Desalination and Water Treatment
www.deswater.com
doi: 10.1080/19443994.2014.940207

55 (2015) 2526–2535
August

Taylor & Francis
Taylor & Francis Group

Palmachim Seawater desalination plant—seven years of expansions with uninterrupted operation together with process improvements

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Received 25 May 2014; Accepted 12 June 2014

ABSTRACT

The Palmachim Seawater desalination plant supplies to the Israeli water net potable water in accordance with all contractual requirements of water quality and quantity. The plant was commissioned in 2007 and produced up to 110,000 $m^3 d^{-1}$ (30 million m^3/year). During 2009–2010, the plant production capacity was expanded up to 150,000 $m^3 d^{-1}$ (45 million m^3/year). Recently, the plant production capacity was further increased, doubling production rate up to 300,000 $m^3 d^{-1}$ (90 million m^3/year). This paper provides a general overview of the work undertaken along the years to accomplish the final assembly of the plant. The main plant characteristics are described, notably the small footprint, high operational flexibility, low energy consumption, and low chemicals usage. In addition to the physical constructions, the recent expansion incorporated several significant process modifications, aiming to improve the efficiency of the plant. A description of the characteristics of two main modifications is displayed: the use of new generation seawater reverse osmosis membranes in the desalination trains that enabled a reduction in energy cost and changes in the post-treatment hardening that led to a significant reduction in the chemicals consumption.

Keywords: Seawater desalination; Expansion; New generation membranes; Energy consumption; Product hardening; Chemicals consumption

1. Introduction

Palmachim Seawater desalination plant is located in the central part of Israel, north to the port city of Ashdod. Plant construction started in May 2005 and completed in May 2007. The agreement with the Israeli government involved the production of 30 million m^3 of water annually, in accordance with all contractual requirements of water quantity and quality.

The agreement with the government is of the Build, Own, and Operate structure type for 25 years. According to this agreement structure, the plant remains in the ownership of the seller at the end of the agreement term. Palmachim desalination plant is operated by via-Maris operation Ltd.

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Presented at the Conference on Desalination for the Environment: Clean Water and Energy
11–15 May 2014, Limassol, Cyprus

In April 2010, the production capacity of the Palmachim desalination plant was enlarged to 45 million m^3 of water per year. This expansion, named "Palmachim 2", was completed within 10 months. During 2012–2103, the production capacity of the Palmachim desalination plant was doubled to 90 million m^3 of water per year. This expansion, named "Palmachim 3", was completed within 18 months. Both plant enlargements were executed on the original plant footprint (Picture 1). without any interruption of potable water supply.

2. Unique original design of the plant

A major consideration in the original design of the Palmachim desalination plant was the demand for vast operation flexibility, enabling plant operation at variable production rates during a day, according to the Time of Use (TOU) electricity tariff. The TOU electricity tariff prevailing in Israel varies significantly during the day and could be up to four times higher at "peak" hours in comparison with "off peak" hours. Thus, vast operational flexibility can significantly reduce the energy cost that dominates the operating cost.

In order to reduce the electricity cost, the plant was designed and constructed according to an "independent parallel RO trains" design concept. Implementation of smooth start-up and shut-down procedures allows full production capacity during "off peak" hours and shut down of trains (up to a complete plant), during "peak" hours.

The Palmachim desalination plant incorporates the following treatment units:

- Coarse screen filtration.
- Deep-bed multi-media filtration (gravity and pressurized).
- Cartridge micron filtration.
- Seawater reverse osmosis (SWRO) system with a partial split.
- Ion-exchange softeners.
- Second pass of reverse osmosis system of rear-end permeate of the SWRO system.
- Product stabilization (rehardening, pH adjustment, and chlorination).

The first enlargement of the plant ("Palmachim 2") included modification of the energy recovery units, from Pelton turbines to pressure exchange (PX0 modules, as described elsewhere [1].

3. Second plant enlargement ("Palmachim 3")

The increasing demand for potable water in Israel led the government to request the plant production enlargement. Via-Maris (VMD) targeted to achieve this enlargement without interrupting the potable water supply. The plant was enlarged from 45 to 90 million m^3/year (up to 12,000 m^3/h, 300,000 m^3/d (80 MGD)).

The plant enlargement was performed with emphasis on the following goals—keeping the same operational flexibility, maintaining the same plant footprint, and minimizing capital cost investment. An additional goal was to improve the efficiency of the plant in terms of reducing energy and chemicals consumptions.

3.1. "Palmachim 3" time table—constrains and solutions

Tight schedule was a request by the Israeli government, driven by a severe drought that took place in Israel during 2010–2011. The government dictated full water production within 18 months.

The agreement between VMD and the government was signed in November 2011. The project officially started at January 2012. Financial closure took place at the end of January 2012 and allowed early purchasing.

The project was divided into two phases:

Phase 1—enlargement of the six operating RO units (skids) from 1,200 to 1,500 m^3/h. Time frame for this stage was completion by the end of 2012.

Phase 2—construction of two new RO units (skids) of 1,500 m^3/h by the end of July 2013 with all required auxiliary systems.

No free ground around the facility was available for the enlargement of the plant. Therefore, the design team had to provide solutions for increasing production capacity while maintaining at the same time the original footprint of the plant (32,000 m^2, 3.2 ha). In order to accomplish the goal of building the plant in the tight time frame, the following measures were taken:

- The full design was undertaken in house, allowing full control and adjustment to the existing operating plant. The plant team undertook a major role in the process design.
- In order to minimize trouble shooting and commissioning time, new concepts were pretested in the field during the construction period using pilot systems.
- Bearing in mind that construction works and equipment installations play a major role in causing delays in such projects, the concept of using prefab units was adopted.

3.2. Water intake and pretreatment

As doubling seawater flow into the plant was a necessity, a second marine intake pipeline was installed. An HDPE pipe of 1,600 mm diameter was connected to the plant intake pit. A cut and cover marine operation in the sea bed was conducted and the pipe was connected to the new, second, intake head.

The original pumping pit was designed to allow installation of five pumps. A new pump was installed having a capacity of 9,500 m^3/h, allowing a total pumping capacity of up to 33,000 m^3/h.

3.3. Pretreatment

The original pretreatment system was based on 16 multi-media gravity filters, operating at a flow velocity of 8 m/h. During the years, the media type was alternated and the flow velocity was increased up to 15 m/h. The modified system provided a filtrate having a low SDI level as evident from the data points of Fig. 1. When checking the design for the required expanded capacity, the filters outlet product pipes were found to constitute a bottleneck. As part of the expansion project, a second outlet product pipe was installed for each filter, including all required controls. All filters now work in parallel and deliver the necessary hourly flow of 1,500 m^3/h per filter.

However, even the enlarged gravity filters battery was not able to supply the requested enlarged amount of filtered water and furthermore steps were needed to be taken.

Pressurized filters were selected as the solution. The filters were mounted on top of the gravity filters using a steel structure to distribute the weight to the support structure points. Feed water to the filters is supplied by a vertical turbine pump, located in the inlet channel of the gravity filters. The filters are used only when necessary and are not activated during electricity "peak tariff" hours.

Fig. 1 displays RO feed water SDI levels measured along the years. Regardless of filtration system configuration used (media type, gravity filters only, low or high filtration velocity, or gravity plus pressurized filters), the SDI level of the RO feed water is characterized by a relatively low level, amounting to 2.5 ± 0.6%/min.

3.4. Membranes arrangement and pumping system

One of the major tasks in the expansion project was to enlarge the six RO operating skids to fit the increased production of up to 1,500 m^3/h. Two major endeavors were involved: enlargement of the membrane skids and extension of the pumping and piping system to provide the required increased water quantity.

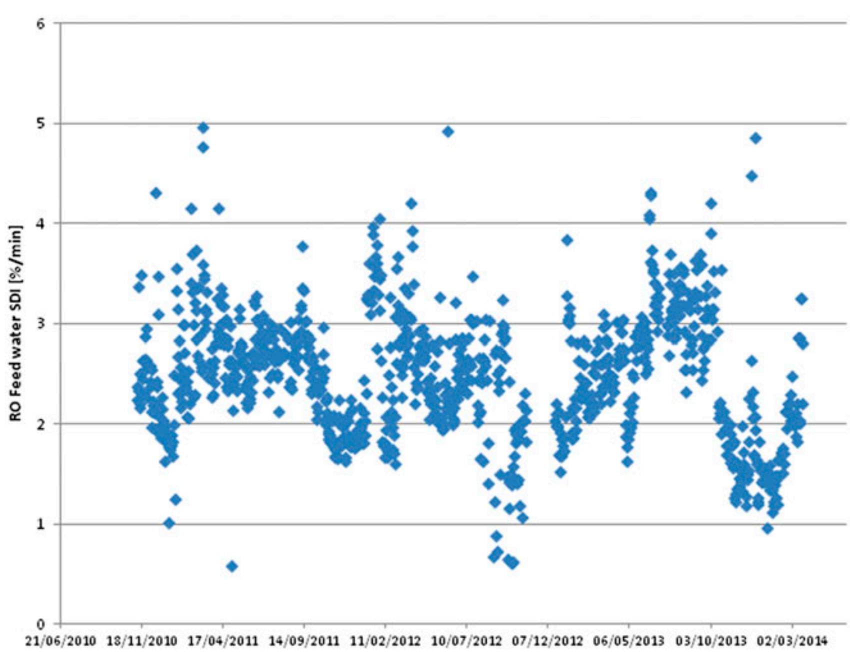


Fig. 1. Palmachim desalination plant—RO feed water SDI.

The original ("Palmachim 2") RO skids were composed of 264 pressure vessels each housing eight elements of 400 ft^2. The expansion included partial replacement of the original 400 ft^2 (37 m^2) membranes with new-generation membranes, some having 400 ft^2 active area and the rest having 440 ft^2 (40.9 m^2). In order to accommodate the increased water productivity, a new high-pressure piping system and low-pressure permeate collector piping system had to be installed.

The expansion of the skids took most of the floor area of the membranes hall leaving limited space for piping and auxiliaries. The adopted solution was to construct above the skids a steel platform, 2 m below the ceiling and 12 m above ground, allowing a wide open space for all piping, flow meters, and other required controls, as can be seen in Picture 2(a) and (b).

3.5. Pumping system

The original hybrid [1] was composed of a high-pressure pump (HPP) of 1,500 m^3/h, a conjugated energy recovery turbine (ERT) (two wheel Pelton turbine) for up to1,000 m^3/h and an energy recovery device of PX type for 830 m^3/h. Bearing in mind that more water is now required and not willing to change the old power scheme, an additional new PX array was added. A total of 1,750 m^3/h could now be transferred to the skid through 2 PX arrays while letting the turbine run idle. Since no power was now transmitted through the ERT, the pump was connected to a more powerful motor of 3 MW. Fig. 2 shows the new pumping scheme.

Working in full isobaric scheme while keeping the turbine to assist easy start ups and shut downs provided several advantages:

- Power consumption of the first pass was reduced to 2.3–2.7 kWh/m^3 (18–31 °C).
- Easy start ups and shut downs were achieved using the turbine as a soft starter.
- Availability was increased—dual PX manifolds assembly increases availability since the turbine may back-up one PX unit allowing the isolation of one PX array for maintenance.

3.6. Second pass

In order to meet the required water quality of the final product, a second RO pass of rear-end permeate is used. The main goal of the second pass is to reduce the boron content. The original design of the plant included three parallel RO trains, operating at a water recovery level of 98%. Each train is composed of four stages in series. With the expansion of the first RO pass, an enlargement of the second pass capacity was also needed. Three additional trains were installed between the three operating trains, within the same hall. An additional annex to the building was constructed to house the three HPP and the three interstage booster pumps.

4. Process improvement in "Palmachim 3" project

"Palmachim 3" project involved also process improvements, aiming to augment plant efficiency. The two main process modifications were: (a) the use of new-generation SW membranes in the desalination trains that enable additional reduction in energy cost and (b) changes in the post-treatment hardening that enables significant reduction in chemicals consumption.

4.1. Implementation of new-generation membranes

The recent plant expansion included partial replacement of the original 400 ft^2 (37 m^2) membranes with new-generation membranes, some having 400 ft^2 active area and the rest having 440 ft^2 (40.9 m^2). The membranes were acquired from several manufacturers.

New-generation membranes are characterized by an augmented production capacity as well as by a significant improvement in salt rejection. In the past 25 years, considerable improvements have been made in seawater spiral wound elements; production capacity has been doubled and salt passage reduced by about threefold [2].

Fig. 3 displays membrane water permeability values of three trains: train A which contains the original membranes and Trains B and C which contain the new new-generation membranes. It is important to note that in the original train, membranes (Train A) were replaced during the years, according to the manufacturer guidelines.

Fig. 3 shows a significant increase in membrane permeability levels of the new-generation membranes in comparison with the levels of the original membranes—from levels around 0.6 to levels around 0.8 lmh/bar. Such an increase has a major beneficial effect on the energy consumption of the plant. Table 1 illustrates this effect in terms of energy cost. Since part of the new-generation membranes has 400 ft^2 while the others have 440 ft^2 of active area, the saving lies in between the listed values.

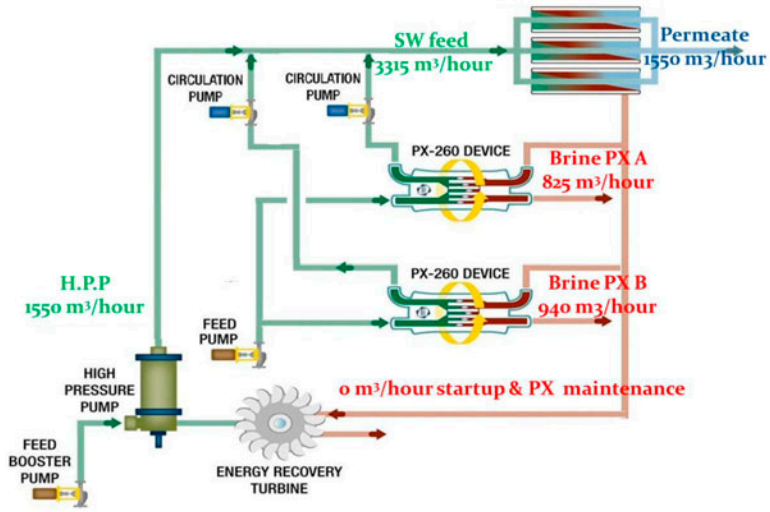


Fig. 2. Palmachim desalination plant—new expanded RO power scheme.

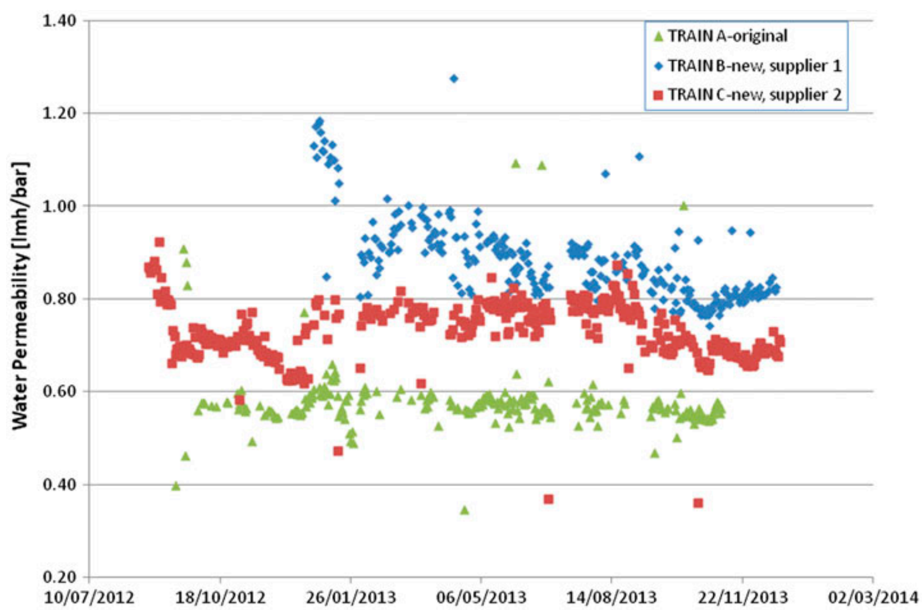


Fig. 3. Membrane permeability, original membranes (Train A) vs. new-generation membranes (Trains B and C).

A significant reduction in energy consumption is thus anticipated. For a plant, such as the Palmachim plant (90 MCM/year), energy cost saving due to a permeability increase in the first SWRO pass only is in the range of 1.7–2.2 million US dollars per year.

A secondary impact of the reduced energy cost is in providing an improved product water quality. The need to achieve the required final product quality in terms of salinity level and Boron content, dictates the amount of SWRO product to be further desalinated in the second-pass plant (the "split"). New-generation membranes produce improved quality permeate (Fig. 4) leading to a higher split ratio in the first SWRO pass (Fig. 5), throughout the year, especially during winter time.

Although Fig. 5 presents split values that seem practically identical, it should be noted that the existing difference is not negligible at all; this can be seen in Table 2 which displays energy cost saving due to the reduced amount of water, desalinated in the second pass.

Table 1
Illustration of energy cost saving when replacing original membranes with new-generation membranes due to an increase in membrane permeability

Production capacity	m^3/year	90,000,000	90,000,000	90,000,000	90,000,000
Production hours	h	8,700	8,700	8,700	8,700
Single membrane area	ft^2	400	440	400	440
Single membrane area	m^2	37	40.9	37	40.9
Calculated total membrane area	m^2	833,536	921,395	833,536	921,395
Permeability	lmh/bar	0.6	0.6	0.8	0.8
Calculated water flux	lmh	12.41	11.23	12.41	11.23
Osmotic pressure	bar	48	48	48	48
Calculated applied pressure	bar	68.68	66.71	63.51	62.03
Specific energy consumption	kWh/m^3	2.54	2.47	2.35	2.30
Energy price	$/kWh	0.10	0.10	0.10	0.10
Energy cost	$/m^3$	0.254	0.247	0.235	0.230
Energy cost	M$/year	22.89	22.24	21.17	20.68
Energy saving	M$/year	–	0.65	1.72	2.21

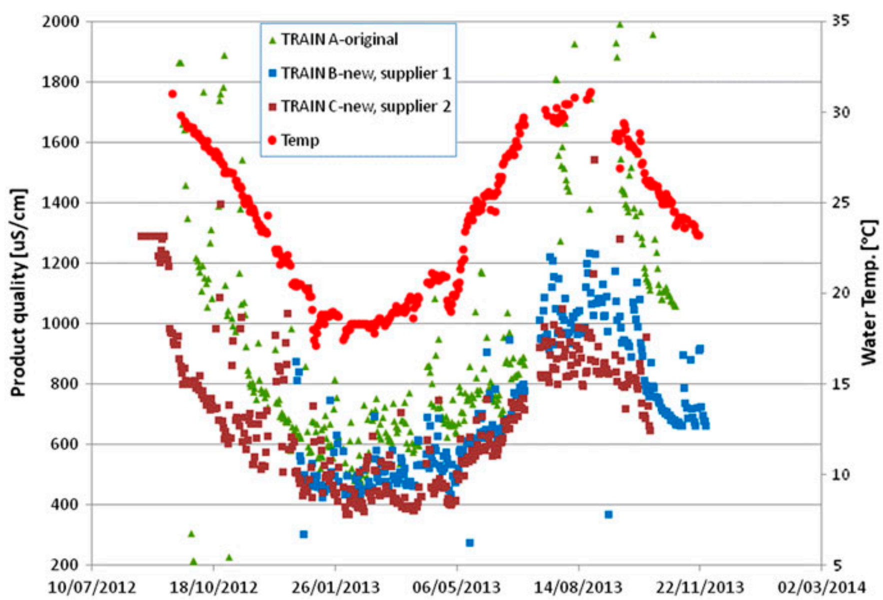


Fig. 4. Permeate quality, original membranes (Train A) vs. new-generation membranes (Trains B and C).

It should also be noted that the improved rejection is not only due to the higher water flux in which the new-generation membranes operate at but is mainly due to their lower salt passage coefficient *B* value, as can be seen in Fig. 6.

An additional prominent contribution of the new-generation membranes to the operation of the Palmachim plant stems from their increased production capacity that enables reduction in the number of expensive operating hours of electricity "peak tariff". Trains that are characterized by a higher permeability are able to produce the same daily amount of product at shortened periods. For example, during summer time, all eight trains of 1,250 m^3/h must operate constantly for a daily production capacity of 240,000 m^3/d. Using new-generation membranes of 1,500 m^3/h the same production capacity is obtained by three trains operating constantly and five trains shut down during peak electricity tariff hours (7 h a day). This mode of operation can save up to 7 millions of US dollars a year (based on summer time tariff only).

In summary, replacement of new-generation membranes had three effects on energy cost in the Palmachim desalination plant:

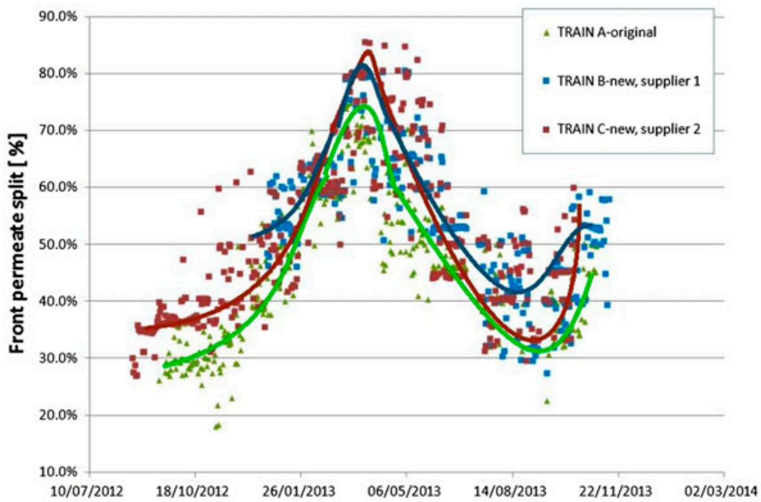


Fig. 5. Front permeate split, original membranes (Train A) vs. new-generation membranes (Trains B and C).

Table 2
Illustration of energy cost saving when replacing original membranes with new-generation membranes due to an improvement in salt rejection

	Skids with new-generation membranes	Skids with original membranes
Typical *front split* at summer time	40%	30%
Typical annual flow to pass 2, m^3/year (based on 45,000,000 m^3/year)	27,000,000	31,500,000
Energy cost of second pass, M$/year (0.1 $/kWh, 0.6 kWh/$m^3$)	1.62	1.89
Energy saving, M$/year	*0.27*	–
Typical *front split* at winter time	85%	70%
Typical annual flow to pass 2, m^3/year (based on 45,000,000 m^3/year)	6,750,000	13,500,000
Energy cost of second pass, M$/year (0.1 $/kWh, 0.6 kWh/$m^3$)	0.41	0.81
Energy saving, M$/year	*0.40*	–

(1) The new-generation higher permeability membranes are using less energy for the same production capacity.
(2) The new-generation higher rejection level membranes require less SWRO product capacity to be further desalinated in the second RO pass.
(3) The new-generation higher permeability membranes allow operation in a reduced number of expensive "peak tariff" hours.

4.2. Changes in the design of rehardening post-treatment system

The rehardening system is a major contributor to the chemicals consumption of the plant. The design of a rehardening plant is complex due to numerous factors involved [3]. The selected design and in particular the extent of retention time, granules size, and flow velocity have a major impact on the chemicals consumption.

The rehardening process in the Palmachim plant is as follows: first, sulfuric acid is dosed (Eq. (1)) to enable the dissolution of limestone in the rehardening chambers by direct dissolution (Eq. (2)) followed by an indirect dissolution, generated by the formed CO_2 (Eq. (3)). Subsequently, caustic soda is dosed in order to stabilize the product water by neutralizing excess CO_2 (Eq. (4)).

(1) $H_2SO_4 \rightarrow 2H^+ + SO_4^{-2}$
(2) $2H^+ + SO_4^{-2} + CaCO_3 \rightarrow Ca + SO_4 + CO_2 + H_2O$

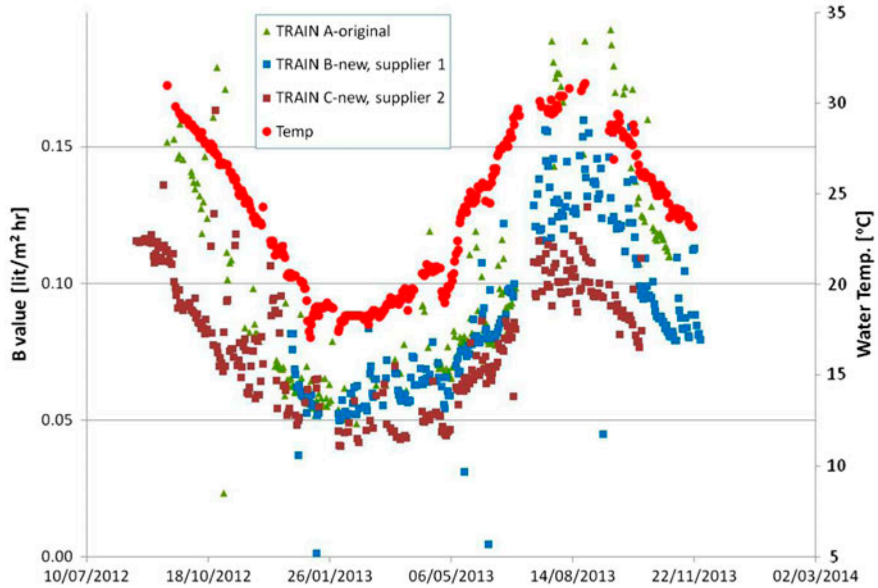


Fig. 6. Salt passage *B* value, original membranes (Train A) vs. new-generation membranes (Trains B and C).

(3) $CO_2 + H_2O + CaCO_3 \rightarrow Ca(HCO_3)_2$
(4) $CO_2 + H_2O + NaOH \rightarrow NaHCO_3 + H_2O$

According to the original design of the plant, a blend of the second-pass product and front SWRO product was delivered to the rehardening chambers. This low salinity stream is characterized by a relatively high pH level, amounting to 10.5–11.0.

The new design of the plant, in practice since the last expansion, involves the delivery of only part of the front SWRO permeate to the rehardening system. This stream has higher salinity but is characterized by a significantly lower pH level of 7.9–8.3.

The most important modification of the rehardening system involved the installation of a first stage of eight pressurized glass fiber-reinforced polyester columns. The product of the first stage is delivered to a second stage in which the original gravity chambers are operating. The objectives of this expansion were: (a) increase in retention time thus approaching equilibrium (i.e. maximum calcium dissolution level) and (b) protection of the construction of the gravity chambers that are made of concrete by feeding them with a reduced acidity level solution having a pH level of 6.0–7.0 rather than a solution having a pH level of 2.5–3.0.

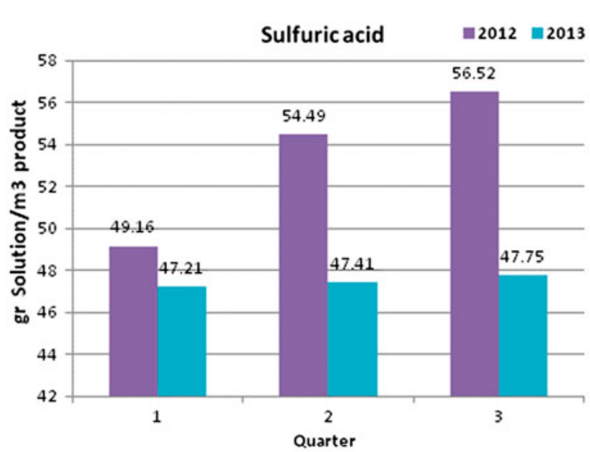


Fig. 7. Reduction in sulfuric acid consumption.

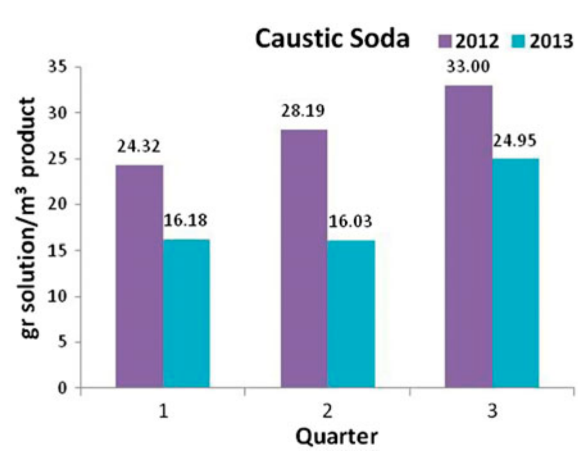
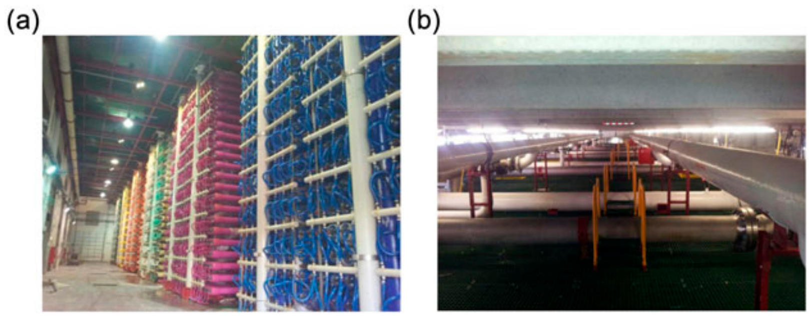


Fig. 8. Reduction in caustic soda consumption.

Picture 1. Palmachim Desalination Plant—Aerial view, 2014.



Picture 2. (a) SWRO membrane hall, on the top side of picture the steel beams of the upper platform can be seen. (b) SWRO membrane hall upper platform: HP, LP, and CIP piping.

Optimization between capital cost (construction of additional columns) and operating cost (sulfuric acid do be dosed in order to reach the desired calcium content) led to the installation of eight rehardening columns upstream of the four operating gravity rehardening chambers. Typical contact time is around 10 min in each system, 20 min in total. Superficial velocity is 30–50 m/h in the pressurized column while in the gravity chambers the velocity is in the range of 12–20 m/h. About 70% of the total product flow bypasses the rehardening system.

The modification of the rehardening system resulted in a dramatic decline in chemicals consumption for both sulfuric acid (Fig. 7) and caustic soda (Fig. 8).

It should be mentioned that sulfuric acid and caustic soda consumption displayed in Figs. 7 and 8 is common to the rehardening system and to the operation of the second pass. Sulfuric acid is also dosed to the second-pass brine stream; reducing its pH from a level of around 11.0 to 6.0 (brine serves downstream to softeners regeneration). Caustic soda is also dosed to second-pass feed stream, elevating its pH level from around 8.0 to 10.0–10.5 (enabling improved boron rejection in the RO system). Although available plant control provides no option to differentiate between these two consumptions, chemicals consumption reduction is certain and is attributed only to the modification in the rehardening system as no modifications have been incorporated in the second-pass operation.

5. Concluding remarks

The Palmachim SWRO desalination plant was recently enlarged for the second time, doubling its capacity from 45 to 90 million m^3/year. The plant expansion was completed within 18 months without any interruption in the supply of potable water to the Israeli water network.

The expanded plant enabled a doubled production capacity within the original plant footprint. Significant reductions in energy cost and chemicals consumption were achieved mainly by implementation of new-generation SWRO membranes and modification of the rehardening system. These cost savings contributed to a reduction in the operating costs of "Palmachim 3", making the project feasible and allowing a price reduction to the water price dictated by the Israeli government.

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