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EXPERIMENTAL AND ANALYTICAL STUDY OF A REVERSE OSMOSIS DESALINATION PLANT

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دراسة عملية وتحليلية لمحطة تحلية مياه بالضغط الأسموزي

الخلاصة:

نتيجة للزيادة المستمرة فى معدل استهلاك مياه الشرب، خاصة فى المناطق الصحراوية والبعيدة، فإن تطوير مصادر أخرى لتحلية المياه بطرق غير تقليدية فى مصر يعتبر ضرورة قصوى. تعتبر أنظمة تحلية المياه بالتناضح العكسى (RO) هى الأكثر تقدماً وجاذبية فى هذا المجال. فى هذا البحث، تمت دراسة حالة Case study لمحطة تحلية مياه بطاقة 5000 m^3/day تعمل بالتناضح العكسى RO فى مدينة نويبع بسيناء فى جمهورية مصر العربية. لهذا السبب تم تسجيل البيانات المقاسة فى هذه المحطة خلال خمس سنوات من التشغيل المنتظم للمحطة. وأيضاً قد تم خلال هذه الفترة إجراء تجارب عملية على المحطة لبحث تأثير أهم عوامل التصميم والتشغيل على أداء المحطة. وأظهرت النتائج حساسية RO system لتغيرات درجة حرارة مياه التغذية والضغط ودرجة الملوحة. كما أكدت القياسات أن برامج الصيانة المتبعة مناسبة لتشغيل المحطة حيث أن التغير فى بيانات المحطة خلال فترة الدراسة كانت غير ملحوظة. كما تم عمل تحليل اقتصادى على مكونات محطة التناضح العكسى وقد وجد أن أهم العوامل المؤثرة فى تكلفة إنتاج المياه من هذه المحطة هى التكلفة الرأسمالية واستهلاك الطاقة الكهربية. وقد جاءت النسبة المئوية لتكاليف المعالجة الكيميائية (من غير المتوقع) كأحد أقل المكونات فى التكلفة الكلية لإنتاج المياه. فى هذه الدراسة شاركت استهلاك الطاقة الكهربية بنسبة 35.1% والتكلفة الرأسمالية بنسبة 33.6% والصيانة والإصلاح بنسبة 4.9% فقط. أما النسبة المئوية لتكاليف المعالجة الكيميائية فقد كانت 10.6% من التكلفة الكلية لإنتاج المياه.

ABSTRACT

Due to the continuously increasing demand for fresh water in the desert and remote areas, the development of non-conventional water resources in Egypt is essential. The most advanced and promising desalination system is the reverse osmosis (RO) system. In this paper, a 5000 m^3/day RO desalination plant in the city of Nuweiba in Sinai, Egypt is taken as a case study. The measured data of the plant are recorded during 5 years of its normal operation. Also, experimental tests are carried out on site to investigate the influence of the main design and operating parameters on the plant performance. The RO system is found to be sensitive to the variation in the feed water temperature, pressure and salinity. The used maintenance schedule is also seen to be suitable for the plant, since the change in plant performance during the operation period is not noticeable. On the other hand, a cost analysis is carried out on the RO plant components. The major factors affecting the cost of product water of this plant are the power consumption and capital cost. Surprisingly, the chemical treatment cost is one of the lowest in percentage. In this case, the power consumption cost is 35.1% and the capital cost is 33.6% and that of maintenance and repairs represent only 4.9% while the chemical treatment represents 10.6% of the total cost.

Keywords: Desalination; Reverse osmosis plant; Seawater; Case study; Nuweiba city.

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1. INTRODUCTION

Desalination is a process in which dissolved minerals are removed from saline water. Many technologies have been developed for sea and brackish water desalination, including thermal, reverse osmosis (RO), electrodialysis and vapor compression systems. The most common and widely used process is reverse osmosis [1,2]. All desalination processes involve three liquid streams; the saline feed water, low-salinity product water (permeate), and the very saline concentrate (brine). The RO plants produce water with salinity from 10 to 500 ppm TDS (Total Dissolved Solids). The market share of RO desalination systems has significantly increased in recent years due to the progress in membrane technology.

Cost is a major factor in implementing desalination technologies and usually is site specific. The factors affecting desalination costs are the quality of feedwater (TDS concentration in feedwater), plant capacity (large capacity plants require high initial capital investment, however the unit production cost for large capacity plants can be lower), site characteristics (land condition, proximity to water source and concentrate discharge point, …) and regulatory requirements (local/state permits and regulatory requirements) [3].

The main disadvantages of the RO process are: the cost of the facility (both initial and operating costs), the limited recovery (typically 35–50% for seawater), the pretreatment requirements, the high pressures required to run the process because of the dense structure of RO membranes, the variation in production rate if the raw water quality changes, the harmful effects of rejected brine on the environment and ecosystems, concentration polarization and membrane fouling (especially under high pressures), and progressive performance decline due to irreversible fouling. Concentration polarization promotes membrane fouling and reduces the productivity of membrane processes.

The RO desalination plant consists of four major systems: pretreatment system, high-pressure pumps, membrane systems, and post-treatment. Pre-treatment system removes all suspended solids to keep salt precipitation and microbial growth to the minimum on the membranes. Pre-treatment involves chemical feed followed by coagulation, flocculation, sedimentation and sand filtration. Micro filtration and ultra filtration may also be used. High-pressure pumps supply the required force to drive the feed water through the semi-permeable reverse osmosis membrane. The reverse pressure ranges from 17 to 27 bar for brackish water, and from 52 to 69 bar for seawater. RO membranes are two types; spiral wound and hollow fiber. Spiral wound elements are actually constructed from flat sheet membranes. In the hollow fiber design, a large number of hollow fiber membranes are placed in a pressure vessel. This type is not widely used like the spiral wound membranes for desalination. The post-treatment is often employed to ensure meeting the health standards for drinking water as well as recommended aesthetic and anti-corrosive standards. Post-treatment consists of stabilizing the water (adjusting the pH and disinfection) and preparing it for distribution.

The major parameters affecting the RO plant performance are the feed water temperature, pressure and salinity. The membrane compaction, fouling and maintenance also affect membrane performance. The influence of operating parameters on the RO plant performance has been the focus of many investigations [4-11]. The RO desalination system has been subjected to extensive theoretical work [12-14]. Numerical results have also shown the effects of operating conditions and concluded that increasing the operating pressure and feed flow will generally lead to higher water recoveries and salt rejection. However, increasing the pressure beyond a certain maximum value led to the deterioration of the quality of the product water.

Many case studies are available on the performance analysis and cost estimation of RO desalination units in Egypt, few of them are mentioned. Hafez and El-Manharawy [15] presented a techno-economic study to estimate the fixed and operating costs of five seawater RO plants of 250, 500, 2000, 3500 and 4800 m^3/d in Egypt. They found that the production cost of small seawater RO desalination plants was much higher than the average world cost (US$ 1/m^3 in 2002).

Abou Rayan and Khaled [16] presented a case study of the operation and maintenance of a 2000 m^3/d RO desalination plant over 6 years of operation. They concluded that the reverse osmosis system is sensitive to changes in feed water temperature, and the product quality is sensitive to the change in feed water pressure.

Djebedjian et al. [17] carried out an extensive experimental work to study the effect of the same parameters (feed water pressure, temperature and salinity) on the performance of a small-scale brackish water RO test rig.

The present case study is carried out to study the influence of main design and operating parameters on the RO plant performance. The following objectives are also studied:

1. The cost analysis of the RO plant.
2. The evaluation of the overall system reliability for long-term automatic operation for a certain maintenance procedure.

The plant is still working under continuous operation without any significant operational problems.

2. CASE STUDY

The considered plant has been constructed at Nuweiba city in south Sinai, Egypt and started production in August 2001. The system is conceived in such a manner to conserve energy. The energy rejected from the discharged brine is recovered in the recovery turbine. The required electrical power for the plant is supplied from the local electrical power network. The saline water is supplied from 8 beach wells near the coast of the Aqaba Gulf. The salinity of feed seawater is in the order of 44,000 ppm. The plant consists of 5 units; each has a capacity of 1000 m^3/day. The plant specification of the RO facility is listed in Table 1.

The plant consists of the following main systems; the intake, the raw water pretreatment unit and cartridge filters, the high-pressure pump, the RO membrane unit, the turbocharger, and the post-treatment system as illustrated in Fig. 1.

The major systems of the RO plant are described below.

Table 1 Nuweiba reverse osmosis plant specification

Plant:	
Number of units	5
Capacity of unit (m^3/day)	≈ 1000
Unit:	
Product water flow rate (m^3/day)	1128
Reject water flow rate (m^3/day)	2472
Total water feed flow rate (m^3/day)	3600
Recovery ratio (%)	31.33
Operation condition:	
Temperature (°C)	28
Bulk seawater concentration (ppm)	44000
Permeate water concentration (ppm)	350
Pressure difference, ΔP (bar)	65.845
Average pH value	7.7
Membranes:	
Membrane type	TORAY SU 820
Number of vessels	15
Number of membranes in vessel	5
Total number of membranes	75
Maximum operating temperature (°C)	45
Maximum operating pressure (bar)	80

2.1. Raw Water Intake

The RO plant uses an indirect seawater intake with beach wells. Eight beach wells are constructed to supply seawater to 5 RO units. Each RO unit requires 3600 m^3/day flow rate of raw seawater to produce 1000 m^3/day. Each beach well is equipped with a multistage submersible pump which has a nominal discharge at due point of 3600 m^3/day. The depth of the well is about 100 meters. A PVC pipe of 11-inch diameter is introduced in the well bore hole. Saline water is pumped from the beach wells through the submersible pumps to a PVC header.

2.2. Pretreatment System

The pretreatment is used to improve the raw water quality, and to conform the pretreated water with the reverse osmosis membranes requirements. The pretreatment includes injection of chemicals and filtration to remove particulate matter and to minimize biological fouling and scaling.

Seawater chlorination system comprises a PE solution tank and chemical feed pumps. During this process, the water is subjected to sterilization by sodium Hypo-chlorine to prevent the growth of bacteria and algae.

In sand filters the sand traps residual suspended material and bacteria and provides a physical matrix for bacterial decomposition of nitrogenous material, including ammonia and nitrates, into nitrogen gas.

Activated carbon filters absorb impurities from water as it passes through a carbon cartridge. Activated carbon (AC) filtration is most effective in removing organic contaminants from saline water.

2.3. Cartridge Filter

The plant is provided with one cartridge filter which ensure that particles larger than 5 microns, carried over from the dual media filters will not enter the membranes. This filter is constructed from stainless steel for total corrosion resistance.

2.4. High-Pressure Pump

The high-pressure pump supplies a very high pressure required for reverse osmosis process. The required pressure depends on the concentration and temperature of the feed water. The operating pressure must exceed the osmosis pressure corresponding to the concentration of the seawater. The RO desalination plant in Nuweiba city is operating in the range of 60 – 70 bar.

2.5. RO Membrane Unit

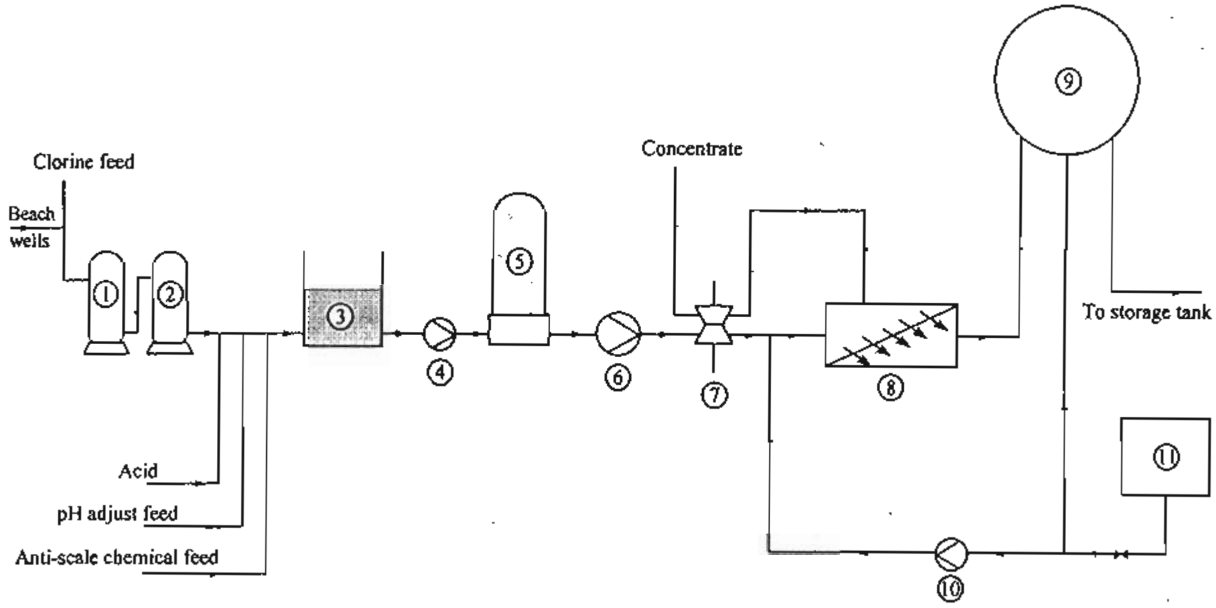
The membranes stainless steel skid consists of 15 vessels; each one contains 5 elements of spiral wound membrane type. The membrane is only a skin of about 0.0025 mm thick. The membranes are rather porous plastic with active chemical sites. Its permeability is affected by water chemical contents, temperature, pressure and salinity. The pressure required to operate the RO plant in Nuweiba city (where TDS is 45,000 ppm) is equal to about 60 bar.

2.6. Hydraulic Turbocharger

The hydraulic turbocharger is a simple energy recovery system and the energy saving is achieved because the high pressure pumps operates in smaller pressure. It is a single turbine mounted on a common shaft with a single-stage centrifugal pump. The turbine recovers and uses the hydraulic energy from the high pressure brine to drive the integral centrifugal pump. The pump impeller boosts the pressure of the feed stream. The pump-turbine root is free to seek its own speed of rotation.

2.7. Post Treatment

Post treatment of the product water consists of chlorinating to allow chlorine and pH adjustment within the acceptable range of 7.5 to 8.5 ppm.



1- Sand filter
2- Carbon filter
3- Raw water tank
4- Feed pump
5- Cartridge filter
6- High-pressure pump
7- Turbocharger
8- RO membrane
9- Aerated tank
10- Flushing pump
11- Chemical tank

Fig. 1. Schematic diagram of the RO desalination plant in Nuweiba city

3. BASIC REVERSE OSMOSIS RELATIONSHIPS

The reverse osmosis process involves fluid flow across a semi-permeable membrane barrier as shown in Fig. 2.

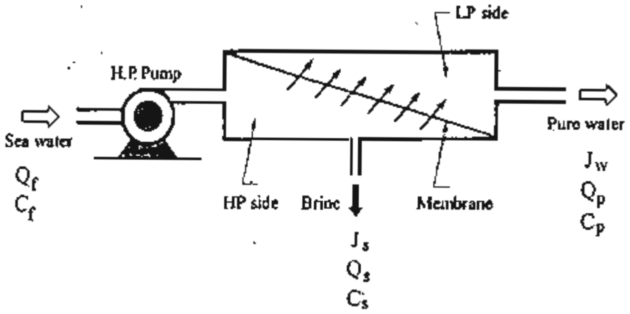


Fig. 2. Reverse osmosis membrane module and nomenclature

The overall water and salt mass balance equations around the membrane are:

$$Q_f = Q_p + Q_s \quad (1)$$

$$Q_f C_f = Q_p C_p + Q_s C_s \quad (2)$$

where subscripts *f*, *p* and *s* refer to the feed, permeate and brine streams. Q (m^3/h) and C (kg/m^3) refer to the flow rate and salt concentration, respectively.

The solvent or water flux J_w is defined as the volume of water passing through a unit area of the membrane. The water volumetric flux, J_w, and the solute mass flux, J_s according to solute-diffusion model are given by, (Lonsdale et al. [18]; Soltanieh and Gill [19]):

$$J_w = a\left(\Delta P - \Delta\pi\right) \quad (3)$$

$$J_s = b\left(C_{wall} - C_p\right) \quad (4)$$

where

$$J_s = J_w C_p \quad (5)$$

$$J_w = Q_p / A \quad (6)$$

where ΔP $(= P - P_p)$ is the applied pressure difference across the membrane, P the pressure in the bulk solution at the high pressure side, and P_p is the pressure in the permeate. $\Delta\pi$ is the osmotic pressure difference of solute across the membrane. C_{wall} is the solute (wall) concentration at the membrane surface, C_p is the permeate side solute concentration, a and b are the solvent (membrane) and the solute (salt) permeability coefficients, and A is the membrane area.

The osmotic pressure, π (in bars), is obtained from the data given by Sourirajan [20] for the NaCl–H$_2$O system at 25°C (concentration range: 0 - 49.95 kg/m^3) and is correlated as:

$$\pi = 0.7949C - 0.0021C^2 + 7.0\times10^{-5}C^3 - 6.0\times10^{-7}C^4 \quad (7)$$

The performance of RO processes is measured generally by water recovery ratio and salt rejection.

The permeate recovery ratio, RR, is defined as the ratio of the permeate flow rate Q_p to the feed water flow rate Q_f:

$$RR = \frac{Q_p}{Q_f} \times 100 \quad (8)$$

The salt rejection, SR, is a good indicator for the product water quality. It is defined as:

$$SR = 1 - \frac{C_p}{C_f} \quad (9)$$

where C_p is the salt concentration of the permeate and C_f is the salt concentration in the feed water.

The variation of product water flow rate as a function of temperature for a reference temperature of 25°C is described as, [21]:

$$Q_{p\,t^\circ C} = Q_{p\,25^\circ C} \cdot TCF \quad (10)$$

In this equation, the temperature correction factor TCF is evaluated by, [7] and [21], respectively:

$$TCF = \exp\left[K \cdot \left(\frac{1}{273+t} - \frac{1}{298}\right)\right] \quad (11)$$

$$TCF = \exp\left[0.0299(t - 25)\right] \quad (12)$$

where K is a constant characteristic for a given membrane material. The change in product flow rate is about 3% per degree Celsius increase in water temperature, [7].

4. EXPERIMENTAL PROCEDURE

During the normal operation of the RO plant, the following data have been recorded daily from 2001 up to 2006:

1- The pressure before and after each filter, pump, turbocharger and RO element.
2- Temperature before and after each RO element.
3- Thermal conductivity before and after each RO element. Salinity of a stream is calculated from the measured thermal conductivity.
4- The flow rates of the permeate water and brine.

On the other hand, site experimental work has been carried out on one RO unit of the plant to study the effect of feed water temperature, pressure and salinity on the product flow rate of the unit. The change in the salinity of feed water was carried out by adding product water to the feed saline water. The pressure of the feed water was changed by the pump and by passing the feed water. To study the effect of temperature of the feed water, tests are carried out during different times of the year with different ambient temperatures. The product mass flow rate, pressure and temperature are measured by the same instrumentation attached to the RO desalination plant.

5. SYSTEM PERFORMANCE

The five RO units of the plant are normally in continuous operation and show similar performance and trends. As an example, the data of one unit is discussed. The readings are taken during 24 hours with one hour interval on the first day of each month. The daily average values of the measured data are calculated for testing the performance of each component and detect any changes of the plant performance. The recorded data for the years 2002 and 2005 are shown in Appendix A. The measured data are recorded from the attached instruments to the plant in which the pressure is recorded in psi. Figure 3 shows the product water and reject water flow rates, membrane inlet and outlet pressures and product water conductivity. The change of the plant readings during the period of operation is not significant.

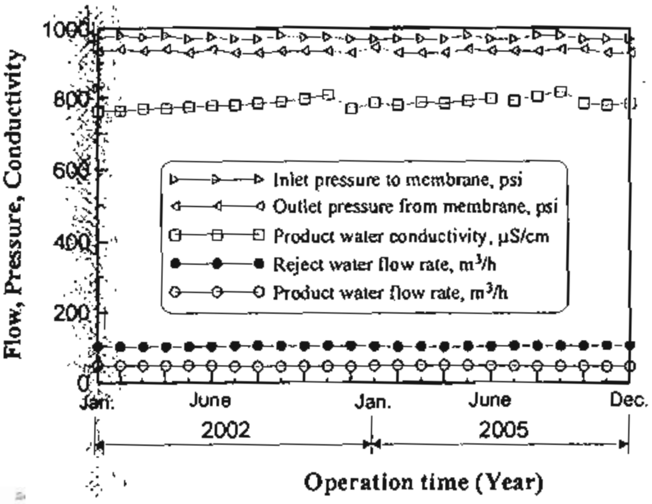


Fig. 3. Actual operating data of one unit for years 2002 and 2005

To study the effect of a certain parameter on the system performance, other parameters are kept constant during the experimental test, Table 2. These tests are achieved on one unit with a feed water flow rate of 3600 m^3/day. Results of the site experimental work that explain the influence of the main operating parameters are graphically depicted in Figures 4 to 8.

From the analysis of these data, the parameters and correlations needed to calculate the values of product water flow rate and product salinity are generated.

5.1. Feed Water Pressure

Feed water pressure affects both the product water flow rate and salinity of RO membranes.

The maximum allowable operating pressure for the TORAY membranes as set by the manufacturer is 80 bar. The maximum pressure used in the experiments was 72.4 bar experiments.

The effect of the feed water pressure on the product flow rate is shown on Fig. 4 at a feed water temperature 28°C and salinity 44,000 ppm. The product flow rate increases as the feed pressure increases. The dashed lines on the figure shows the normal operating condition of the RO unit. The productivity is expressed as a percentage of the nominal value of the unit (1000 m^3/day or 41.67 m^3/hr). The product flow rate increases from 72 to 1248 m^3/day corresponding to an increase in the feed pressure from 41.37 to 72.4 bar respectively. The relationship is almost linear between the feed pressure and the product flow rate.

The increase of product flow rate is expected with increasing feed pressure as it pushes more water through the membrane.

Equation (3) indicates the effect of feed water pressure on product flow rate. Similar to Eq. (10), the pressure coefficient factor PCF is used for the product flow rate for pressure variation:

$$Q_{PP} = Q_{PP_{ref}} \cdot PCF \qquad (13)$$

where $Q_{PP_{ref}}$ is the product flow rate at a reference pressure P_{ref}. The expression of PCF yields to 1 when the pressure equal to P_{ref}.

Table 2. Operating conditions in RO system

Experiment	Operating Conditions			Measured Data	
	P_f (bar)	T_f (°C)	TDS_f (ppm)	Q_p (m^3/day)	TDS_p (ppm)
Feed Water Pressure, P_f	Varied 41.37-72.4	28	44,000	Measured	Measured
Feed Water Temperature, T_f	63	Varied 10-32	44,000	Measured	Measured
Feed Water Salinity, TDS_f	63	28	Varied 15,000-45,000	Measured	Measured

Noting from Eq. (3) that the relationship of the product flow rate and the pressure is linear, therefore, the following equation and goodness of fit R^2 parameter can be deduced for the given feed pressure range and excluding the very low pressure point data:

$$PCF = 2.1064\left(\frac{P}{P_{ref}} - 1\right) + 1$$

$$(R^2 = 0.9973) \qquad (14)$$

where the reference pressure P_{ref} is 65.5 bar.

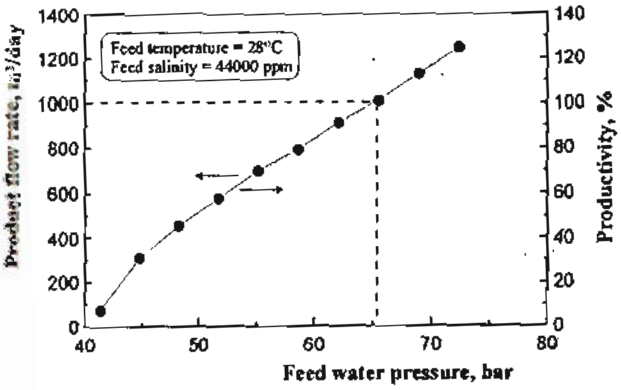


Fig. 4. Effect of feed water pressure on the product flow rate and productivity

Increasing the feed water pressure reduces the product water salinity as shown in Fig. 5. The product salinity decreases from 1500 to 300 ppm corresponding to an increase in the feed pressure from 41.37 to 72.4 bar respectively, at a feed water temperature 28°C and an average feed water salinity of 44,000 ppm. The decrease in the product salinity is seen to be rapid when the feed pressure decreases down to 50 bar. At larger feed pressures, the decrease in the product salinity is much slower.

Salt rejection increases with feed water pressure up to an asymptotic value which is the upper limit in the salt rejection curve. The fact that RO membranes are imperfect barriers to dissolved salts in feed water, so there is always some salt passage through the membrane. Increasing feed water pressure increases this salt passage, but water is pushed through the membrane at a faster rate than salt can be transported.

The product salinity, TDS_p for the given feed pressure range may be approximated by the following expression:

$$\frac{TDS_p}{TDS_{p\,ref}} = \left[-1.4437\left(\frac{P}{P_{ref}} - 1\right)^2 + 1.4981\left(\frac{P}{P_{ref}} - 1\right) + 1\right]^{-1}$$

$$(R^2 = 0.9934) \qquad (15)$$

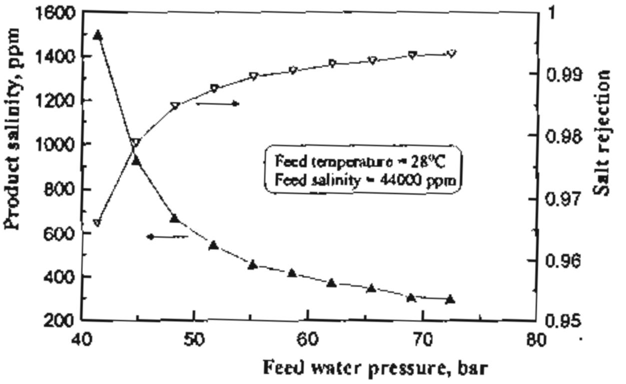


Fig. 5. Effect of feed water pressure on product water salinity and salt rejection

5.2. Feed Water Temperature

The maximum allowable operating temperature for the TORAY membranes as set by the manufacturer is 45°C for pH range of 2-10, [22]. The experiments were carried out with maximum temperature of 32°C.

Figure 6 shows the effect of feed water temperature on the product flow rate of the RO plant. The results of this experiment are taken at different times of the year to obtain different values of feed water temperatures. The figure demonstrates that product flow rate is very sensitive to changes in feedwater temperature. The product flow rate increases from 744 to 1128 m^3/day corresponding to an increase in the feed temperature from 10 to 32°C respectively, at a feed pressure of 63 bar. Therefore, in hot and arid zone, where water temperature is high, the RO product flow rate can be increased which resulted in low power consumption and cost.

The increase of feed water temperature has two effects; firstly, this results in an increase in osmotic pressure and consequently a decrease in the net driving pressure and product water flow rate, Eq. (3). Secondly and meanwhile, it leads to an increase in the water permeability coefficient due to the decrease in both viscosity and density. The latter one will outweigh the effect of decreasing net driving pressure, leading to an overall increase in product flow rate. Some researchers have observed similar phenomena and attributed it to an increase in membrane pore size with temperature.

The product flow rate for temperature variation, Eq. (10), is applied with the temperature correction factor given by Eq. (11). However, for the given data, the constant K has diverse values. Alternatively, the temperature correction factor, TCF, can be expressed simply as follows:

$$TCF = \exp[0.0196(t-25)] \qquad (R^2 = 0.9764) \qquad (16)$$

which is similar to Eq. (12) proposed by Tanigushi and Kimura [21] with a different constant due to the type of used membrane. The rate of increase of product flow rate averaged around 2% for every 1°C increment. This value is less than that reported in the literature of 3% [7].

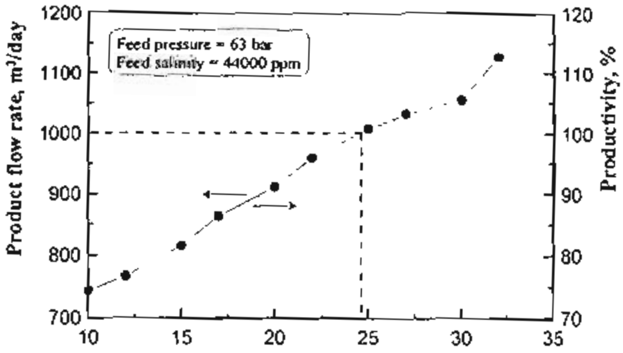


Fig. 6. Effect of feed water temperature on the product flow rate and productivity

5.3. Feed Water Salinity

The salt concentration measurements were obtained using a conductivity meter and converted to the corresponding TDS value.

The salinity of feed water has a significant influence on the product flow rate of the RO plant. As the feed water salinity increases, the product flow rate of the plant decreases as shown in Fig. 7. The plant product flow rate decreases from 1200 to 1008 m^3/day as the feed water salinity increases from 15,000 to 45,000 ppm respectively.

The concentration of salts in the feed water is a measure of osmotic pressure as given in Eq. (7). Increasing TDS$_f$, the osmotic pressure difference across the membrane, $\Delta\pi$, increases and therefore, the product water flow rate decreases, Eq. (3). The higher feed concentration leads to fouling by salt. A higher pressure would be required to maintain the water product flow rate.

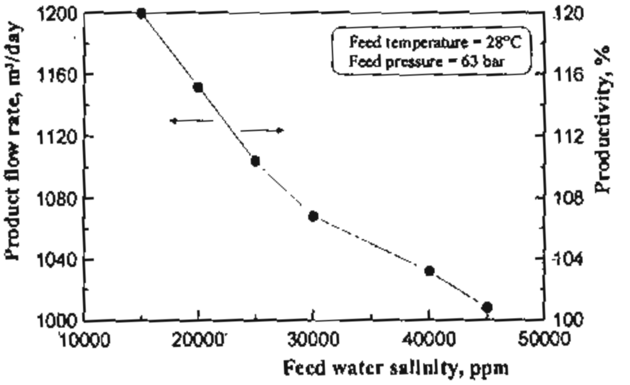


Fig. 7. Effect of feed water salinity on the product flow rate and productivity

Similar to the formulation for the effects of pressure or temperature on the product flow rate, the salinity coefficient factor *SCF* is used for feed water salinity variation:

$$Q_{p\,TDS_b} = Q_{p\,TDS_{bref}} \cdot SCF \tag{17}$$

where $Q_{p\,TDS_{bref}}$ is the product flow rate at a reference feed water salinity which is 45,000 ppm, resulting in $SCF = 1$.

For the given range of feed water salinity, the salinity coefficient factor can be calculated from Eq. (18):

$$SCF = \frac{TDS_{f\,ref}}{TDS_f}\left[-1.98\times10^{-5}\left(TDS_{f\,ref} - TDS_f\right)+1\right]$$

$$(R^2 = 0.9992) \tag{18}$$

where the reference value for $TDS_{f\,ref}$ is 45,000 ppm. The constant in Eq. (18) is obtained from the given data. The previous equation is a simplified equation to that obtained by combining Equations (4), (5), (6) and (17).

The salinity of feed water affects also the salinity of the product water as shown in Fig. 8. The salinity of product water increases by increasing the salinity of the feed water. The salinity of product water increases from 67 to 350 ppm corresponding to an increase in the feed water salinity from 15,000 to 45,000 ppm respectively. This experiment is carried out at a feed pressure 63 bar and feed water temperature of 28°C. Figure 8 also illustrates the corresponding salt rejection data which decrease with the increase of feed water salinity.

The relationship between the salinity of product water TDS_p and the feed water salinity TDS_f is given as:

$$\frac{TDS_p}{TDS_{p\,ref}} = 1.0849\left(\frac{TDS_f}{TDS_{f\,ref}}-1\right)^2 + 1.92\left(\frac{TDS_f}{TDS_{f\,ref}}-1\right)+1$$

$$(R^2 = 0.9977) \tag{19}$$

where the reference values $TDS_{p\,ref}$ and $TDS_{f\,ref}$ are 350 and 45,000 ppm, respectively.

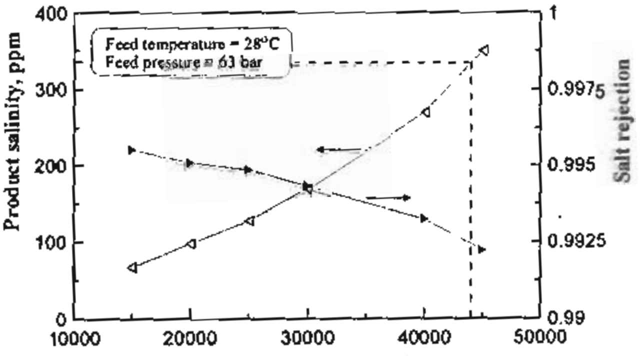


Fig. 8. Effect of feed water salinity on the product salinity and salt rejection

5.4. Recovery Ratio

The evaluation of RO system performance is achieved by the calculation of the recovery ratio and the salt rejection. The water product flow rate can be expressed as the water product flow rate at a reference point multiplied by the correction factors for feed pressure, temperature, and concentration as in Eq. (20):

$$Q_p = Q_{p_{ref}} \cdot PCF \cdot TCF \cdot SCF \qquad (20)$$

This equation could be used for calculating the water product flow rate at new conditions when the RO plant is working under different conditions of feed pressure, temperature, and concentration. The respective equation is as follows:

$$Q_{p2} = Q_{p1} \cdot \frac{PCF_2}{PCF_1} \cdot \frac{TCF_2}{TCF_1} \cdot \frac{SCF_2}{SCF_1} \quad (21)$$

where 1 and 2 are two different operating conditions, one of them could be the reference operating condition.

The recovery ratio *RR*, Eq. (8), and the coefficients *PCF*, *TCF* and *SCF* are calculated for the three previous experimental tests and plotted in Fig. 9.

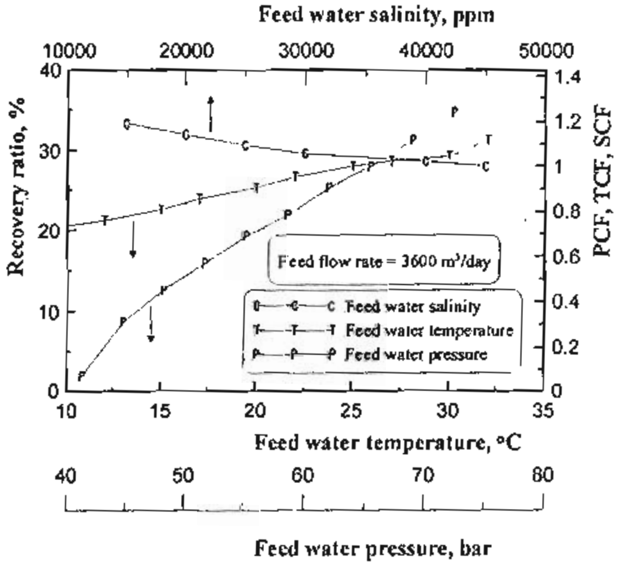


Fig. 9. Effect of feed water pressure, temperature and salinity on the recovery ratio and the coefficients PCF, TCF and SCF.

The average rate of increase of recovery ratio is about 2% for every 1°C increment in feed water temperature, and about 3.96% for every 1 bar increment in feed water pressure. The later value is calculated excluding the 2 very low pressures with very low recovery ratios.

The average rate of decrease of recovery ratio, RR, is about 0.62% for every 1000 ppm increment in feed water salinity.

6. COST ANALYSIS

In order to evaluate precisely the RO process, an economical analysis is important. The analysis is made for one unit ($1000\ m^3$/day). In addition to the capital cost, the major factors that influence the cost are the power consumption, running and maintenance costs. In the literature, the calculation of the desalination cost is based on different assumptions (e.g. interest rates and life expectancy of the equipment) or neglecting the investment cost or one of the operation costs. The major components of desalinated water production cost in commercial RO plants are: capital recovery cost, energy cost and operating and maintenance costs (labor, spares, membranes, chemicals, etc.). Their contributions vary respectively between 30–50%, 30–50%, and 15–30% of the cost of water produced. Energy is usually the major component cost over the useful service life of RO plants. The operating and maintenance cost depends mainly on the plant capacity, Poullikkas [23].

In this study, all costs are given in US$; the present currency rate is 1 US$ = 5.5 Egyptian Pounds (LE).

The unit cost of water can be expressed as:

$$C_{unit} = C_{capital} + C_{civil} + C_{elect} + C_{chem} + C_{maint} + C_{labor} \qquad (22)$$

where $C_{capital}$, C_{civil}, C_{elect}, C_{chem}, C_{maint}, and C_{labor} are the unit cost components for capital cost, civil works, electricity consumption, chemicals, maintenance and repair, and labor.

6.1. Capital Cost

The unit cost component for capital cost is calculated as:

$$C_{capital} = \frac{D_{capital}}{V_L} \tag{23}$$

where $D_{capital}$ is the capital cost for one unit (1,000,000 \$) and V_L is the total volume of water produced during the life time (i.e. 10 years) of the system. The annual working period is taken as 335 days. Therefore, V_L = 335 x 10^4 m^3. The unit cost component for capital cost is:

$$C_{capital} = 0.29851\,\$/m^3 \tag{24}$$

6.2. Cost of Wells and Plant Civil Work

The cost of wells and plant civil work is estimated as:

$$C_{civil} = 0.04982\,\$/m^3 \tag{25}$$

6.3. Power Consumption Cost

The following individual power consumption for each component of the plant is recorded and illustrated in Table 3.

Table 3 Energy requirements for Nuweiba RO plant

Pump	Power, P_{pumps} (kW)
Intake pump	18
Filter pump	18
Additive pumps	1
Product pump	3
RO high-pressure pump	285
Total	**325**

The energy consumption for pumping is estimated as:

$$E_{pumps}\ (kWh/m^3) = \frac{P_{pumps}\ (kW) \times L}{V_L} \tag{26}$$

where P_{pumps} is the total pump work and L is the life time of the system in hours (L = 80,400 hr). The estimated energy consumption is 7.8 kWh/m^3.

The unit cost component for electricity cost is calculated as:

$$C_{elect} = E_{pumps} \times \text{Electricity Rate (LE/kWh)} \tag{27}$$

The source of electrical energy used in the plant is the Egyptian National Electrical Network and its present rate is 0.04 \$/kWh (0.22 LE/kWh). Therefore, the unit cost component for electricity is:

$$C_{elect} = 0.312\,\$/m^3 \tag{28}$$

6.4. Chemical Requirements

The cost of chemicals depends mainly on the design, the feed water quality and chemicals prices. Table 4 shows the costs of chemical treatment as an average during the operation period. In this table, other chemicals are those used to adjust the pH value, cleaning, reducing algae gross ... etc.

Table 4 Chemical cost per m^3 product water for Nuweiba RO plant

Chemical doses	g/m^3	Cost, \$/m^3
Calcium hypochlorite CaOCl (Pre + Post)	20	0.00545
Hydrochloric acid HCl (30%)	100	0.01455
Antiscalant	10	0.04545
Sodium Hydroxide NaOH	80	0.00727
Other chemicals	---	0.02182
Total		**0.09454**

Therefore, the chemicals cost is:

$$C_{chem} = 0.09454\ \$/\mathrm{m}^3 \tag{29}$$

6.5. Maintenance and Repair

Maintenance of process equipment is necessary to guarantee stable and reliable operation throughout the lifetime of the RO desalination plant. The average cost values of maintenance and repair during the normal operation of Nuweiba RO plant are shown in Table 5.

Table 5 Maintenance and repair costs per m^3 product water for Nuweiba RO plant

Operation	Cost, $/$m^3$
Cartridge filter	0.00545
Pumps and motors	0.01455
Controls and electrical, etc.	0.00909
Instrument, etc.	0.00545
Miscellaneous	0.00909
Total	**0.04364**

Then the maintenance and repair costs for Nuweiba RO plant are given from:

$$C_{maint} = 0.04364\ \$/\mathrm{m}^3 \tag{30}$$

6.6. Labor and Administration

Labor and administration costs of Nuweiba RO plant are estimated as average value from:

$$C_{labor} = 0.09091\ \$/\mathrm{m}^3 \tag{31}$$

Finally, the unit cost of water is estimated using Eq. (22) as:

$$C_{unit} = 0.88942\ \$/\mathrm{m}^3 \tag{32}$$

From the above cost analysis, it is clear that the major factors affecting the product water cost are the capital and power costs as shown in Fig. 10. Surprisingly, the chemical treatment cost is one of the lowest in percentage. This is because the plant membranes are new and in a good condition.

The RO system is reliable for operation; it does not require any skilled operator and is simple to install. The only inconvenience is its high operating cost. In this case the high operation cost comes from two items; power cost 35% and capital cost 33.6%. Maintenance and repairs present only 5% and chemical treatment 10%. Desalination is a high energy consumption process. The energy sharing amounts to 30-50% of total production cost. Due to the rapid progress in seawater reverse osmosis technology, the cost has decreased.

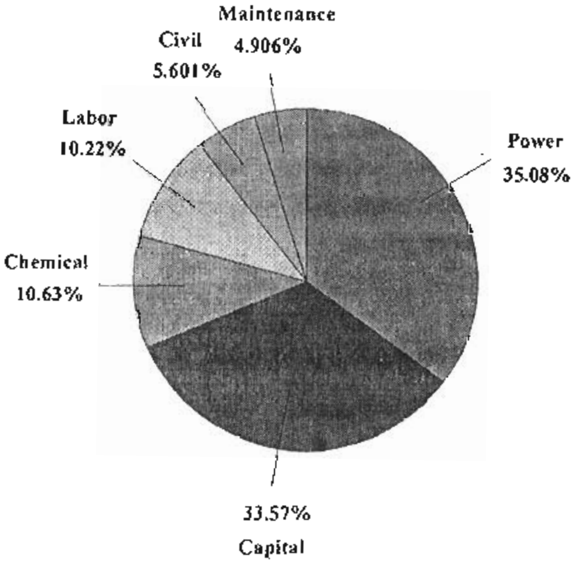


Fig. 10. Capital, energy and operating and maintenance costs of Nuweiba RO plant.

The cost of seawater desalination by RO has significantly decreased in the last years. For units with capacity 1000–5000 m^3/day the cost of product water ranges from 0.70 $/$m^3$ to 3.94 $/$m^3$, Karagiannis and Soldatos [24]. The production of water of Nuweiba RO desalination plant costs 0.89 US$/$m^3$ which is in the acceptable range compared with other RO installed units.

The RO plant energy consumption is approximately 6–8 kWh/m^3 without energy recovery. Installing an energy recovery device reduces the energy consumption quite dramatically to 4–5 kWh/m^3, Khawaji et al. [25]. The specific energy of a SWRO system of 1,000 m^3/day permeate flow, 45% recovery and 69 bar nominal membrane feed pressure with turbocharger is 4.29 kWh/m^3, [26]. The energy consumption rate of Nuweiba RO desalination plant is 7.8 kWh/m^3, which is relatively high compared to other existing RO systems. The power consumed in ventilation, lightening and air conditioning systems (not recorded) is believed to be the reason. The high pressure pump consumes about 88% of the total power consumption. An optimization study can be undertaken to minimize the power consumption of the plant.

The life of the RO membrane depends on local water chemistry and proper maintenance, e.g., regular filter changes. Under typical conditions, the RO membrane life ranges from 18 months to three years.

7. MAINTENANCE SCHEDULE

Maintenance of RO plant and equipment is essential to keep good performance during its operation period, [27]. Since all the components are new and satisfy the design conditions, the performance of the new RO desalination plant is very good. An objective of this case study is to evaluate the maintenance schedule of the RO plant. Therefore, the maintenance processes are recorded during the operation of the RO plant as shown in Appendix B. Maintenance schedule, Tables 8-17, includes filters (sand, cartridge), pumps (feed, high-pressure, brine and back wash, dosing), tanks (product, dosing), pumping station, RO units and power panels. This maintenance schedule is strictly applied. Therefore, unnoticeable change of the plant readings during the period of operation was observed, Appendix A.

8. CONCLUSIONS

Reverse osmosis desalination plant in Nuweiba city in Sinai, Egypt (5000 m^3/day) is taken as a case study. Experimental tests are carried out on site to evaluate the plant performance. The following conclusions are obtained based on 5 years of operation period from 2001 of the RO desalination plant:

1- The RO system is found to be sensitive to the variation in the feed water temperature, pressure and salinity;
   a) Higher feed water temperature increases the plant product flow rate.
   b) Increasing the feed water pressure increases the plant product flow rate, but decreases the permeate salinity.
   c) Higher feed water salinity causes lower product flow rate and higher product water salinity.

2- The cost analysis of the RO plant reveals that the major factors affecting the product water cost are the power consumption cost (35.1%) and capital cost (33.6%) while the chemical treatment represents 10.6% of the total cost.

3- The used maintenance schedule (for 5 years operation) is seen to be suitable for the plant, since the change in plant performance during the operation period is not noticeable.

Symbols

A — Active area of membrane (m^2)
a — Permeability coefficient for water (m/h.bar)
b — Permeability coefficient of salt (m/h)
$C_{capital}$ — Unit cost component for capital cost
C_{chem} — Unit cost component for chemicals
C_{civil} — Unit cost component for civil works
C_{elect} — Unit cost component for electricity consumption

C_f — Salt concentration of the feed water (kg/m^3)
C_{labor} — Unit cost component for labour
C_{maint} — Unit cost component for maintenance and repair
C_p — Salt concentration of the permeate (kg/m^3)
C_s — Salt concentration of the brine (kg/m^3)
C_{unit} — Unit cost of water (US\$/m^3)
C_{wall} — Concentration at the membrane wall (kg/m^3)
J_w — Volumetric flux of water (m/h)
J_s — Mass flux of salt (kg/m^2.h)
P — Pressure (bar)
PCF — Pressure coefficient factor
Q_f — Feed water volumetric flow rate (m^3/h)
Q_p — Permeate volumetric flow rate (m^3/h)
Q_s — Brine volumetric flow rate (m^3/h)
RR — Recovery ratio
SCF — Salinity coefficient factor
SR — Salt rejection
t — Temperature (°C)
TCF — Temperature coefficient factor

Greek

Δp — Pressure drop across the membrane (bar)
π — Osmotic pressure (bar)
ρ — Density of seawater (kg/m^3)

Subscripts

f — feed
o — outlet
p — permeate
s — brine

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APPENDIX A

Normal readings of Nuweiba RO plant for years 2002 and 2005

Table 6 Measured data for year 2002

Date	Sand Filter Pressure (psi)		Cartridge Filter Pressure (psi)		HPP Pressure (psi)	Turbo Pressure (psi)	Membrane Pressure (psi)		Product Water Flow Rate (m^3/h)	Reject Water Flow Rate (m^3/h)	Product Water Conductivity (μS/cm)
	In	Out	In	Out	Out	In	In	Out			
1/1/2002	7	1	38	29	700	630	975	935	47	103	764
2/1/2002	11	1	38	28	700	630	980	940	48	102	765
3/1/2002	11	1	38	26	700	630	975	935	48	102	770
4/1/2002	11	1	38	25	700	630	980	940	47	103	771
5/1/2002	7	1	38	21	690	625	970	930	48	102	775
6/1/2002	11	1	38	19	690	625	975	940	47	103	779
7/1/2002	7	1	38	18	690	625	970	930	45	105	780
8/1/2002	7	1	38	19	695	625	970	930	45	105	785
9/1/2002	12	1	38	19	690	625	980	935	45	105	790
10/1/2002	12	1	38	18	690	625	975	935	46	104	798
11/1/2002	11	0	38	14	690	620	975	935	45	105	810
12/1/2002	12	1	38	32	705	620	970	930	45	105	770

Table 7 Measured data for year 2005

Date	Sand Filter Pressure (psi)		Cartridge Filter Pressure (psi)		HPP * Pressure (psi)	Turbo Pressure (psi)	Membrane Pressure (psi)		Product Water Flow Rate (m^3/h)	Reject Water Flow Rate (m^3/h)	Product Water Conductivity (μS/cm)
	In	Out	In	Out	Out	In	In	Out			
1/1/2005	12	0	38	33	705	615	970	945	47	103	786
2/1/2005	12	1	38	33	705	625	970	930	48	102	780
3/1/2005	12	1	38	33	705	620	970	930	48	102	789
4/1/2005	12	0	38	33	700	620	970	930	49	101	785
5/1/2005	7	0	38	32	700	625	980	940	48	102	792
6/1/2005	11	0	38	32	700	630	970	935	47	103	799
7/1/2005	11	1	38	32	695	625	970	935	46	104	793
8/1/2005	12	1	38	31	700	625	980	935	46	104	806
9/1/2005	8	1	38	30	700	620	980	940	46	104	819
10/1/2005	8	0	38	29	700	625	970	940	46	104	785
11/1/2005	12	0	38	27	700	625	970	930	45	105	780
12/1/2005	12	1	38	25	690	620	970	930	45	105	784

* HPP: High-Pressure Pump

APPENDIX B

Maintenance procedure of Nuweiba RO plant

Table 8 Periodical maintenance for sand filters

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Filter body and filter cleaning	✓					
2	Checking for leakage	✓					
3	Tightening flanges and valves	✓					
4	Checking valves	✓					
5	Discharging water from sump	✓					
6	Checking dosing connections	✓					
7	Recording pressure gauges readings	✓					
8	Manual back wash		✓				
9	Checking leakage in air lines		✓				
10	Checking the control panel			✓			
11	Checking the auto valves sequence			✓			
12	Calibration of pressure transmitters				✓		
13	Checking filter media					✓	

Table 9 Periodical maintenance for feed pumps

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning for pump body	✓					
2	Checking the oil and lubricant level	✓					
3	Checking (heat-noise-vibration)	✓					
4	Checking for leakage	✓					
5	Tightening flanges and valves	✓					
6	Checking valves	✓					
7	Recording motor current	✓					
8	Recording pressure gauges readings	✓					
9	Checking the control panel		✓				
10	Checking the circuit breakers		✓				
11	Checking the contactors		✓				
12	Checking the motor cable		✓				
13	Checking pump parts			✓			
14	Checking the motor				✓		

Table 10 Periodical maintenance for cartridge filters

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning pump body	✓					
2	Checking oil and lubricant levels	✓					
3	Checking for (heat - noise - vibration)	✓					
4	Checking for leakage	✓					
5	Tightening flanges and valves	✓					
6	Checking valves	✓					
7	Recording motor current	✓					
8	Recording pressure gauges readings	✓					
9	Checking the control panel		✓				
10	Checking the circuit breakers		✓				
11	Checking the contactors		✓				
12	Checking the motor cable		✓				
13	Checking pump parts			✓			
14	Checking the motor				✓		

Table 11 Periodical maintenance for high pressure pumps

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning for pump body	✓					
2	Greasing the moving parts and bolts	✓					
3	Checking for (heat - noise - vibration)	✓					
4	Checking for leakage	✓					
5	Tightening flanges and valves	✓					
6	Checking valves	✓					
7	Recording motor current	✓					
8	Recording operating hours and stop hours	✓					
9	Recording flow and pressure	✓					
10	Checking oil level		✓				
11	Checking the soft starter			✓			
12	Checking the control panel			✓			
13	Checking the circuit breakers			✓			
14	Checking the contactors			✓			
15	Checking the motor cable			✓			
16	Checking pump alignment					✓	
17	Checking pump parts						✓
18	Checking the motor						✓

Table 12 Periodical maintenance for RO units

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Cleaning unit area	✓					
2	Recording flow, pressure and TDS	✓					
3	Recording TDS for each pressure vessel	✓					
4	Tightening flanges and valves	✓					
5	Checking for leakage	✓					
6	Checking for leakage in air lines	✓					
7	Checking the auto valves sequence	✓					
8	Flushing unit after stop	✓					
9	Checking turbine operation	✓					
10	Checking turbine parts			✓			
11	Calibration of pressure transmitters				✓		
12	Calibration of flow transmitters				✓		
13	Calibration of conductivity meter				✓		
14	Calibration of feed valve				✓		
15	Chemical cleaning for units					✓	

Table 13 Periodical maintenance for product tanks

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Checking Chlorine and pH + dosing	✓					
2	Flushing tanks			✓			
3	Cleaning inlet sleeves			✓			
4	Taking samples for analysis			✓			
5	Chemical cleaning of tanks				✓		
6	Calibration of level switches				✓		

Table 14 Periodical maintenance for power panels (MMC)

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning for panels	✓					
2	Cleaning internal components with air		✓				
3	Changing burned led		✓				
4	Checking fuses		✓				
5	Tightening cables fixation			✓			

Table 15 Periodical maintenance for brine and back wash pumps

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning for pump body	✓					
2	Checking the oil and lubricant level	✓					
3	Checking for (heat - noise - vibration)	✓					
4	Checking for leakage	✓					
5	Tightening flanges and valves	✓					
6	Checking valves	✓					
7	Recording motor current	✓					
8	Recording operation hours	✓					
9	Checking water levels in tanks	✓					
10	Discharging water from sump	✓					
11	Checking the control panel			✓			
12	Checking the circuit breakers			✓			
13	Checking the contactors			✓			
14	Checking the motor cable			✓			
15	Checking pump parts				✓		
16	Checking the motor				✓		

Table 16 Periodical maintenance for dosing pumps and tanks

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning for pump body	✓					
2	Checking tanks levels	✓					
3	Checking pumps flow	✓					
4	Checking for leakage	✓					
5	Checking level switches		✓				
6	Cleaning tanks and lines			✓			

Table 17 Periodical maintenance for pumping station

No.	Maintenance steps	Daily	Weekly	Monthly	Yearly¼	Yearly½	Yearly
1	Dry cleaning for pump body	✓					
2	Checking the oil and lubricant level	✓					
3	Checking for (heat - noise - vibration)	✓					
4	Checking for leakage	✓					
5	Tightening flanges and valves	✓					
6	Checking valves	✓					
7	Recording motor current	✓					
8	Recording pressure gauges readings	✓					
9	Checking city tanks levels	✓					
10	Checking storage tanks levels	✓					
11	Discharging water from sump	✓					
12	Checking the operation of ventilation system	✓					
13	Checking the control panel		✓				
14	Checking the circuit breakers			✓			
15	Checking the contactors			✓			
16	Checking the motor cable			✓			
17	Checking pump alignment			✓			
18	Checking pump parts				✓		