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Research Article

Operational Performance and Monitoring of a Reverse Osmosis Desalination Plant: A Case Study

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Abstract

The operational performance of a reverse osmosis (RO) desalination plant in Howtat Bani Tamim city 190 kms south of Riyadh Saudi Arabia was evaluated. The plant was monitored for a period of 40 months starting from January 2011 and ending in April 2014 and the raw water supply was obtained from six well. All operational parameters were measured and discussed. The raw water was initially treated for total solids (TS) and iron removal to reduce membrane fouling and the feed water was injected into two sets of RO membranes both operating as a two stage one pass system. Each set consists of 36 vessels in the first stage and 18 vessels in the second stage and both stages have 7 membranes in each vessel. The overall product output of the plant is 26282 m³/day with an average total solids (TDS) content of 500 mg/lit after blending the permeate water with feed water. The TDS concentration of the feed water was 2000 mg/lit and the permeate water was 28.79 mg/lit yielding a percentage removal of 98.56%. The overall efficiency of the plant with regards flow capacity was about 87.68%. The rejected water with an average flow of 3529.4 m³/day and TDS values of 13170.40 mg/lit was disposed in evaporation tanks.

Keywords: *Desalination, reverse osmosis, total dissolved solids, total solids, feed water, permeate, pre-treatment, silt density index, reject pressure, salt recovery.*

1. Introduction

The last five decades have experienced rapid growth in the number of desalination plants for producing drinking water in many parts of the world; adopting all the different techniques available in the market. The Gulf countries, by necessity, have become the world leader in desalination of sea and brackish water, and currently have more than 65% of the world's total capacity (Al-Faifi*et al,* 2010; GWI, 2000; Al-Zamel, 2001). The strategy of these countries to meet present and future demands for water resources has shifted attention to the role of desalination technology in alleviating water shortages using sea, ground and brackish water as feed sources. Also in these countries membrane technology is widely used for water recovery in industries as it is responsible for nearly 60% of the freshwater withdrawals (Stover, 2014).

Desalination is a general term for the process of removing salt from water to produce fresh potable water. Fresh water is defined as containing less than 1000 mg/lit of salts or total dissolved solids (TDS) (Sandia, 2003). Above 1000 mg/lit, properties such as taste, color, corrosion propensity, and odor can be adversely affected. Many countries have adopted national drinking water standards for specific contaminants, as well as for TDS, but the standard limits vary from country to country or from region to region within the same country (Greenlee *et al,* 2009).

Reverse osmosis (RO) is a process that uses semi-permeable spiral wound membranes to separate and remove dissolved solids, organic, pyrogens, submicron colloidal matter, color, nitrate and bacteria from water.

Feed water is delivered under pressure through the semi-permeable membrane, where water permeates the minute pores of the membrane and is delivered as purified water called permeate water. Impurities in the water are concentrated in the reject stream and flushed to the drain and called reject water (Garud*et al*, 2011; Norouz 2015). These membranes are semi-permeable and reject the salt ions while letting the water molecules pass. The materials used for RO membranes are made of cellulose acetate, polyamides and other polymers. The membrane consists of hollow-fiber, spiral-wound used for treatment; depend on the feed water composition and the operation parameters of the plant (Mohsen & Gammah 2010). Reverse osmosis is playing a fundamental role to ensure sufficient and reliable water supply for all the different

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purposes (irrigation, potable, process water, etc…). Together with the growth of the technology implementation, certain unmet market needs start to acquire more and more importance (Molina & Antonio 2010). Membrane material has also advanced in the recent years in order to achieve high efficiency both in product and in cost (Rodríguez-Calvo*et al*, 2014).

Better and efficient operation of reverse osmosis (RO) desalination plants can be obtained when maintaining good plant performance. Product quantity and quality may vary during operation due to feed variations and/or unexpected operating conditions. Operation of RO plants is highly improved and operation period of the membranes is extended by the efficient pre-treatment of the raw water to reduce the total solids (TS) content as much as possible to make suitable feed for RO plants (Shenoy*et al*, 2014). If the raw water has a high suspended solids (SS) in it, the life of the RO membrane is expected to reduce exponentially. Also the silt density index (SDI) and iron content in the feed water are key parameters in RO plants operation reflected in the membranes lifespan.

The main objective of this research work is to technically compare the full scale operation of a reverse osmosis desalination plant. The different operational parameters are discussed to assess the performance and effects.

Howtat Bani Tamim Desalination plant

Howtat Bani Tamim (HBT) city is located 190 kms south of Riyadh city on Al Kharj road. The desalination plant serving the city is situated in the south-east part of the city on Baher Belhowtah Wadi. The plant has an average daily product water flow of 26282 m^3/day (1095 m^3/hr) and is supplied with raw water by six deep wells; three working and three standby; operated alternately. The average raw water flow rate is about 29975 m^3/day (1250 m^3/hr) with an average influent total dissolved solids (TDS) concentration of 2000 mg/lit and a high iron concentration ranging between (4-7) mg/lit. Raw water from the wells is pretreated prior to flow to the desalination units.

The pretreatment stage consists of two square aeration tanks for the oxidation of the high iron concentration together with the addition of chlorine gas, caustic soda and polymers. The aeration tanks are followed by two circular sedimentation tanks; water from the sedimentation tanks then flows to the cooling towers and storage tanks prior to the inflow to the sand filters. Filtered water is then stored prior to being fed to the desalination units in the reverse osmosis building. Figure 1 shows an aerial satellite view of the desalination plant while figure 2 shows a schematic diagram of the desalination plant. The rejected water from the RO units, the sludge collected from the sedimentation tanks and the filters wash water are disposed into 16 evaporation tanks with a total area of 200000 m^2 and distributed among three different locations. Excess drainage water is discharged to Baher Belhowtah Wadi.

The desalination units are comprised of two sets of reverse osmosis (RO) membranes both operating as a 2 stage 1 pass system. In a two-stage system the concentrate (or reject) from the first stage then becomes the feed water to the second stage. The permeate water collected from the first stage is combined with permeate water from the second stage. Additional stages increase the recovery from the system. In each set, the first stage consists of 36 vessels with 7 membranes per vessel giving a total of 252 membranes. While the second stage consists of 18 vessels with 7 membranes per vessel giving a total of 126 membranes. This gives an overall membrane capacity of 378 membranes for each set and 756 membrane for the whole plant. Figure 3 shows a schematic diagram of one set of the RO units with the average discharges and concentrations recorded for each stage. While figure 4 shows the mass balance for the required amount of blend water for each set.

Each set of RO vessels is fed with two high pressure pump groups each with two pumps (1+1) for the two stages with a specification: for the first stage stainless steel 304, 550 m^3/hr – 17 bars max, kw 358, IP 55, HP 480 and class F. For the second stage stainless steel 304, 200 m^3/hr – 17 bars max, kw 145, IP 55, HP 195 and class F. The membranes are spiral wound polyamide with a diameter of 20.32 cms (8 inches) and a length of 1.016 ms (40 inches) nominal active surface area is 7.6 m^2; its permeate flow rate ranges from (23-28) m^3/day and the minimum salt rejection is 99.5%. Two flow meters are available for each set of RO membranes to measure the in-and-out water flow rate. Finally, the RO plant is controlled by electrical control panels.

The plant was monitored for a period of 40 months starting from January 2011 to the end of April 2014. The plant was monitored for all operational parameters starting from raw water feed rate and ending with silt density index (SDI).

Results and Discussion

A series of parameters were analyzed during the monitoring period for the overall evaluation and assessment of the operational efficiency of the desalination plant. Analysis of the data obtained during the monitoring period are demonstrated as follows:-

Flow Rates

The raw water is obtained from six (3+3) deep wells operating alternately. During the 40 months monitoring of the plant, data for four months were not recorded due to technical problems in the plant and these months are July 2012, August 2012 & 2013 and October 2013. Figures 5 & 6 show the data recorded during the monitoring period while table 1 shows the summary of the maximum, minimum and average values recorded together with their respective dates. Generally, it can be deduced that the operation of the desalination plant with regards flow rates is not stable as the fluctuations and deviation of the readings is high as seen in table 1.

Figure 1 Aerial view of HBT desalination plant

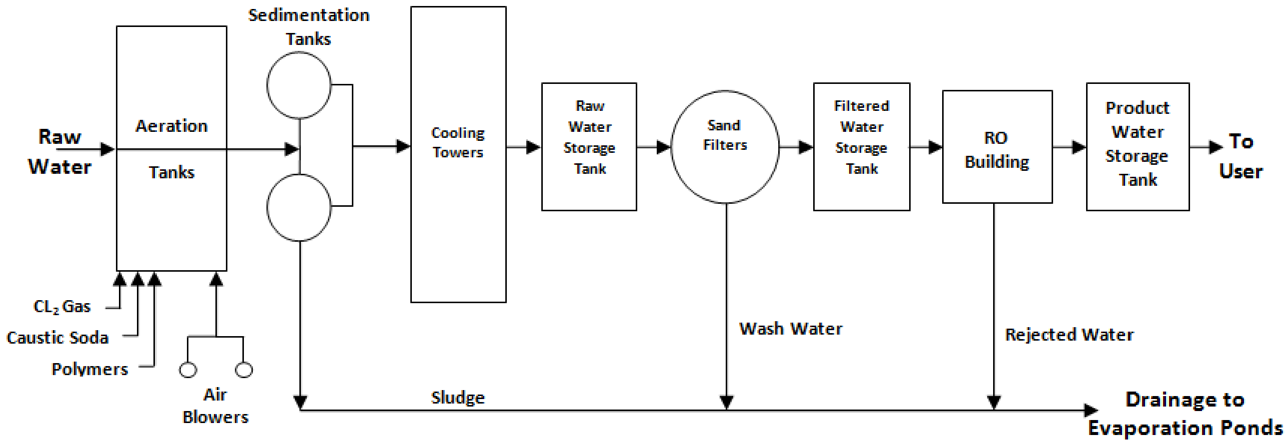


Figure 2 Schematic diagram of HBT desalination plant

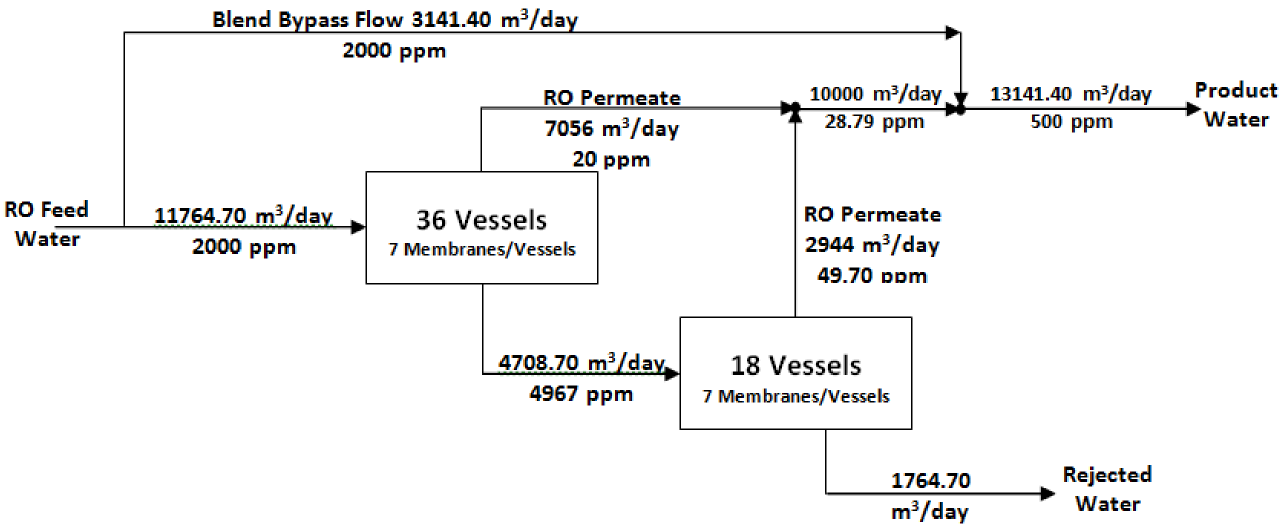
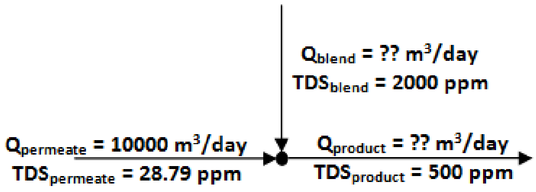


Figure 3 Schematic diagram of one set of the HBT desalination units

This is attributed to the problems associated with the operation and maintenance of desalination plants especially membrane failure and replacement. Also the high iron content of the raw water was a source of nuisance throughout the monitoring period. The loss of water in the pretreatment stage (evaporation, sludge and filter backwash) amounts to 0.55% of plant capacity. While the rejected water from the RO units amounts to 11.77% of the plant capacity. This yields a total water loss value of 12.32% of the plant capacity.



$$10000 + Q_{blend} = Q_{product}$$
$$(10000)*(28.79) + 2000*Q_{blend} = (10000+ Q_{blend})*(500)$$
$$(10000)*(28.79) + 2000*Q_{blend} = (10000)*(500) + 500*Q_{blend}$$
$$1500*Q_{blend} = (10000)*(500) - (10000)*(28.79)$$
$$Q_{blend} = 3141.40 \text{ m}^3/\text{day}$$

Figure 4 Calculating the quantity of blending required to reach 500 ppm for one set of HBT desalination units

Table 1 Maximum, minimum and average flow rates

Type of Flow	Minimum Flow rate (m^3/day)		Maximum Flow rate (m^3/day)		Average Flow rate (m^3/day)
	Value	Date	Value	Date	
Raw Water	23172	March 2013	34532	April 2012	29975.00
Pretreated Water	23000	March 2013	34352	April 2012	29812.20
RO Feed	16840	March 2013	28584	Dec. 2013	23529.40
Permeate Flow	15000	March 2013	25000	Dec. 2013	20000.00
Blending Flow	5090	March 2011	7916	Feb. 2011	6282.80
Product Flow	21160	March 2013	30650	Nov. 2011	26282.80
Rejected Water Flow	972	April 2013	7400	March 2011	3529.40

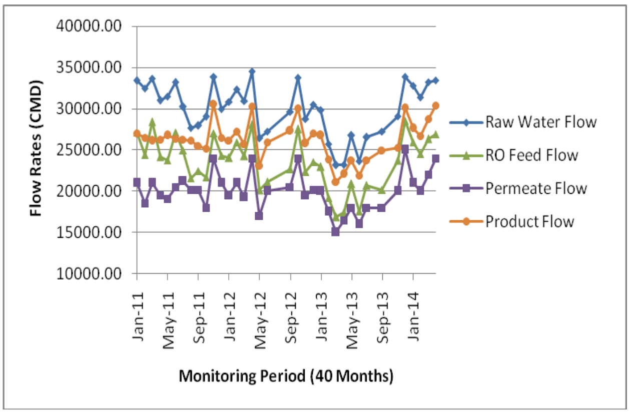


Figure 5 Recorded flow rates during the monitoring period

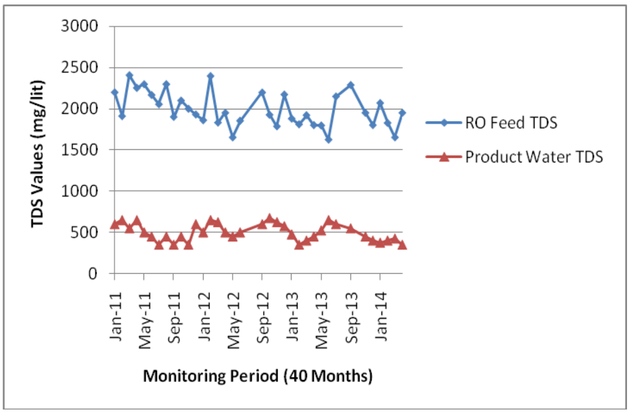


Figure 7 Recorded RO feed and product water TDS values

Total Dissolved Solids (TDS)

The TDS values were recorded daily during the monitoring period for the RO feed, RO permeate, product and rejected waters. The average, minimum and maximum values are shown in table 2 together with the corresponding dates. While the average values of the data recorded are plotted in figures 7, 8 & 9. From the table and figures we can see that there is a noticed disparity between the recorded values especially in the feed water with a deviation of about 25%. The product water recorded the lowest deviation and the most stable curve compared with the other three curves.

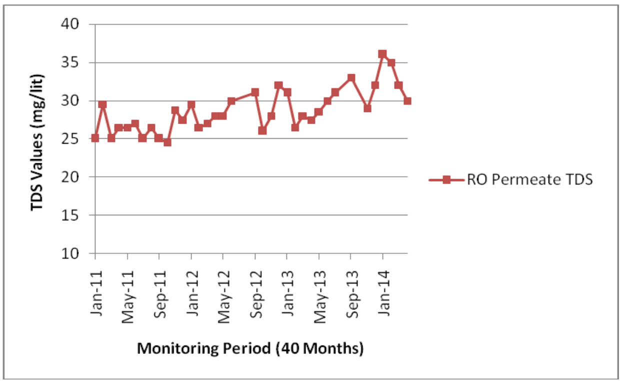


Figure 8 Recorded RO permeate water TDS values

Table 2 Maximum, minimum and average TDS values

Type of Flow	Minimum Values (mg/lit)		Maximum Values (mg/lit)		Average Values (mg/lit)
	Value	Date	Value	Date	
RO Feed	1622	June 2013	2410	March 2011	2000.00
Permeate Flow	24.50	Oct. 2011	36.00	Jan. 2014	28.79
Product Flow	350	Jan. 2011	675	Jan. 2013	500.00
Rejected Water Flow	11500	May 2011	14350	April 2012	13170.40

Table 3 Maximum, minimum and average pH values

Type of Flow	Minimum Values		Maximum Values		Average Values
	Value	Date	Value	Date	
RO Feed	6.30	Jan. 2011	6.89	March 2011	6.00
Permeate Flow	6.00	March 2013	6.69	March 2011	6023
Product Flow	6.80	March 2012	7.60	Feb. 2011	7.06

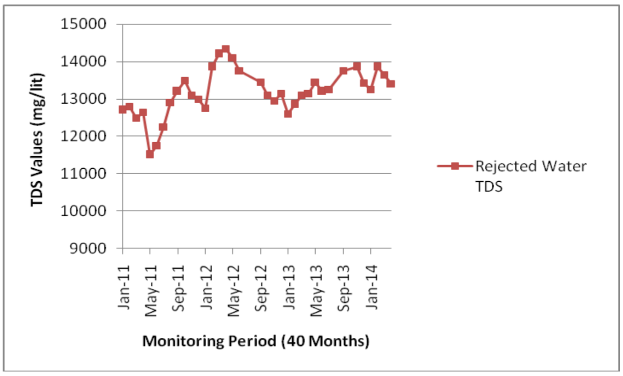


Figure 9 Recorded flow rates during the monitoring period

This is attributed to the fact that the RO permeate water is constantly blended with feed water to adjust the product water TDS to 500 mg/lit. The RO TDS removal efficiency is about 98.56% for both stages and 75% percent for the whole system after mixing with blending water. The average percentage of the blending water is 23.90% of the total product water flow depending on the RO feed & permeate TDS values.

pH

The hydrogen ion concentration is important in defining the alkalinity equilibrium levels of carbon dioxide, bicarbonate, carbonate and hydroxide ions. The pH values were adjusted using sulfuric acid and caustic soda. Table 3 shows the average and extreme values recorded during the monitoring period which were almost neutral while figure 10 shows a plot of the values recorded.

The pH of the product water is typically higher than the feed due to the higher concentration of bicarbonate/carbonate ions relative to the concentration of carbon dioxide.

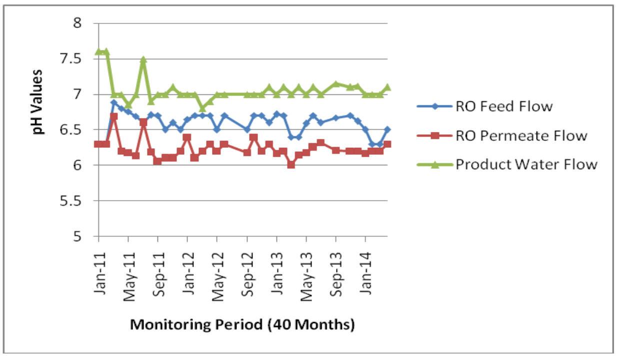


Figure 10 Recorded pH values during the monitoring period

Pressure

The average working RO feed pressure was 15.75 bars and in some cases it reached over 16.5 bars. While the minimum recorded working pressure was 14.50 bars. The average reject pressure for the first stage was 12.73 bars while the average reject pressure of the second stage was 10.55 bars. The pressure drop in the first stage was 3.03 bars and in the second stage was 2.18 bars. Figures 11 & 12 show the data collected.

Iron

The iron concentration in the raw water was high and above the limits permissible for RO feed water (0.10 mg/lit). High iron concentration in RO feed water leads to membrane fouling and consequently reduces the life span of the membranes. The raw water was aerated to oxide and removes the iron by sedimentation. The high iron concentration have high deteriorating effects on all the pre-treatment facilities which were constantly recorded during the monitoring period. Figure 13 shows the adverse effects of the high iron concentration on the sedimentation tanks in the plant.

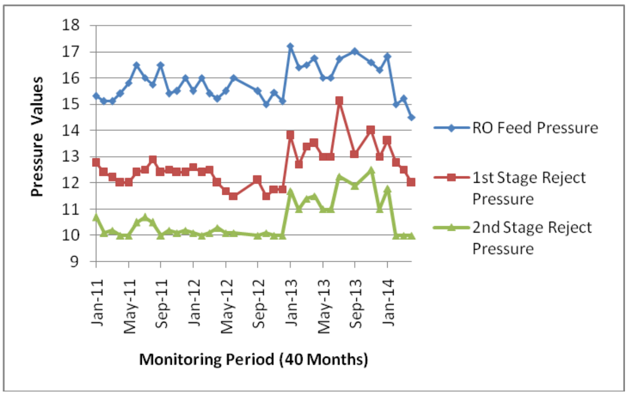


Figure 11 RO feed pressure and reject pressure for both stages

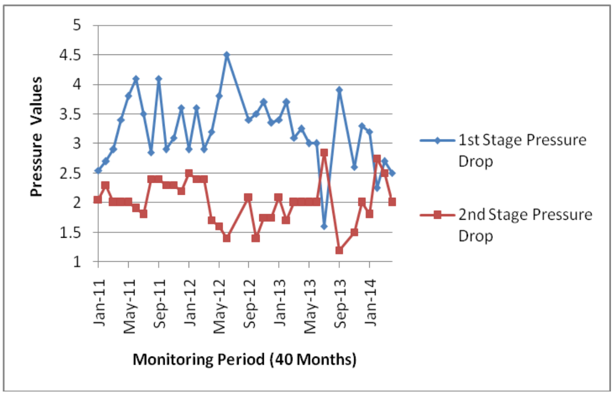


Figure 12 Pressure drop across the vessels for each stage

Figure 13 Photograph of the sedimentation tank showing the effect of high iron concentration

The average RO feed iron concentration recorded was 0.19 mg/lit and this high compared with the permissible standards. This relatively high concentration was a continuous source of trouble shooting during the monitoring period as many RO vessels were constantly running out of operation and this is reflected on the marked variations in the flow rates of the plant. Figure 14 shows the values recorded during the monitoring period and peak values indicate periods during dropout of the sedimentation tanks in the pre-treatment stage.

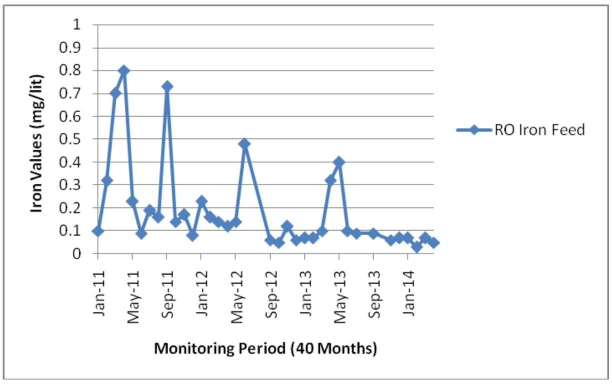


Figure 14RO feed iron influent values

Silt Density Index

Silt density index (SDI) is the measurement of the fouling potential of the RO feed water. Typical RO element warranties list a maximum SDI of 5.0 at 15 minutes for the feed water. The average SDI value recorded during the monitoring period was 1.36 with lowest value recording 0.24 and the highest value 4.28. Figure 15 shows the data recorded during the monitoring period.

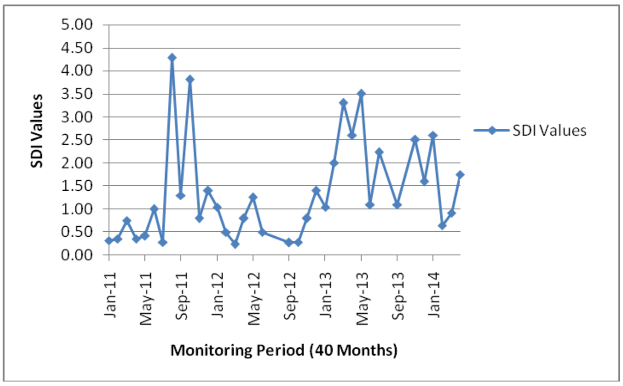


Figure 15 SDI values recorded during the monitoring period

Recovery Rate

Percent recovery is the amount of water that is being recovered as good permeate water. The calculation for % Recovery is given by:

$$\% \text{ Recovery} = \frac{\text{Permeate Flow Rate (gpm)}}{\text{Feed Flow Rate (gpm)}} \times 100$$

Figure 16 shows the overall recovery rates recorded during the monitoring period with the lowest value being 73.94% and the highest value 94.79%; while the average value is as calculated above.

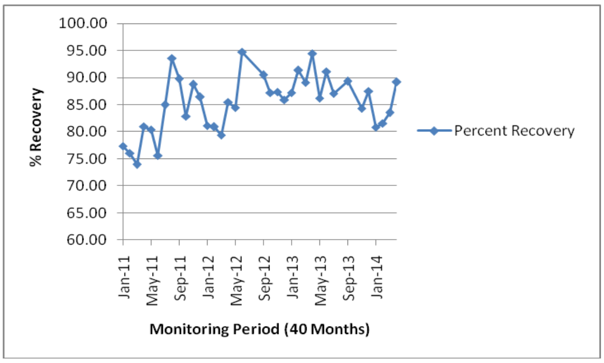


Figure 16 Percentage recovery rate during the monitoring period

Salt Rejection Rate

The percentage salt rejection rate is a measure of the efficiency of the RO system and it is calculated using the following equation

$$\%\ \text{Salt Rejected} = \frac{\text{TDS Raw Feed - Permeate TDS}}{\text{TDS Raw Feed}} * 100$$

$$\%\ \text{Salt Rejected} = 98.54\%$$

The salt rejection percentage calculated during the monitoring period was all above 98% with an average value as calculated above.

Salt Passage Rate

Salt passage is the inverse of the salt rejection rate discussed in the previous section. This is the amount of salts expressed as the percentage passing through the RO system. It is calculated as follows

$$\%\ \text{Salt Passage} = 1 - \%\ \text{Salt Rejected}$$

$$\%\ \text{Salt Passage} = 1 - 0.9854 = 0.0146$$

$$= 1.46\%$$

Oxidation Reduction Potential (ORP)

Oxidation‐reduction (redox) reactions can affect drinking water treatment and distribution in significant ways. Measurements of oxidation‐reduction potential (ORP) in water reflect the tendency of major constituents in the water to accept or lose electrons. Although ORP measurements are valuable and can provide useful information toward protecting public health, they are not widely undertaken by the drinking water community for a variety of reasons. The permissible values is within the range of (175-200) mV (Copeland & Lytle, 2014). Measurement of ORP in HBT plant started in October 2012 to the end of the monitoring period (17 months) with an average recorded value of 178.23 mV.

Radionuclides

Radium 226 & radium 228 (combined radium) were measured only six times during the monitoring period. The values ranged from (5-12.6) pCi/L in the permeate water. The values in the feed water were about 4 pCi/L higher than those measured in the permeate flow.

Acknowledgements

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Conclusions

This research work has considered the monitoring of a water desalination plant for a period of 40 months. All operational parameters were monitored and analyzed and the following conclusions are summarized:

- The average raw water flow rate is about 29975 m^3/day, while the product water is 26282 m^3/day giving an overall flow efficiency of 87.68%.
- The RO TDS removal efficiency is about 98.56% for both stages and 75% percent for the whole system after mixing with blending water.
- The average percentage of the blending water is 23.90% of the total product water flow depending on the RO feed & permeate TDS values.
- The average reject pressure for the first stage was 12.73 bars while the average reject pressure of the second stage was 10.55 bars.
- The pressure drop in the first stage was 3.03 bars and in the second stage was 2.18 bars.
- The average RO feed iron concentration recorded was 0.19 mg/lit
- The relatively high iron concentration was a continuous source of trouble shooting during the monitoring period as many RO vessels were constantly running out of operation and this is reflected on the marked variations in the flow rates of the plant
- The average SDI value recorded during the monitoring period was 1.36 with lowest value recording 0.24 and the highest value 4.28.
- The average recovery percentage is 84.99%.
- The average salt rejection percentage is 98.54%.
- The average salt passage percentage is 1.46%.
- The average oxidation‐reduction potential recorded value was 178.23 mV.

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