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Seabed gallery intakes: Investigation of the water pretreatment effectiveness of the active layer using a long-term column experiment

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Abstract

Seabed gallery intake systems used for seawater reverse osmosis facilities employ the same principle of water treatment as slow sand filtration in freshwater systems. An investigation concerning the effectiveness of the active layer (top layer) in improving raw water quality was conducted by using a long-term bench-scale columns experiment. Two different media types, silica and carbonate sand, were tested in 1 m columns to evaluate the effectiveness of media type in terms of algae, bacteria, Natural Organic Matter (NOM) and Transparent Exopolymer Particles (TEP) removal over a period of 620 days. Nearly all algae in the silica sand column, 87% ($\sigma=0.04$) of the bacteria, 59% ($\sigma=0.11$) of the biopolymer fraction of NOM, 59% ($\sigma=0.16$) of particulate and 32% ($\sigma=0.25$) of colloidal TEP were removed during the last 330 days of the experiment. Total removal was observed in the carbonate sand column for algal concentration, while the bacterial removal was lower at 74% ($\sigma=0.08$). Removal of biopolymers, particulate and colloidal TEP were higher in the carbonate column during the last 330 days with 72% ($\sigma=0.15$),

66% ($\sigma=0.08$) and 36% ($\sigma=0.12$) removed for these organics respectively. Removal of these key organics through the 1m thick column, representing the active layer, will likely reduce the rate of biofouling, reduce chemical usage and minimize operating cost in SWRO systems. The data show that the media will require several months at the beginning of operation to reach equilibrium so that high organic removal rates can be achieved. No development of a “schmutzdecke” layer occurred. The experimental results suggest that unlike freshwater slow sand filtration wherein most water treatment occurs in the upper 10 cm, in seawater systems treatment occurs throughout the full active layer depth of 1 m. The results of this study will help in designing and operating seabed gallery intake systems in varied geological conditions.

Keywords; Seawater reverse osmosis, Membrane fouling/biofouling, Gallery intakes, Slow sand filtration, Natural organic matter

1. INTRODUCTION

Membrane biofouling is a major problem in the operation of seawater reverse osmosis water treatment (SWRO) plants and has a significant impact on the energy consumption and economics of a given facility (Flemming, 1997; Vrouwenvelder et al., 1998; Missimer et al., 2010; Ghaffour et al., 2013). Most large-capacity SWRO facilities use an open-ocean intake system to obtain raw seawater. This requires that a high degree of pretreatment must be employed to remove turbidity, algae, bacteria, and natural organic matter to the highest degree possible to slow, but not stop the membrane biofouling process (Mansouri et al., 2010; Matin et al., 2011). As an alternative to using a conventional surface intake and complex

pretreatment, a subsurface intake system can be used to provide initial higher quality seawater to a facility, thereby requiring a less complex pretreatment train (Missimer et al., 2013).

Types of subsurface intake systems can be classified into two groups; wells and galleries (Missimer et al., 2013). Research conducted on well systems has demonstrated that significant reductions in concentrations of turbidity, algae, bacteria, TOC, NOM fractions, and TEP occurs as seawater is transported through an aquifer into production wells (Missimer et al., 2013; Rachman et al., 2014; Dehwah et al., 2015a, b; Dehwah and Missimer, 2016; Dehwah et al., 2016). Recent research also found that the use of well systems to extract raw seawater for SWRO desalination plants will help reduce biopolymers and Assimilable Organic Carbon (AOC) concentrations during aquifer transport into the well system (Schneider et al., 2012). Reduction of the AOC concentration during aquifer transport shows that raw seawater produced from wells makes the membranes less vulnerable to biofouling (Weinrich et al., 2016). However, well intake systems have practical capacity limitations with regard to SWRO plant operation and are economically used to supply small and medium capacity facilities. The largest capacity SWRO plant using a well system occurs in Sur, Oman at 80,000 m³/day (wellfield capacity at 160,000 m³/day) (David et al., 2009).

Gallery intake systems have the potential to supply raw seawater to large-capacity SWRO facilities (Dehwah et al., 2014). There are two types of gallery intake systems, which are beach galleries that are constructed beneath the intertidal part of the beach (Maliva and Missimer, 2010) and seabed galleries which are constructed in offshore subtidal areas (Missimer, 2009; Missimer et al., 2015). There are no large-capacity beach gallery intake systems being used to supply an SWRO facility and only one large-scale operational SWRO plant using a seabed

gallery. The Fukuoka, Japan SWRO plant uses an offshore seabed gallery system with an installed capacity of 103,000 m³/day (Missimer et al., 2013; Fig. 1). This facility has been operating successfully for 9 years and has produced very high quality feedwater with a silt density index under 2 (Missimer et al., 2013). While the facility operates well, little is known regarding the differences in the raw water quality between the infiltrated seawater and the discharge from the gallery.

Seabed galleries are designed and operated similar to slow sand filter systems used for nearly two centuries in water treatment. However, they are constructed in the seabed, rather than in the treatment plant facility which saves space and reduces capital and operating costs. A medium to fine size sand is placed at the top of a slow sand filter which is commonly operated at infiltration rates ranging from 1.2 to 4.8 m/day (Crittenden et al., 2005). During slow sand filtration of freshwater, more than 90% of the water treatment occurs in the upper 10 cm of the media and a thin biologically-active layer known as a “schmutzdecke” forms at the filter surface (Huisman and Wood, 1974). A pilot-scale test of slow sand filtration was conducted over a 13-month period at the City of Santa Cruz, California in 2008-2009 and the downstream SWRO membranes did not require cleaning, had the lowest flux decline, and showed the lowest amount of foulant on the membrane surface compared to other pretreatment processes (Desormeaux et al., 2009).

A number of conceptual designs for seabed gallery intake systems have been developed based on site-specific investigations along the Red Sea, Saudi Arabia (Sesler and Missimer, 2012; Dehwah and Missimer, 2013; Lujan and Missimer, 2014; Mantilla and Missimer, 2014; Al-Mashharawi et al., 2014). Each of the preliminary designs used a different thickness (1-3 m) of

the uppermost “active” layer of the filter where most water treatment is expected to occur during the corresponding retention time within the filter. Typical slow sand filtration design calls an active bed thickness of 0.9-1.5 m (Crittenden et al., 2005).

The composition of the active layer may also impact the efficiency or rate of organic matter removal during filtration. Typical slow sand filtration media consists of medium to fine grain size quartz sand. Since the gallery intake would be constructed within the seabed, the composition of the upper part of the media in the Red Sea and many other subtropical or tropical locations will vary between quartz sand and carbonate sand (Missimer et al., 2015). It has been suggested that carbonate sand may be more bioactive compared to quartz sand based on organic compound assimilation studied in reef sediments. Marine biological research has been conducted in the Red Sea and it suggests that carbonate sediments are more bioactive in the removal of organic carbon compared to siliciclastic sediments (Rasheed et al., 2003; Wild et al., 2005).

The goal of this research is to evaluate the removal process efficiency of an active layer using media of differing composition at the bench scale using columns. Assessment of the removal of algae, bacteria, TEP, TOC and the various fractions of NOM that occur in seawater was conducted along with investigation of the ripening period to equilibrium, the impact of media composition and thickness, and if a “schmutzdecke” layer forms in a similar manner to slow sand filtration in a freshwater system. If a “schmutzdecke” would form, it should be observable at the surface of the columns and would cause reductions in hydraulic conductivity that, in turn, would cause a reduction in the infiltration rate necessitating an increase in

pumping pressure to maintain the desired flow rate. The observed data are needed to enable the design of gallery intake systems in varied geologic settings.

2. MATERIAL AND METHODS

2.1. Design, construction and operation of the sand columns

Two columns were constructed using transparent acrylic plexiglass material. The columns were 100 cm in length and 10 cm in diameter. Two screens made from acrylic plexiglass were installed inside each column, one at the top with 0.2 mm pore size to ensure uniform water distribution into the columns while the other screen with 0.1 mm pore size was placed at the bottom of the column to prevent the loss of media with the discharged water. Sampling ports were installed at three intermediate depths of 10, 25 and 50 cm from the top of each column (Fig. 2). The sampling ports are tubes that were perforated using a laser to avoid the infiltration of the media into the tubes during sampling. In addition to the sampling ports, two sampling points were added at the inflow portal and at the discharged flow to measure the quality of inlet water versus the outlet water. The columns were painted black in order to prevent light penetration into the column media to avoid algal growth or other biological activity.

Different media were used for each column with the first column containing siliciclastic sand (primarily quartz) collected from a local interior dune near the village of Thuwal, Saudi Arabia located near the Red Sea coast. The second column was filled with natural carbonate sand collected from the beach at King Abdullah Economic City (KAEC) located north of Thuwal, Saudi Arabia. Both sediment types were separated into 34 different size fractions using sieves. A mix of these fractions was used to create the properties of the desired media. Design of the media

was accomplished using a computer program that makes an accurate prediction of hydraulic properties for a known mix of sand size fractions (created media) (Rosas et al., 2014). The mix of sediment for both columns was as follows: 16% of 0.07 mm fraction, 19% of 0.09 mm fraction, 26% of 0.11 mm fraction, 16% of 0.13 mm fraction, 8% of 0.15 mm fraction, 8% of 0.18 mm fraction, and 6% of 0.21 mm fraction. The media is classified as a fine to very fine sand. The mean grain diameter, porosity and hydraulic conductivity of the media of the two columns were kept as close as possible to allow a detailed comparison of column performances. The sediment properties for effective porosity were 0.40 and 0.41 and for hydraulic conductivity were 5.38 and 5.95 m/day respectively for the siliciclastic and carbonate sand media.

Based on the hydraulic conductivity values obtained from permeameter testing of the media, an infiltration rate of 6 m/day with 4 hours of hydraulic retention time was established as a goal for the experiment to make sure that each column was always filled with water (to avoid the column becoming dry). A Masterflex peristaltic pump with a capacity greater than required was used to operate the experiment. A pumping rate of to 13 mL/min was used to transfer seawater from the source into both columns.

Before starting the experiment the different grain size fractions for each column were mixed together (homogenized) and then heated in an oven to remove any naturally-occurring organic material. The sterile media were loaded into each column separately. The media was packed carefully while adding water to remove gaps or macro pores in the column. After that, the columns were saturated from bottom to top with MilliQ (MQ) water to make sure that all the air gaps were removed from the column.

A standard tracer test was conducted on each column to determine a sustainable infiltration rate and to assess the initial retention time. The tracer was seawater followed by MQ water. The inflow rate of seawater was controlled to be as close to 5 m/day as possible. The results of the initial tracer test showed that the 5 m/day infiltration rate could be maintained and the retention times were both very close to 4.7 hours (Fig. 3). A similar test was conducted after completion of the experiment to determine changes in the retention time based on the retained organic matter within the column. The freshwater was purged from the columns using filtered seawater before the experiment began.

The experiment started on January 5, 2014 and was run until the middle of September 2015. Samples were collected from the inflow portal, from the three sampling ports and the discharge location (outflow portal) for each column. Algae, bacteria, TOC, NOM fractions, and particulate and colloidal (TEP) were measured in the samples to study the behavior of the organic matter as it moves through the media in each column. The frequency of sampling was on a weekly basis for the first month then it was on a monthly basis for the first year. The frequency of sampling was reduced later during the second year. The experiment was run for a total period of 21 months (620 days).

Both columns were supplied with feed seawater from a pipe coming directly from the Red Sea located at the SWRO plant intake about 3 km from the laboratory. Seawater was constantly circulated from the pipe (open system) and was directed into an opaque tank (painted black on the outside) to avoid biological growth inside the tank. The tank was cleaned and filled every 6 days, but samples were collected within 24 hours of filling the tank to avoid any potential change in water parameters. Water samples were collected from the inlet water rather than

the tank to avoid any variation in the measured parameters within the tank. The intermediate sampling ports and the outlet were all sampled close to the same time as the inlet tube. The water temperature in the column inlet varied between 21-23°C and was the same at the column outlet. The same method was followed during the entire duration of the experiment.

2.1 Measurement of organic matter concentrations

The methods used to analyze the concentrations of algae, bacteria, TOC, the fractions of NOM (biopolymers (BP), humic substances (HS), building blocks (BB), low molecular weight acids (LMWA) and neutrals (LMWN)), and particulate and colloidal TEP are presented in Dehwah and Missimer (2016). It was also placed in the supplementary materials.

3. RESULTS

3.1 Analysis of retention time from the tracer tests

Tracer tests were conducted before and after the column experiment period to assess the hydraulic retention time in both the silica and carbonate sand columns (Fig. 3). The silica sand column showed a retention time of 4.7 hr before the experiment began and 5.8 hours at the end of the experiment. The carbonate sand column had a retention time of 4.7 hr at the beginning of the experiment and 6.9 hr at the end of the experiment.

3.2 *Total algae and bacteria*

During the 21-month column experiment the concentration of algae entering the inlet of the columns ranged from close to zero to over 50,000 cells/mL (Fig. 4). The very low concentrations of algae in the early part of the experiment may have been caused by a laboratory preservation problem. Spikes of higher concentrations occurred on September 18, 2014 (after 251 days of operation) and an upward trend occurred from Spring of 2015 (after 400 days of operation) and peaked in September of 2015 (621 days). While the algal concentration varied considerably in the inlet water, the outlet water contained no algae, except on a few occasions (carbonate sand column on one occasion). The data collected from both columns show a generally regular reduction in concentration, but most algae were removed in the upper 10 cm. No significant differences were found in the removal efficiency between the two columns. The percentage of algae removed with time was mostly 100% with a single minor exception.

Bacteria concentration varied widely during the experiment period from about 20,000 to over 800,000 cells/mL (Fig. 5). Note the some differences in the inlet concentrations between the columns occurred in the early part of the experiment which could have been influenced by a laboratory sample preservation problem (first few samples). There was a difference in the removal pattern between the two columns with the silica sand column reaching a more stable removal rate and an equilibrium beginning about 5 months into the experiment. The outlet bacteria concentration was below 80,000 cells/mL for the last 11 months of the experiment.

The carbonate sand column showed rather unstable behavior from the beginning of the experiment to 330 days at intermediate depths within the column. These depths showed higher concentrations of bacteria compared to the outlet. Stability was reached earlier in the silica sand column at 220 days into the run time. The bacteria concentration generally stabilized in the outlet at about the same time as the silica sand column, but at the end of the experiment the concentration was about double that found in the silica sand column. The bacteria concentrations at intermediate depths in the carbonate column showed more erratic behavior throughout the experiment compared to the silica sand column.

3.3 TOC

The TOC concentration in the inlet seawater ranged from about 0.7 to 1.7 mg/L with an average close to 1 mg/L (Fig. 6). The behavior of the TOC concentration was quite erratic with depth in both columns. The concentration at the 10 cm depth commonly was higher than the inlet concentration beginning a few months into the experiment (Fig. 6). The overall pattern of TOC concentration behavior within the two columns was essentially the same. During the last 3 months of the experiment, there was consistent reduction in concentration occurring between the inlet and outlet which appears to be about 20-30%. It appears that little difference occurs in the TOC reduction between the two columns.

3.4 NOM fractions

3.4.1 Biopolymers

There was a general correspondence between increases in algae and bacterial concentrations entering the columns and the biopolymer concentrations (Figs. 4, 5, 7). Biopolymer movement through the columns showed a somewhat erratic behavior in the silica sand column, but was more regular in the carbonate sand column. In both columns the removal of biopolymers was not regular with depth. In the silica sand column at or after a spike in the inflow biopolymer concentration, the intermediate depths produced a higher degree of removal, sometimes greater than the outflow concentration. Similar behavior occurred within the carbonate column in a few cases, but the outflow concentration was generally lower than those within the intermediate concentrations. During the last 6 months of the experiment, the removal of the biopolymer fraction in the outflow of the silica and carbonate sand columns averaged 60 and 81% respectively. Based on the removal behavior within the columns, it appears that a quasi-equilibrium was reached between the inflow concentration of biopolymers and its removal during passage through the full thickness of the columns starting in December, 2014 (after 330 days of operation).

3.4.2 Humic substances

The behavior of humic substances was much different compared to biopolymers as it passed both columns (Fig. 8). In most cases, only a minor amount of the inflow concentration was removed within the columns when comparing inflow to outflow concentrations. However, when spikes in the inflow concentration occurred, removal was significant, particularly in the carbonate sand column with the highest removal being up to 30%. Beginning in the fall of 2014

(after 257 days of operation), it appears that an equilibrium state began to occur within both columns showing little variation between the inflow and outflow concentrations. During this time period there was little variation in the concentrations throughout the depths within each column.

3.4.3 Building blocks

The building block fraction of NOM showed rather scattered results in the first several months of the column experiment (Fig. 9). By summer of 2014 (after around 196 days of operation), the concentrations settled into a general equilibrium with the inflow concentrations being higher than the outflow with the intermediate column depths generally lying between them (with some exceptions). The removal of building blocks was at a low percentage in both columns and showed little difference between them. At the end of the experiment the removal percentage was 15 and 20% for silica and carbonate columns respectively.

3.4.4 Low molecular weight neutrals

The concentration of the low molecular weight neutrals varied greatly with depth between the inlet and outlet within both columns (Fig. 10). An interesting observation is that the concentration at the intermediate depths considerably exceeded the inlet and outlet concentrations. In particular, the highest concentrations occurred at the 10 cm depth. Beginning in about February, 2015 (after 400 days of operation), the concentrations began to equilibrate and become more regular with little difference between inlet and outlet concentrations.

3.4.5 Low molecular weight acids

The low molecular weight acids fraction of NOM had a significantly lower concentration in the inlet seawater compared to the low molecular weight neutrals (Figs. 10 and 11). The early data shows some scatter with intermediate column depth concentrations being higher than both inlet and outlet concentrations. Roughly halfway through the 21-month experimental period, the pattern of concentrations within the two columns began to equilibrate and toward the end of the experiment showed a regular pattern with the inlet being the highest and the outlet being the lowest. The intermediate depth measurements still showed some variation outside the range of inlet and outlet values. The removal of the low molecular weight acids was quite low and there was no significant difference between the removal percentage between the silica and carbonate sand columns.

3.5 Particulate and colloidal TEP

Particulate TEP concentrations in the inlet seawater ranged from about 50 to nearly 600 $\mu\text{g Xeq./L}$ (Fig. 12). Some differences were found in the inlets between the two columns which may be indicative of variations within the seawater in the holding tank (samples were collected from the inflow tubes in each column and not the tank). Because of the long time required to measure TEP, it was collected only from the inlet and outlet and not at the intermediate depths in the columns. The general pattern of TEP removal is similar in both columns. During the last 6 months of the experiment, the removal percentage in the silica sand column was 41 to 67% and

in the carbonate was 63 to 76%. Removal of particulate TEP was significantly greater in the carbonate column compared to the silica column at specific sampling times with up to a 10% difference. The highest percentages of particulate TEP removal occurred during spikes in the inlet concentration.

In general, the colloidal TEP concentrations from in the inlet seawater were less than 50% of the concentrations of particulate TEP (Figs. 12 and 13). Some removal of colloidal TEP occurred in each of the columns and was highest during spikes in the inlet concentration. The average removal is about 32% for the silica column and 35% for the carbonate column for the entire period of the experiment. Large variations in the removal percentage did occur during the experiment.

4. Discussion

4.1. Assessment of algae and bacteria removal with time

With an exception of a few measurements, the 1 m columns of silica and carbonate sand removed 100% of the algae that entered through the inlet. This occurred even during high concentrations associated with minor algal blooms which produced concentrations at or above 50,000 cells/mL. No significant differences between the removal efficiency based on media composition were observed.

A quite high degree of removal of bacteria, reaching up to 85% by the end of the experiment period, occurred in both columns. The same general pattern of removal was

observed in both columns, but the average percentage of removal was higher during the last year of operation in the silica sand.

4.2 Assessment of TOC and NOM fractions removal with time

Removal of TOC was nearly equal in both columns which both required over one year of operation to achieve some type of quasi-equilibrium. Within the column, the intermediate concentrations of TOC were higher than both the inlet and outlet values likely indicating that the transport of organic carbon within the column reaches this level and pauses. Then, the “collected” organic carbon is subjected to additional microbial activity before leaving the column. During the last 4 months of the experiment, the TOC concentrations occurring between the inlet and outlet were comparatively lower, suggesting that biological activity removed the higher concentrations previously occurring within the mid-column.

The biopolymers fraction of NOM, which contains many polysaccharides and proteins that impact biofilm development, was significantly removed during passage through both columns. However, the carbonate sand media appears to create a higher degree of removal, particularly during the last half of the experiment. Within the carbonate sand column, a quasi-equilibrium state was reached after about one year of operation and the intermediate concentrations were enveloped between the inlet and outflow concentrations. This state was never reached in the silica sand column. Therefore, the supposition by Rasheed et al. (2003) and Wild et al. (2005) that the carbonate sands in the reef sediment of the Red Sea are more bio-reactive compared to silica sands is supported by these data for this NOM fraction. The cause of the higher bio-

reactivity of the carbonate sands is likely a combination of the higher porosity of some carbonate skeletal grains (e.g. corals) and/or the occurrence of naturally-occurring organic compounds on the surface of the grains which could encourage adsorption of additional organics perhaps as a biofilm.

Removal of the lower molecular weight humic substances and building blocks was substantially lower in both columns. The humic substances concentrations were in general consistently higher than the building blocks. There was little difference in removal of these NOM fractions between the columns. Little variation in concentrations occurred during the last half of the experiment period. There were considerable variations within the intermediate depths in the columns during the first 7 months of experiment operation in the building block fraction of NOM.

The low molecular weight neutrals fraction of NOM showed an interesting pattern of concentration variation within the intermediate depths in both columns, being commonly higher than both the inlet and outlet concentrations. This was most pronounced in the first year of the experiment. It is likely that the higher molecular weight substances trapped within the columns were being biochemically degraded within the column, likely mediated by bacteria, to produce these substances. During the last several months of the experiment all of the measured concentrations showed a narrow range with the inlet and outlet being nearly equal. It appears that a quasi-equilibrium state was reached for these substances within the column. The average removal in the last 11 months for LMWN was 13% and 14% for silica and carbonate columns respectively.

The least abundant fraction of NOM measured during the experiment was the low molecular weight acids. In general they showed a rather minor pattern of fluctuation during the experiment compared to the low molecular weight neutrals fraction. They do not appear to be significantly affected by the biochemical process occurring with the two columns and there is no apparent impact of the media composition. The average removal in the last 11 months for LMWA was 24% and 20% for silica and carbonate columns respectively.

4.3 Assessment of particulate and colloidal TEP removal with time

The particulate TEP (P-TEP) showed concentrations nearly double that of colloidal TEP in the inlet seawater. Removal of the P-TEP was greater compared to the C-TEP in both columns which may be caused by the higher molecular weight and perhaps a greater abundance of acidic polysaccharides in the P-TEP. The average removal of P-TEP was higher for silica columns at 57% while the average removal for the carbonate column was 47% for the entire period of the experiment. The average removal of C-TEP for the same period was almost the same with 35% for the carbonate column and 32% for the silica column. It is likely that a greater removal rate could be achieved by increasing the length of flow (greater bed thickness) and the corresponding hydraulic retention time.

4.4 Operational maturing of treatment in comparison to slow sand filtration

Experimental work on the “ripening” of slow sand filters shows that the “schmutzdecke” forms in time periods of a few days to two weeks in freshwater systems. Without the formation of this surface layer, slow sand filtration is ineffective at removal of organic materials and the filtered water quality is poor (Huisman and Wood, 1974). Slow sand filtration in freshwater systems removes 1-3 log units of coliform bacteria, 2-4 log units of *Giardia* cysts, and >4 log units of *Cryptosporidium* which are similar in size to some seawater algae (Collins, 1998). Dissolved organic carbon (DOC) is removed at 15-25% and trihalomethane precursors at 20-30% (Collins, 1998). Higher and lower removal rates for DOC have been documented at some locations, but are dependent on the infiltration rate and water temperature (Collins et al., 1992). Biochemical activity within freshwater slow sand filter systems is concentrated in the upper 10 cm of the media and declines with depth.

The column experiment that was conducted for 620 days showed no development of a “schmutzdecke” layer as found by physical observation. In addition, evaluation of breakthrough curves at the beginning and at the end of the experiment showed that the flow rate within both columns was relatively consistent through the entire experiment duration which also indicates that no “schmutzdecke” layer was formed. Also, by monitoring the performance of pump flow and the outlet flow of both columns during the whole period of the experiment, it was observed that there was no change in the outlet flow which would not be the case if a “schmutzdecke” was present (the flow rate will be reduced greatly). No cleaning of the top of either column was required during operation of the experiment.

The data clearly show that various organic materials were removed throughout the columns rather than only in the first 10 cm (Table 1). While the highest percentage of the particulate

organic carbon forms, algae and bacteria, were removed in the uppermost 10 cm in both columns, the dissolved organic compounds were removed throughout the column depth. Considerable variability in the percentages did occur which is to be expected in a biological active media. Biochemical processes acting within the columns likely had rate changes based on compositional changes occurring within the feed water and uneven breakdown rates of the large organic compounds.

Removal of algae was nearly 100% except for some of the sampling events at the beginning of the experiment. The bacteria removal also occurred without a “schmutzdecke” formation. The removal of the NOM fractions was more effective after the columns stabilized which occurred several months into operation. It appears that seawater slow sand filtration operates in a different biochemical regime compared to freshwater slow sand filtration systems.

5. Conclusions

The effectiveness of a seabed gallery intake system in terms of improving raw seawater quality was assessed through the use of a long-term bench scale columns experiment. Two different media compositions (silica and carbonate) with a 1 m fixed column length were used in this study for a period of 620 days. The role of media type and penetration in the column (10, 25, 50 cm and 1 m depth) in improving the raw seawater quality was also evaluated at this study. Analysis included the measurement of algae, bacteria, TOC, NOM and TEP concentrations. The results showed that the 1m length column significantly improved raw seawater quality once it came into quasi-equilibrium. The columns required several months to

reach the equilibrium state in which the removal pattern became more stable with higher percentage of removal efficiency.

Almost all algae and 87 % ($\sigma=0.04$), and 74% ($\sigma=0.08$) of the bacterial population for silica and carbonate sand columns respectively were removed through the 1m length column for the last 11 months of the experiment. Biopolymers were removed at 59 % ($\sigma=0.11$) for silica column and at 72% ($\sigma=0.15$) for the carbonate column for the same period as well. The average removal of P-TEP was 59% ($\sigma=0.16$) and 66% ($\sigma=0.08$), while C-TEP removal rate was 32% ($\sigma=0.25$) and 36% ($\sigma=0.12$) for silica and carbonate columns respectively. TOC concentration showed the lowest percentage of removal with an average of 16% ($\sigma=0.07$) and 15% ($\sigma=0.15$) for silica and carbonate sand columns respectively for the same period.

The lower degree of TOC removal is due to the short length of the column which indicates that 1m path length is not enough to significantly lower the TOC concentration. This finding is consistent with the results observed from the wells having longer flowpath lengths and associated residence times being more effective in removing TOC. The removal efficiency within the intermediate depths was significant for the 10 cm depth in which the average removal was about 90 % for algae, 72% and 64 % for the bacterial population for silica and carbonate sand columns respectively for the last 11 months. The biopolymer removal percentage at the 10 cm length was 47% for silica column and 54% for the carbonate column for the same period. There was no clear difference observed between the average removal at 10 cm and the other two intermediate depths of 25 and 50 cm. It is clear that for NOM fractions a thicker active bed will be required to increase the removal efficiency while for algae and bacteria most of the removal occurs in the top layers by straining, but still the full column is contributing to the removal of

both of them (Table 1). In general, the removal efficiency of the carbonate sand media is higher for biopolymers and TEP, but it is lower for the bacterial population.

The reduction of these organics, which are known to enhance biofilm formation, will help decrease the potential rate of biofouling on an SWRO membrane surface. Therefore, a less complicated pretreatment system would be needed with less chemical usage within the SWRO plant which would ultimately reduce the operating cost. In addition, this natural seabed intake system is not harmful for the environment since impingement and entrainment cannot occur. Also, it was demonstrated that no “schmutzdecke” layer formed during the experiment period of 620 days suggesting that use of this intake type for seawater pretreatment may require less maintenance than its use in freshwater treatment systems.

The findings of this study will help the desalination plant designer in deciding about the appropriate thickness of the active layer for a seabed gallery as well as the type of media used. Moreover, for planning purposes it will be important to run the seabed intake system ahead of time before the commissioning of the desalination plant in order evaluate the full benefit of the seabed system with more biological stability and ultimately higher removal efficiency. Furthermore, the findings will help operators to identify the cleaning requirements for the gallery system which was shown to be minimal at the only existing operating system in Japan.

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608 Table 1: Comparison of organic carbon removal at the different depths through the 1m column
609 (reference is the inlet seawater)
610

611

612 Supplemental materials

613 (Organics analyses methods)

614

615

Table 1. Comparison of organic carbon removal at the different depths through the 1m column (reference is the inlet seawater)

Media type	Silica				Carbonate			
Media thickness	10 cm depth	25 cm depth	50 cm depth	1 m depth	10 cm depth	25 cm depth	50 cm depth	1 m depth
Algae	91%	95%	97%	100%	93%	97%	99%	100%
Bacteria	72%	72%	72%	87%	64%	68%	68%	74%
TOC	4%	2%	1%	16%	2%	3%	9%	15%
BP	47%	59%	61%	59%	54%	67%	69%	72%
HS	7%	9%	8%	4%	7%	12%	10%	10%
BB	11%	12%	8%	17%	10%	12%	14%	15%
LMWN	+11%	0%	+6%	13%	+18%	+15%	+17%	14%
LMWA	25%	25%	18%	24%	11%	22%	12%	20%
P-TEP	59%				66%			
C-TEP	32%				36%			

* (+) indicates that measured value at that sampling port was higher than the corresponding value at the inlet seawater

Highlights for review

- Long-term column conducted to assess slow sand filtration pretreatment of seawater
- No schmutzdecke layer formed at the surface of the columns
- Biochemical treatment occurred throughout the 1 m columns, not only in the upper 5-10 cm
- High percentages of biopolymers and TEP were removed which reduces potential for biofouling of SWRO membranes
- Sand filtration media difference (silica vs. carbonate) can enhance specific organic substances removal