

Reverse osmosis as one-step wastewater treatment: a case study on groundwater pollution

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The present case study is focused on performance evaluation of a Reverse Osmosis (RO) membrane based pilot plant to treat the ground/surface drinking water sources polluted by flood, rivers and/or canals. The RO plant was designed, fabricated and then operated with polluted water. Two feed water samples having a TDS of $2.000 \text{ mg} \cdot \text{L}^{-1}$ and $10.000 \text{ mg} \cdot \text{L}^{-1}$ respectively, were taken and analyzed for physical, chemical and microbiological contaminants. The RO plant was run once through over a span of 100 hrs at an operating pressure of 15 bar. TDS rejections were found to be more than 94% while permeate flux was measured to be $25.82 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ to $40.55 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$. Results show that RO plant has a potential to remove physical, chemical and microbiological contaminants like Total Coliform and *E. Coli* in one step.

Keywords: Reverse Osmosis (RO), membrane separation, Total Dissolved Solids (TDS), Total Coliform, *E. Coli*.

INTRODUCTION

Due to rapid growth in world's population and scarcity in natural resources, the significance of clean drinking water is increasing, both in terms of quantity and quality. As the drinking water has to pass through different channels, it mostly gets contaminated. The contaminated water sources have both direct and indirect effects on human health such as diarrhea, cholera, typhoid, and fever^{1, 2}.

The traditional treatment of pathogenic microorganisms has been analyzed in different studies on tertiary/chemical treatments³⁻⁷. However, the conventional wastewater treatment methods are not able to completely remove the suspended particles and/or smaller inorganic salts. In contrast, membrane processes have proved to be an efficient technique in removing almost all kinds of contaminants and producing the finest quality of drinking water. The most common membrane processes are the microfiltration (MF), ultrafiltration (UF), nanofiltration (NF) and reverse osmosis (RO). Membranes can produce a better quality water but at the expense of cost. Operating cost increases with increasing removal of ions and particles by the membrane⁸⁻¹¹.

Being one of the finest filtration techniques, RO is now widely used for effective and economical treatment of brackish as well as seawater. Design considerations of RO system depend on total dissolved solids, organic contaminants, suspended solids and desired quality of produced water. The RO membrane acts as a barrier to all dissolved salts and inorganic molecules, as well as organic micro molecules. Water molecules, on the other hand, pass freely through the membrane, thus creating a purified product stream. The water produced (Permeate) satisfies most of the water quality standard parameters^{8, 10, 12}.

RO membranes have the potential to remove the organic, inorganic and biological contaminants from saline and ground water¹³. But membrane fouling in RO membrane, limit the use of this process for water treatment. The main fouling mechanisms in RO membranes include colloidal fouling (particulate deposition),

biofouling (microbial adhesion and growth), organic fouling (adsorption of organic compounds), and inorganic fouling (scaling)¹⁴. To address this problem, a pre-treatment step is always preferred before treating the effluent with RO. Beside this, fouling can be eliminated by choosing benign design and operating conditions. However, at commercial competitive fluxes, fouling is ubiquitous. Though, routine cleaning of membrane at the end of each day (experiment) with chemicals reduces the part of adsorption resistance, irreversible fouling of membrane can not be completely eliminated¹⁵. Winfield found that role of dissolved solids is greatly important in RO membrane fouling as compared to the effects of suspended solids^{16, 17}. RO membranes can easily be fouled due to microbial growth^{17, 18}.

Likewise, concentration polarization also reduces the plant efficiency¹⁹. Concentration polarization is the accumulation or depletion of solutes near an interface. As a result of water crossing the membrane, the solute is concentrated on the feed side of the membrane surface and diluted on the permeate side. As, an asymmetric membrane is used in RO which comprises of a thin dense layer on top of a porous supported layer, concentration polarization occurs externally on the dense layer and internally on the supported layer side^{20, 21}.

Hastutu and Wardiha studied the treatment of brackish water in Indonesia's coastal area with UF and RO. They found the coupled UF and RO process to be a better choice for obtaining drinkable water from brackish coastal water²². Afonso et al. studied the techno-economical aspects of brackish ground water treatment by MF and RO. They found that potable water could be produced by RO/NF at reasonable price²³. Nataraj et al. found hybrid RO/NF as a useful technique to treat wastewater like one from distillery that is highly polluted with physical and biological pollutant load²⁴.

Some of the researchers studied one step membrane based wastewater treatment unit and found satisfactory results. Bruggen et al. carried out experiments on nanofiltration and found it to be a suitable technique for treatment of ground and surface water contaminated with micro pollutants, viruses and bacteria¹⁰. In another study

Bruggen et al. removed pesticides and hardness in one-step with NF¹¹. Yavuz et al. used spiral wound FilmTecTM SW30-2540 RO membrane to treat the geothermal water for boron rejection. A rejection of 84% was noted at 20 bar²⁵. Jawad et al. considered RO membranes suitable for urban wastewater treatment at Kuwait²⁶. Additional research is needed to verify and test the theory to remove all the physical, chemical and biological pollutants through RO in one step. Such research will be helpful in providing drinkable water in flood affected remote areas of undeveloped or underdeveloped regions of the world.

Contaminated drinking water is one of the major health hazard issues in Pakistan. In order to facilitate the community with quality drinking water, a domestic level RO plant may solve the problem in a better way. The present study is aimed to evaluate the performance of a Reverse Osmosis (RO) pilot plant to treat the ground/surface drinking water sources polluted by flood, rivers or canals. The RO Plant was fabricated and then tested to remove the suspended solids, total dissolved solids, turbidity and pathogenic microorganisms from source water. The RO plant was operated continuously for 20 days with 5 hrs of plant operation per day.

MATERIAL AND METHODS

Raw water characteristics

A model solution of raw feed water was prepared according to the pollutant strength equivalent to the mean pollutant strength of water taken from the surface/ground of rural areas inundated by rivers, canals or flood. The main quality parameters of raw water are shown in Table 1.

Membrane and experimental setup

A pilot scale RO unit was fabricated with vertically installed membrane module. Schematics of the unit are shown in Figure 1. Dow FilmtecTM BW30-4040 RO membrane was used in the plant. Specifications of the membrane are given in Table 2. Samples from the wastewater to be treated were analyzed for physical, chemical and bacteriological parameters. In the experimental setup, wastewater from feed tank was first passed through a 5 µm filter cartridge. It was then pumped to the RO

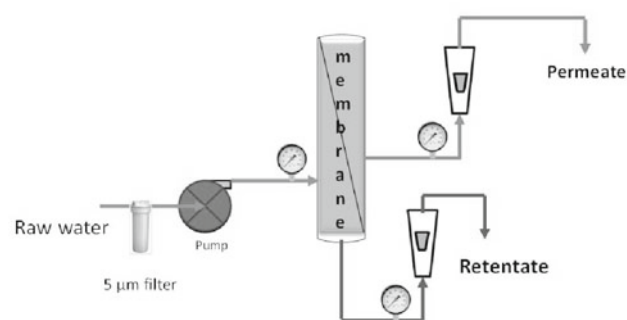


Figure 1. Reverse Osmosis (RO) based pilot scale unit for wastewater treatment

Table 2. Dow FilmtecTM BW30-4040 Industrial Reverse Osmosis Membrane Specifications (provided by manufacturer)

Dimensions	3.9" W X 40" L
Maximum Operating Temperature	113°F (45°C)
Active surface area	78 (7.2) ft ² (m ²)
Permeate Flow Rate	2400 gpd (3.2 m ³ /d)
Maximum Operating Pressure	600 psi (41 bar)
Maximum Feed Flow Rate	16 gpm (3.6 m ³ /h)
Stabilized Salt Rejection	99.5%
pH Range, Continuous Operation	2–11
pH Range, Short Term Cleaning	1–12
Membrane Type	Polyamide Thin-Film Composite

membrane with a pressure of 10–20 bars, which split the feed water into permeate and retentate streams. Gradual increase in pressure at the membrane inlet caused an increase in permeate flux with an improved water quality. Permeate and retentate streams were stored in separate storage tanks. A part of retentate stream was recycled back to the feed tank in batch process. The permeate flow rate was 22–27% of the feed flow rate. 73–78% of the feed water was recycled back to the feed tank during experimentation. The feed flow rate was kept

Table 1. Raw water (feed) quality parameter

Quality parameters	WHO Standards [25]	Raw water quality [Avg]
Colour	≤ 15 TCU	15–25
Taste	Acceptable	Bad
TH	< 500 mg/L	650–1100
TDS	< 1000	2000–10000
Turbidity	< 5 NTU	7–23
PH	6.5–8.5	6.5–8
NO ₂	≤ 0.5 mg/L	1.6–5.5
NO ₃	≤ 50 mg/L	40–60
Chlorides as Cl	250 mg/L	500–1000
Total Plate Count (TPC)	100 CFU/ml	1000–3500
Total Coliform	0/100 ml	356– > 1000
Fecal Coliform	0/100 ml	+
<i>E. Coli</i>	0/100 ml	+

constant at 12.60 L/hr while permeate flux varied from 20–30 L · m⁻² · h⁻¹ due to an increase in concentration of feed water by recycling retentate streams. Continuous process was employed in most of the experimentation and there was no recycle stream. The feed water quality was maintained constant throughout the process. Gate valves were installed on permeate and retentate streams to control flow and pressure thus managing water quality. Pressure gauges were installed at pump's discharge, membrane outlet, and permeate and retentate lines to monitor the pressure at each point.

Methodology

The Plant was operated continuously in a total recycle mode. Permeate and retentate streams were recycled back to the feed tank to keep the feed concentration constant. The plant was operated for twenty days with five hours a day and having ten minutes break after half time period. Quality parameters were measured at the start and end of each day (experiment). These included tests like TDS, pH, Nitrate, Nitrite and microbiological analysis of water including *E. Coli*, Total Plate Counts and Total Coliform.

Turbidity, TDS and pH of the water samples were measured with digital Turbidity meter and pH/TDS meter, respectively. Nitrate and Nitrite were measured with Hanna Photometer. Microbiological analysis were carried out by using Lauryl Sulfate Agar as a selective method for measuring fecal and total coliform in water. This media enhances the bacterial growth while inhibits the growth of other micro-organisms. A known volume (60 ml) of water was passed through microporous membrane filter and the filter was then placed on absorbent pads (in petri dishes) containing culture media (Membrane Lauryl Sulfate Agar). The petri dishes were then placed in an incubator at a temperature of 37°C and observed after 24–48 hours. The fecal coliform, *E. coli* and total coliform unit was monitored for each sample analyzed.

After each experiment, routine cleaning and maintenance procedure was performed. The RO unit was cleaned with 0.1% NaOH and 0.2% HCl solutions to remove organic and inorganic contaminants deposited on membrane surface and pipes. The unit was then rinsed with distilled water at a pressure of 5 bar and maximum feed flow rate of 12.60 L/min. The maintenance period was 35 to 40 minutes.

During each experimental run, the feed flow rate was kept constant at 756 L · hr⁻¹ and trans-membrane pressure was maintained at 15 bar. The temperature of initial feed was 24–26°C. Each single experiment was run continuously for 5 hours a day. Same experimental procedure was repeated for two different model raw water solutions having a TDS of 2.000 mg · L⁻¹ and 10.000 mg · L⁻¹ respectively.

After wastewater treatment, the post-water quality analysis were carried out and compared with pre-treatment results. Plant efficiency was then calculated from salt rejection, permeate flux and water quality parameters. For the evaluation of water treatment efficiency, raw water and permeate samples were collected periodically. Water quality parameters including pH, turbidity, total dissolved solids, nitrate and nitrite, total coliforms and *Escherichia Coli* were measured. Salt rejection (R) was

measured by $R = (1 - C_p/C_F) \cdot 100$ where C_p is the salt concentration in the permeate solution, and C_F is the salt concentration in the feed solution.

RESULTS AND DISCUSSION

Effect of TDS rejection and permeate recovery as continuous function of time

Most of the quality characteristics of drinking water are described by Total Dissolved Solids (TDS). Permeate water was tested for TDS as a function of operation time. Samples were taken from permeate stream after every 15 minutes. Thus 4 samples in one hour and 20 samples in a single day were tested. Likewise, the next day, wastewater treatment was restarted.

In Figure 2, percent rejection in TDS against operation time is plotted for an initial wastewater of TDS 2.000 mg · L⁻¹ and 10.000 mg · L⁻¹, respectively. Plot shows a decrease in % rejection of TDS as a function of time. The initial TDS rejection is found to be 98.6% and 94.1% for the feed water of TDS 2.000 mg · L⁻¹ and 10.000 mg · L⁻¹, respectively. A decrease in percent rejection was observed with the passage of operating time. However, routine maintenance at the end of the day improved TDS rejection. After a week of operation, plant performance was found to be decreased. Moreover, TDS rejection dropped rapidly if the plant operated consecutively over 100 hours of continuous operation, although routine maintenance cleaned the membranes to some extent. Such kind of behavior was shown irrespective of feed water pollutants strength. Nevertheless, less effect on TDS rejection was observed for low feed strength as shown in Figure 2, for an initial feed TDS of 2.000 mg · L⁻¹. For feed water of initial TDS 2.000 mg · L⁻¹, decrease in TDS rejection was noticed to be 2.7% at the end of 1st day and 12.5% at the end of 20th day of operation. TDS values in permeate water increased from 36 mg · L⁻¹ on 1st day to 343 mg · L⁻¹ on 20th day of operation. Similarly, for feed water of initial TDS 10,000 mg · L⁻¹, decrease in TDS rejection was noticed to be 6.8% at the end of 1st day and 24.5% at the end of 20th day of operation. The development of biofilm layer and treating of highly concentrated wastewater increased concentration polarization which resulted in low salt rejection. The addition of low dose chlorine in CIP process and treating for a longer period of time

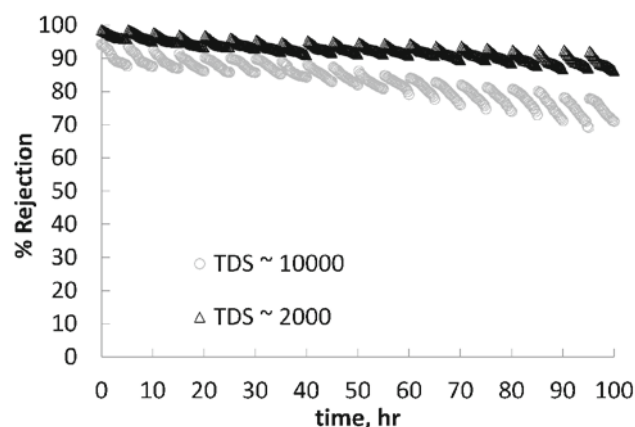


Figure 2. TDS rejection as continuous function of time, 5 hrs · day⁻¹

(50–60 minutes) with NaOH and HCl solution improved the performance of the RO unit.

Similarly, when the feed of initial TDS $10.000 \text{ mg} \cdot \text{L}^{-1}$ was treated, the permeate flux dropped from 36.5 to $33.0 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ on the first day and 28.3 to $25.7 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ on the 20th day of operation. Likewise, as shown in Figure 3, the permeate recovery was noted to be 33.6 – 35.2% on the first day and 25.7 – 28.2% on the 20th day of operation. It can be observed from Figure 2 and 3 that when feed water TDS increases, a sharp decline in permeate flux and recovery occurs. For example, permeate flux decline and rejection was 6.8% on the first day, while 8.7% on the 20th day of operation. Similar behavior was observed for feed with initial TDS of $2000 \text{ mg} \cdot \text{L}^{-1}$ as shown in Figures 2 and 3.

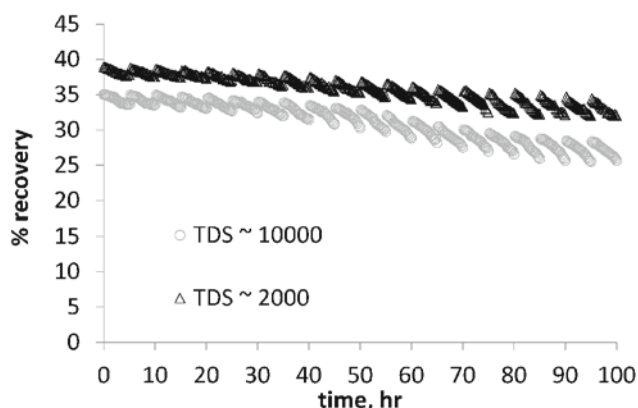


Figure 3. Permeate recovery as continuous function of time, $5 \text{ hrs} \cdot \text{day}^{-1}$

It was found that permeate flux and recovery depends upon the hydrodynamic conditions like pressure loss, pump power loss, leakages and membrane fouling²⁸. Several researchers have explained the effect of operating conditions (feed water quality, pressure and temperature) on performance parameters (permeate flux and recovery). Hastuti and Wardiha operated the brackish coastal water RO treatment plant at lower applied pressures e.g. 5 and 8 bars and noticed the TDS and turbidity removal to be greater than 96% . Permeate flux was measured to be 52 – $56 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ and 28 – $40 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ for applied pressure of 8 and 5 bar, respectively²². Similarly, Afonso et al. operated the brackish ground water treatment plant with FilmTec™ RO membrane (SW30-2521) at a pressure of 20 – 30 bars and temperature of 40°C . They obtained water recovery ratio upto 77.5% for brackish (feed) water having a TDS range of 948 to $2.288 \text{ mg} \cdot \text{L}^{-1}$ ¹⁵. The feed water quality used by Afonso et al. has almost the same TDS concentration as the one used in present experimental work.

Turan et al. studied dairy wastewater treatment with RO and found that permeate flux is dependent on trans-membrane pressure, feed flow rate and feed pollution load. They observed permeate flux of $25 \text{ L} \cdot \text{m}^{-2} \cdot \text{hr}^{-1}$ for a feed flow rate of $550 \text{ L} \cdot \text{hr}^{-1}$, COD of $10.000 \text{ mg} \cdot \text{L}^{-1}$ and applied pressure of 14 bar. A decline of 19% was observed in permeate flux when feed COD increased from 5.000 to $10.000 \text{ mg} \cdot \text{L}^{-1}$ ²⁸. All these studies support our experimental results and give a similar relation of the effect of operating parameters on performance parameters of the RO plant.

Removal of microbial pollutants in continuous wastewater treatment

Microbial analysis of treated water was carried out by calculating Total Plate Counts (TPC), Total Coliform (TC) and *E. Coli*. Lauryl sulfate Agar was used as a feed for measuring Total Coliform and *E. Coli*. These analysis depict a clear picture of most hazardous bacteria present in wastewater. These analysis were performed at the start and end of the experiment, each day. As discussed in previous paragraphs, each experiment on a single day lasted for 5 hours of continuous operation followed by routine maintenance at the end of the experiment. It can be observed from Figure 4 that TPC counts were in the safe range throughout. However, in a very few samples, it was found that TPC counts were greater than the allowable limits for drinking water. The excess level of TPC counts were noticed in the samples taken at the end of the day. Interestingly, the samples taken at the start of the day showed that TPC counts were within the allowable limits for drinking water.

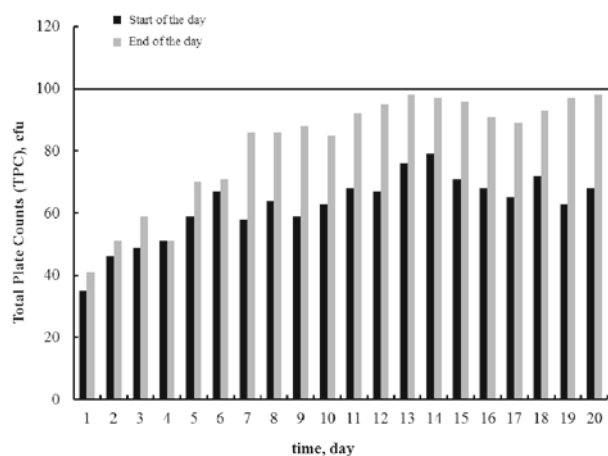


Figure 4. Total Plate Counts (TPC) analysis in continuous wastewater treatment; $5 \text{ hrs} \cdot \text{day}^{-1}$

On the other hand, as indicated in Figures 5 and 6, TC and *E. Coli* analysis do not show satisfactory results. “0” indicates the absence and “1” indicates the presence of TC and *E. Coli*. TC and *E. Coli* were found to be absent in the samples analyzed at the start and end of each day except a few samples. The primary reasons of

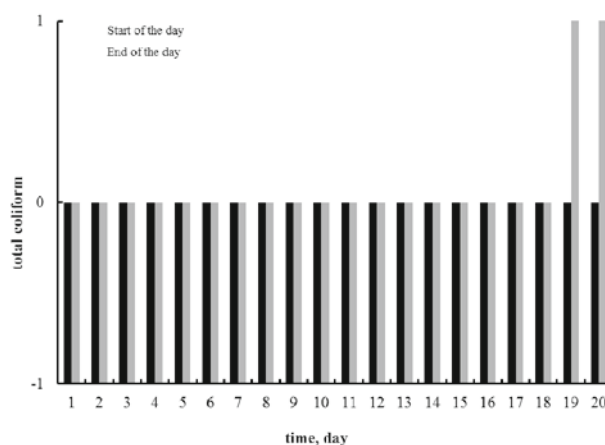


Figure 5. Total Coliform (TC) analysis in continuous wastewater treatment; $5 \text{ hrs} \cdot \text{day}^{-1}$; 0: not detected, 1: detected

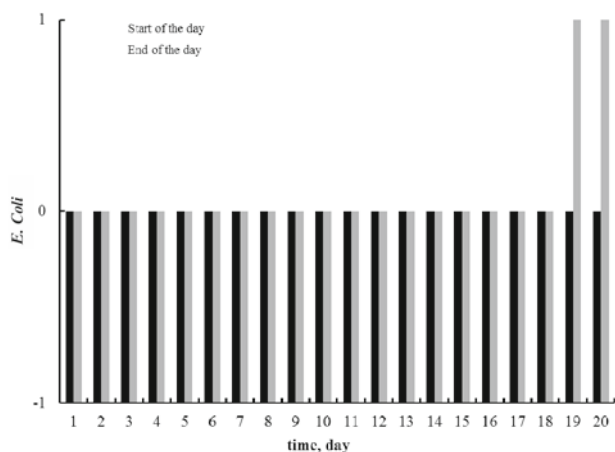


Figure 6. *E. Coli* analysis in continuous wastewater treatment: 5 hrs · day⁻¹, 0: not detected, 1: detected

membrane fouling are insufficient routine cleaning of the membrane, O-ring leakage, glue line damage or improper handling of the plant or membrane. It was observed that MF and RO can not guarantee the complete removal of microbial contaminants. The presence of these contaminants in permeate water can be attributed to the degradation of membrane surface and inferior packing of module/elements. After each experiment, CIP process (treating membrane with 0.1% NaOH and 0.2% HCl solution) was adopted to remove organic and inorganic deposits on the membrane surface. Improper cleaning process (like insufficient cleaning time or HCl and NaOH concentration) leads to an increase in TPC on membrane surface, as well as TPC in permeate water.

Wintgens has broadly reviewed the role of membrane technology in municipal wastewater reclamation and use. It is reported that UF or MF are the indispensable pretreatment steps before NF or RO to retain the microbial contaminants⁹.

Effect of applied feed pressure on permeate flux and recovery

The efficiency of RO membrane unit was also measured by calculating the mean permeate flux and mean recovery at different operating feed pressures. Permeate flux and percent recovery at various feed pressures, were measured for distilled water and wastewater (model raw water), at the start and end of each day. It can be noticed in Figures 7 and 8 that permeate flux and percent recovery increased with increase in applied pressure. However, a marginal decrease in flux and recovery was observed for wastewater despite the fact that the membrane was cleaned properly at the end of each day in 20 days experimental run.

Percent rejection of the pollutants like Nitrite as NO₂, TDS and TH as CaCO₃ were also measured as a function of applied feed pressure. As shown in Figure 9, rejection of these pollutants increased with the increase in pressure. There was a nominal effect on TDS and TH above the applied pressure of 20 bar. Rejection of Nitrites as NO₂ can further be enhanced if applied pressure is increased above 25 bar. Rejection of TH as CaCO₃ was found to be 97% and 98% at applied pressures of 20 and 25 bar, respectively. For an applied pressure of 25 bar, TDS and Nitrites as NO₂ were found to be 75%

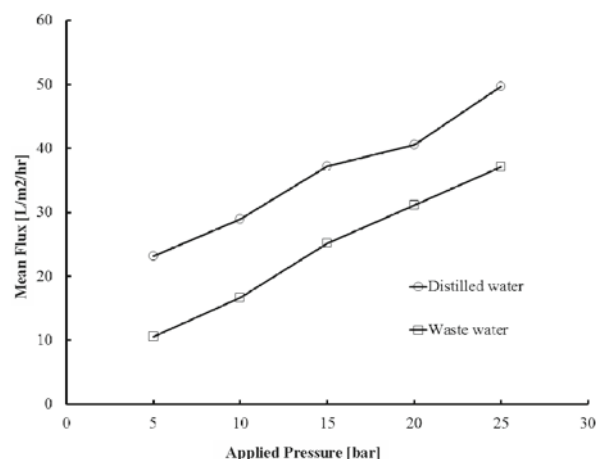


Figure 7. Effect of applied feed pressure on permeate flux

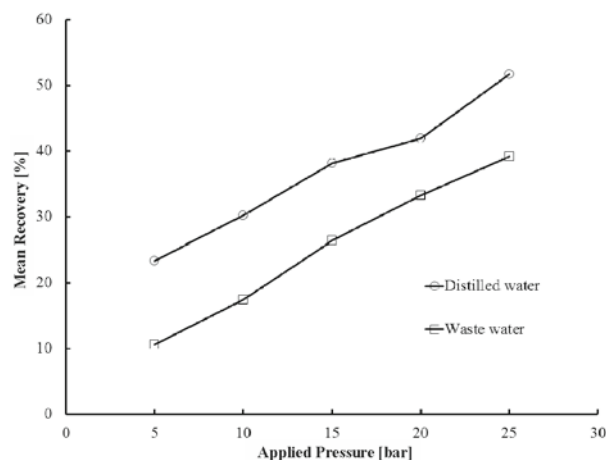


Figure 8. Effect of applied feed pressure on permeate recovery

and 88%, respectively. Nevertheless, it should be noted that percent rejection of the pollutants as a function of applied pressure is strongly effected by strength of pollutants in raw water and temperature of the system. Goncharuk et al. in their experimental investigation showed the removal of Nitrates at low pressure operation of reverse osmosis²⁹.

Effect of applied feed pressure on rejection of different pollutants

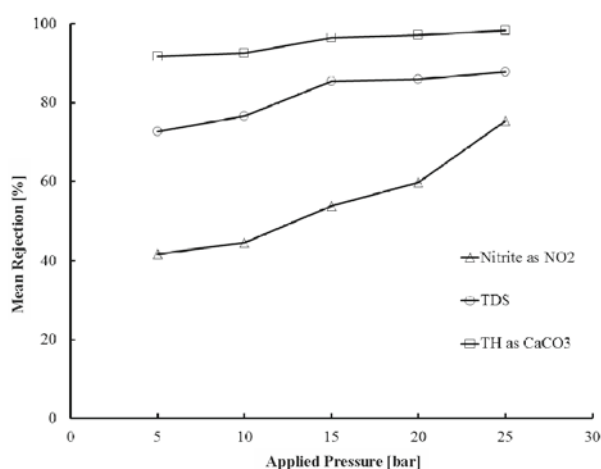
In Table 3 the raw (feed) and permeate water analysis with average values of $\pm 5\%$ error are summarized. These results were obtained from a series of repeated experiments for wastewater treatment for which the plant was operated in a total recycled mode at feed pressures of 5–25 bar. The temperature varied between 24 and 26°C. An increase in feed pressure resulted in a better rejection of pollutants but at the expense of specific power. Figure 9 shows the effect of applied pressure on percent rejection of different pollutants. There was maximum pollutant rejection at feed pressure of 25 bar above which there was no significant increase in rejection.

CONCLUSION

In the present study, RO process was evaluated for the treatment of polluted surface/ground water containing physical, chemical and microbiological contaminants. The RO plant was operated over a total time span of 100

Table 3. Raw (feed) and permeate water analysis with average values of $\pm 5\%$ error; Operating Pressure 20–30 bar

Parameter	Raw (feed) water	RO permeate
pH	7.4	6.4
Turbidity, NTU	8.0	0.95
Total suspended solids (TSS), mg/L	4.27	–
Total dissolved solids (TDS), mg/L	504.7	21.6
Alkalinity (HCO_3^-)	35.5	11.1
Chloride as Cl^-	700.0	53.7
Sulphate as SO_4^{2-}	287.6	25.6
Sodium as Na^+	264.6	27.2
Nitrate as NO_3^-	50.0	5.74
Total Coliform /100 mL	10	<1
<i>E. Coli</i> /100 mL	60	<1

**Figure 9.** Effect of applied feed pressure on rejection of different pollutants

hours. After each experiment, thorough cleaning with NaOH and HCl solutions was performed to counter the buildup of organic and inorganic deposits on membrane surface. With microfiltration as a pre-treatment step, RO process rejected more than 94% of TDS at an operating pressure and temperature of 15 bar and 24–26°C, respectively. A permeate flux of 20–30 $\text{L} \cdot \text{m}^{-2} \cdot \text{h}^{-1}$ was achieved. It is thus concluded that RO process can offer an easy and efficient one-step wastewater treatment process for the removal of various contaminants. However, the process strongly depends on pollutants load and therefore may vary from point to point. For complete removal of microorganisms, an effective pre or post-treatment step must be coupled with RO. In the absence of such pre or post-treatment step, RO membranes can suffer higher fouling; higher membrane cleaning cost and lower permeate flux, thus resulting in reduced membrane life and higher clean water cost.

NOMENCLATURE

Q_p	– Permeate Flow Rate
Q_f	– Feed Flow Rate
Q_R	– Retentate Flow Rate
R	– Recovery ratio
X	– Salt Concentration

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