparent seasonal variability in the median value was observed only for TDS and $CaCO_3$ hardness box plots. As shown in Fig. 6, there are apparent relative increases in the median values of TDS and $CaCO_3$ hardness during the months May, June, July, and August. These months are hottest months of the year in Kuwait. However, this could not be explained from available data, and therefore, further investigations are recommended. The same figure also shows that the spread of the data for these quality parameters is almost the same for all month of the years. That is, the monthly ranges of these two quality parameters remained almost the same throughout the year.

Knowledge of effluent distribution is of fundamental importance in design and reliability assessment of wastewater treatment plants. Usually effluent data follow normal or log-normal distributions [13–15]. The above-mentioned analysis, however, clearly indicates that it is not reasonable to assume that the random errors in the measured quality parameters of SWTRP's final product water are normally distributed. Therefore, incorrect decisions will be made more than any confidence level for an inference to be made using the

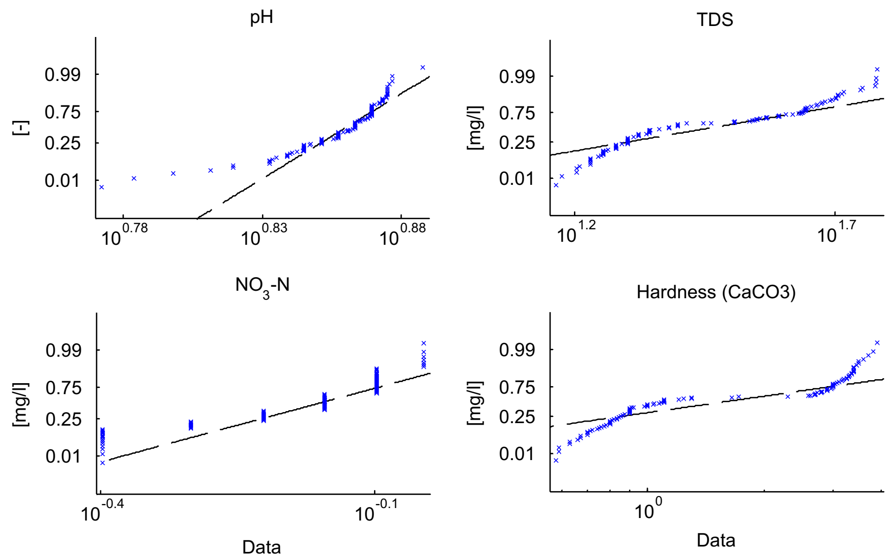


Fig. 3. Log-normal plots of some of the final product water quality parameters.

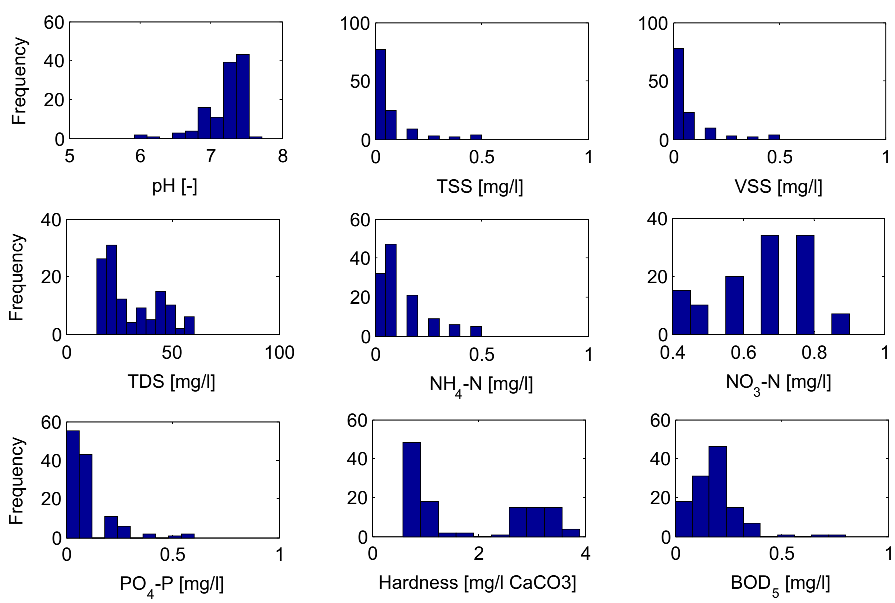


Fig. 4. Histograms of the final product water quality parameters.

calculated descriptive statistics given in Table 1. This will greatly impact the efforts to improve or control the process, since they are usually based on the values of statistical parameters such as the mean and the standard deviation. For such highly skewed data, engineers need to use special techniques to transform the data into approximately normally distributed data [16,17].

However, a more comprehensive study is needed to investigate potential relationships between the plant design, the input characteristics, the plant operating conditions and the high variability found in the values of the quality parameters of the final product water. Such correlations are important for a broad assessment of the reliability of the treatment processes, early identification of system failure, and redesigning of the treatment processes or their control systems.

Table 1 also shows that the average recovery rate at SWTRP was about 75%, which means that about 25% of the plant influent was lost as sludge and RO

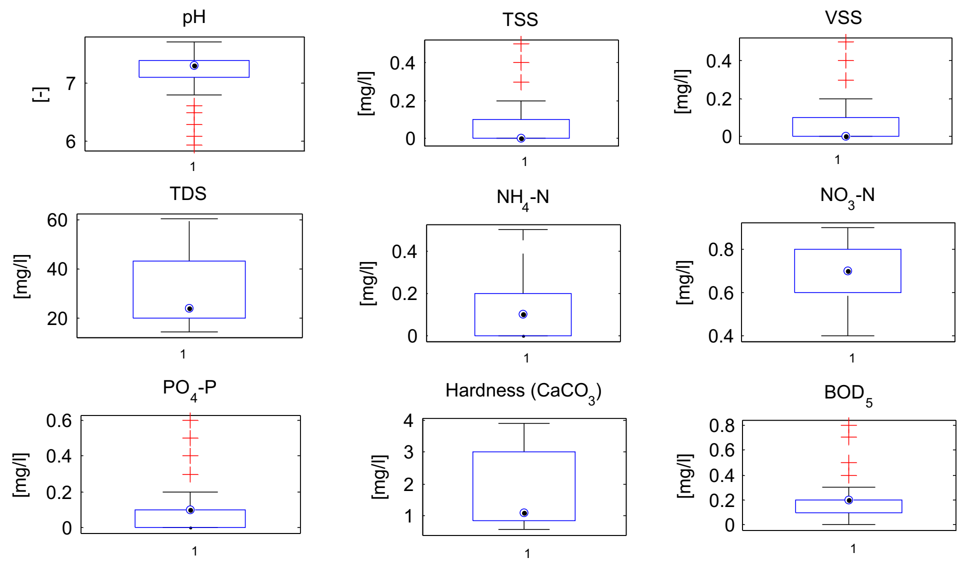


Fig. 5. Box plots of the final product water quality parameters.

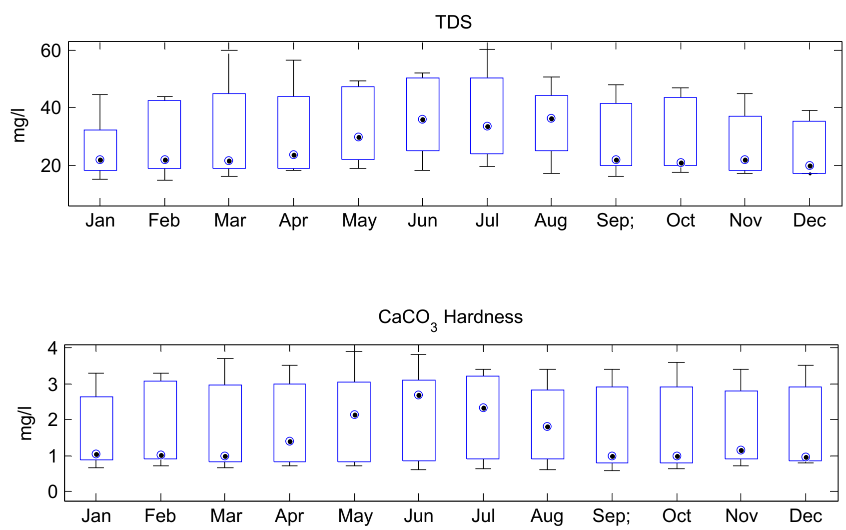


Fig. 6. Monthly variations in TDS and $CaCO_3$ hardness qualities of the product water.

reject (brine) water. This indicates that RO brine on average was more than 20%. Treatment, management, and disposal of RO brine are a worldwide critical issue [18]. It usually contains high concentrations of nutrients, salts, and inorganic materials, but it is devoid of organic matters, and therefore, its treatment is a great challenge [19]. At present, RO brine water of SWTRP is diluted and discharged into the Gulf.

In an attempt to treat and reuse SWTRP's brine water, the Kuwait Institute for Scientific Research (KISR) has conducted a study to remove nutrients from the brine water. The following three promising systems were studied at bench-scale levels using synthetic brine water. System A was a biological process of up-flow filtration (USBF), System B was a cascaded biological aerator system with partial anaerobic condition, and System C was a denitrifying process with bacterial growth on fixed anaerobic porous media followed by an algae pond. System C was found to be the best performing system. Nitrogen and phosphorus removals of system C were found to be 81–85% and 87–92%, respectively. This system was then studied at a pilot scale using actual RO reject water. It had achieved 76% of the total nitrogen and 86% of the total phosphorus [20]. However, there is a need for a more comprehensive treatment of the brine water to remove all potential pollutants. Until that will be achieved, it is recommend to bypass the RO treatment or to limit the amount of wastewater that will undergo RO treatment to the actual demand for such a high quality water final product water, e.g. for industrial reuse or groundwater recharge.

## 4. Conclusion and recommendations

A long-term assessment of the quality of SWTRP's final product of has been carried out. The following conclusions and recommendations were drawn from the obtained results.

(1) The final product water of SWTRP meet all the time the targeted design values. However, the variability of the quality parameters was found to be very high.
(2) Distributions of the effluent quality parameters do not follow normal or log normal distributions, indicating that the basic assumption behind the calculated descriptive statistics is violated. This was confirmed from the results obtained from histogram and box plots, which indicated clearly that the distributions were highly skewed to right for most of the quality parameters. Knowledge of effluent distribution is very essential in design and assessments of wastewater treatment plants' reliability.
(3) Box plot has shown that TDS and $CaCO_3$ hardness have seasonal patterns, where summer values are relatively higher than winter values.
(4) There is a need for a study to investigate the potential relationships between the found high variability in the quality parameters of the final product water and the design and operation of the plant treatment processes.
(5) Huge amounts of the wastewater treated at SWTRP are lost as RO brine water which is laden with high concentrations of nutrients, salts, and inorganic materials. Despite the promising results obtained from KISR's study for the removal of nitrogen and phosphorus from the brine water, there is a need for a more comprehensive treatment of the brine water before it can be reused. Until that will be achieved, it is recommended to bypass the RO treatment stage.


## Acknowledgment

Data used in this study were obtained from the databases of the quantity and quality of wastewater in Kuwait, which were developed during the execution of one of projects of Kuwait Institute for Scientific Research, namely: "Development of Wastewater Quality Database and Assessment of Effluent Quality for potential Reuse in Kuwait (WT013C)." The project WT013C was partially financed by the Kuwait Foundation for the Advancement of Sciences.


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