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Seawater filtration for fouling prevention under stormy conditions

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Abstract

Seasonal weather changes cause southern high-speed winds in the northern Red Sea coast, mixing the seawater column and releasing nutrients from the bottom of the sea. Turbidity level instantly rises and micro-algae of the *Synechococcus* type start blooming, fouling the RO membranes, and eventually causing shut-off of the plant. Our objective was to evaluate the design and operational parameters of deep-bed filters for pretreatment of the seawater, primarily, under such extreme conditions in order to reduce membrane fouling. The main parameters of study were filtration rate, filter bed depth, sand grain size (fine vs. coarse), iron chloride dose and polymer aid. Membrane feed water quality criteria were turbidity less than 0.2 NTU and SDI less than 3. Flocculation, simulated contact and direct filtration of artificial and natural seawater with various clay-algae-pH combinations were studied in the laboratory. A dual-column pilot filtration system was later installed at the Sabha RO plant in Eilat. When seawater was not turbid, the specific algae (grown *in situ*) and clay were injected into the feed stream to simulate storm conditions up to 10^5 cells/ml and 5 NTU, respectively. Residual turbidity, iron, SDI, particle size distribution (PSD), pH, temperature, microbial count and head loss across the filter columns were monitored. Modified Jar Tests with clay/algae mixtures resulted in 95–99% removal at natural pH at wide range of flocculant dose (0.5–20 mg/l). Column pilot experiments showed good results with deeper (1.2 m) and coarser (1.0 mm effective grain size) than usually applied. A filter run period under storm conditions reached 35 hours with satisfactory filtrate quality. An iron chloride dose of 0.3 mg/l during normal conditions and 0.5 mg/l for stormy condition should be injected, mixed well before the filters, while maintaining 10 m/h filtration rate and pH 6.8.

Keywords: Pretreatment; In-line filtration; Silt Density Index; Membrane fouling; Reverse osmosis

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1. Introduction

Reverse osmosis is a leading process in recent years for seawater desalination. Mekorot started field testing of seawater reverse osmosis (SWRO) in the mid 70's. The tests led to the successful planning and operation of the first SWRO unit (Sabha C) in Eilat in June 1997 [1].

The raw Red Sea water is pumped from sea surface of the Eilat bay where there are northern winds, but during the autumn and spring, changes in the wind direction cause mixing of the seawater layers and release of nutrients from the bottom of the sea. As a result, hours later, turbidity levels increase rapidly.

From a few days to two weeks later micro-algae of *Synechococcus* type start blooming as a result of the seawater enrichment due to nutrient release [2]. These two events bring about organic fouling and poor feed water quality, which can not be applied to the RO membranes and eventually cause plant shut down [4–5].

While raw water turbidity ranges 0.3–0.5 NTU under normal conditions, during southern storms it reaches values higher than 100 NTU and corresponding *Synechococcus* concentration increase from 10^3 cells/ml to 10^5 cell/ml in a couple of weeks, while the turbidity values are low [3].

Pretreatment is an essential consideration in designing a RO plant to ensure long-term performance of the RO membranes by eliminating RO failures, membrane fouling and replacement. Membrane manufacturers determine the seawater feed of suitable quality for the RO membranes, which largely relate to two main parameters: turbidity of up to 0.2 NTU and Silt Density Index (SDI) of up to 3.0. The existing pretreatment facility in Sabha C includes pressure sand filters and a 90 cm mixed sand bed which do not function properly under stormy conditions.

This paper presents the results of investigation made for the pretreatment system in Sabha C whose purpose is to provide feed seawater of stringent specifications. The objective here was to recommend filtration rate, filter depth, media grain size (fine or coarse), ferric chloride dose, pH conditions and the use of polymer aid. In order to obtain long filtration runs under stormy conditions, there must be low head loss development and filtrate quality that meets membrane feed water quality demands.

2. Materials and methods

The investigation first took place in the laboratory where Jar Tests (coagulation-flocculation-sedimentation) and Modified Jar Tests (coagulation-flocculation-filtration) were made with artificial and natural seawater and different combinations of clay, algae, pH and ferric chloride. This helped to establish a working range, the various parameters, before continuing with pilot plant experiments. A dual-column pilot filtration system was installed at Sabha C plant in Eilat. Simulating stormy conditions, *Synechococcus*, which was grown *in situ*, and clay were injected into the influent of the two filter columns up to 10^5 cells/ml and 5 NTU, respectively.

Synechococcus, the major representative of the Cyanobacteria (1 μ), is the main component in the overall ultraphytoplankton in the Red Sea water "spring blooming" [2].

To obtain optimized growth of these microscopic algae, a special growing medium was used. In order to test different conditions of coagulation, some of the filtration runs were performed in pH 6.8 and 8.2 (the natural pH of Red Sea water). The primary coagulant used in this research is ferric chloride hexahydrate, $FeCl_3.6H_2O$, which is used commercially. The coagulant aid (used in the dual-columns only) was NALCOLYTE 8103, which is a strong cationic polymer.

The Modified Jar Test is a similar procedure to the conventional Jar Test, but is followed by filtration through filter paper or granular media. In this work, Whatman paper (No. 0) of 11 μ pore size was used.

The dual-column pilot filtration system (Fig. 1) was made of plexiglass. Each column

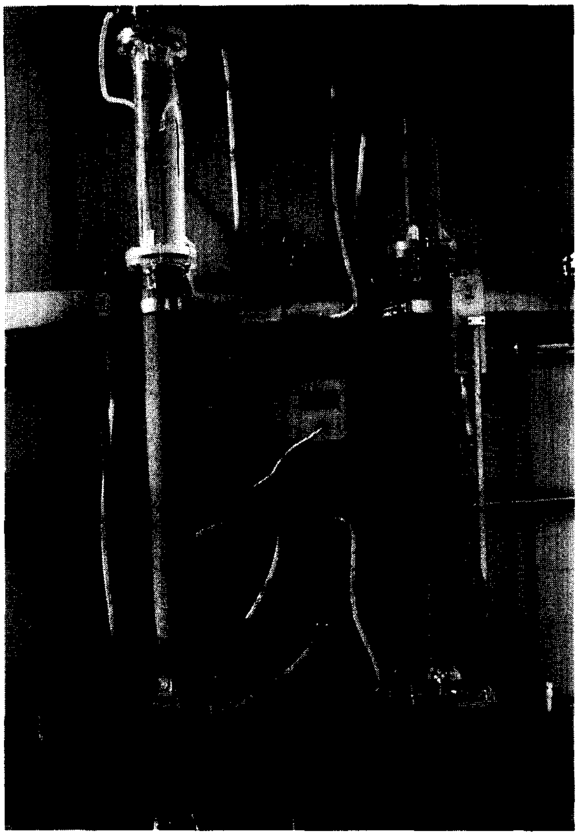

Fig. 1. Dual-column pilot filtration system.

is 1.5 m long and 0.1 m in diameter. Sand grain effective sizes tested were 0.5 mm and 1 mm uniformity coefficiency of 1.36 and 1.1, respectively. Media depth of 0.9 m and 1.2 m was compared. Head loss is measured via differential pressure gauge of FUJI FCX Series. The system was held at a constant pressure of 2.5 atm in order to enable SDI measurements of the filtrate.

Eighteen filtration experiments were performed during February–May 1998. Testing the Red Sea water at under various conditions: filtration velocities (10, 15 and 20 m/h), media depth (0.9 and 1.2 m), pH (6.8 and 8.2), coagulant dose (0.3, 0.5, 0.8, 1.0, 3.0, and 5.0 ppm), feed water quality also had varied turbidities (0.5–5.0 NTU), SDI (3.0–18.0) and algae concentration of 10^3–10^5 cells/ml. Five dosing pumps were used for clay, algae, acid and flocculant aid and primary coagulant injection. Static mixers ensured homogeneity of the injected materials in the incoming stream.

3. Results and discussion

3.1. Jar Test

The preliminary experiments were done by Jar Test with different combinations of clay, algae (10^5 cells/ml), pH and coagulant dosing, at turbidity levels of 2, 5 and 10 NTU and pH levels of 6.0 and 7.5 (Table 1).

3.2. Modified Jar Test

Two different methods of Modified Jar Test were tested: in-line filtration and direct filtration. Table 2 presents the results of in-line filtration and direct filtration for various operating modes. Each test was done at pH 6 and pH 7.5–7.7 with different initial turbidities of 2, 5 and 10 NTU. To the artificial seawater composition was added clay and algae with coagulant dose of 0, 0.5, 1.0, 5.0, 10.0, and 20.0 ppm.

3.3. Filtration tests

During the months February–May 1998, 18 filtration tests were executed. The different filtration tests were composed of two feed water qualities: seawater under normal conditions and seawater injected with clay and algae to simulate stormy conditions.

3.3.1. Filtration tests at normal conditions

These tests obtained initial turbidities of 0.5 NTU and algae concentration of 10^3 cells/ml.

3.3.1.1. Filtration velocity combined with grain size influence

Turbidity. The filtration velocities tested were 10, 15 and 20 m/h. In Fig. 2, the comparison among the various velocities is presented and also with respect to different effective grain sizes of 0.5 and 1.0 mm. The filter media

Table 1
Jar Test results

Initial turbidity (NTU)	pH 7.5–7.7: Optimum FeCl3.6H2O dose* (ppm)	Residual turbidity (NTU)	Removal (%)	FeCl3.6H2O dose for microflocs** (ppm/NTU)	pH 6.0: Optimum FeCl3.6H2O dose (ppm)	Residual turbidity (NTU)	Removal (%)	FeCl3.6H2O dose for microflocs (ppm/NTU)
Clay only								
2	20	0.95	52	5/4.5	20	0.8	60	5/1.95
5	40	1.00	80	2/4.9	15	1.00	80	5/5.1
10	40	1.00	90	–	25	1.00	90	–
Algae only								
1.3–1.4	15	0.95	27	5/1.95	20	0.95	27	5/1.65
Clay and algae								
2	10	1.00	50	5/2.3	20	0.9	55	5/2.5
5	15	1.00	80	5/4.3	15	1.00	80	5/4.5
10	20	1.05	89	5/8.95	40	1.00	90	5/8.9

*Optimum dose, ferric chloride dose for turbidity values below 1.00 NTU. **FeCl3.6H2O dose for microflocs, ferric chloride dose leading to turbidity higher from the initial turbidity.

Table 2
Modified Jar Test results

Initial turbidity (NTU)	pH 7.5–7.7: Optimum FeCl3.6H2O dose* (ppm)	Residual turbidity (NTU)	Removal (%)	FeCl3.6H2O dose for min. turbidity (ppm/NTU)	pH 6.0: Optimum FeCl3.6H2O dose (ppm)	Residual turbidity (NTU)	Removal (%)	FeCl3.6H2O dose for min. turbidity (ppm/NTU)
Clay only								
A 2	0.5	0.7	65	5/0.2	0.5	0.35	82	10/0.05
5	1.00	0.75	85	20/0.1	1.00	0.65	87	10/0.05
10	1.00	0.4	96	10/0.1	0.5	0.85	91	10/0.1
B 2	0.5	0.45	77	5/0.15	0.5	0.4	80	10/0.05
5	1.00	0.75	85	20/0.05	0.5	0.95	81	10/0.05
10	1.00	0.75	92	5/0.15	1.00	0.9	91	10/0.07
Algae only								
A 1.5–1.7	0.5	0.75	50	20/0.1	0.5	0.5	66	5/0.1
B 1.5–1.7	0.5	0.65	56	20/0.1	0.5	0.4	73	5/0.05
Clay and algae								
A 2	0.5	0.2	90	10/0.06	0.5	0.6	70	10/0.1
5	1.00	0.9	82	20/0.05	1.00	0.95	81	20/0.1
10	1.00	0.95	90	20/0.05	5.00	0.4	96	20/0.1
B 2	0.5	0.5	75	5/0.1	0.5	0.5	75	10/0.1
5	1.00	0.4	92	5/0.1	0.5	0.9	82	10/0.05
10	5.00	0.4	96	20/0.15	1.00	0.8	92	10/0.1

A: In-line filtration (1 min rapid mixing only). B: Direct filtration (1 min rapid mixing + 10 min slowly mixing).
*Optimum dose, ferric chloride dose for turbidity values below 1.00 NTU.

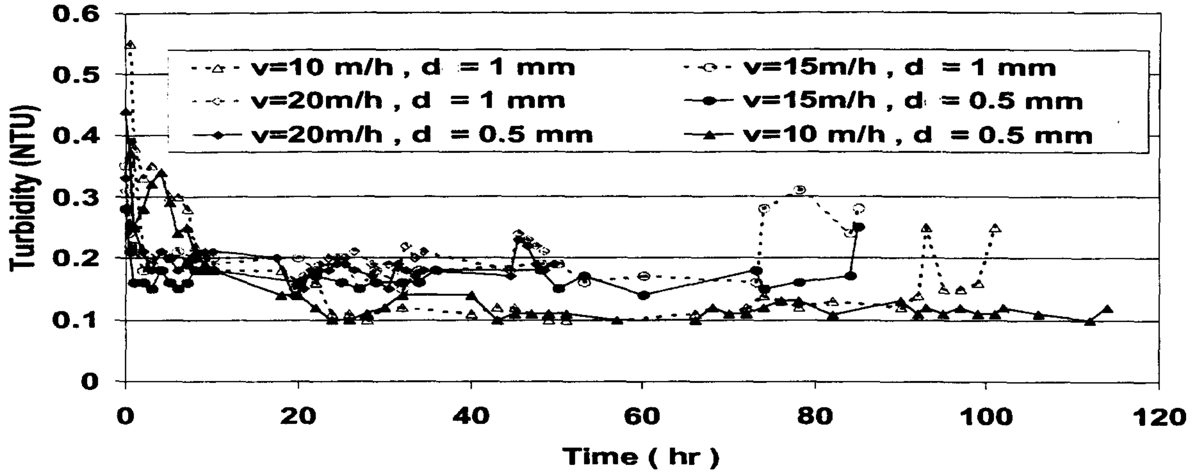

Fig. 2. Filtration velocity influence and grain size influence on turbidity as a function of time. Flocculant dose = 0.3 ppm, pH 6.8, initial turbidity ~0.5 NTU, grain diameter (d) = 0.5, 1 mm, media depth (L) = 0.9 m, filtration velocity (v) = 10, 15, and 20 m/h.

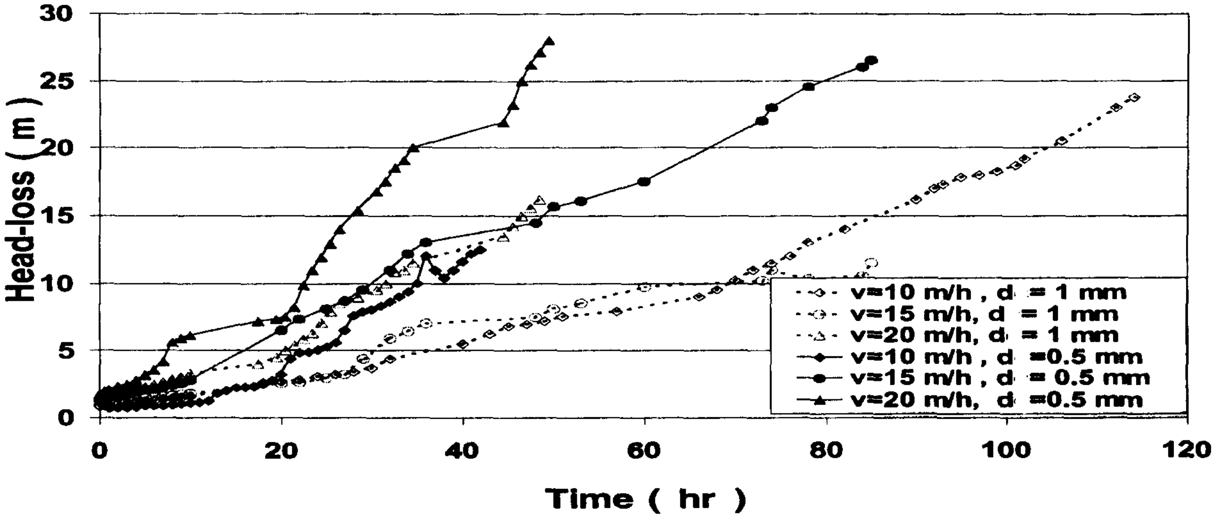

Fig. 3. Filtration velocity influence and grain size influence on head loss development as a function of time. Flocculant dose = 0.3 ppm, pH 6.8, initial turbidity ~0.5 NTU, d = 0.5, 1 mm, L = 0.9 m, v = 10, 15, 20 m/h.

depth was 0.9 m, the coagulant dosing was 0.3 ppm, of total iron and pH 6.8. The turbidity values obtained in the "working stage" were 0.1–0.23 NTU.

It can be clearly observed, that the higher the filtration velocity, the worse the filtration quality. There was an average turbidity of 0.12, 0.16 and 0.18 NTU, respectively.

Head loss. Fig. 3 presents the head loss development as a function of filtration time. The higher the filtration velocity, the quicker the head loss develops. It can be explained attributed to the shear forces that are stronger at higher filtration velocities. The end of the filtration cycle is defined by diff. pressure of 10 m. The filtration time until reaching this

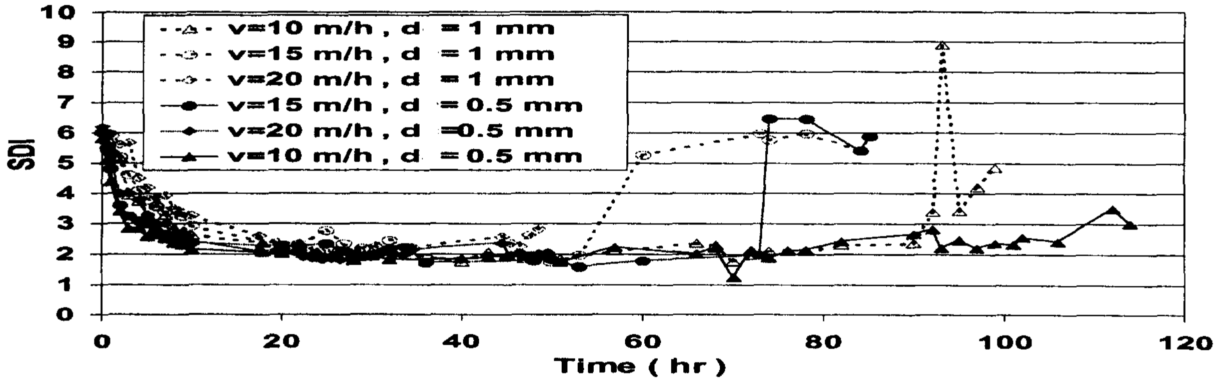

Fig. 4. Filtration velocity influence and grain size influence on SDI as a function of time. Flocculant dose = 0.3 ppm, pH 6.8, initial turbidity ~0.5 NTU, d = 0.5, 1 mm, L = 0.9 m, v = 10, 15, 20 m/h.

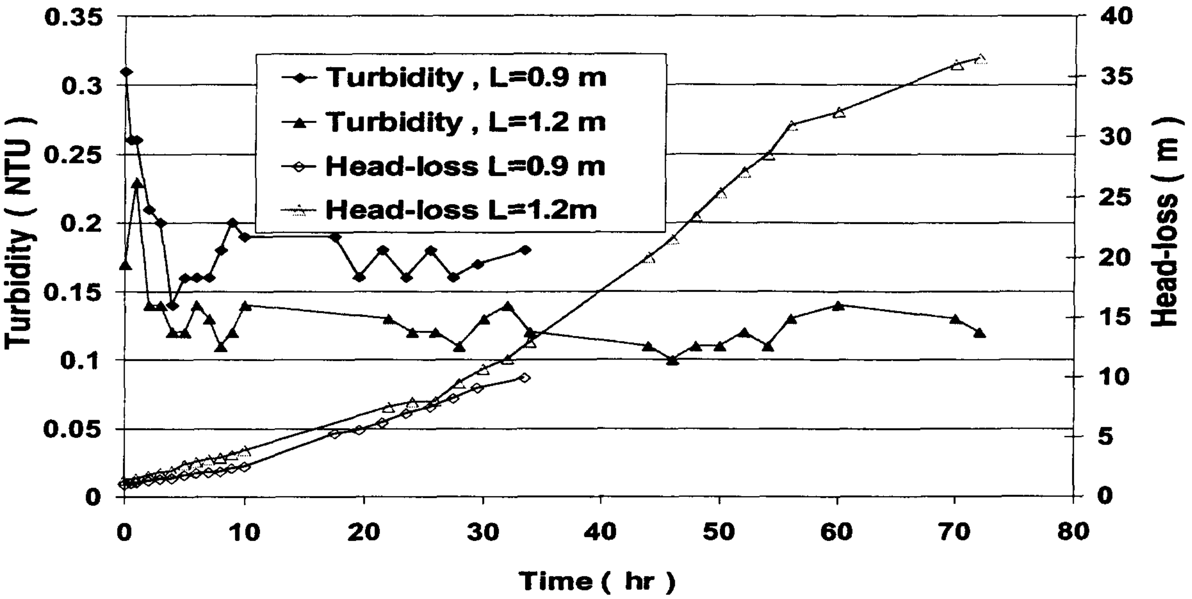

Fig. 5. Simulated storm. Depth influence on turbidity and head loss development as a function of time. Flocculant dose = 0.5 ppm, pH 6.8, initial turbidity ~5 NTU, d = 0.5 mm, v = 10 m/h, algae concentration = 10^5 cells/ml.

value at 10, 15 and 20 m/h were 70, 30 and 25 hours, respectively. In the filtration tests which were done under the same conditions but with a coarser grain size of 1 mm, the filtration cycles for the same limitation of diff. pressure of 10 m, were longer, 85, 63 and 35 hours, respectively.

SDI. Fig. 4 presents the SDI values as a function of filtration time. There is a direct relationship between the filtration velocity and the ripening time of the granular media. The higher the filtration velocity, the longer the ripening stage regarding the SDI values.

The limitation value of SDI, lower than 3.0, the value recommended by manufactures, is determining the ripening stage. With respect to the described velocities, the ripening stage

Table 3
Particle size distribution as a function of grain size (T = 0 h)

	Particle size (μm) 2–3	3–5	5–10	10–15	15–20	20–40	40–80
d = 1 mm	35	21	4	4	2	0	0
d = 0.5 mm	35	19	4	3	2	0	0
Inlet seawater	201	127	26	25	8	2	0

v = 15 m/h, initial turbidity ~0.5 NTU, d = 0.5, 1 mm, L = 0.9 m, flocculant dose = 0.3 ppm, pH 6.8.

Table 4
Particle size distribution as a function of grain size (T = 10 h)

	Particle size (μm) 2–3	3–5	5–10	10–15	15–20	20–40	40–80
d = 1 mm	35	22	3	3	0	0	0
d = 0.5 mm	28	16	2	2	0	0	0
Inlet seawater	259	170	36	22	5	2	0

v = 15 m/h, initial turbidity ~0.5 NTU, d = 0.5, 1 mm, L = 0.9 m, flocculant dose = 0.3 ppm, pH 6.8.

Table 5
Particle size distribution as a function of grain size (T = 27 h)

	Particle size (μm) 2–3	3–5	5–10	10–15	15–20	20–40	40–80
d = 1 mm	11	10	2	0	0	0	0
d = 0.5 mm	13	9	2	0	0	0	0
Inlet seawater	216	137	28	23	6	2	0

v = 15 m/h, initial turbidity ~0.5 NTU, d = 0.5, 1 mm, L = 0.9 m, flocculant dose = 0.3 ppm, pH 6.8.

is 5, 8 and 10 h, respectively. At the "working stage" the SDI values are around 2.0 in the various filtration velocities, while of example, at 10 m/h, for 30 hours (starting from the 25th hour) the SDI values are definitely below 2.0.

At filtration velocities of 15 and 20 m/h, SDI values below 2.2 were obtained from the 20th and 25th hour of filtration, for time period of 30 and 10 hours, respectively.

With respect to the SDI values only, the filter breakthrough stage in filtration velocities of 10 and 15 m/h were after 107 and 75 h, respectively (at a filtration velocity of 20 m/h breakthrough stage was not observed during the 48 h of testing).

In filtration experiments at filter depth of 0.9 m and grain size of 1 mm, similar trend was obtained. SDI values below 3.0 were reached after 12, 8 and 10 hours, respectively with the filtration velocities. The breakthrough stage of the granular media is much quicker in the coarser grain size of 1 mm and is 90 and 55 hours of filtration.

PSD. Particle size distribution measurements were done at the filtration velocity of 15 m/h and grain size of 0.5 and 1.0 mm. The total particle count of the Red Sea was in range of 350–389 counts/ml.

Tables 3–5 present the PSD (>2 μ) of the filtrates at the initial stage of filtration, 10 h, and after 27 hours of filtrating. At the beginning of the filtration the two filter media (0.5 and 1.0 mm) behave the same and had the same PSD (>2 μ) of 35 counts/ml. After 10 hours of filtration the fine media had lower PSD (>2 μ) counts with respect to the coarse grain size 35 vs. 28 counts/ml, this trend continued while after 27 hours the differences diminished and the two filters showed similar PSD counts of 13 vs. 11 counts/ml.

3.3.2. Filtration tests under stormy conditions

These tests were obtained at initial turbidity of 5 NTU and algae concentration of 10^5 cells/ml and filtration velocity of 10 m/h, pH 6.8 and flocculant dose of 0.5 ppm.

3.3.2.1. Media depth influence

The media depth tested were 0.9 m and 1.2 m, at grain effective size of 0.5 mm.

Turbidity. Fig. 5 presents the influence of the media depth on the filtrate turbidity levels at effective grain size of 0.5 mm. Performance of the deeper media significantly improved in comparison to the shorter media depth, with filtrate turbidity of 0.13 NTU after ripening stage of 2 h vs. 0.18 NTU after 5 h.

Head loss. Comparing the head loss development of the two depth media in Fig. 5, it can be observed that the deeper filter (1.2 m) reaches diff. pressure of 10 m after 27 hours while the second filter reaches the same ΔP after 35 hours.

SDI. Fig. 6 displays the SDI values as a function of media depth. The two curves present similar ripening and working stages. SDI value below 3 were achieved after 3 hours, in both filters, while the average value of SDI was around 2.0 with a small advantage to the 0.9 m media depth. (This experiment was stopped after 25 hours, so it is difficult to regard this advantage as significant).

Residual total iron. Fig. 6 presents the filtrate residual total iron values as a function of media depth and filtration time. The ripening stage of the filter, regarding iron values lower than 0.02 ppm lasted for 5 h at 0.9 m and 2 hours for the deeper media.

3.3.3. Grain size influence

The grain size tested were 0.5 mm and 1.0 mm at media depth of 1.2 m.

Turbidity. Comparison of the turbidity values (Fig. 7) shows some better performance of the fine media, in the ripening stage and also in the working stage with typical values of 0.15 NTU vs. 0.17 NTU in the coarse media with ripening time of 4 hours.

Head loss. The head loss development is presented in Fig. 7. Diff. pressure of 10 m was achieved in the fine media after 27 hours, while the same head loss was achieved after 40 hours in the coarse media.

SDI. Fig. 8 displays the filtrate SDI values. It can be seen that the two have ripening stage of 3 hours until the filtrate SDI values get below 3.0. From the fourth hour both filtrate operated with similar results with average SDI value of 2.5.

Residual total iron. The ripening stage of the fine filter regarding residual total iron was 3 hours until reaching values below 0.020 ppm vs. 5 hours in the course filter (Fig. 8).

3.3.4. Filtration tests at "edge of a storm" conditions

During the period of these experiments, a "real storm" was taking place in the Red Sea. After the storm settled down, the turbidity values increased to 0.7–1.0 NTU (instead of 0.3–0.5 NTU). The flocculant dose injected was 0.5 ppm of total iron at pH 6.8.

3.3.5. Media depth influence

The media depth tested was 0.9 m and 1.2 m at grain size of 1 mm.

Turbidity. Turbidity values below 0.2 NTU were reached in the deeper filter after one

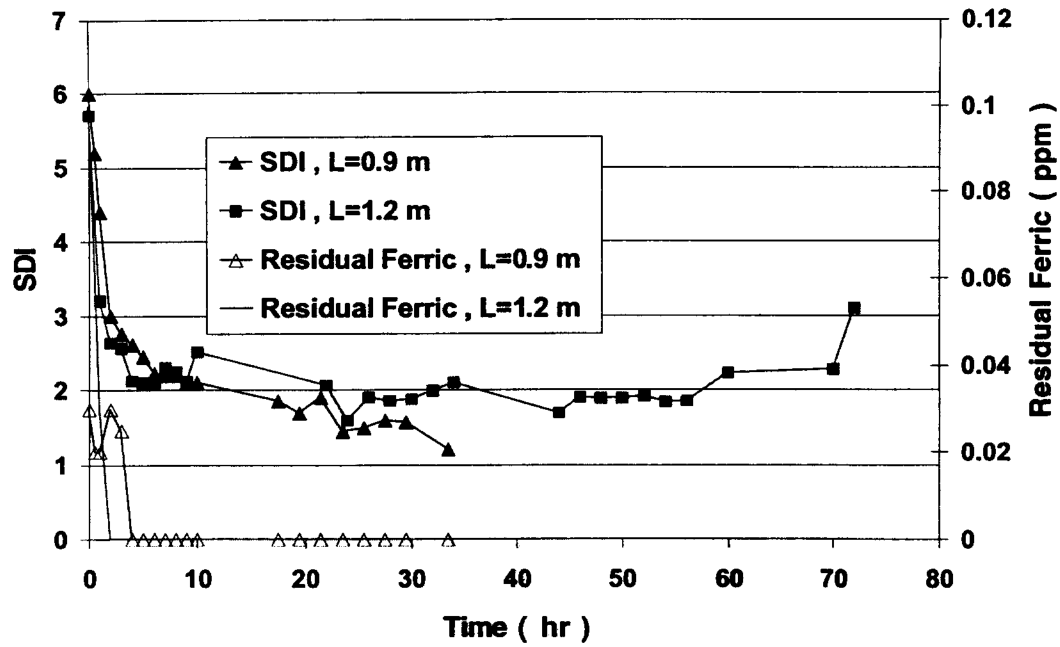

Fig. 6. Simulated storm. Depth influence on SDI and residual ferric as a function of time. Flocculant dose = 0.5 ppm, pH 6.8, initial turbidity ~5 NTU, d = 0.5 mm, v = 10 m/h, algae concentration = 10^5 cells/ml.

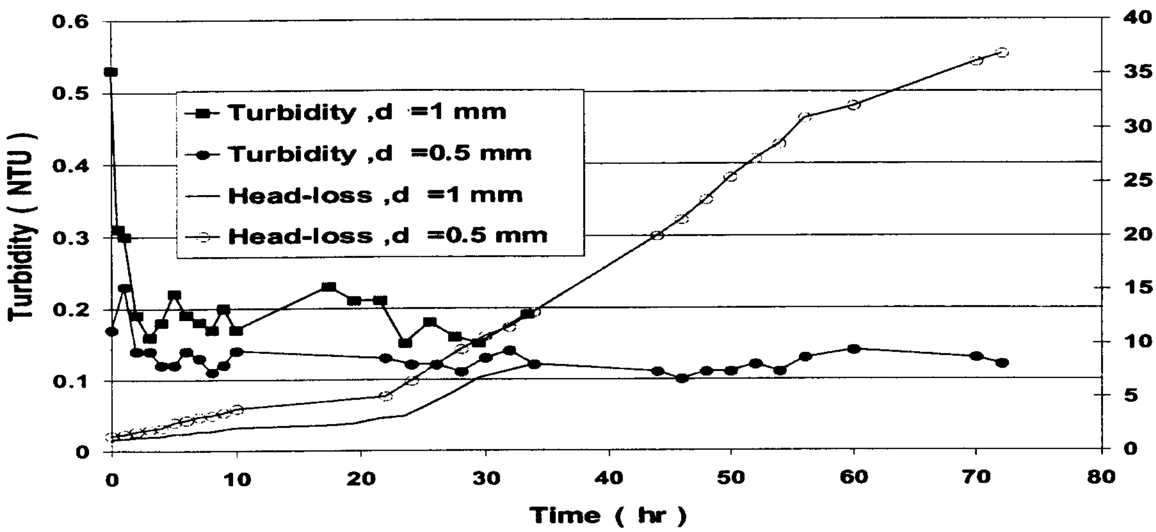

Fig. 7. "Storm". Grain size influence on turbidity and head loss development as a function of time. Flocculant dose = 0.5 ppm, pH 6.8, initial turbidity ~5 NTU, d = 0.5 mm, L = 1.2 m, v = 10 m/h, algae concentration = 10^5 cells/ml.

hour vs. two hours at the shallow media. The two filters resulted in similar turbidity values average 0.2 NTU vs. 0.18 NTU.

Head loss. Although the initial head loss different, 0.55 m vs. 0.9 m, the two filter media depths were similar, reaching ΔP of 10 m after about 98 hours (by extrapolation).

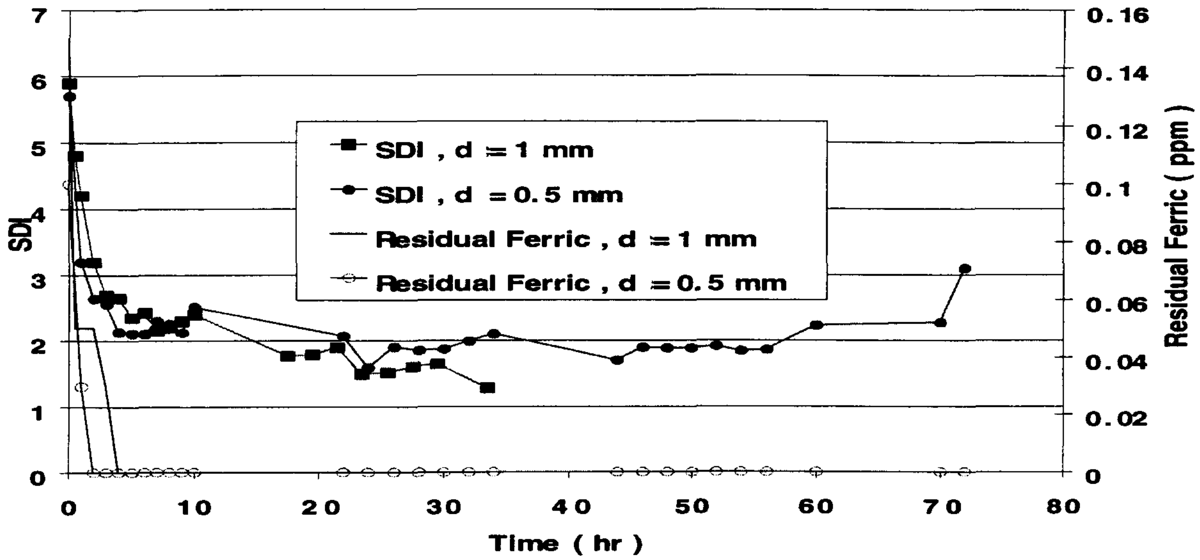

Fig. 8. "Storm". Grain size influence on SDI and residual ferric as a function of time. Flocculant dose = 0.5 ppm, pH 6.8, initial turbidity ~5 NTU, d = 0.5 mm, L = 1.2 m, v = 10 m/h, algae concentration = 10^5 cells/ml.

SDI. The 1.2 m media depth with grain size of 1 mm resulted in better filtrate SDI values vs. the 0.9 m, since the latter did not go low SDI 2.0, while the former had a ripening stage of 3 hours. The feed SDI values were around 4.5 and the deeper media (1.2 m) reached SDI values of less than 75% after 3 hours.

3.3.6. Physico-chemical pretreatment influence

The physico-chemical pretreatments tested were 0.5 ppm ferric chloride, with or without an addition of cationic polymer. The polymer dose was 0.1 ppm, based on the Jar Test. The media depth was 0.9 m and 1.2 m with grain size of 1 mm.

Turbidity. The addition of polymer reduced the turbidity values at the "working stage", but the ripening stage performed better without it. Reaching turbidity values below 0.2 NTU was obtained after two hours of filtration without polymer vs. four hours with polymer. The average filtrate turbidity values were 0.2 NTU vs. 0.16 NTU, respectively.

Head loss. Addition of polymer had a very significant influence on the head loss development, while after 10 hours of filtration, the difference in head loss was almost one meter higher in the experiment using polymer. By extrapolation, using polymer will last for 50 hours vs. 80 hours without it to a ΔP limitation of 10 m.

SDI. Polymer addition caused higher SDI values in the ripening stage, but in fact the filter ripened quicker with it present.

3.3.7. Filtration tests at real storm conditions

During the reported period a real storm occurred in the Red Sea due to southern winds. In the middle of the storm, the turbidity values of the feed stream were 20–30 NTU; after about five hours the turbidity settled to 2.5–6 NTU. The experiment was done at a filtration velocity of 10 m/h, a media depth of 0.9 m, grain size of 1 mm and flocculant dose of 0.8 ppm (the two columns were with a same sand depth and grain size).

Turbidity. The ripening stage was very short regarding the filtrate turbidity values; shorter than two hours achieving turbidity of 0.2 NTU in both columns.

Head loss. The head loss development curve was similar in both columns and reached a ΔP of 10 m, which would be after 80 hours (by extrapolation).

SDI. While the sea SDI values ranged between 17–18, the filtrate SDI was 3.7–4 units. An important note is that the filtrate SDI (only in this test) was taken for 10 min (instead of 15 min), so it can be expected that the SDI values for 15 min would be lower.

The described filter, which was found not to be the most efficient (0.9 m and 1 mm), succeeded in reducing the SDI values by more than 80% at the simulated stormy conditions with fine grain size. It can be estimated that the same filter depth (0.9 m) and grain size of 0.5 mm will achieve much better results.

4. Conclusions

- Recommended design and operation parameters for the existing pretreatment plant are: Media depth of 0.9 m, grain effective size of 0.5 mm, pH 6.8, filtration velocity of 10 m/h, ferric chloride concentration dose of 0.3 mg/l as Fe at non-stormy/normal sea conditions and 0.5 mg/l for stormy Red Sea conditions.
- Contact (in-line) filtration is the recommended filtration technique for pretreatment system of the desalination unit.
- Recommended design parameters for the following unit are: 1.2 m media depth, 1.0 mm grain effective size, pH 6.8, 10 m/h filtration rate and coagulant dosing as recommended above.
- Filtration pilot tests of Red Sea water were performed at pH 6.8, with a ferric chloride dose of 0.3 mg/l as Fe, initial turbidity of 0.5 NTU and filtration velocities of 10, 15 and 20 m/h. Media depth of 0.9 m and grain effective size of 1 mm, enables filtration runs of 73, 47 and 25 hours, respectively. Media depth of 1.2 m and 0.5 mm grain size resulted in shorter filtration runs of 65, 22 and 15 hours, respectively.
- Filtration tests simulating stormy conditions of Red Sea water containing clay and algae (10^5 cells/ml) and turbidity of 5 NTU, produce longer filtration run of 35 hours. Filtration parameters in that case were pH 6.8, ferric chloride concentration of 0.5 mg/l as Fe, filtration velocity of 10 m/h, depth media of 1.2 m and grain size of 1 mm.
- Filtration of similar water composition and operational conditions, at depth media of 0.9 m led to a filtration run of 32 hours. Filtration tests under same conditions with the coarser media, using cationic polymer, enabled a filtration run of 40 hours. Filtration tests at "edge of a storm" conditions (feed turbidity of 0.7–1.0 NTU), pH 6.8, ferric chloride dose of 0.5 mg/l as Fe and velocity of 10 m/h are expected to impart a longer run for media depth of 1.2 m and grain size of 1.0 mm, than for 0.5 mm media deep 0.9 m. For "real storm" Red Sea occurrence at similar filtration operational conditions, a similar tendency was observed.
- Clay turbidity removal in the Jar Test was affected by lowering pH from 8.2 to 6.8 for 5 NTU. 2 NTU clay suspension was better removed at the more acidic pH, probably due to better kinetics in first case. Jar Tests using algae only at concentrations of 10^5 cells/ml led to removal efficiency of up to 50% with no dependency on pH. Combined clay and algae suspensions were better removed at acidic pH of 6.
- Modified Jar Test using clay alone resulted, as expected, in higher removal efficiency at higher initial turbidity. For 10 NTU turbidity removal by contact filtration and by direct filtration was 99%. At lower initial turbidity acidic pH performed better. According to these experiments, direct filtration is preferential. Direct filtration is also recommended in using an algae

concentration of 10^5 cells/ml, at pH 6, although the removal efficiency is lower. Applying contact or direct filtration to artificial Red Sea water containing clay and algae resulted in 95–99% turbidity removal efficiency at a coagulant dose of 0.5–20 mg/l as Fe at natural pH.

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