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Performance evaluation of five years operation experience of WMZM RO desalination plant

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ABSTRACT

The main two supply of potable water to Amman city are Zai water treatment plant (represent 60%) and Wadi Ma'in, Zara, and Mujib (WMZM) water treatment plant (represent 30%). WMZM receives raw water from three main sources originally flowing to the Dead Sea, now collected and conveyed to a raw water reservoir at the treatment plant to produce about 110,000 m^3/day. WMZM was commissioned in 2006 and still operating at the original design capacity. WMZM water treatment plant and its conveyance system are presently operated by Jordan Water Company—Miyahuna. This paper covers the plant description, original design parameters, and RO membrane performance after more than five years of operation.

Keywords: WMZM water treatment plant; Brackish water RO desalination; Pretreatment; Reminerlization; Pumping stations; Water cost

1. Introduction

The Ministry of Water and Irrigation in the Hashemite Kingdom of Jordan developed in 2002 the preliminary design of a project to desalinate surface raw water collected from Wadi Ma'in, Zara springs, and Wadi Mujib and conveying about 47 million cubic meters per Year of potable water to the city of Amman serving more than one million inhabitants.

It was constructed by the consortium Morganti Group Inc. and Infilco Degremont/Suez and water production started on August 2006; the plant was officially handed over to WAJ on 1 September 2009 operated by Jordan Water Company— Miyahuna.

After more than five years of operation, WMZM is still producing at its original RO design capacity and no membrane replacement (Fig. 1).

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2. Plant and process description

2.1. Raw water

2.1.1. Raw water origin

The origin of raw water is from three main sources:

2.1.1.1. Wadi Zarqa Ma'in. This source consists of a discharge of about 18 thermal springs located on the course of Wadi Zarqa Ma'in, 270–470 m above the Dead Sea level. The flow from this source is 2,625 m^3/h (23 MCMY) representing 38% of the total flow.

2.1.1.2. Zara and Abu Khusheiba. These springs are located about 3–4 km south of Wadi Zarqa Ma'in and are 100–250 m far from the Dead Sea shore. The average flow from Zara Springs is 420 m^3/h. And that of

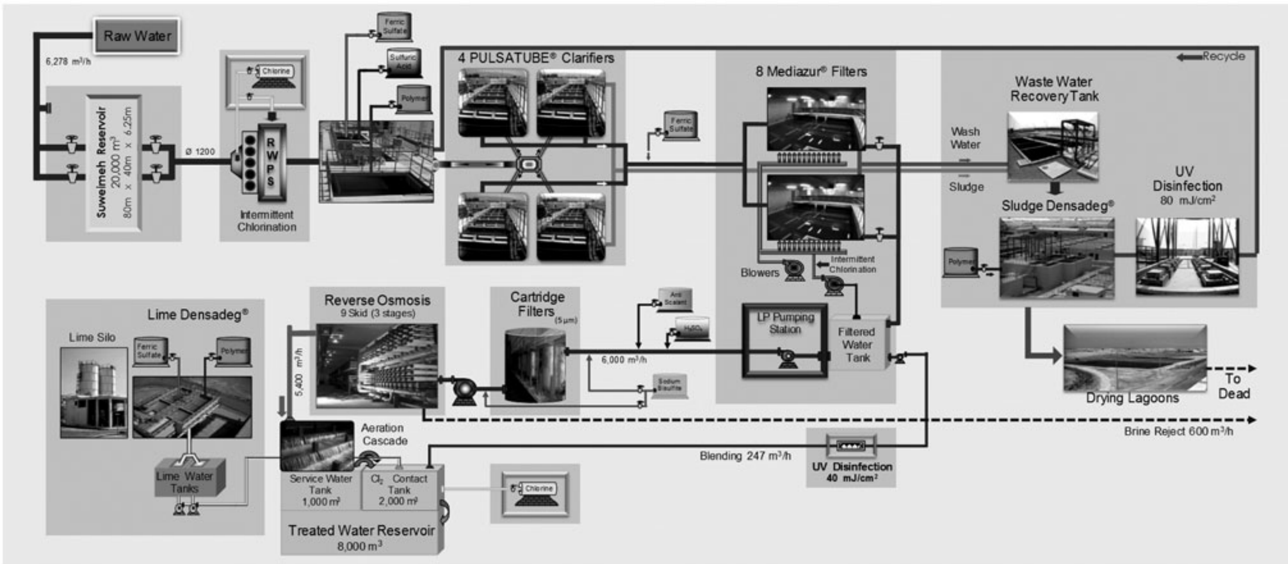


Fig. 1. Water treatment plant block diagram.

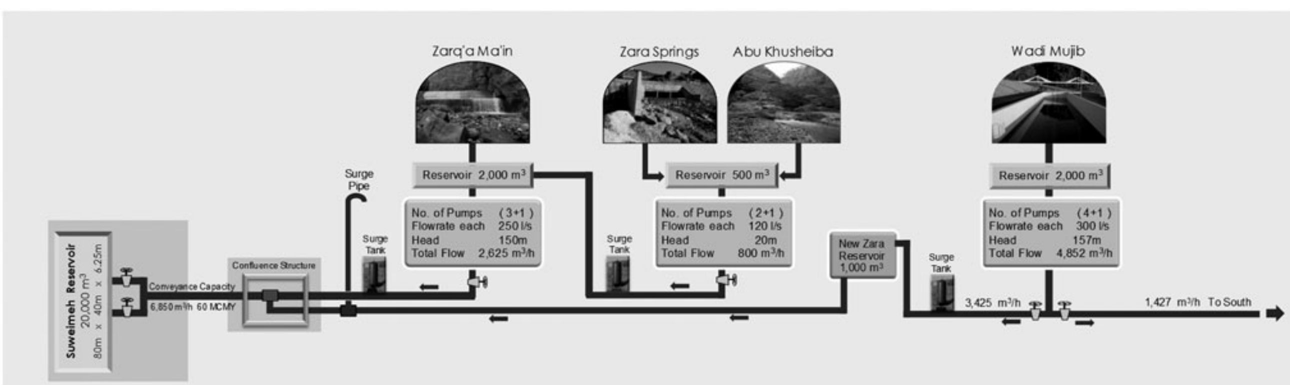


Fig. 2. Raw water conveyance system.

Abu Khusheiba is 380 m3/h giving a total flow of 800 m^3/h (7 MCMY) from these springs. This represents 12% of the total flow to the plant.

2.1.1.3. Wadi Mujib. This consists of drainage of several Wadis in the Jordan Highland (Mujib. Wala) 300–500 m above the Dead Sea level. The flow from this source is 3,420 m^3/h (30 MCMY) representing 50% of the total flow (Fig. 2).

2.2. Raw water pre-treatment

2.2.1. Chemical conditioning/static mixer

Raw Water contains clay, minerals, bacteria, inert solids, microbiological organisms, oxidized metals, organic color producing particles, and other suspended materials (Table 1).

From the raw water pumping station it is pumped to the static mixer where chemicals are added to initiate coagulation and flocculation in the sludge blanket clarifier (Pulsatube).

A coagulant and a coagulant aid are added to the raw water to increase the rate of settling of these colloidal particles. Chemicals are added to the raw water in the static mixer before entering the Pulsatube Clarifier where per design dosing 2–8 mg/l ferric sulfate depending on raw water turbidity and jar test, sulfuric acid when there is a need to adjust pH to the coagulant optimum pH range, and 0.02–0.1 mg/l polyelectrolyte.

Table 1
Raw water analysis

Water analysis[a]	Unit	Zarqa Ma'in	Zara	Wadi Mujib	Average WTP influent
Temperature	℃	31.2	39.7	22.4	27.0
pH	–	7.9	7.9	8.2	8.0
Conductivity	μS/cm	2,892	2,073	2,211	2,451
TDS	mg/l	1,706	1,231	1,356	1,475
Turbidity	NTU	23	9	5	12
TSS	mg/l	59	29	78	67
M-Alkalinity	mg/l as $CaCO_3$	125	159	165	150
TH	mg/l as $CaCO_3$	404	376	466	436
Calcium	mg/l	104	110	127	117
Magnesium	mg/l	38	29	48	43
Nitrate	mg/l	3	3	5	4
Sulfate	mg/l	204	150	205	200
Chloride	mg/l	735	472	484	575
Barium	mg/l	0.086	1.000	0.084	0.160
Iron	mg/l	0.22	0.23	0.36	0.30
Strontium	mg/l	9.9	8.8	6.6	8.0
Silica	mg/l	24.8	23.5	13.4	18.4
TCC	MPN/100 ml	1,391	4,322	4,577	3,385
TFCC	MPN/100 ml	313	1,981	316	444
E. coli	MPN/100 ml	5,000	8,000	8,000	6,896

[a]Date of sample: April 2006.

The reaction of ferric sulfate can be represented as follows:

$$Fe_2(SO_4)_3 + 3Ca(HCO_3)_2 \longrightarrow 2Fe(OH)_3 \downarrow + 3CaSO_4 + 6CO_2 \uparrow \quad (1)$$

$$Fe_2(SO_4)_3 + 3Mg(HCO_3)_2 \rightarrow 2Fe(OH)_3 \downarrow + 3MgSO_4 + 6CO_2 \uparrow \quad (2)$$

This static mixing chamber has a net volume of 210 m^3, with a retention time of about 2 min. This enables tiny particles to agglomerate into larger dense particles which will settle more quickly in the Pulsatube.

2.2.2. Pulsatube clarifier

The Pulsatube is a high rate pulsed sludge blanket clarifier that combines flocculation and clarification within the same area.

As raw water is introduced through the inlet pipe, the vacuum system creates low pressure within the chamber, causing water to rise. When the vent valve opens, the hydraulic head created within the chamber forces the water downwards into the bottom and passes upwards through the holes in the distribution pipes and the sludge blanket which agglomerates the newly formed flocs and helps the suspended and colloidal particles adhere to the already formed flocs creating larger flocs and so on until it settles.

When the water level in the vacuum chamber reaches a low level, the water flow slows and the sludge blanket begins to settle. The vent valve closes and the vacuum is applied again to the vacuum chamber and the pulsation cycle of about one minute will repeat.

Clarified water separates from the sludge blanket and is collected in the channels near the surface and excess sludge will be removed after being concentrated through an automatic sludge extraction system during the pulsation cycles (Fig. 3).

PULSATUBE main characteristics:

Number of clarifiers	4
Clarifier dimension	19.6 × 20 m
Water height	5.0 m
Sludge concentrator height	2.6 m
Total area per unit	392 m^2
Sludge blanket area per unit	322 m^2
Lamellar modules area per unit	337.9 m^2
Vacuum chamber inner dimension	2.9 × 3.1 m
Vacuum chamber inner area (S_4)	9.0 m^2
Sludge concentrator area	57 m^2

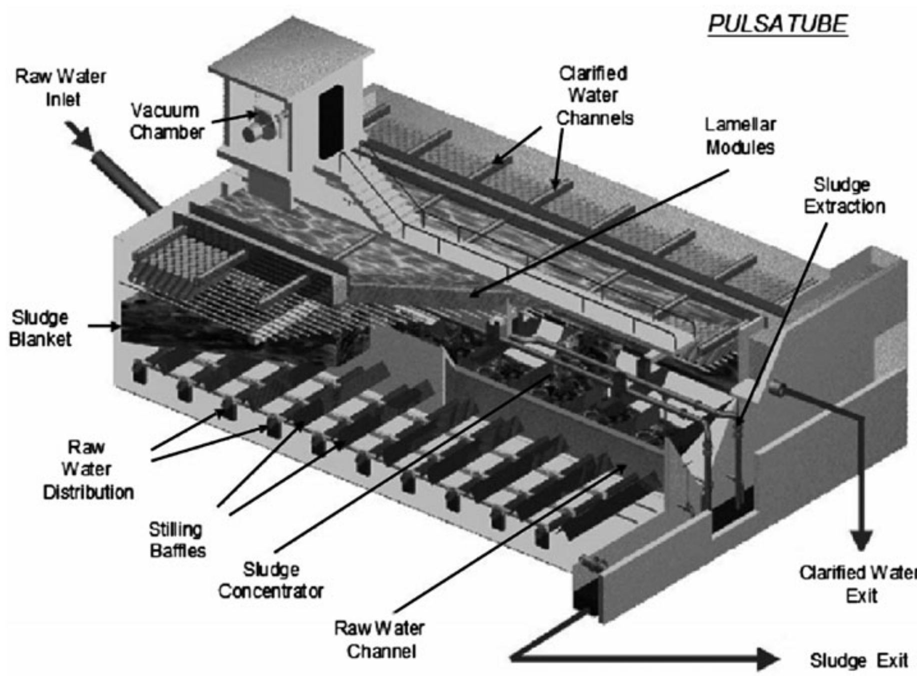


Fig. 3. PULSATUBE clarifier.

Table 2
Dual media filter layers details

Layer	Depth	Effective size	Density	Uniformity coefficient
Gravel support	10 cm	2–4 mm	2.4–3.0 kg/dm^3	
Sand	40 cm	0.26–0.3 mm	2.4–2.8 kg/dm^3	<1.45
Anthracite	70 cm	0.95–1.06 mm	1.25–1.45 kg/dm^3	<1.5

2.2.3. Dual media filters

The purpose of this unit operation is to remove large quantities of small-sized suspended particles that were previously formed and not settled in the Pulsatube.

To ensure the maximum retention of coagulated flocs, Ferric Sulfate is injected in the clarified water before passing through the filters.

This is the post-coagulation stage. These media entrain micro-organisms, algae and colloidal solid matter, causing a progressive blocking of the porous material, and increasing the head loss thus clogging the filter.

During the filtration process, suspended solids penetrate the layers to a sufficient depth until the bed becomes laden with retained matter.

A preset differential pressure across the filter occurs, and the turbidity of filtered water increases. At this time, the filter bed is backwashed.

The Filter bed consists of the following layers: (Table 2)

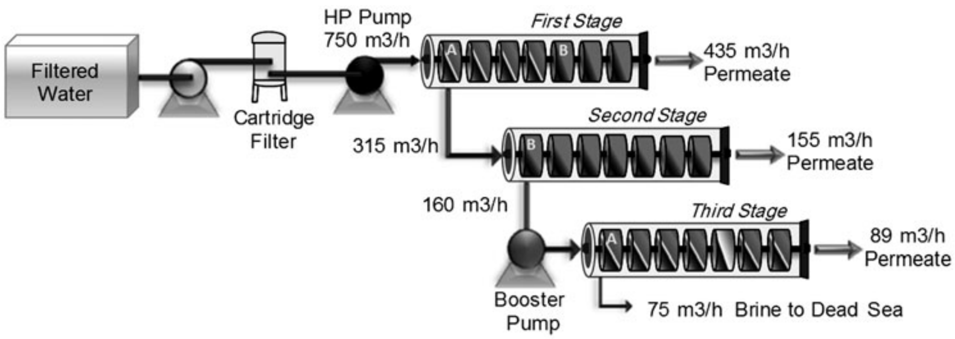
2.2.4. Sludge and backwash water treatment

The sludge extracted from the Pulsatube (~20 g/l) and the backwash water from the dual media filters are collected in the wastewater recovery tanks equipped with submersible mixers maintaining sludge in suspension. The mixture is pumped to the sludge lamellar thickener where it is separated into clarified water and sludge.

Clarified water flows by gravity to the UV disinfection unit before being recycled to the distribution chamber at the inlet of the static mixer and the sludge produced is diverted to the three sludge drying lagoons for de-watering.

2.2.5. Cartridge filtration

The last stage of the pre-treatment is achieved by passing the filtered water through a five microns cartridge filtration unit. These eight micro-filters act as



Stages	PV	Elements	Membranes
First	66	462 (7x66)	6) A + (3x66) B
Second	31	217 (7x31)	217 B
Third	16	112 (7x16)	112 A
A is BW30-400 FR		*B is LE-400 from Dow Filmtec*	

Fig. 4. RO skid configuration.

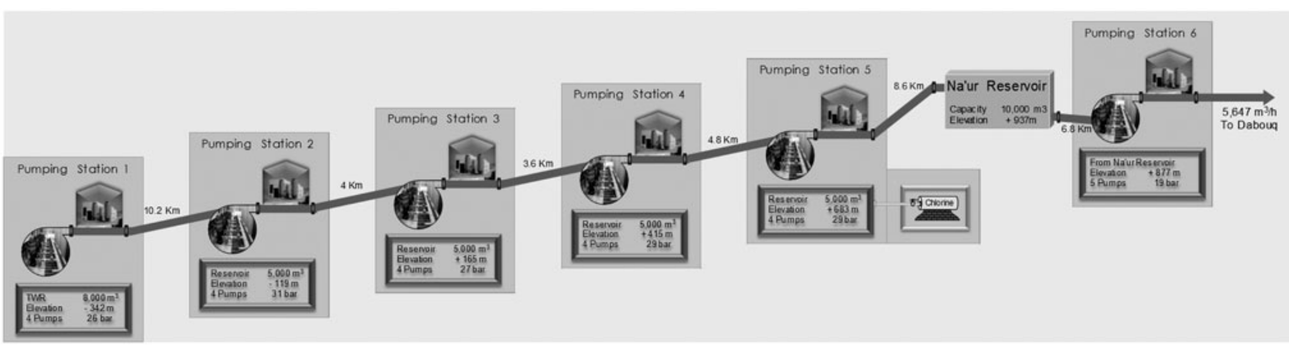


Fig. 5. Treated water conveyance system.

safety filters to protect the RO membranes against fouling.

Cartridge filters are continuously monitored and inspection of the entire elements is done on a monthly basis. From the last five years of operation, we found that cartridges need to be replaced every six months.

Before passing the cartridge filters, three chemicals are injected in the filtered water before flowing to the RO plant:

- Sulfuric Acid: 20–30 mg/l to adjust pH between 6.6 and 6.8 in order to optimize the antiscalant injection.
- Scale Inhibitor: 1–4 mg/l to prevent and reduce scaling and fouling of the membranes. This antiscalant inhibits mineral scale formation such as Calcium Carbonates, Calcium Barium and Strontium Sulfates.
- Sodium Bisulfite: 2–3 mg/l to protect the membranes against residual Chlorine when pre-chlorination is used.

2.3. Reverse osmosis

The RO plant consists of nine skids or trains each is fed by a high pressure pump.

Eight trains are sufficient to produce the required quantity of RO water operating with a conversion rate between 85 and 90%.

The brine from the plant discharges to the Dead Sea. Each skid has the following three stage configurations: (Fig. 4).

2.4. Remineralization

2.4.1. Physical remineralization

The permeate of the RO plant is conveyed through an aeration cascade in which CO_2 is stripped from water, increasing its pH, thus reducing the amount of Lime needed for remineralizing and stabilizing water.

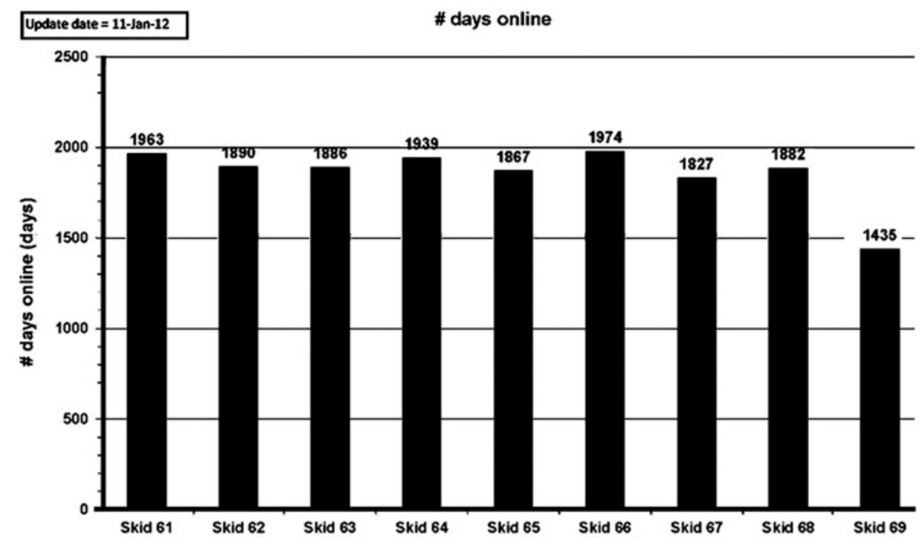


Fig. 6. Number of operational days for RO units at WMZM.

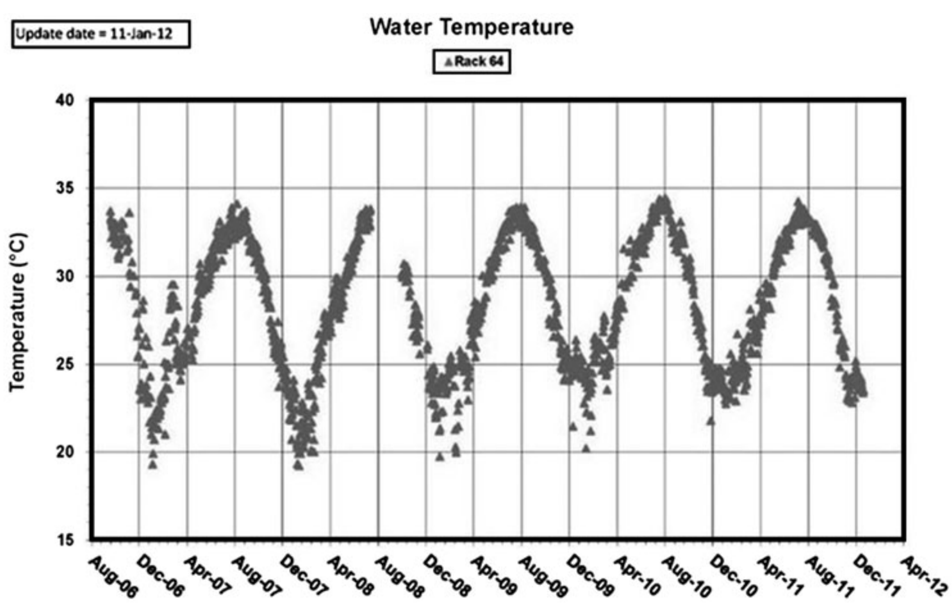


Fig. 7. Feed water temperature.

2.4.2. *Chemical remineralization*

To adjust the alkalinity, pH of water, Lime is injected in the inlet of the Chlorine contact tank at a dosing rate of 30–50 mg/l. Langelier saturation Index (LSI) provides an indicator of the degree of saturation of water with respect to calcium carbonate.

2.5. *Disinfection*

2.5.1. *UV disinfection*

Treated filtered raw water passes through the UV disinfection system before being blended with RO water in the chlorine contact tank. The UV disinfection system use medium pressure, high output UV lamps.

2.5.2. *Chlorination*

Chlorine is injected at the entrance of the chlorine contact tank which is equipped with baffles to ensure maximum effective retention time through a perforated injection pipe.

The dosing rate of chlorine is 1.0–1.5 mg/l.

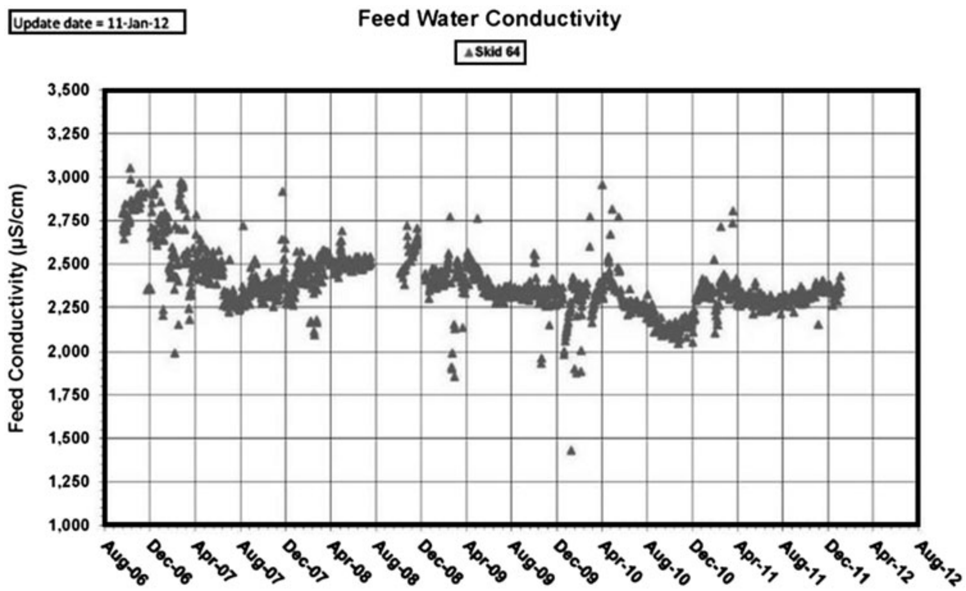


Fig. 8. Feed water conductivity.

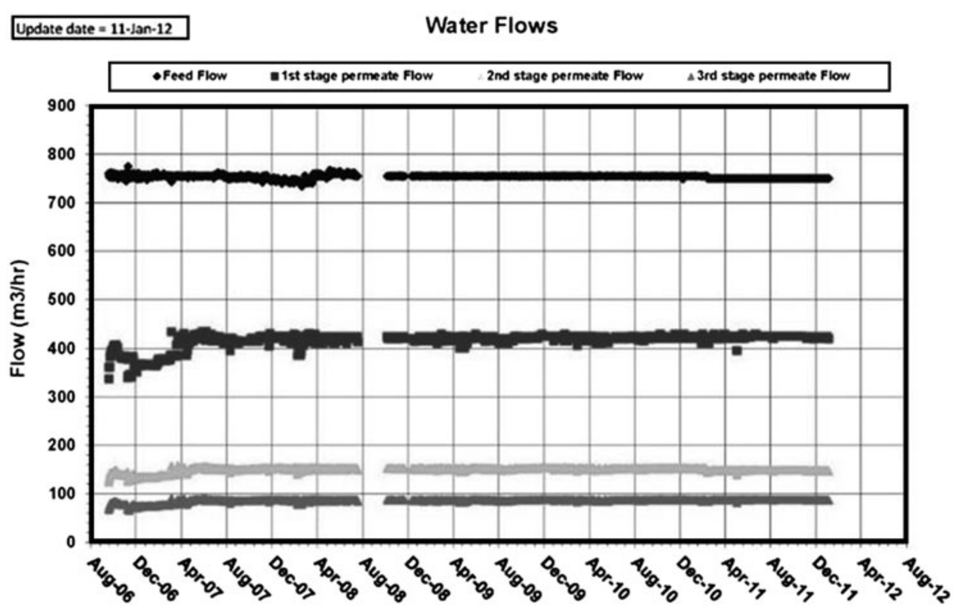


Fig. 9. Water flows.

Chlorine is also injected in Pumping Station No. 5 to ensure a final Chlorine residual.

2.6. Treated water conveyance system

A 40 km transmission pipeline conveys the potable water to Amman (Dabouq Reservoir) through six pumping stations with a total head of around 1,300 m. Cathodic protection of the pipeline from corrosion through a sacrificial anode system is used. The pumps used in all pumping stations are vertical turbine pumps with suction cans.

Two hydro-pneumatic surge tanks filled with compressed air are installed at the discharge of each of the pumping stations in case of power failures and/or pump start-up and shut downs, the surge pressures in the pipe are controlled by two hydro-pneumatic surge tanks installed at the discharge of each of the

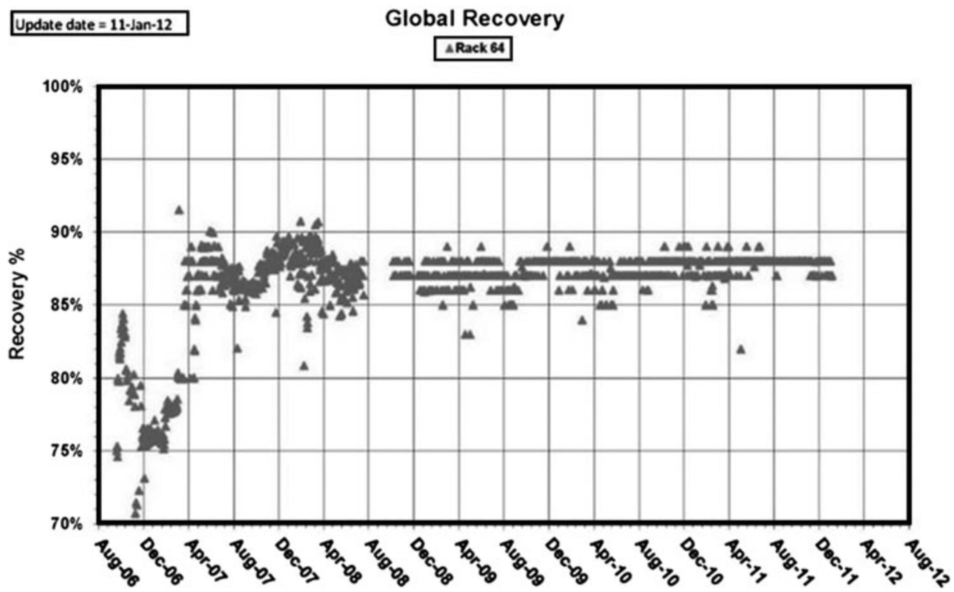


Fig. 10. RO skid recovery rate.

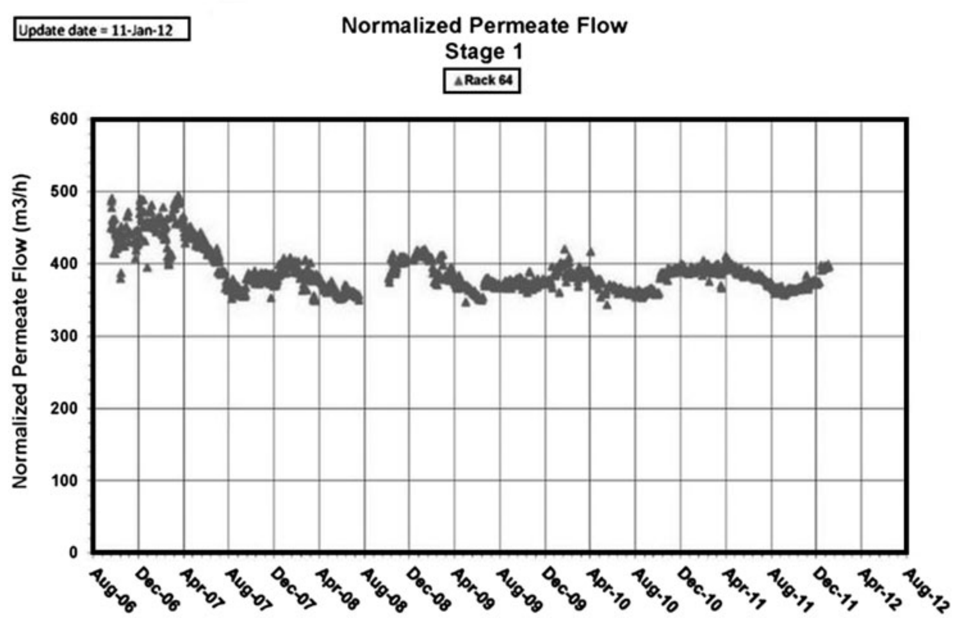


Fig. 11. First stage normalized permeate flow.

pumping stations. Surge tanks are filled with air from two compressors in each of the pumping stations (Fig. 5).

3. Plant performance over a five years period

As raw water is coming from three sources with different chemical and physical characteristics, plant was designed to operate at different recovery rates based on feed water quality. Raw water quality is continuously monitored by operation staff in addition to online analyzers to keep pre-treatment running efficiently by determining the optimum chemical doses and other operation variables. On the other hand, feed water quality is used to determine RO recovery rate and antiscalant dosing rate.

Over more than five years of operation (see Fig. 6: Number of operational days for RO units at WMZM)

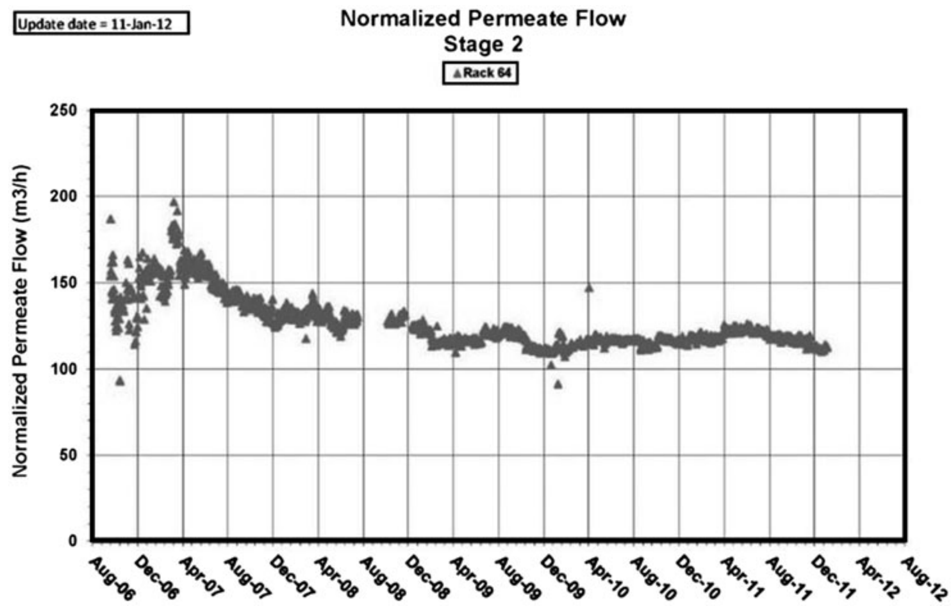


Fig. 12. Second stage normalized permeate flow.

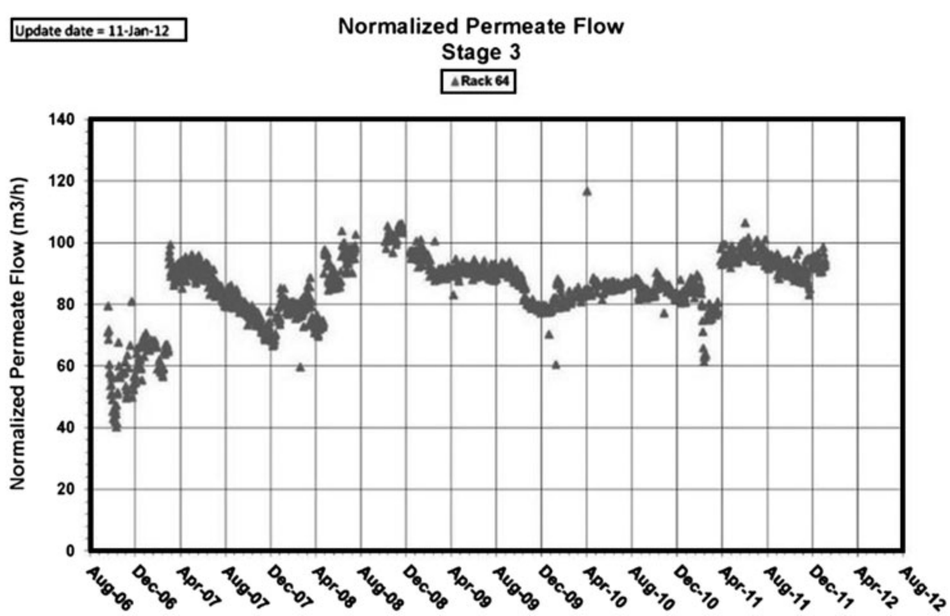


Fig. 13. Third stage normalized permeate flow.

and none of the original installed membranes were replaced, plant's operation parameters were collected in daily basis to evaluate membranes performance.

3.1. Feed water temperature

Raw water temperature at WMZM varies between 20°C in winter and about 35°C in summer see Fig. 7: Feed water temperature chart below.

3.2. Feed water conductivity

Raw water conductivity at WMZM changes when blending ratio of the three raw water sources is changed see chart below (Fig. 8).

3.3. Water flows

As shown in figure below, feed water flow kept constant all the time and permeate water produced by

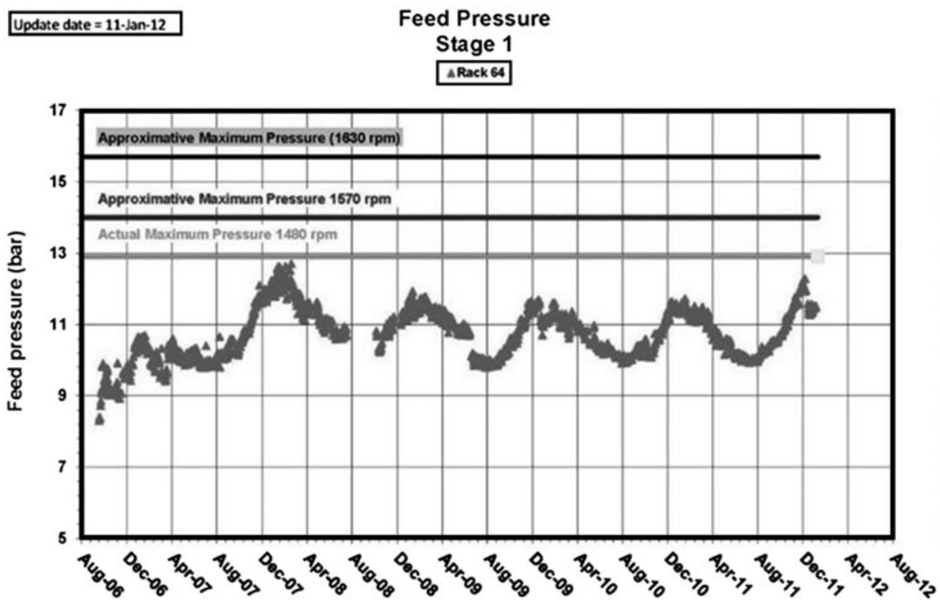


Fig. 14. First stage feed pressure.

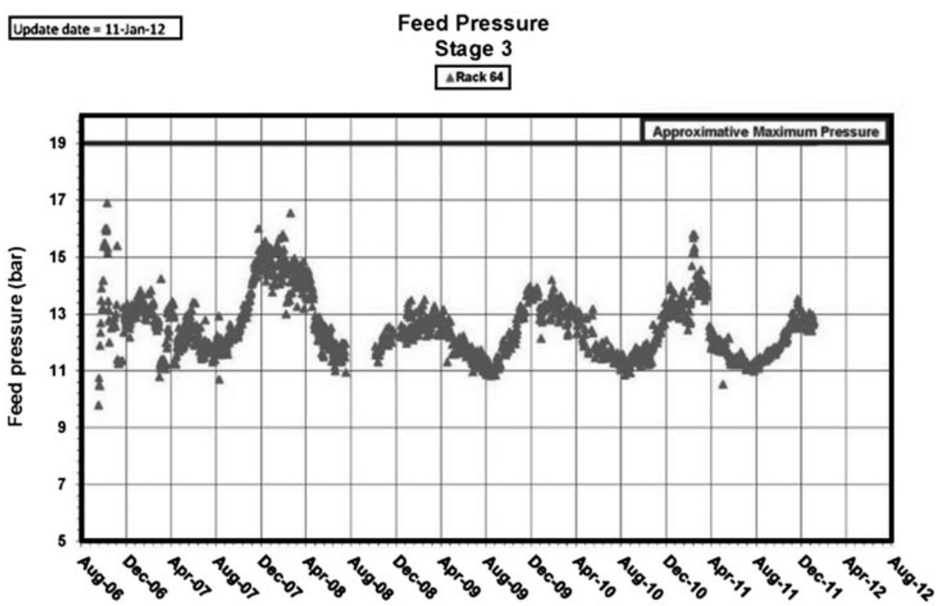


Fig. 15. Third stage feed pressure.

each stage is changing due to recovery change. SCADA system, variable speed drives, flowmeters, and control valves control the operation of RO units (Fig. 9).

3.4. Recovery rate

The recovery rate of reverse osmosis units at WMZM is calculated based on feed water quality in order to keep the chemical composition of brine water constant. So, it is changing when critical parameters like silica (SiO_2), Sulfate (SO_4), Alkalinity, Calcium (Ca), etc… are changed. That is the most important factor for extending membranes life (Fig. 10).

Recovery is calculated and controlled by control system by the flowing equations:

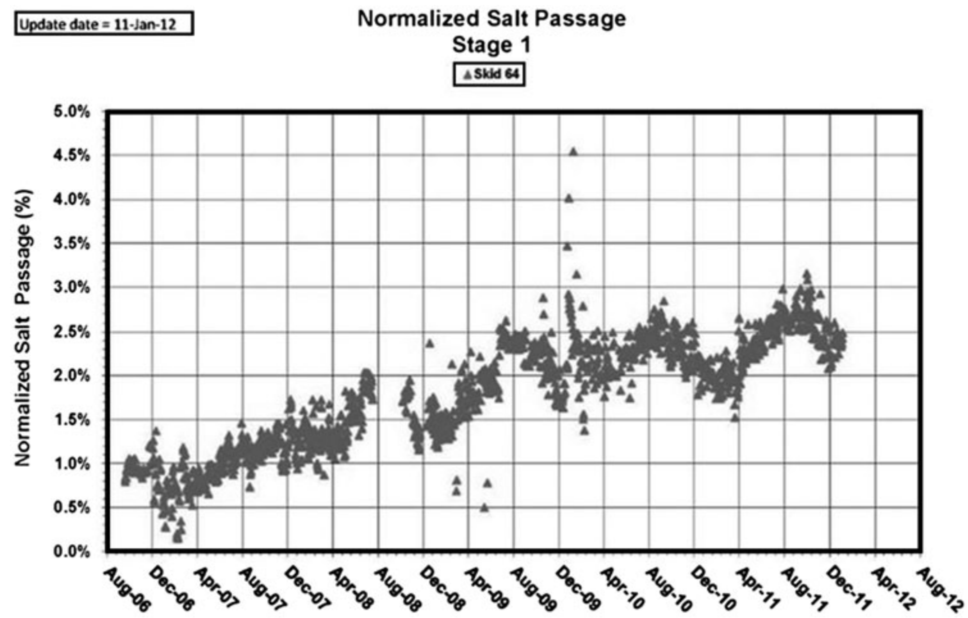


Fig. 16. First stage normalized salt passage.

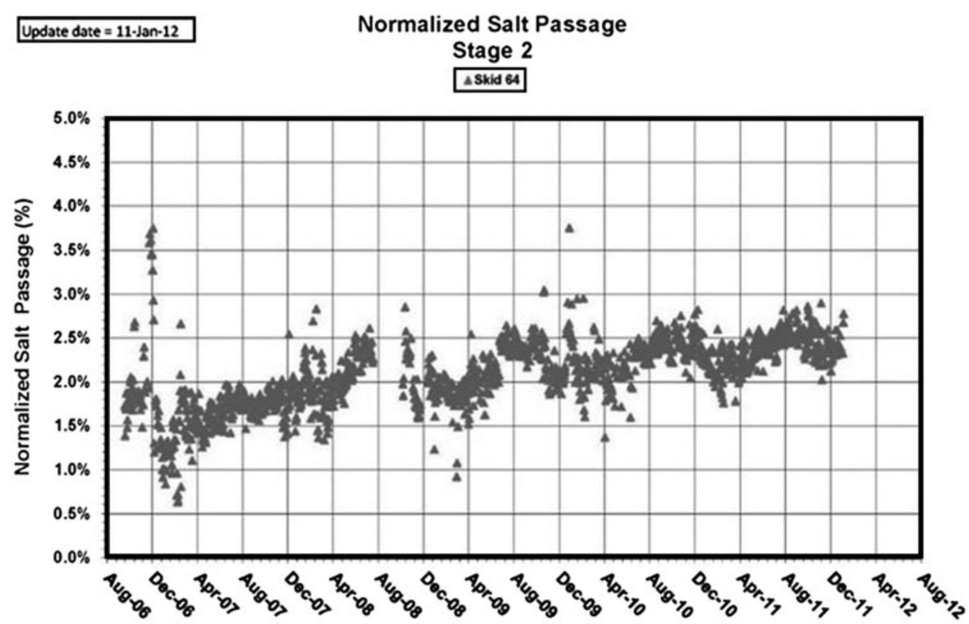


Fig. 17. Second stage normalized salt passage.

$$\text{Recovery } (\%) = \frac{\text{Sum of permeate flow}}{\text{Feed flow}} \times 100\% \tag{3}$$

or

$$\text{Recovery } (\%) = \frac{\text{Sum of permeate flow}}{\text{Sum of permeate flow} + \text{Brine flow}} \times 100\% \tag{4}$$

3.5. Normalized permeate flow

The effects of temperature, pressure, and concentration on the permeate flow can be removed by normalization.

$$\text{NPF} = Q_{\text{Pa}} \times \frac{\text{NDP}_\text{s} \times \text{TCF}_\text{s}}{\text{NDP}_\text{a} \times \text{TCF}_\text{a}} \tag{5}$$

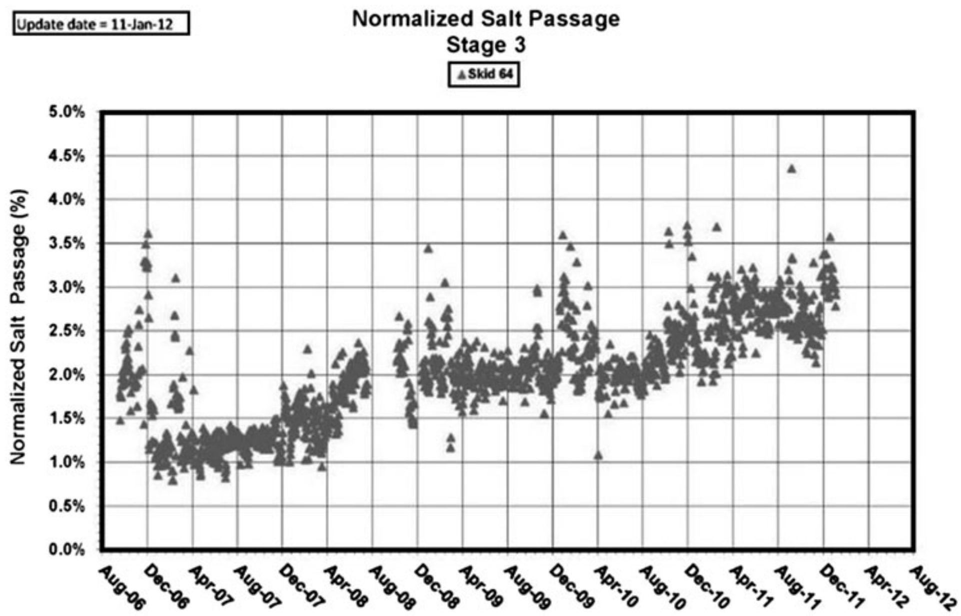


Fig. 18. Third stage normalized salt passage.

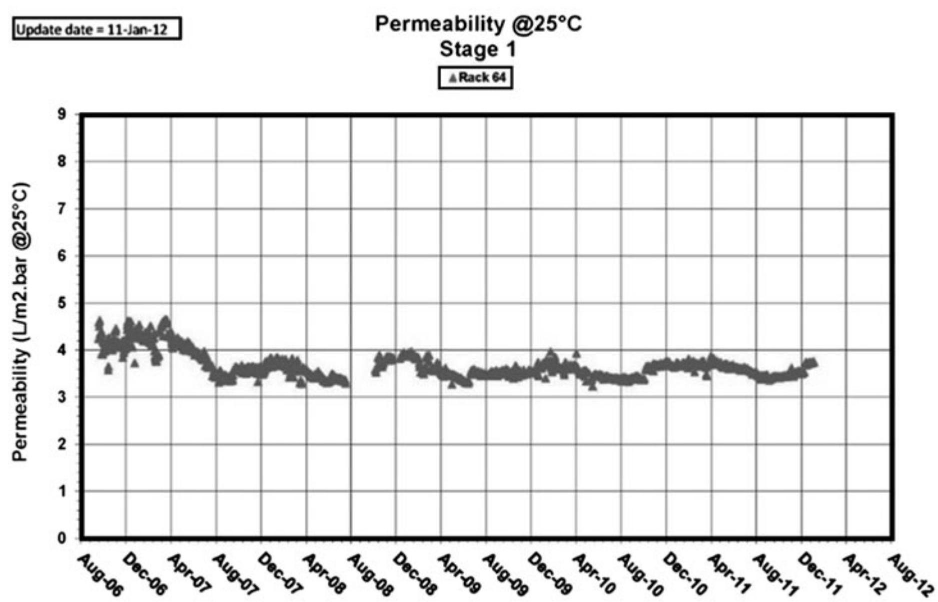


Fig. 19. First stage permeability.

where NPF, normalized permeate flow; QP, permeate flow; NDP, net driving pressure; TCF, temperature correction factor; "a", subscript for "actual" conditions; "s", subscript for "standard" conditions.

Chart below is showing slight changes in normalized permeate flow of the first stage which was recovered several times by chemical cleaning using alkaline solution. During the last five years of operation, chemical cleaning of the first stage was done per annum to recover the loss of normalized permeate flow (Fig. 11).

Normalized permeate flow of the second stage had drop decrease after one year of operation then start to be more stable (Fig. 12).

During the first six months of operation, this sample skid was operated at very low recovery rate for

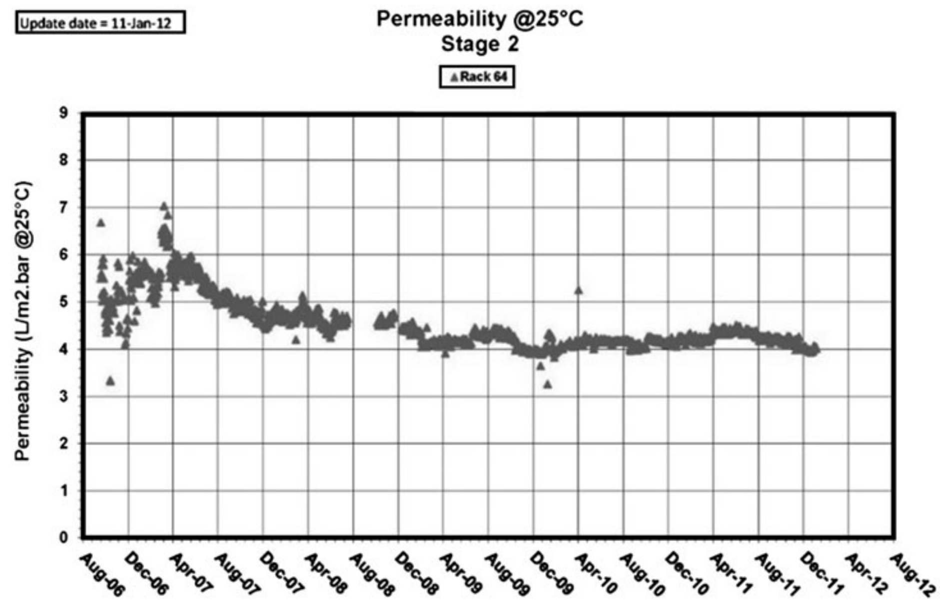


Fig. 20. Second stage permeability.

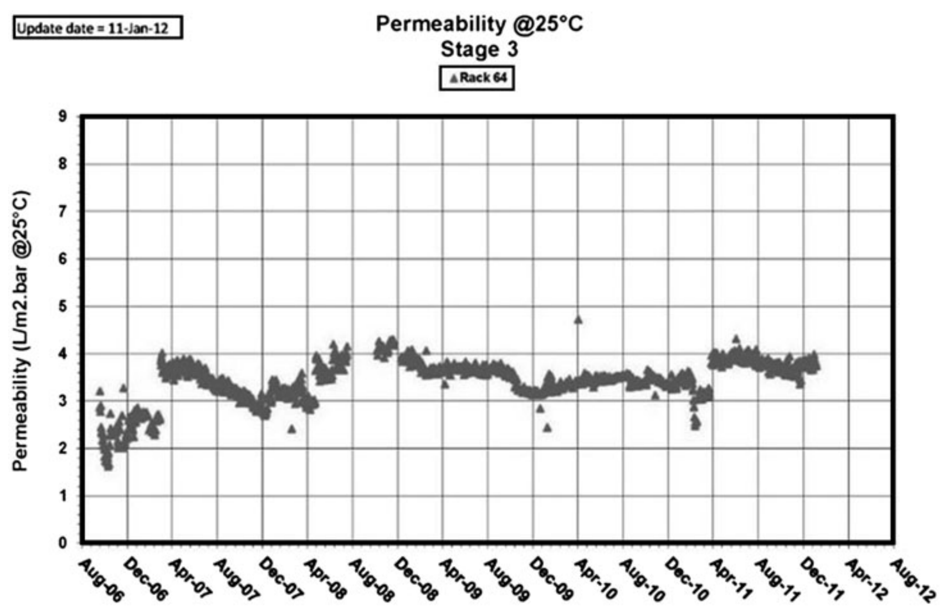


Fig. 21. Third stage permeability.

commissioning purposes which describes the low permeate flow on chart below.

Third stage is the most affected by scaling because it has the highest feed water salinity. During the last five years of operation, chemical cleaning of the third stage was done per annum to recover the loss of normalized permeate flow (Fig. 13).

3.6. Feed water pressure

Each reverse osmosis unit has two pumps, high pressure pump to feed first and second stages and booster pump to boost feed water pressure of third stage.

Feed water pressure is directly proportional to water temperature and salinity, the most difficult

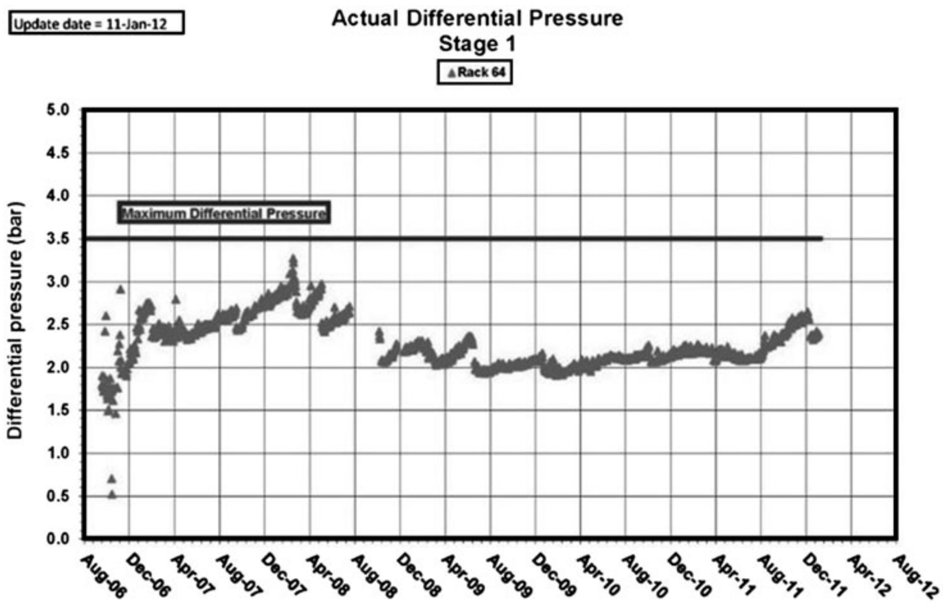


Fig. 22. First stage actual differential pressure.

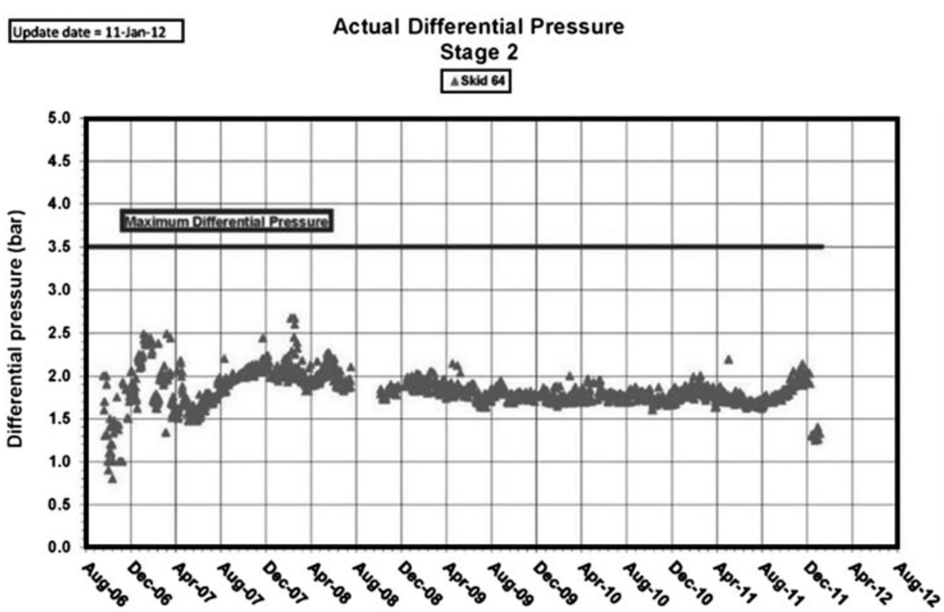


Fig. 23. Second stage actual differential pressure.

operation condition at WMZ is during winter when feed water temperature reach to 20˚C, see self-explanatory charts below (Figs. 14 and 15).

3.7. Normalized salt passage

Normalizing the salt passage takes out the concentration and temperature variables, allowing the passage at any one time to be compared to that at any other time.

$$\mathrm{SP}\ (\%) = \frac{C_P}{C_F} \times 100\% \tag{6}$$

where SP, actual salt passage; C_P, permeate concentration; C_F, feed concentration.

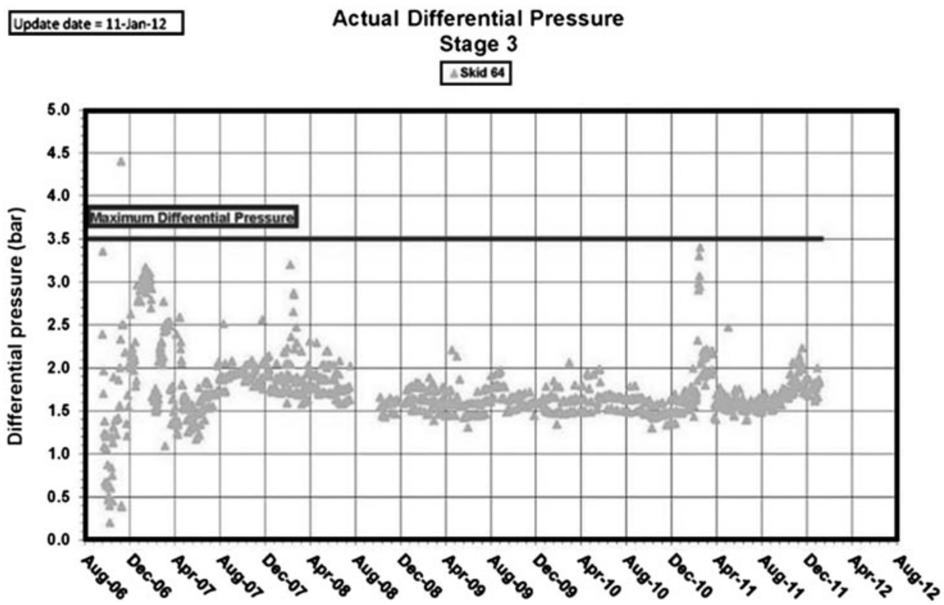


Fig. 24. Third stage actual differential pressure.

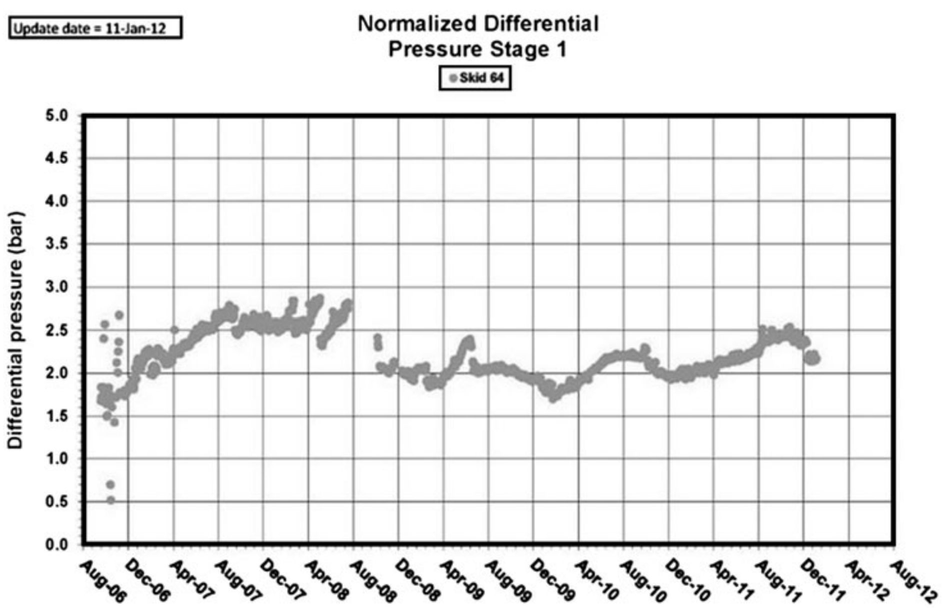


Fig. 25. First stage normalized differential pressure.

$$\text{Normalized SP } (\%) = \text{SP}_a \times \frac{\text{Permeate flow}}{\text{Normalized permeate flow}} \times \frac{\text{TCF}_\text{s}}{\text{TCF}_\text{a}} \times \frac{(\text{C}_\text{F}/\text{B})_\text{s}}{(\text{C}_\text{F}/\text{B})_\text{a}} \times \frac{\text{C}_\text{F}}{\text{C}_\text{Fs}} \tag{7}$$

where SP, salt passage; TCF, temperature correction factor; $C_{F/B}$, feed/brine average concentration; C_F, feed concentration; "a", subscript for "actual" conditions; "s", subscript for "standard" conditions.

As shown below, normalized salt passage of the three stages is about 3% after more than five years of operation (Figs. 16–18).

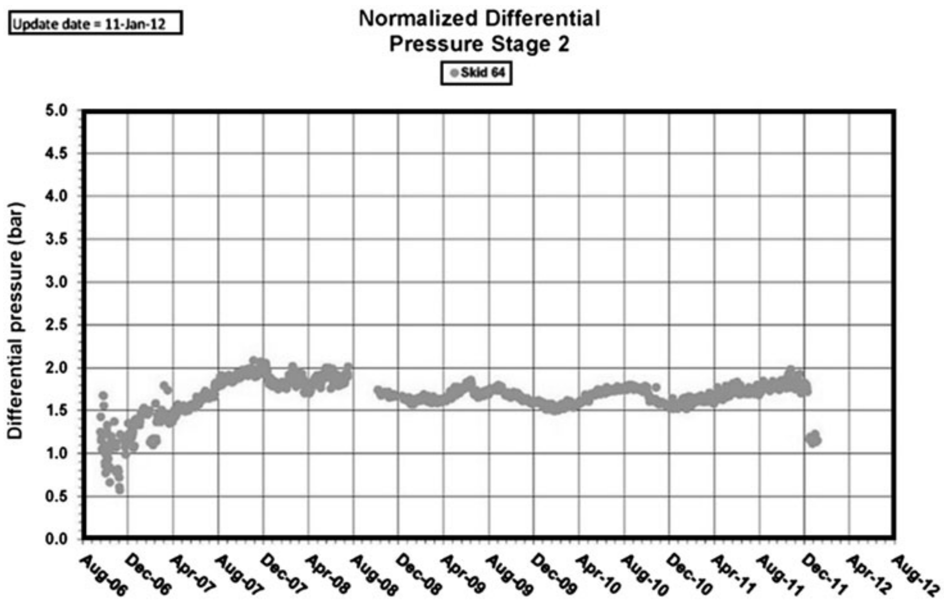


Fig. 26. Second stage normalized differential pressure.

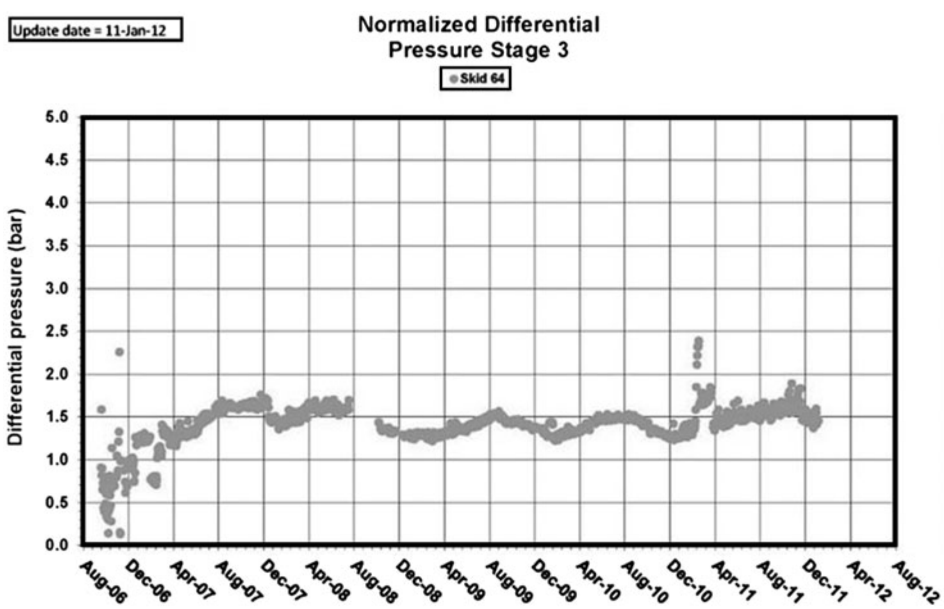


Fig. 27. Third stage normalized differential pressure.

3.8. Membrane permeability

Permeability or specific flux is calculated by this equation: (Figs. 19–21)

$$\text{Permeability} = \frac{\text{Flux}_{25^\circ\text{C}}}{\text{Net driving pressure}} \tag{8}$$

3.9. Differential pressure

3.9.1. Actual differential pressure (ΔPa)

Actual differential pressure of the entire stages never exceeded the maximum accepted value per membrane manufacturer. Charts below explain the increase of ΔPa of the three stages during the last five years (Figs. 22–24).

Table 3
2011 Water cost

Description	Cost (JOD)	Cost (USD)
Power[a] (5.967 kWh/m^3), power cost = 0.054 JOD/kWh	12,448,148	17,532,603
Salaries	622,026	876,093
Spare parts	239,092	336,749
Chemicals	640,848	902,603
Others	69,255	97,542
Total cost	14,019,369	19,745,590
Total water production—2011	38,630,352 m^3	
Unit water cost	0.363 JOD/m^3	0.511 $/m^3

[a]Power consumption is 0.726 kWh/m^3 for the treatment process and 5.242 kWh/m^3 for pumping stations.

3.9.2. Normalized differential pressure

Because the RO units at WMZM are operating at different recovery rates due to feed water quality changes, actual differential pressure for each stage is not the same at different recoveries. In order to eliminate the effect of variable recovery, normalized differential pressure is used to evaluate membrane performance (Figs. 25–27).

$$\text{Normalized } \Delta P = \Delta P_a \times \left(\frac{(F_{F/B})_s}{(F_{F/B})_a}\right)^{1.5} \tag{9}$$

where ΔP, differential pressure; $F_{F/B}$, average feed/brine flow; "a", subscript for "actual" conditions; "s", subscript for "standard" conditions.

4. Water cost

Table 3 is showing water cost at WMZM. Values of 2011 were used for calculation: (Table 3).

5. Conclusion

The excellent pre-treatment design, the correct commissioning of the plant, the investment in proper training, and incentives to maintain the trained staff from construction to commissioning to operations, and the strong standard operating procedures lead to the sustainability of production at the same level throughout the operating years of the plant so far.