



Performance evaluation of reverse osmosis desalination plant: A case study of Wadi Ma'in, Zara and Mujib Plant

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ABSTRACT

Reverse osmosis (RO) desalination systems are being increasingly used in the world as an efficient, reliable and cost-effective technology. It is widely used for the production of municipal and industrial grade water treating seawater and brackish water. For instance, RO desalination has been widely and successfully used in Middle Eastern oil-producing countries. However, utilization of membrane plants has been spread throughout every region of the world as a viable economic alternative to traditional water treatment. To date, desalination of either seawater or brackish water in Jordan has been limited. In the case of seawater, Jordan has a very short shoreline on the Gulf of Aqaba and this is very distant from the main centers of population. This is further aggravated by the fact that these centers of population are at high elevations (Amman 1000 m above the mean sea level) and would therefore involve high pumping costs. Jordan does have reserves of brackish water, and a small number of brackish water desalination plants have been built. The Wadi Ma'in, Zara and Mujib desalination plant was officially inaugurated on the 18th of November 2007, the water production started on the 22nd of August 2006. Desalination is carried out using the reverse osmosis techniques. This is a Design-Build-Operate contract. The plant includes desalination of 55 MCM per year of water with a salinity of 1500–2000 mg/l. It shall provide Amman with 38 MCM per year with a TDS of 250 mg/l. This paper describes the performance evaluation of this plant so as to bring out the state of the art of its operation and maintenance. Detailed information on the plant design and engineering, water quality, plant personnel, and cost of operation and maintenance will be collected since commissioning of the plant. The performance of the plant is characterized according to the main parameters: quantity of water produced and quality of water.

Keywords: Desalination plant performance evaluation; Brackish water desalination; Jordan

1. Introduction

Jordan's experience in brackish water desalination has been fairly limited. All of the plants built to date have been small and built for commercial/industrial use or for agriculture. Most of them RO plants, but there are at

least two EDR plants. Various studies have shown that Jordan has a considerable brackish water resource. The studies indicate that there is a maximum of 80 million m³ of water that can be used in the Jordan Valley. Salinity in the valley is maximum 7000–8000 ppm, but on average it is about 3000 ppm [1–4].

Brackish water is available in the south of Ghore between the Dier Alla town and the Dead Sea with salinity

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of about 5000–7500 ppm and a yield of about 60 MCM/y as drinking water is one of the sources of brackish water in Jordan. Other resources are the saline springs east and west of the Jordan Valley with the capacity of about 10 MCM/y. The third source is brackish water distributed all over the country estimated at hundreds of millions m³ [5].

However, it is very difficult to exploit these resources due to the topography of the country, the distance between these scattered resources, the need for special treatment to remove some sorts of chemicals such as manganese, sulfates and iron, as well as gases such as hydrogen sulfide, and, finally, the main problem is the disposal of the brine which can cause environmental problems.

Unlike many of its Arab neighbors, Jordan has virtually no indigenous energy sources. Consequently any desalination project will be very carefully examined with regards to capital and operating costs. It is therefore almost certain that RO will be selected as the optimum process for large-scale desalination.

Studies and projects were carried out to evaluate the feasibility of water desalination in Jordan. Some of the proposed actions focused on utilizing the water in the Gulf of Aqaba for water supply and desalination for major industries. Technologies used and proposed were multistage flash (MSF) or reverse osmosis (RO) and electrodialysis (ED). Currently, there are few, very small desalination plants which are used for industrial purposes. Technologies used in these plants are RO and ED, i.e., Hussein thermal station, oil refinery, Electricity Authority, and medical industries. Moreover, the JICA [1] carried out a study on the evaluation of brackish groundwater resources potential and brackish groundwater Hisban, Kafraïn, Karameh, and Abu Zieghan areas. The study formulated a brackish groundwater resource development strategy for the northern part of Jordan including the Jordan Valley and Amman City. The study concluded that there is a potential for producing 60 MCM/y of desalinated brackish water in the study area. A pilot plant producing 5 MCM/y of desalinated water was proposed in the Kafraïn/ Hisban area, and recently studies were carried out to desalinate 30 MCM from Kafraïn/Hisban for the urgent need in Amman, as well as 10 MCM from seawater at Aqaba, mainly for industrial purposes, in addition to some small desalination units in the desert area.

Recently, the Ministry of Water and Irrigation (MWI) developed two large desalination projects, the RO plant at Abu Zieghan and Wadi Ma'in, Zara and Mujib desalination plants. The Abu Zieghan plant delivers some 40,000 m³/d (18 MCM at maximum capacity). The TDS of the feed water for this plant is around 7000 ppm. The Ministry of Water and Irrigation (MWI) and Jordan Water Authority (WAJ) have signed the construction agreement for the Wadi Ma'in, Zara and Mujib desalination plant and conveyance project in September 2003. The desalination

is carried using the reverse osmosis techniques. This is a Design-Build-Operate contract. The plant will be operated for 2 years before being handed over to the Government. The plant includes desalination of 55 MCM per year of water with a salinity of 1500–2000 mg/l. It shall provide Amman with 38 MCM per year with a TDS of 250 mg/l [6]. In this way more drinking water can be supplied to major water consumers.

This paper describes the performance evaluation of Wadi Ma'in, Zara and Mujib desalination plant so as to bring out the state of the art of its operation and maintenance. Detailed information on plant design and engineering, water quality, plant personnel, and cost of operation and maintenance will be collected since commissioning of the plant. The performance of the plant is characterized according to parameter such as: quantity of water produced and quality of water.

2. Reverse osmosis

Reverse osmosis (RO) is a physical process that uses the osmosis phenomenon, i.e., the osmotic pressure difference between the saltwater and the pure water to remove salts from water. In this process, a pressure greater than the osmotic pressure is applied on saltwater (feedwater) to reverse the flow, which results in pure water (freshwater) passing through the synthetic membrane pores separated from the salt. A concentrated salt solution is retained for disposal. The RO process is effective for removing total dissolved solids (TDS) concentrations of up to 45,000 mg/L, which can be applied to desalinate both brackish water and seawater. Reverse osmosis needs energy to operate the pumps that raise the pressure applied to feedwater. The amount of pressure required directly relates to the TDS concentration of the feedwater. For brackish water, the pump pressure requirement is between 140 and 400 psi. For seawater, pumps may need to generate up to 1200 psi. Therefore, the TDS concentration of the feedwater has a substantial effect on the energy use and the cost of the product water. Two common types of membranes used in RO process for desalination include cellulose acetate (CA) membranes and non-CA membranes. Cellulose acetate membranes were developed in the 1960s and various modified and improved blends of CA membranes are currently used in the desalination process. The CA membrane has a relatively smooth surface that is resistant to fouling. It is theorized that if the membrane surface is rather smooth, the material that may cause fouling cannot deposit in the membrane crevices [7]. Non-CA membranes, typically called "thin-film composite membranes" include aromatic polyamide (PA) membranes and composite membranes using common organic materials such as polysulfone. These membranes have a higher flux rate (volume of freshwater per membrane surface area) and, compared to CA membranes, allow passage of lower salt concentra-

tion. Non-CA membranes are more stable over a broader pH range than the CA membranes, but are susceptible to degradation by chlorine [8]. Pre-treatment of feedwater is essential in order to protect the RO membrane, reduce energy costs, and increase salt retention. It should be free of large particles, organic matter, bacteria, oil and grease. Typical pre-treatment involves multimedia, cartridge, and sand filtration to remove larger particles, organic matter and other materials; and adding chemicals to prevent the formation of precipitates and scaling of the membrane. Often, pH adjustment is also needed. Certain membrane materials are sensitive to oxidants such as chlorine; therefore, additional chemicals may be needed in order to remove the oxidants from the feedwater prior to membrane treatment. Post-treatment of RO permeate may also be needed depending on the intended use of the product water. For example, carbon dioxide and soda ash may be added to increase alkalinity of the treated water and to reduce corrosiveness of the product water.

Recovery rate is a major parameter for evaluating membrane effectiveness. Recovery is defined as the volume of freshwater produced as a percentage of the volume of feedwater processed. Typical recovery rates for RO systems can be 30–80% depending on the quality of feedwater, pressure applied, and other factors. Reverse osmosis membranes that operate at low pressures but maintain high recovery rates have been developed. Typically, these ultra low-pressure reverse osmosis membranes (ULPRO) are made of thin film composites of polymers, with an active surface layer that is negatively charged with improved fouling resistance properties [9–12].

3. Parameters of the RO process

The operating parameters of seawater RO system are mainly function of feed water salinity and temperature. For example, for seawater feed of about 38,000 ppm TDS salinity and water temperature in the range of 18–28°C, the RO systems are designed to operate at a recovery rate in the range of 40–45% and with an average permeate flux in the range of 11.9–13.5 l/m²-h. At the above operating conditions the feed pressure is in the range of 800–1000 psi (55–70 bar) and permeate salinity is in the range of 300–500 ppm TDS. For a given feed water salinity and salt rejection of the membrane elements used, the permeate salinity is a function of feed water temperature, recovery rate and permeate flux. An increase in feed water temperature results in an increased rate of salt and water diffusion across the membrane barrier at the rate of about 3% per degree Centigrade. Because RO plants usually operate at a constant flux rate, the changes of permeate salinity follow closely the changes in feed water temperature [13].

Permeate salinity is inversely proportional to the average permeate flux. Higher permeate flux increases

the dilution of salt ions which passed the membrane, and therefore results in lower permeate salinity. The average permeate flux rate in seawater systems is maintained at relatively low values: 7–8 gfd for surface seawater feed and 10 gfd (16.8 l/m²-h) for seawater from beach wells. The difference in flux rates between the two water source types results from better quality of the well water and therefore, a lower fouling rate of the membranes. These flux values are relatively low and only about 50% of the permeate flux values used in brackish RO systems. Attempts to operate seawater systems at higher flux rates have usually resulted in irreversible flux decline. Until recently, the design recovery rate of new commercial seawater RO systems has been increased subsequently to the availability of membrane elements with increasingly higher salt rejection. So far, the maximum recovery in seawater RO systems has been mainly limited by the membrane salt rejection or the ability to produce permeates water of potable quality. The obvious questions are what is the optimum recovery rate of seawater systems in respect to product water cost, is such recovery achievable with the current performance of commercial seawater membranes, and is it possible to operate RO membranes on surface seawater at a higher flux rate.

4. Wadi Ma'in, Zara and Mujib desalination plant

4.1. Background

The Wadi Ma'in, Zara and Mujib Desalination Facility was initiated in 2001 and completed in 2007. The desalination facility and associated pumping and conveyance facilities were implemented to increase potable water supplies to Amman, the capital of Jordan as well as tourists visiting the Dead Sea. The desalination facility treats brackish water from three nearby wadis; Mujib, Zara, and Ma'in and has a maximum treatment capacity of 55 million m³ (MCM) per year or approximately 40 million US gallons per day (mgd).

The desalination facility provides treatment through conventional pretreatment (coagulation, sedimentation, and filtration) and reverse osmosis (RO) membranes for desalination. The desalination facility receives brackish water from three different sources: Zara Springs, Wadi Mujib and Wadi Ma'in. The capacity of each source and its contribution are summarized in Table 1.

Per contract requirements, the RO system at the desalination facility is required to operate between 85–90% recovery based on the average and worst case water qualities from the ratios of flows from each of the three source waters. The RO system recovery is limited primarily by the silica content, total dissolved solids (TDS), and temperature in the source water. A minimum recovery of 90% is to be achieved under combined average conditions (TDS = 1475 ppm and silica = 18.55 ppm) and 85% under the worst case water quality conditions (TDS = 1664 ppm

Table 1
Source water flows to Wadi Ma'in desalination facility

Source	Capacity (MCM/y)	Corrected flow for 55 MCM/y	Contribution to total plant influent
Zara Springs	7	6.4	11.7%
Wadi Mujib	30	27.5	50.0%
Wadi Ma'In	23	21.1	38.3%
Total	60	55	100%

with silica = 18.55 ppm or TDS = 1571 ppm with silica = 26.26 ppm).

Initial start-up and operation of the Wadi Ma'in, Zara and Mujib desalination facility was conducted by JV commissioning team from 22 August 2006 through the performance acceptance test completed on 6 June 2007. A decrease in RO production was observed when the RO system was operated per contract requirement of 85–90% recovery. Minimal operating data from the RO system is available during the period when it was operated by the commissioning team. Operation of the facility was turned over to the JV's operation and maintenance (O&M) team after the performance acceptance test, 7 June 2007.

4.2. RO system design

The basis of the design for the RO system as provided by ONDEO Degremont is briefly summarized below:

- Operating temperature 20–40°C
- Maximum TDS of 1980 ppm
- Silica range of 18.55 ppm (average) to 26.26 ppm (worst case)
- pH range within 6.8 and 7.2 upstream of Pustules and maintained between 6.6 and 6.8 upstream of the RO system
- Iron concentration of less than 0.02 ppm after pretreatment
- Aluminum concentration of less than 0.02 ppm after pretreatment

The design criteria of the RO system are summarized in Table 2.

4.3. Review and observations of plant operating data

Plant operating data for the RO system from August 2006 through April 2008 was reviewed to evaluate its performance to date. A review of the RO operating indicated that there are two distinct operating trends for RO skids 61–68. During the first 100–150 days of operation for each skid, the performance of the RO system (i.e. system recovery, permeate production, ΔP , etc.) was less stable than typical standard operating procedures. After about 150 days of operation, the performance of the RO system was more stable. Observations of the operating data are summarized in Table 3 and are divided into two parts based on the two different trends observed.

Table 2
RO design criteria

Parameter	Value
Raw water flow	145,000 m ³ /d (~38 mgd)
Number of RO trains	9
Max number of trains in service	8
Feed flow per rack (constant)	755 m ³ /h (~3324 gpm)
Number of stages	3
Raw water silt density index (SDI)	<3 normally Maximum of 5
Membrane type	Spiral wound = 400 ft ² Type 1: BW30-400FR Type 2: LE-400
Recovery	85% minimum

Table 4 summarizes the average performance of the RO plant, the daily average water production is 100,000 m³ with a TDS value of 185 mg L⁻¹. The observed feed water rate is 5100 m³ h⁻¹ with a value of 1460 mg L⁻¹ TDS, where the designed values are 6000 m³ h⁻¹ and 1500 mg L⁻¹ for feed water input rate and feed water TDS, respectively. The design and observed percent of product water recovery is 87.5. The operating inlet pressure is 14 bar and the differential pressure across the membrane is 2.31 kg cm⁻²; there is an increase trend of this pressure across the membrane through the three stages.

The physico-chemical characteristics of feed, product and reject water from the RO desalination plant are shown in Table 5. For the product water, the pH and TDS are 8 and 180, respectively.

The combination of lower RO recovery, lower differential pressure across the RO system, and higher permeate production during the first 150 days of operation (as indicated in Figs. 1–3) may suggest that the operating conditions during this period are better suited for the RO system design than at a higher recovery. A higher permeate production was observed at the lower recoveries (between 75–85%) than when operated above 85%. The data given and observed trends in Figs. 1–3 are fairly representative of all the RO skids. In addition, a lower differential pressure across each stage during 0–150 operating days indicate that the membranes may have been

Table 3
Observations of RO operating data (August 2006–April 2008)

Operating period	Comments on RO operating data
0–150 days of operation	<ul style="list-style-type: none"> The overall RO system recovery during this operation time frame was consistently below 85%, the minimum target value for the project. Normalized permeate flow per RO skid averaged approximately 675 m³/h (ranging from 606–708 m³/h). The normalized permeate flow during this time period was very erratic, but was at its highest over the entire two year operation period. The normalized differential pressure (or ΔP) across the RO system was the lowest during this period. Salt rejection of the RO system was the highest during this period, although with more variability.
150 days onward	<ul style="list-style-type: none"> The controlled set points were much more stable and consistent after the first 150 days of operation. The RO system was operated at a recovery consistently above 85%. Normalized permeate flow decreased about 10% from the first 150 days of operation and stabilized around 600 m³/h on average. The operating feed pressure for Stage 1 and 3 increased by approximately 2–3 bar over the next 300 days of operation. The normalized ΔP across the RO system gradually increased by approximately 50–100%. Salt rejection of the RO membranes decreased during this period.

Table 4
Performance of the RO plant at glance

Parameter	Design value	Observed value
Feed water input rate, m ³ h ⁻¹	6000	5100
Product water production rate, m ³ h ⁻¹	5250	4460
Reject water output rate, m ³ h ⁻¹	749	640
Product water recovery, %	87.5	87.5
Feed water TDS, mg L ⁻¹	1500	1460
Product water TDS, mg L ⁻¹		185 + blending
RO inlet pressure range, kg cm ⁻²		14 bar
Differential pressure across the membrane, kg cm ⁻²		2.31 bar
Plant utilization (mean of 54 months), h/d	24	24
Product water production (mean of 54 months), m ³ /d		100,000

cleaner during this time period and/or that the feed flow to the RO membranes was better distributed amongst the RO elements. An increase in differential pressure could suggest that the RO elements toward the end of each stage may have experienced higher concentrations on the membrane surface than desired which could lead to scaling of the membranes.

The decrease in permeate production at higher recovery could indicate the presence of membrane fouling and/or scaling. Fouling occurs when particles or solids deposit on the membrane surface, reducing the effective surface area of the membrane. Scaling occurs when sparingly soluble salts are concentrated above its saturation limit.

When scales are formed on the RO membrane surface, it decreases the effective surface area for water to pass through leading to a decrease in permeate production.

Fouling/scaling of the RO membranes at the higher operating recoveries (above 85%) is further supported by the increase in the differential pressure across the membranes. Both fouling and scaling of the membranes results in a reduced surface area of the membrane, resulting in greater pressure required to be applied, causing a greater differential pressure across each RO stage. In addition, the operating pressure of the RO system gradually increased during this period as well, which also suggests that fouling, may have occurred on the membrane system.

Table 5
Physico-chemical characteristics of feed, product and reject water from

Parameter	Feed water	Product water	Reject water
pH	6.75	8.0	7.37
Conductivity, $\mu\text{S cm}^{-1}$	2358	350	14770
Turbidity, NTU	<0.1	<0.1	
TDS	1390	180	8700
Alkalinity	105	49	684
Total hardness, CaCO_3	443	<300	
Calcium, Ca^{2+}	274	52	2100
Magnesium, Mg^{2+}	0.05		0.249
Chloride, Cl^-	570	47	
Sulphate, SO_4^{2-}	278	23	2300
Nitrate, NO_3^-		0.47	
Fluoride, F^-		<0.2	3.60
Silica, SiO_2	19.1		154
Iron, Fe	0.01	<0.01	0.04
Manganese, Mn^{2+}	0.022		

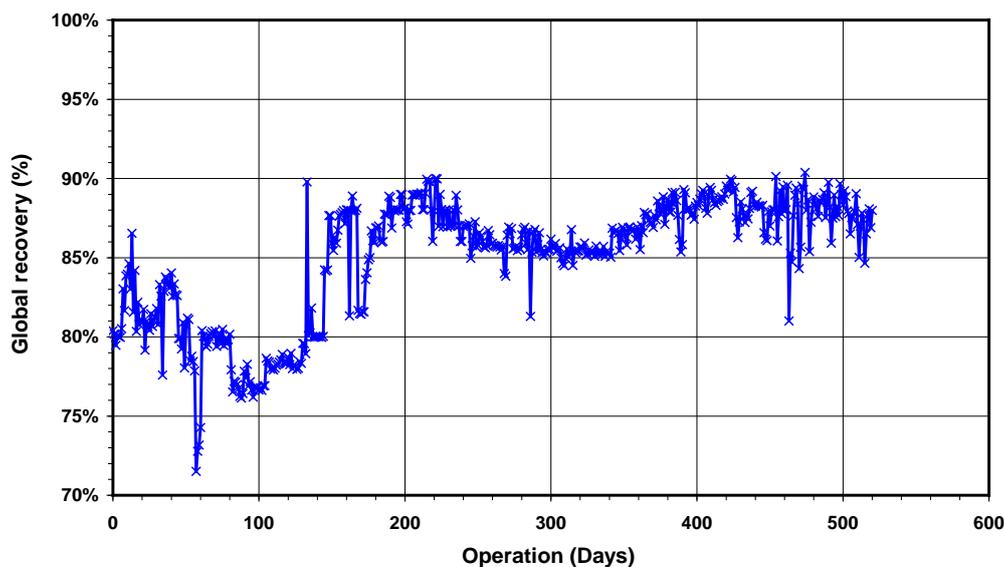


Fig. 1. Global recovery.

4.4. Evaluation of RO chemical cleanings

Chemical cleanings of the RO membranes were evaluated to determine their effectiveness at restoring the RO membrane's initial permeability and indirectly determine if fouling has occurred on the membranes. General observations on the effectiveness of the chemical cleanings conducted, based on the chemical cleanings evaluation data provided:

Chemical cleaning evaluation data provided indicate that chemical cleanings conducted on the 1st stage of the

RO skids had good impact on improving the normalized permeate flow through the RO system. However, the chemical cleanings did improve the normalized pressure drop within the RO system.

The normalized permeate flow for the 1st stage on the majority of the RO skids was lower after each chemical cleaning compared to the reference normalized permeate flow for each respective RO skid.

Chemical cleanings conducted on stage 3 exhibited improvements (10% improvement on average) in both normalized pressure drop and permeate flow for all skids.

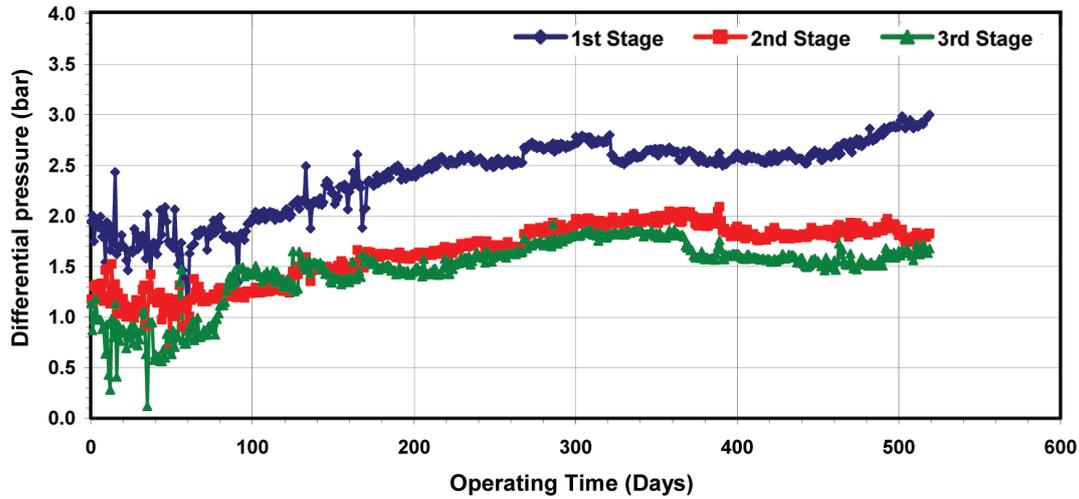


Fig. 2. Normalized differential pressure.

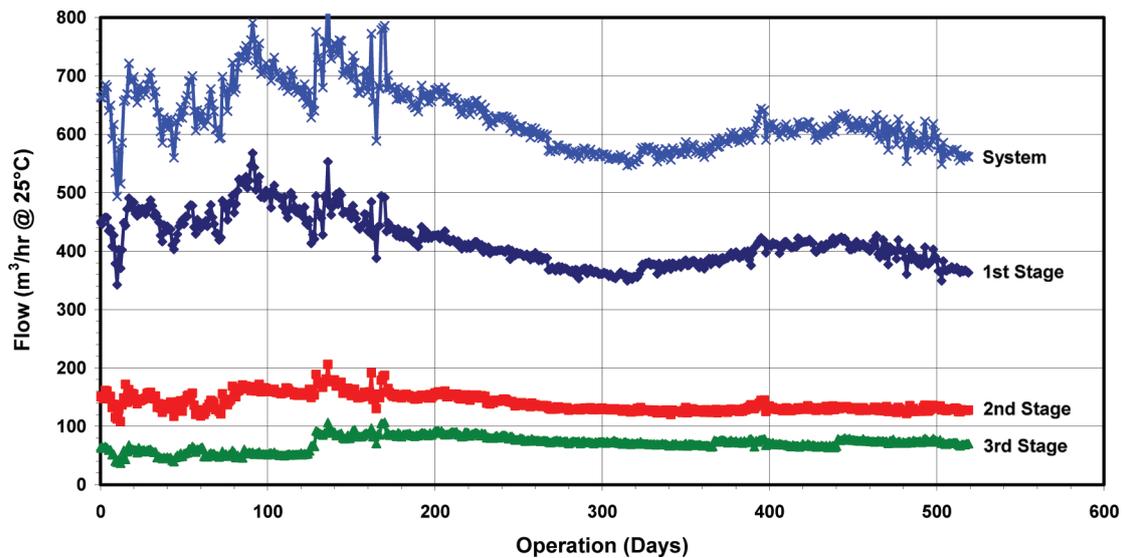


Fig. 3. Normalized permeate flow.

On average, chemical cleanings on stage 3 membranes were able to reasonably restore the normalized permeate flow to the reference point.

In general, the chemical cleaning analysis indicates that each chemical cleaning conducted improved the differential pressure (decrease in differential pressure) across the membrane stage with respect to differential pressure recorded for the day prior to chemical cleaning (Day 1). The chemical cleanings were able to improve the normalized permeate flow production with respect to Day 1. The chemical cleanings conducted on RO skids was effective in improving membrane operating conditions.

4.5. Reservoirs and pumping stations layout and hydraulic gradient profile

A 40 km transmission pipeline conveys the potable water to Amman through 6 pumping stations with a total head of around 1300 m. Elevations and distances between the finished Water reservoir No. 1 up to the terminal reservoir at the National Park site in Amman are also shown in Fig. 4. Cathodic protection of the pipeline from corrosion through a sacrificial anode system is used. Two hydro-pneumatic surge tanks filled with compressed air are installed at the discharge of each of the pumping stations.

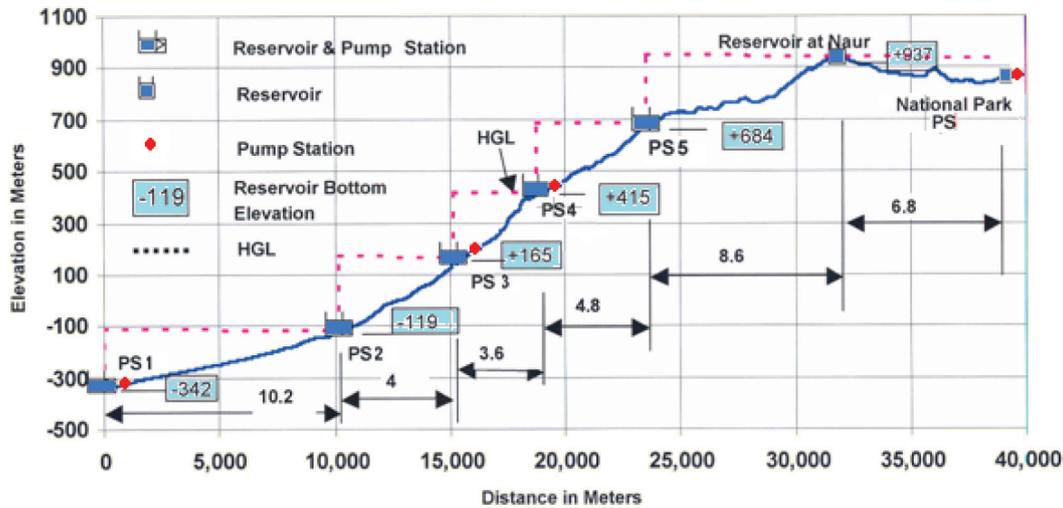


Fig. 4. Transmission pipeline layout and profile.

5. Summary and conclusions

For efficient and dependable water supply in Jordan, at which water potable water is scarce, RO desalination plants offer the practical option. To look into the feasibility of such an option, the Wadi Ma'in, Zara and Mujib RO desalination facility, indicate success. The plant performed with normal designed flux rate of water. During the first 150 operating days, the overall RO system recovery during this operation time frame was consistently below 85%, the minimum target value for the project. Normalized permeate flow per RO skid averaged approximately 675 m³/h (ranging from 606–708 m³/h). The normalized permeate flow during this time period was very erratic, but was at its highest over the entire two year operation period. The normalized differential pressure across the RO system was the lowest during this period. Salt rejection of the RO system was the highest during this period, although with more variability. After one hundred fifty days, the controlled set points were much more stable and consistent after the first 150 days of operation. The RO system was operated at a recovery consistently above 85%.

Normalized permeate flow decreased about 10% from the first 150 days of operation and stabilized around 600 m³/h on average. The operating feed pressure for Stage 1 and 3 increased by approximately 2–3 bar over the next 300 days of operation. The normalized ΔP across the RO system gradually increased by approximately 50–100%. Salt rejection of the RO membranes decreased during this period.

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