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Challenges and achievements in the expansion of the Granot BWRO plant: A part of Israel's coastal aquifer rehabilitation project

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ABSTRACT

The Granot inland BWRO (brackish water reverse osmosis) desalination plant is a part of the Aquifer Rehabilitation Project, which aims to prevent the salinization of the Israeli coastal aquifer. The main flow gradient of groundwater in the region is from a brackish aquifer in the east, to one of Israel's main freshwater aquifers (the coastal aquifer) in the west. To prevent salinization of the freshwater aquifer, a buffer zone has been created in-between the two aquifers, comprised of approximately 40 wells. These wells act as a barrier to salinization by pumping the brackish water before it reaches the coastal aquifer. This brackish water feeds the Granot BWRO and Lahat BWRO desalination plants. This aquifer rehabilitation project consists of three main parts: (1) a line of wells along the boundary between the two aquifers, (2) the BWRO desalination plants, and (3) a unique, exceptionally long (30 km) brine disposal pipeline to the Mediterranean Sea. From the outset, this project was designed to accommodate expansions in the production capacity of the system as well as to cope with increasing salinity of the source water. Accordingly, since 2004 there has been a gradual expansion over the years, in the number of desalination units within the Granot Plant. Currently, three desalination units are in operation, and a fourth unit is targeted to initiate production in June 2015. The total capacity at the Granot plant will be 41,600 $m^3 d^{-1}$ in 2015, and subsequent to the planned fifth unit, production is expected to reach 52,900 $m^3 d^{-1}$. This paper discusses the optimal design of the desalination plant, including considerations of RO membrane type, configuration, and post-treatment processes. This design is chosen to meet the permeate water quality regulations, and to minimize energy consumption. The design and construction of the Granot Plant meets all of the regulations of the Israeli Water Authority and the Israeli Ministry of Health, including respective boron and chloride concentration limits in the permeate, of 0.35 ppm and 20 ppm, respectively. Mekorot has also overcome several issues in the design phase as a result of an expected increase TDS and silica concentrations which might increase the scaling tendency. TDS and silica concentrations (and consequently, scaling) are expected to increase further by more than 20% during the coming decade. Experiments were carried out to address the challenge of preventing scaling on the RO membrane and within the brine disposal pipeline. These experiments have led to adjustments in the design features of the desalination units, including the operational conditions and chemical usage.

Keywords: Reverse osmosis desalination; Expansion of an existing plant; Scaling

1. Introduction

The "Aquifer Rehabilitation Project" aims to prevent salinization of the southern part of the Israeli Coastal Aquifer. This aquifer contributes a significant proportion of Israel's natural water supply, which is transported through the national water supply system. The east side of the aquifer is characterized by relatively high salinity, due to decades of over extractions, other anthropogenic activities, and the presence of a neighboring high salinity aquifer [1,2]. The

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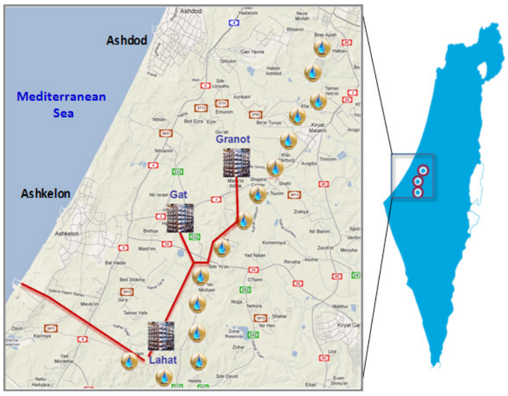

Fig. 1. A Schematic map identifying the location of the Coastal Aquifer Rehabilitation Project, and its three components: the row of wells along the "buffer zone", the inland Granot and Lahat desalination plants, and the brine disposal pipeline (red), [4].

region's main groundwater flow gradient is from the high salinity (brackish) aquifer in the east to the high quality freshwater coastal aquifer.

A barrier was created between the two aquifers, by drilling a line of approximately 40 wells along the boundary between them. The brackish water from the eastern aquifer is thereby extracted before it can reach the Coastal Aquifer [2]. These brackish water wells feed two inland BWRO desalination plants; the Granot Plant and the Lahat Plant, both of which located in southern Israel, near the city of Ashkelon (Fig. 1).

The brine from these two desalination plants is drained by a unique (30 km long) brine disposal pipeline (marked in red in Fig. 1). This unique brine disposal pipeline drains the concentrate from the Granot Plant, the Lahat Plant, and an additional nearby BWRO desalination facility; the Gat Plant. The brine flows the full 30 km (underground pipe), to reach the Mediterranean Sea. The brine is released into the Mediterranean Sea in full adherence to strict regulations set by Israel's Ministry of Environmental Protection [3].

Hence, this large "Aquifer Rehabilitation Project", which is managed by Mekorot, Israel's national water company, consists of three components (Fig. 1): a continual line of approximately 40 wells, two BWRO desalination plants and a uniquely long brine disposal pipeline.

It is important to emphasize, that from the outset this project (and particularly the desalination plants) was designed to accommodate expansions to the production capacity of the system as well as coping with the increasing salinity of the source water. Accordingly, since 2004 there has been a gradual expansion over the years, in the number of desalination units within both the Granot and Lahat Plants, as shown in Table 1. The first desalination unit in Granot Plant initiated production in 2004 and today produces a daily capacity of 9000 m^3. Subsequently, in 2011, an additional (Granot 2) unit initiated operation, in parallel with the operation of two new units in the Lahat Plant. Each of these new units produced a daily capacity of 10,000 m^3 with an 80% recovery rate. Thus, until the year 2013, the total annual capacity for the Granot and Lahat Plants were 6.3 and 6.6 Mm^3, respectively. In 2014, another expansion of Granot 3 unit was carried out, resulting in a daily capacity of 11,300 at a 84% recovery rate (Table 1). A fourth unit in the Granot Plant (Granot 4) and another two in the Lahat Plant (Lahat 3 and Lahat 4), are targeted to initiate production in 2015, with a production rate of 11,300 m^3 d^{-1} and 84% recovery per unit. Subsequent to the 2015 expansions, the annual production capacity of the Granot and Lahat Plants will be approximately 30 Mm^3 in 2015.

The Lahat and Granot Desalination Plants have two main achievements: (a) To prevent saline water from reaching the Coastal Aquifer (>50,000 ton TDS y^{-1}) by removing it at the boundary between the two aquifers. (b) Supply of 30 Mm^3 per year to the national potable water supply system and as a consequence replenishing of approximately 70 Mm^3 per year of fresh water to the coastal aquifer.

This document focuses on the achievements and challenges of the optimal gradual design expansion of the BWRO Granot Plant units, as part of the larger "Aquifer Rehabilitation Project". The targets of the Granot Plant design meets all of the regulations of the Israeli Water Authority and the Israeli Ministry of Health, including respective boron and chloride concentration limits in the permeate, of 0.35 ppm and 20 ppm, respectively.

Table 1
Gradual expansion in the production capacity of the Granot and Lahat BWRO plants from 2004–2016

Operation year	Desalination unit	Recovery rate [%]	Desalination unit capacity [m^3 d^{-1}]	Total production capacity of all units [1000 m^3 y^{-1}]
2004	Granot 1	80%	9,000	2,970
2011	Granot 2	80%	10,000	12,870
	Lahat 1		10,000	
	Lahat 2		10,000	
2014	Granot 3	84%	11,300	16,599
2015	Granot 4	84%	11,300	27,786
	Lahat 3		11,300	
	Lahat 4		11,300	
2016	Granot 5	84%	11,300	31,515

Mekorot faced challenges in the design of these facilities, due to the predicted significant steady increase in TDS (total dissolved solids) and high silica concentrations during the years. One of the challenges was involved in the design of facilities according to *anticipated future adjustments* in feed water quality features and increases in production. Theoretical calculations, combined with pilot plant experiments were carried out to address the challenge of preventing insoluble salt and silica scaling on the RO membrane and within the brine disposal pipeline. Scaling can be expected to be directly associated with TDS and silica concentrations. These pilot-scale preliminary assessments led to adjustments in the design features of the desalination units, including the operational conditions and chemical usage.

2. Description of the Granot Industrial-Scale and Pilot Plant

2.1. The industrial plant

Each industrial unit in the Granot BWRO plant is similar in its overall design and process. This includes the pretreatment, alignment of the desalination units, and post treatment systems, as illustrated in Fig. 2. The pretreatment of the raw water consists of two filtration types of screen filters: 80 mesh filters followed by Micronics 5 µm filters. Additional pretreatment of the raw well-water includes chemical injection of acid to reduce the pH level to approximately pH = 6.9–7 (from about 7.3) and the addition of an antiscalant, to prevent insoluble salt precipitation such as calcium carbonate or silica. Each unit in the Granot plant involved both BWRO and SWRO membranes, to provide produced water that complies with Israel's water quality regulations.

2.2 Feed water quality predictions

Table 2 represents predicted water quality characteristics at the Granot 3 and Granot 4 Plants in each of two hydrological feed water streams: (1) at the initiation of operations, and (2) ten years after operation first commenced. These analyses were used for the design of the Granot 3 and Granot 4 Units at the Granot Plant. Several issues are highlighted in these predictions. The first is a gradual increase in TDS of approximately 20% over the 10 y period. It is challenging to design a desalination plant to accommodate this predicted rate of increase in TDS. Adjustments must be made to the desalination membranes themselves, as well as to the operational equipment that is exposed to high pressure, such as pumps and pipes.

The second issue relates to high (approximately 30 ppm) silica concentrations in the feed water. The typical range in dissolved silica concentrations within Mekorot's wells range between 20–30 ppm (SiO_2). The prevailing forms of observed silica are meta silicic acids such as $(H_2SiO_3)n$, with low *n*. Predicted water quality conditions of the Granot 3 Unit (Table 2) indicate high expected concentrations of silica of approximately 29 ppm. The concentration of silica within the concentrate will increase by approximately 6-fold (~180 ppm) at an 84% recovery rate. At such concentrations, the silica can cause irreversible damage to the RO membranes. Therefore, experiments were conducted, to identify the optimal antiscalant application for the prevention of silica precipitation. This experimental work was

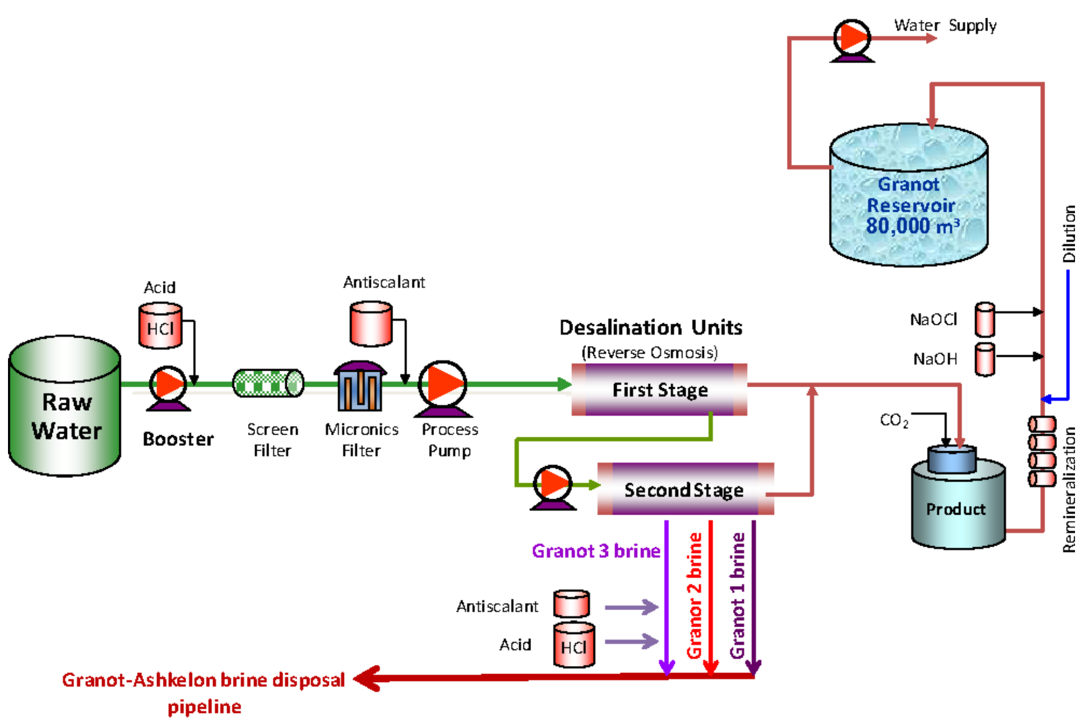

Fig. 2. Schematic plot of the entire desalination process for each of the units in the Granot BWRO Plant. Included are the pretreatment, desalination and post treatment processes.

Table 2
Predicted hydrological feed water quality at operational startup and after 10 years, at the Granot 3 and Granot 4 BWRO Plant

Parameter	Predicted [ppm]	Predicted after 10 Years [ppm]
Ca	120	155
Mg	80.6	121
K	5.5	5
Na	309	409
Ba	0.17	0.22
HCO_3	379	379
SO_4	84.5	95
Cl	685	803
NO_3	58	83
B	0.44	0.54
SiO_2	29.2	29
F	0.79	0.79
TDS	1,497	1,832
pH	7.3	

accomplished ata pilot plant replica of the Granot Industrial Plant, as described in the following section.

2.3 The pilot plant

The on-site pilot plant at Granot (Fig. 3) consists of two separate systems: an RO desalination system and a brine recirculation component. The RO desalination phase of the experiment was run first, and subsequently, the brine from each RO desalination experiment was tested in the brine recirculation experiment. Together, the two simulation systems were designed to identify the optimal antiscalant for preventing silica precipitation that provides a combination of good membrane performance (in a range of recovery rates) without incurring salt precipitation (inorganic scaling) on the either the RO membrane or along the lengthy brine disposal pipeline experimental design of the brine recirculation system was based on the results from a preliminary laboratory. Potential precipitants as such, included calcium carbonate or silica. Importantly, the experimental assessment that was conducted at the Technion Institute, by Professor R. Semiat's research teams [5].

The entire experimental setup is illustrated in Fig. 3. The upper section of Fig. 3 illustrates the *desalination system* wherein the pretreatment setup resembles the pretreatment component of the industrial plant (see Section 2.1). This treated feed water is subsequently pumped at 20 $m^3 h^{-1}$, to the RO unit. Desalination section involved two stages, with two pressure vessels (PV) at the first stage, and a single pressure vessel at the second stage. Each PV contains 7 industrial 8-inch diameter RO membranes.

The targeted test period for each new antiscalant in the desalination system of the pilot plant was approximately 3 mo, using a low recovery rate. During this period, membrane performance was monitored, including the pressure drop on the RO membranes; permeate flow and salt passage through the membrane. Subsequently, an evaluation was made as to whether each of the antiscalants warranted further examination on the basis of the results from the membrane performance data. If the data were considered satisfactory (membrane performance was considered to have remained stable), the experiment was continued at a higher recovery rate.

The second experiment examined the *brine recirculation simulation system* (lower section of Fig. 3) for identifying suitable brine flow conditions and salt precipitation potential within the brine pipeline. For each antiscalant type, and specific recovery rate the brine was tested in a follow-up experiment within the brine recirculation system. This experiment involved the circulation of 200 L of brine within the system for 100 h, thereby stimulating the flow of brine along the 30 km "Granot-Ashkelon" pipeline.

Throughout this experiment, several field and laboratory parameters were monitored, to measure the extent of precipitation that occurred within the system. The field parameters, such as pH, temperature and turbidity are clear

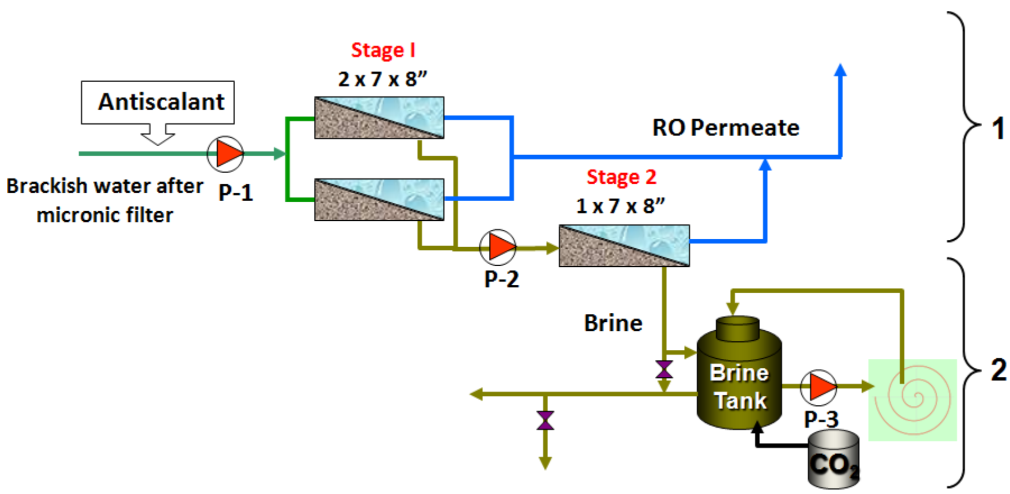

Fig. 3. A principle flow diagram of the Granot Pilot Plant for identifying antiscalant types with highest efficiency in each of two experimental systems: 1) The upper RO desalination system and 2) The lower brine recirculation system.

indicators of salt precipitation (if it occurs). All additional laboratory-measured parameters, such as calcium, bicarbonate, silica and TDS, are also indicators of the potential for precipitation during the 100 h brine recirculation period. Moreover, in order to maintain a comparable flow regime to that which occurs in the industrial-scale pipeline, CO_2 was injected into the pipeline during the flow.

3. Results and discussion

3.1. Design achievements in meeting water quality regulations

3.1.1. Boron and chloride removal

Predicted raw water of Granot 3 Unit ranges between 0.44 to 0.54 ppm boron. Following Water Authority demand, boron level in the permeate will not exceed 0.35 ppm. In comparison to global standards, Israel's standard for boron is relatively strict. This is due to the fact that a large proportion of the potable (and desalinated) water that is consumed in Israel is ultimately treated and re-used in the agricultural sector. Boron concentrations must be kept low for irrigation, due to the fact that some crops are boron-sensitive, such as citrus, grapes, avocado and peaches.

The optimal design of membrane type, configuration and minimum energy consumption were projected with the membrane manufacturer's software, using the predicted raw water quality from 10 y after initial operation of the facility (Table 2). Currently, the common solution for boron removal from brackish water is to employ the use of high rejection membranes (BWRO or SWRO), either at the first or second stage.

Our assessment identified a combination of both SWRO and BWRO types (DowFilmtec Company) as providing the optimal configuration and best membrane performance for boron and chloride removal. The selected configuration for the first stage was for 51 PV, and was achieved with open SWRO membranes and permeate flow rate of 12,000 gpd (45.4 $m^3 d^{-1}$). The selected configuration for the second stage stand for 21 PV was carried out with closed BWRO membranes and a permeate flow rate of 12,650 gpd (48 $m^3 d^{-1}$). Each PV contains 8 membranes, each with a 440 ft^2 (40 m^2) surface areas. Table 3 represents the measured concentrations obtained for boron and chloride using these membranes and this configuration in the industrial-scale Granot Plant. Observed product water concentrations of chloride (<10 ppm) and boron (<0.2 ppm) were below the regulatory requirements.

Table 3
Observed concentrations of TDS, chloride and boron, from product water that was obtained using the selected membrane configuration and type at the Granot 3 Industrial Plant

Parameter	Regulation requirement [ppm]	Product concentration [ppm]
TDS		<20
Chloride	20	<10
Boron	0.35	<0.2

3.1.2. Post treatment design

Due to the high salt rejection of the RO membranes (>99%)and low pH level of the desalinated product (permeate), the product water requires post-treatment in order to meet the strict potable water quality regulations of Israeli Ministry of Health. To achieve the regulatory requirements for water hardness, the design of the post treatment process requires a mineralization system to attain approximately 80 ppm Ca^{2+} as $CaCO_3$, >80 ppm alkalinity and 3 < CCPP < 10. To meet additional regulatory requirements, NaOH must be introduced to reach a pH level of 7.5–8.3, a turbidity of less than 0.5 NTU and LSI < 0 must be achieved. The final stage of the post-treatment involves chlorination, in order to reach approximately 0.3–0.4 ppm of chlorine. These post-treatment processes were included at Granot, in order to achieve the above water supply quality (Fig. 2).

The Granot Plant is located at a water supply site (the Granot Water Supply Site) that controls the flow of two different types of water reservoirs: a drinking water reservoir and treated effluent (for agricultural irrigation) reservoir. The effluent reservoir does not require post-treated water (the addition of carbonates to increase pH, chlorine, etc). Since Mekorot is obligated to supply a portion of the desalinated water into the treated effluent reservoir the Granot facility was designed to meet exceptional requirements for a post-treatment component that can be flexibly included or excluded according to its destination. In this way, the quality of the desalinated water can be adjusted for the purpose of drinking, versus for agricultural irrigation, thereby saving production costs. Using this flexible design, the water quality can be determined at a process junction, and is then supplied either for drinking water or to flow to the agriculture reservoir for irrigation.

Eliminating the post treatment process from the irrigation product water is the most cost efficient approach due to (a) the close proximity of the effluent reservoir to the Granot Plant and (b) the fact that no cheaper water sources can be supplied to the effluent reservoir. Most (approximately 75%) of the water in the nearby national potable water grid is desalinated water (with post-treatment), and is therefore equally expensive to produce.

3.2 Design challenges

3.2.1. Gradually increasing salinity

Fig. 4 illustrates the gradual increases in the total product capacity of the Granot and Lahat Plants (see also Table 1), and as a result, the total quantities of TDS and chloride that are removed. These quantities are thereby prevented from contaminating the coastal aquifer. The total TDS that is removed increased from approximately 4,455 ton y^{-1} in 2004 to approximately 46,154 ton y^{-1} in 2015, and is expected to rise to 52,866 ton y^{-1} in 2016. Fig. 4 thereby emphasizes the role of the aquifer rehabilitation project in accomplishing two objectives in parallel, of: (1) removing salt that would otherwise contaminate the coastal aquifer, and (2) producing high quality portable water, that supplements the national water system.

The TDS concentration of raw water of the Granot 3 Plant is expected to be approximately 20% higher 10 years after operations initiated. Similarly, over the first operational decade, chloride, nitrate and boron concentrations are expected to increase by approximately 17, 43 and 22%,

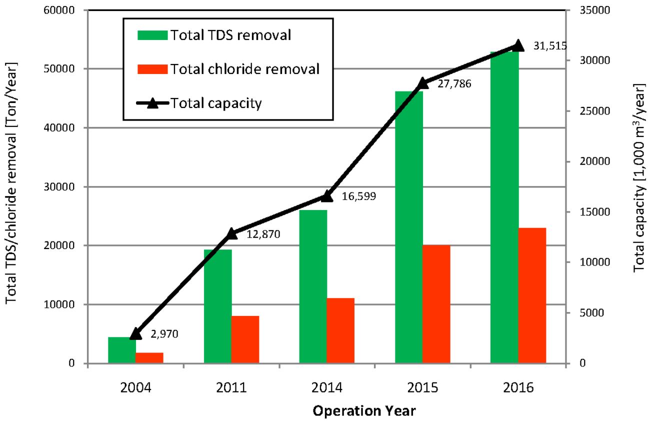

Fig. 4. Gradual increases in desalinated water production, and quantities of TDS and chloride removal from the Granot and Lahat Desalination plant, from the years 2004–2016.

respectively. These predictions are based on hydrological extrapolation calculations and were taken into consideration in the design of a facility that can continue to function well at increasing operational pressures. The software projections of the RO membrane manufacturers show that a 20% increase in TDS concentration will affect the specific energy process consumption by approximately 7%.

Gradual increases in the TDS concentrations of the raw water create difficulties in attaining an optimal design of the desalination process. The main challenges involve selecting the appropriate equipment (such as pumps) and minimizing the capital expenditures. The selected configuration (membrane type, daily capacity) discussed in section 3.1.1, involved finding the most advantageous balance between reaching the targeted product water quality parameters, and minimizing the water price including the capital cost (expenses for equipment and procurements).

It is important to note that the energy of the brine from the second stage is used to send the brine along the 30 km long brine-transport pipeline from the Granot Plant to the Mediterranean Sea [6]. This energy supply is necessary in order to raise the brine flow over topographic heights, from 40 m above sea level at the Granot Plant, to the highest peak along the pipeline route at 100 m above sea level [6].

Table 4
A "regular" antiscalant and two for prevention of silica precipitation were tested in the Granot pilot plant

Antiscalant type*	Organic composition
X-Type	Phosphonate
A-Type	Dispersant blend
B-Type	Carboxylic and phosphonic acids

*The antiscalants Types represented using a letters since Mekorot Company obligates for manufactory confident.

3.2.2. Preventing silica precipitation

To date, several types of antiscalants were tested in the Granot pilot plant [4]. Subsequent to these tests, two types of silica precipitants were tested, as described in Table 4. It is important to note that these experiments were carried out before the operation of Granot 3 Unit, by using Granot 1 and Granot 2 feed water. The Granot 1 feed water has lower TDS (1590 ppm) and silica (26 ppm) concentrations [4] than the Granot 3 feed water which receives water from three eastern aquifer rehabilitation wells. The wells that supply the Granot 3 unit are similar to those that supply the Granot 2 unit. Thus, feed water quality is similar for the Granot 2 and Granot 3 units. The initial experiments were completed with Granot 1 feed water, due to the fact that Granot 2 had not yet been built. Subsequently, in order to replicate the true feed water quality as closely as possible; the feed water for the experiments in the pilot plant was obtained from Granot 2. This feed water contains approximately 30 ppm of SiO_2, similar to the predicted concentrations of SiO_2 in the feed water for Granot 3.

Evidence of silica scaling at the Granot 2 Unit was clearly observed from several measurement methods. Autopsy measurements on the industrial Granot 2 Unit that was carried out in 2013 by Dr. Moshe Herzberg, from Ben-Gurion University, Israel, confirmed the presence of silica on the second stage membranes (end element) [7]. Fig. 5 shows SEM (scanning electron microscopic) images that support that assumption of silica precipitation. These SEM results support the results obtained by the ICP-AES (inductively coupled plasma atomic emission spectrometry) analyses. It was found that the silica

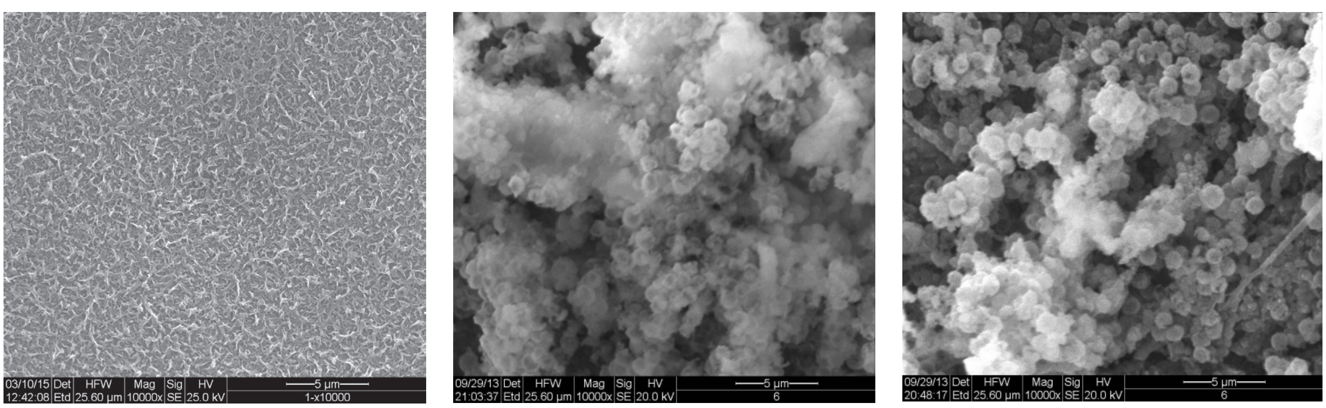

Fig. 5. SEM micrograph images of a clean polyamide membrane (left image), and silica precipitation on second stage Granot 2 membrane layers (magnification X 10,000) at the centre (centre image) and outer edge of the RO module (right image).

was among the main dominant elements that precipitated on the membrane surface [7].Since the Granot 2 Unit receives very similar feed water to the Granot 3 unit, this silica scaling phenomenon could occurred also at Granot 3.

These results emphasize the need for an antiscalant to prevent silica precipitation at both the Granot 2 and Granot 3 plants. It is important to emphasize that the commonly used antiscalant, *X*-Type, was unsuccessful in the prevention of silica precipitation on the RO membranes at Granot 2. Thus, tests were conducted specifically with antiscalants that specialize in preventing silica scaling.

3.2.2.1. Desalination experiments

The first silica precipitation prevention antiscalant that was examined was the A-Type; a dispersant blend. The initial experiments were run with Granot 1 feed water, and since that feed water contained a relatively low silica concentrations (up to 26 ppm), it was possible to use a high recovery rate of 84 and 86%.In these experiments, the membrane performance parameters, such as pressure drop, permeate flow and salt passage, are monitored daily, and normalized to the system's experimental conditions (such as temperature, conductivity, etc.).

We identified the pressure drop parameter, which is easy to monitor, as being the most sensitive and first indicator of the occurrence of precipitation on the RO membranes. Therefore, the following results are focused on the pressure drop parameter. A time series shows changes in the normalized pressure drop, using the *A*-Type antiscalant (Fig. 6). These results show a stable normalized pressure drop (approx. 3.2–3.3 bar) during the experimental period, for both 84 and 86% recovery rates.

Further experiments were executed using Granot 2 feed water, which contains approximately 30 ppm silica (similar to the silica prediction for the Granot 3 unit, Table 2). Previous to examining the alternative antiscalants in the experimental series, the *X*-Type antiscalant (phosphonate, Table 4) was examined at an 80% recovery rate, for system validation. This validation was conducted subsequent to the complete replacement of the first stage RO membranes, as illustrated in Fig. 7. The *X*-Type antiscalant is a well-known phosphorus antiscalant that was used in the Granot and Lahat Industrial Units at that the time of the experiment. Therefore, the *X*-Type was chosen for system validation. We used the *X*-Type in order to validate the pilot plant system, prior running all subsequent tests with the alternative antiscalants. Fig. 7 indicates a stable pressure drop of approximately 1.5 bar, using the *X*-Type phosphonate based antiscalant.

Similar results showed a stable pressure drop (approx. 1.7–1.8 bar) with the use of the *A*-Type antiscalant and Granot 2 feed water at an 84% recovery rate (Fig. 6). Notably, the last experiment of *A*-Type antiscalant at 84% recovery rate using Granot 2 feed water demonstrated a lower initial pressure drop (approx. 1.7 bar) than in the previous experiment (with Granot 1 feed water, approx. 3.2–3.3 bar). This difference is due to a preceding partial membrane replacement at the first stage, which reduced the initial pressure drop value.

However, different results were obtained using the *B*-Type antiscalant, which is composed of carboxylic and phosphonic acids (Table 4). The first experiment was run using Granot 2 feed water at an 80% recovery rate. This experiment (Fig. 7) demonstrated that with the *B*-Type antiscalant, the pressure drop increased by approximately 25%, from approx 1.75–2.2 bar, during the 2 mo experimental period. A follow-up experiment using the *B*-Type antiscalant at a higher (86%) recovery rate shows a significant increase in the pressure drop at the first stage, from about 1.5 to approximately 2.6 bar within approximately 3 mo. This sharp increase in the pressure drop with the use of the *B*-Type antiscalant may be caused by a the fact that *B*-Type contains less phosphonate within its chemical composition (about 11 times less phosphonate) than the other antiscalants in this study. Thus, the *B*-Type antiscalant may behave similar to a phosphorous free antiscalant, as explained widely elsewhere [4]. Again, note that in the *B*-Type experiments, the initial pressure drop of the 86% recovery rate experiment was lower than in the previous experiment at 80% recovery rate. This is due to an entire membrane replacement of the first stage RO membranes, which reduced the initial value of pressure drop from about 2.2 bar to about 1.5 bar.

Fig. 8 indicates the normalized pressure-drop during the first RO stage, on parallel dates at the industrial and pilot plant Granot desalination plants, using Type *A* and

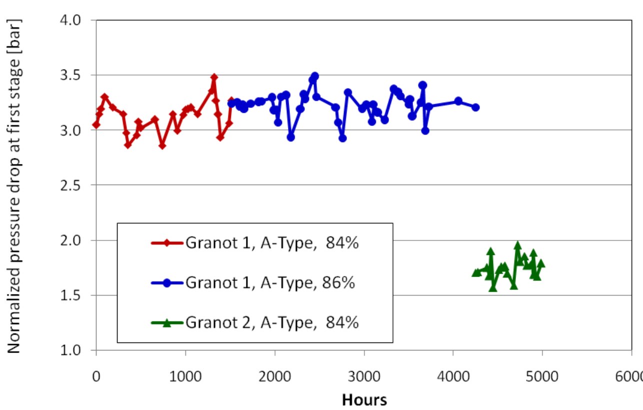

Fig. 6. A time series of the normalized pressure drop in the Granot Pilot Plant experiment, using two types of feed water (Granot 1 and Granot 2) to examine the A-Type antiscalant for preventing silica precipitation at an 84–86% recovery rate.

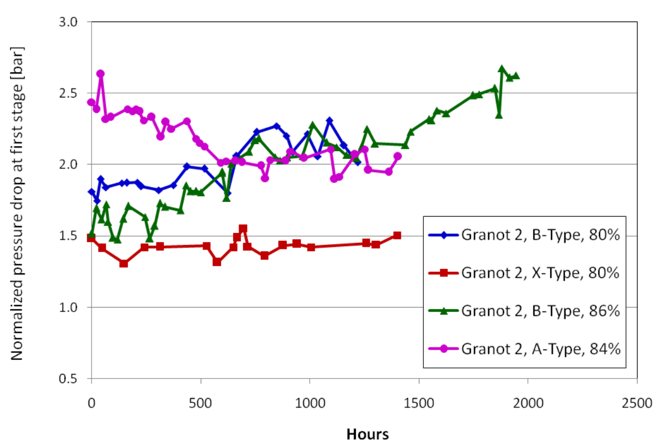

Fig. 7. A time series of the normalized pressure drop in the Granot Pilot Plant experiment, using Granot 2 feed water to examine the relative efficiency of the A-Type, B-Type, and X-Type antiscalants at an 80–86% recovery rate.

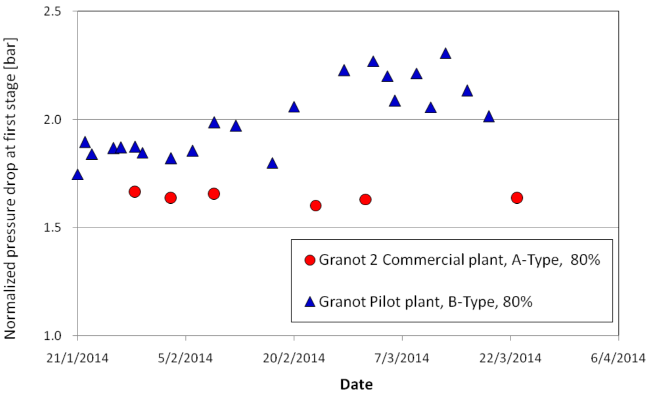

Fig. 8. Comparison between the normalized pressure drops obtained from the Granot 2 industrial and pilot plants, using A-Type and B-Type antiscalants, respectively, on the same date, both at 80% recovery rate.

B antiscalants, respectively, at an 80% recovery rate. A stable pressure drop (range between 1.6–1.7 bar) was clearly observed at the industrial Granot plant. In contrast, over the same time period (January–April 2014) and feed water, the pressure drop at the pilot plant increased rapidly (by approximately 25%). Since the RO system at the pilot plant has similar alignment to that of the industrial plant, the pressure drop is believed to have been caused by the low phosphorous content of the *B*-Type antiscalant.

It is important to emphasize that although the *B*-Type antiscalant lead to a rapidly increasing pressure drop at the first stage of the RO desalination experiment, the normalized pressure drops were stable for both silica precipitation prevention antiscalants during the second stage. Moreover, the other two indicator-parameters: normalized salt passage and permeate flow rate, were stable throughout the experimental period. The stable performance at the second RO stage indicates that salt scaling did not occur at this stage.

In summary, the desalination experiments show up to now, that the *A*-Type antiscalant is more stable than *B*-Type at all tested recovery rates. Since January 2014 the *A*-Type antiscalant was used in all industrial units at the Granot Plant.

3.2.2.2. Brine recirculation experiments

As mentioned earlier, the second phase of the experiment for each antiscalant type was followed by the brine recirculation system. This experiment examines the efficiency of each antiscalant in preventing salt precipitation along the 30 km long "Granot–Ashkelon" brine disposal pipeline. The brine from each desalination experiment was tested in a brine recirculation system with the same setup conditions (antiscalant and recovery rate), as shown in the lower section of Fig. 3. In these experiments, the brine was recirculated over 100 h, to simulate slow flow conditions (industrial-scale) through the Granot–Ashkelon pipeline.

Table 5 summarizes four different brine recirculation experimental results using each of the three types of antiscalants, at 80–86% recovery rates. Table 5 shows that the dissolved calcium ion and bicarbonate concentrations remain almost constant after 100 h of recirculation, and therefore are not precipitating in the form of calcium carbonate salts, according to the following equations:

$$2HCO_3^- \leftrightarrow CO_2^{2-} + CO_3^{2-} + H_2O \quad (1)$$

$$Ca^{2+} + CO_3^{2-} \leftrightarrow CaCO_3 \quad (2)$$

Moreover, Table 5 shows that the silica concentration also remains constant during the 100 h of brine recirculation experiments, and thus didn't precipitate in the pipe. Importantly, Table 5 shows that the other two indicators of salt precipitation; the LSI (Langelier saturation Index) and the turbidity, support the assumption that salt precipitation didn't occur. According to the preliminary lab experiments, a LSI of less than 2 and turbidity of less than 1 certainly indicated that insoluble salt precipitation does not occur.

In summary, all of the results (Table 5) indicate that calcium, bicarbonate and silica, as well as LSI and turbidity remain constant during the 100 h recirculation period. This indicates that no significant salt precipitation occurred along the brine transport system, regardless of which antiscalant was employed.

4. Conclusion

This document reviews the challenges and achievements in the design of a desalination plant that comprises part of a large aquifer rehabilitation project. This project included three main components: a line of approximately 40 brackish water wells that feed the desalination plants, the desalination plants themselves, and a uniquely long (30 km) brine

Table 5
Measured concentration, LSI and turbidity obtained using different types of antiscalants with different operation conditions (Recovery, feed water quality)

		Initial values [0 h, ppm]			After 100 recirculation hours [ppm]				
Antiscalant type	Recovery, %	Ca	HCO_3	SiO_2	Ca	HCO_3	SiO_2	Turbidity [NTU]	LSI
X-Type, Granot 1	83	597	1,770	131	600	1,780	128	0.25	1.57
A-Type, Granot 1	84	628	1,947	141	635	1,947	136	0.17	1.66
X-Type + *A*-Type, Granot 1	80 + 84	582	1,735	110	590	1,740	111	0.17	1.61
B-Type, Granot 2	86	828	1,795	198	828	1,796	194	0.18	1.72

disposal pipeline. The optimal design of the Granot BWRO plant (including configuration and membrane type) conform to the requirements of the Israeli Water Authority and the Israeli Ministry of Health, including limits to respective boron and chloride concentrations in the permeate, of 0.35 and 20 ppm, respectively.

Moreover, the design of the Granot plant overcomes several challenges such as gradually increasing TDS and high silica concentrations, and the consequent increasing propensity for silica scaling. Therefore, silica precipitation prevention antiscalant experiments were carried out at an on-site pilot plant miniature replica of the Granot industrial plant. To date, two different antiscalant types were tested at the Granot pilot plant for preventing silica precipitation.

To some extent, both *A*-Type and *B*-Type antiscalants successfully prevented silica precipitation on the membrane, as evidenced by the fact that silica precipitation didn't occur at the second stage. However, during the first stage, the *B*-Type antiscalant caused an increasing pressure drop, that may similar to phosphorus free antiscalants. The *A*-Type antiscalant was the most efficient in preventing silica and salt precipitation on both the membrane stages and in the brine recirculation pipeline. Consequently, since January 2014, this *A*-Type antiscalant was used in the three industrial units of Granot BWRO desalination plant.

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