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Beach Sand Filtration as Pre-Treatment for RO Desalination

Regular Paper

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Abstract Membrane fouling has a strong negative impact on the efficiency of reverse osmosis membranes in seawater desalination. Although reports indicate that water abstracted by beach sand filtration systems on the Mediterranean and Red Seas leads to less membrane fouling compared to direct seawater intakes, only limited information can be found on the efficiency of such systems in removing biodegradable dissolved organic carbon (BDOC), an important fouling agent.

This article describes different designs of beach sand filtration systems. In order to investigate the reduction during beach sand filtration of parameters relevant to membrane fouling, such as total organic carbon (TOC), turbidity and total nitrogen, column experiments have been carried out using natural and wastewater-spiked seawater with coral beach sand from Hawaii, USA at low and high infiltration rates. Additionally, operational results from existing beach sand filtration sites were collected and supplemented with data from a field site visit of the Dahab beach well desalination plant, Egypt. Preliminary results show good reduction of the targeted parameters and indicate that beach sand filtration would be a valuable pre-filtration step in RO-based drinking water production systems.

Keywords Beach Sand Filtration, Beach Well, Desalination, Membrane Fouling

1. Introduction

In using reverse osmosis (RO) to produce drinking water by desalination, seawater is filtered under high pressure through a semi-permeable membrane. Not only dissolved ions but also colloidal, organic and biological particulate, and dissolved organic matter are retained on the RO membrane surface, causing undesirable membrane fouling (scaling). This has a clogging effect that increases pressure drop across the membrane, decreases flux, raises energy demand and reduces the lifespan of the membrane elements. Lifespan and performance of an RO membrane are therefore strongly dependent on the feedwater quality. Due to the absence of tortuous pores in RO membranes, conventional cleaning methods such as backwashing cannot be applied. Instead, acidic or basic chemicals are used to remove the scale on the membrane surface.

However, nutrients such as biological degradable dissolved organic carbon often persist, serving as the limiting factor for biological growth and the formation of biofilms onto the membrane surface.

Membrane fouling refers to the deposition of colloids, precipitation of dissolved ions, adsorption of dissolved organic substances and formation of biofilms onto the membrane surface. These processes can take place simultaneously and affect each other [1]. Colloidal fouling is the deposition of colloidal particles onto the membrane surface. Inorganic fouling is the precipitation of salts onto the membrane surface when the solubility product is reached or exceeded. Common salts responsible for inorganic fouling are CaSO4, CaCO3, SiO2 and BaSO4 [2]. Organic fouling is the adsorption and deposition of natural organic matter (NOM) onto the membrane surface. Organic fouling by dissolved organic matter (DOM), such as humic substances, polysaccharides, amino acids, proteins and fatty acids, have been found to have the most damaging effect on membranes in surface water treatment [3]. However, the fraction of DOM which has the most severe impact in terms of organic fouling has not yet been clearly identified [4]. Reports indicate that hydrophilic neutral substances like polysaccharides and proteins with high molecular weights are the main cause for organic membrane fouling [5,6]. Biofouling is the deposition and growth of microorganisms on the membrane surface (i.e., biofilms). Biofouling causes operational problems when the biofilm exceeds a certain level, as water must not only pass the membrane but also a layer of gelatinous extracellular polymers [7,8]. As a consequence, flux and membrane permeability decreases, and salt passage and pressure increases. A study of 15 full-scale RO and nanofiltration (NF) membrane installations and an extensive literature study on existing RO fouling studies revealed biofouling as the predominant operational problem in seawater RO [9]. The main factors limiting biofouling and microbial growth are nutrient availability and shear forces. Since the formation of a biofilm starts immediately after a surface is exposed to natural water [10] and RO membranes cannot be backwashed, the key to controlling biofouling lies in limiting the availability of nutrients.

The removal of BDOC and other undesirable constituents using natural filtration processes greatly helps to increase the long-term performance and lifespan of RO membranes, and in the long-term can save money by reducing the frequency and necessary extent of cleaning.

Also, freshwater riverbank filtration systems were found to offer effective pre-treatment for nanofiltration membranes [11]. The cleaning frequency for the conventionally pre-treated membranes for two different surface waters was in the order of eight days, whereas that for RBF-treated membranes ranged from 62 and 75 days. Bank pre-filtered systems lost between 12 and 24 % of their initial fluxes over 62 days of operation, whereas the conventionally treated systems lost between 36 and 50 % of their initial fluxes over the same length of time.

Freshwater bank filtration systems are widely used worldwide because of their high efficacy in removing dissolved organic carbon (DOC), nutrients and pathogens [12]. Attenuation rates for DOC and nitrogen compounds can be >50 % [13], but are highly temperature dependent [14]. In general, natural filtration as applied in bank filtration systems is a reliable low-cost technique for providing good quality water. A similar natural filtration process can be applied as pre-treatment in subsurface seawater intake systems.

2. Design of Beach Sand Filtration Systems

Beach sand filtration is the abstraction of seawater via beach wells or infiltration galleries that are located along a seashore. A downward flow of seawater through the beach sand into the production wells is induced by creating a hydraulic gradient between the aquifer and the ocean. The beach well capacity depends on natural hydrogeologic conditions such as hydraulic conductivity, coastal aquifer thickness, natural groundwater flow direction and velocities, as well as interaction with nearby fresh water aquifers. Sufficient wave movement prevents clogging and bay flushing supports dissipation of retained colloids in the ocean [15]. Through natural attenuation processes, such as size exclusion, adsorption, degradation, chemical precipitation, grazing, inactivation and dilution, beach well intakes can provide higher-quality feedwater in terms of turbidity, DOC, biological stability and bacteria counts than open seawater intakes.

Vertical beach wells are abstraction wells drilled vertically into coastal aquifers with favourable hydrogeologic conditions (Figure 1). They consist of a non-metallic fibreglass-reinforced pipe or PVC casting, stainless steel well screen and are outfitted with a stainless steel pump [16]. Horizontal wells or collector wells are made of a vertical reinforced concrete pump shaft with lateral well screens that are drilled horizontally into the aquifer (Figure 2). Vertical wells are cheaper than horizontal wells and can be used to explore deep aquifers [17], while collector wells have a greater screen intake area than vertical wells and thus yield more water. Vertical wells experience radial inflow from seaward and landward directions, whereas inflow into horizontal collector wells (Figure 2) depends on the lateral well screen design and can be mainly from the seaward as well as landward direction [18].

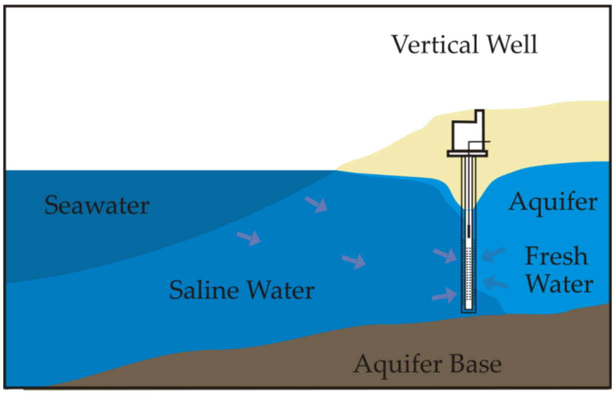

Figure 1. Vertical beach well

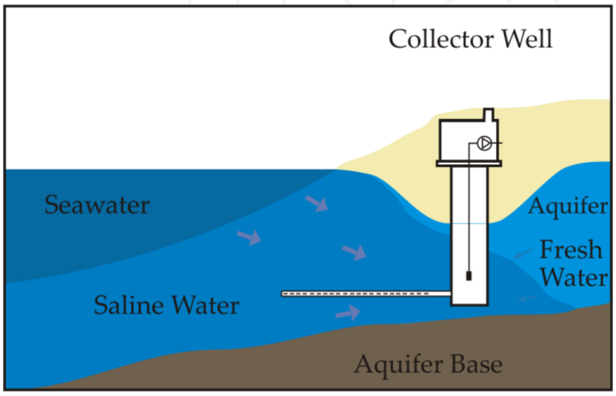

Figure 2. Horizontal beach well

Collector wells can be designed (depending on the method of construction) with lateral lengths of 40 – 70 m for Ranney type wells and up to 110 m for Sonoma method horizontal collector wells [19]. The second largest seawater reverse osmosis (SWRO) plant equipped with vertical wells is the Bay of Palma plant in Mallorca with a total capacity of 46,000 m³/d and a single well capacity of 5,600 m³/d [12]. A large SWRO plant in North America is the Pemex Salina Cruz plant that uses three Ranney type collector wells with a capacity of 15,000 m³/d each [16].

In order to maximize the intake screen area in shallow aquifers, wells can be drilled horizontally from the shore towards the sea linearly at an angle of up to 25° or non-linearly below the seabed as horizontal directional drillings (HDD). Today, the largest SWRO plant in the world is the San Pedro del Pinatar desalination plant in Spain. Through 19 HDD drains the plant is able to abstract more than 150,000 m³/d of seawater [20]. Here, HDD drains were used because the coastal aquifer was hydraulically disconnected from the sea by a vertical geological fault. The HDD intake (Figure 3) was constructed by drilling horizontally through the fault to successfully tap the 5 m shallow, highly productive solid calcarenite marine aquifer [21].

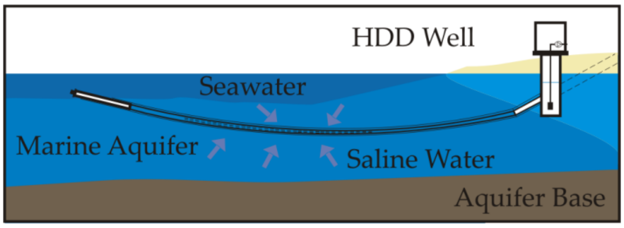

Figure 3. Horizontal directional drain

If the actual capacity of the drain intake turns out to be lower than the projected capacity, HDD systems can be easily converted to open seawater intakes by removing the pipe end cap [20]. In contrast to vertical and horizontal collector wells, HDD drains allow waterworks to exploit solely marine aquifers when nearby fresh waters are contaminated. Another advantage of HDD systems is the flexibility in design. Space limitations or expensive land prices can be overcome or reduced by installing high capacity fan shaped drain batteries which only need a comparably small area for the drain joint and the pump house.

At sites with unfavourable hydrogeologic conditions for beach wells, artificial seabed infiltration galleries can be installed for beach sand filtration. Infiltration galleries are constructed by installing screen pipes in excavated areas a short distance out from the seashore beyond the low-tide line (Figure 4). The excavation is backfilled with porous material and screened pipes are connected to a pump station.

Alternative designs that are conceivable for abstracting beach sand filtrate are illustrated in Figure 5. Designed following the example of the Louisville RBF site in Ohio, USA, galleries of horizontal lateral intake pipe screens that are embedded in individual artificial seabeds are connected to a single collector pipe (Figure 5a). In Figure 5b, seawater is filtered through an artificial seabed and abstracted by a single large-diameter drainage pipe.

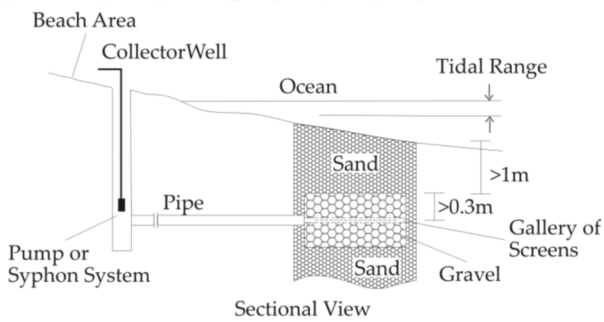

Figure 4. Seabed filtration system, adapted from [23]

Site	Ocean	Geology	Well type	Abstraction rate (m³/d)	SDI SW	SDI BW	Reference
Fukuoka, Japan	Genkai Open Sea	Artificial Sand (3m), d_{10}=0,4mm	Infiltration Gallery	100,000	4.3-5.7	2	[25]
Al Birk, Saudi Arabia	Red Sea	Carbonate silty sand with shell and coral	3 Vertical wells	1,700-2,900 each	3,2	0,4-1,2	[30]
Arucas-Moya, Gran Canaria	Atlantic Ocean	Basaltic rock	1 Vertical well	8,000	2-6	<1	[35]
Pemex Salina Cruz refinery, Mexico	Pacific Ocean	-	3 Ranney Wells	15,000 each	-	<2	[15]
San Pedro del Pinatar, Spain	Western Mediterranean Sea	Limestone	HDD-Neodren	>150,000	(10,6 NTU**)	<5 (2 NTU**)	[22, 36]
Dana Point, US	Pacific Ocean	Alluvial sand	Slant well (23°)	11,400	-	0.35*	[19]

*no significant portion of "young" seawater, only "old" sea and brackish groundwater, ** average value (n=5) 03-05/2006, SDI - silt density index, SW - seawater, BW - beach well

Table 1. Selected sites with subsurface intakes

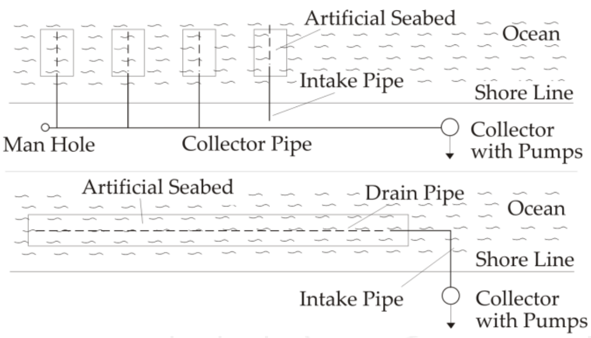

Figure 5. Alternative seabed filtration designs

The Fukoaka district SWRO desalination plant using an infiltration gallery has an abstraction capacity of 100,000 m³/d [18]. The 2.95 m thick artificial multi-media filter bed covers an area of 20,133 m². Water is pumped from perforated intake pipes, which are embedded within a layer of ungraded, crushed gravel, to an intake tank. The infiltration velocity is approximately 5 m/d and adjusted by creating a difference in head between the seawater level and the water level in the intake tank [24, 25]. Care must be taken in designing infiltration galleries. The typically thin layer of artificial sand around the screen pipes is limited in its capacity to retain particles and organic substances, which is difficult to determine. As a result, seabed filtration systems are more prone to pore clogging than conventional beach well intakes [23] and wave action plays a more important role than for other beach well designs.

3. Efficacy of Beach Sand Filtration

In membrane applications, the fouling potential of feedwater is typically estimated using the silt density index (SDI) by setting up a standard dead-end filtration test with continuous flow under pressure [26]. The SDI is determined by the decrease in flux due to the accumulation of foulants onto the membrane surface. In RO desalination, a feedwater SDI <2 – 3 [27] is desirable, but values <4 – 5 are acceptable [26]. Operational experience with existing beach well intakes shows that beach wells can deliver good quality feedwater with an SDI value of 0.3 – 1 with no need for further pre-treatment. HDD drains and infiltration galleries with short retention times can reduce SDI below 5 (Table 1). On the other hand, the demonstration under-ocean seawater floor intake that was installed at Long Beach in 2008 and designed following the example of Fukuoka with a approximately 1.5 m deep artificial seabed did not meet the requirements for RO membrane desalination.

Further pre-treatment was necessary as turbidity and SDI did not improve as desired and SDI was as high as 6 [28]. In comparison to the original seawater, water abstracted by beach wells is characterized by stable temperatures [29] and reduced biofouling potential due to the removal of organic nutrients [30]. It has been shown that a beach sand passage on the western Mediterranean Sea of 0.8 – 1 m at an infiltration rate of 10 m/d reduces DOC by 21 % and removes 70 % of easily degradable biopolymers [31].

Although the Long Beach demonstration under-ocean floor did not meet the RO requirements for SDI and turbidity, it was shown that DOC and biodegradable biopolymers were removed by 30 and 75 % after 1.5 m of sand passage. The highest nitrogen removal measured was by 70 %, as dissolved organic nitrogen originating from biopolymers [32]. Average removal of assimilable organic carbon (AOC) was in the range of 38 – 47 % and in contrast to DOC removal slightly higher at the higher infiltration rate of 5.9 m/d compared to 2.9 m/d [28]. At the Al-Birk SWRO plant on the Red Sea, TOC was reduced after beach well abstraction by 68 %. Easily degradable dissolved carbohydrates and proteins were reduced by 51 – 69 % and 73 – 100 %, respectively [30].

American Water analysed feedwater samples from different desalination plants throughout the world concerning AOC and TOC, which are main indicators for biofouling in SWRO [33, 34]. AOC and TOC were in the range of <51 – 500 µg/l and <1 – >10 mg/l, respectively. Schneider et al. [33, 34] found that feedwater abstracted from beach wells had lower AOC and AOC-substrate utilization rates than direct open water intakes and thus less biofouling potential. Veza et al. [35] measured the biofouling as bioaccumulation on a biomonitor and subsequent analysis of the adenosine triphosphate using a photoluminescence apparatus. The bioaccumulation was significantly lower in water abstracted by beach wells compared to seawater, which corresponds to an open seawater intake.

Mixing with brackish or fresh water can yield a reduced salinity and thus a lower osmotic pressure and energy consumption. Due to the influence of groundwater, beach well water can also be polluted by contaminants such as fuel oil constituents, endocrine disruptors and septic tank leachate [15]. The presence of dissolved iron and manganese accompanied by low dissolved oxygen concentrations in the infiltrate can make pre-treatment of the abstracted water necessary. According to Voutchkov [37], dissolved Fe and Mn-concentrations can be tolerated up to 2 and 0.1 mg/l, respectively. However, mixing of oxic beach sand filtrate with anaerobic groundwater or storage of anaerobic beach sand filtrate in open intake water tanks, iron and manganese are oxidized, causing accelerated fouling at feedwater concentrations of 0.05 and 0.02 mg/l [37].

4. Beach Sand Filtration in Egypt

Most of the Egyptian Red Sea coastal tourism areas meet their fresh water requirements through desalination processes. Reverse osmosis desalination plants are widely used in Egypt and the feedwater is seawater supplied via open seawater intakes and vertical beach wells [38-40]. The permeate water quality complies with both the Egyptian Ministry of Health and WHO regulations concerning drinking water quality [41]. For example, the Dahab SWRO plant has been constructed on the wadi Dahab alluvial fan at Dahab city in the south of the Sinai Peninsula. Wadi Dahab alluvial fan extends submarine for about 25 km and can be traced down to a water-depth of 1000 m within the Gulf of Aqaba [42]. The Dahab alluvial fan facies mainly consists of coarse gravels. Boreholes drillings to about 62 m depth show the occurrence of an overlaying, shallow coral reef bed at 2 m depth below ground surface and an average thickness of about 10 m along the coast. Saline water is supplied from 5 "old" and 10 "new" wells placed at 6 – 41 m distance to the shoreline along the Gulf of Aqaba (Figures 6 and 7). The SWRO station consists of four units, two units with a maximum capacity of 2,000 m^3/d and two units with 3,000 m^3/d (Figure 8). The beach wells have a diameter of 15 and 20 cm and an abstraction rate of 20 – 80 m^3/h (old wells) and 120 – 150 m^3/h (new wells). The wells are drilled down to a depth between 46 and 58.8 m, and the filter screens are located between 10 and 45 m below ground surface. The salinity of the feed seawater is in the order of 44,000 ppm, the salinity of the permeate and the concentrate is about 355 ppm and 52,115 ppm, respectively. The use of beach wells improves water quality, particularly through removal of particles and organic matter. Dahab beach wells deliver good quality feedwater with an SDI value in the range of 0.27 to 0.82 compared to seawater SDI values taken from the nearby Sharm El-Sheik old harbour plant from 2.6 to 2.7 with no need for further pre-treatment. In addition, the chemical consumption rate per month used for pre- and post-treatment is about 30 % to 50 % lower than that at Sharm El-Sheik old harbour plant.

Results from a water quality analysis in February 2012 in Dahab showed a reduction in DOC and UV-254 through beach well filtration by 25 – 50 % and 36 – 67 %, respectively (Table 2).

Parameter	Sea-water	Well 9 old	Well 8 old	Well 1 new	Well 8 new
Distance (m)	0	6	9.5	31	41
DOC* (mg/l)	1.6	1.2	2.3	0.6	0.8
UV-254 (m^{-1})	1.4	0.8	0.9	0.8	0.6
EC (mS/cm)	61.9	62.2	62.0	56.7**	63.4

*detection limit DOC = 1 mg/l, **higher portion of groundwater

Table 2. Dahab beach well water analysis (February 2012)

Lower DOC/UV values at well 8 (new) indicate higher attenuation rates due to a greater travel distance and a corresponding longer travel time. The sand acts as a natural filter and the subsequent chemical treatment cost is low [40].

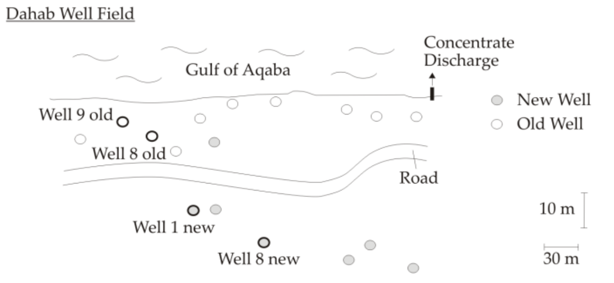

Figure 6. Location of beach wells at Dahab, Egypt

Figure 7. Well field at Dahab desalination plant

Figure 8. Dahab RO Membrane Unit

Due to the corrosive nature of saline water the beach well pumps were corroded shortly after starting operation. Beach sand filtration is evaluated to allow longer use of membranes in the treatment plant, where the cost of the membranes is approximately 20 % of the total cost of the desalination process, but this evaluation was done by the operators in a qualitative way and has not yet been quantified. Another advantage is that the feedwater produced from the beach wells has a stable temperature all year round, since RO systems are sensitive to changes in feedwater temperature. However, the recent occurrence of dissolved iron in one of the new wells at Dahab SWRO plant with concentrations of 0.6 mg/l may increase the investment and operational costs of additional pre-treatment in the future. Today, the iron can be passed through a multi-media bed filter prior to membrane filtration, but remains a problem for raw water supply pipes.

Along the Gulf of Aqaba, open seawater intakes also face other problems besides dissolved iron and landward groundwater contaminations. During summer low tide, the difference in head between the minimum water level in the intake tank of the Sharm El-Sheik old harbour desalination plant and the open sea is below the minimum level required to sustain a constant feed flow rate under gravity alone. Furthermore, the same open intake pipe itself has repeatedly been misused to anchor small- and medium-sized fishing boats, and was thus lifted up or dislocated from its original position, possibly sustaining structural damage.

5. Simulation of Beach Sand Filtration Using Column Experiments

Column experiments have been carried out using natural and wastewater DOC-spiked seawater and coral beach sand from Lanikai Beach, Hawaii (USA) to assess the TOC removal efficiency of coral sand at low and high infiltration rates as a function of the flow path length (travel/contact time).

The experimental flow-through column setup consisted of a 1 m long and 0.1 m diameter acrylic pipe hand-filled to 0.9 m with coral sand (Figure 9).

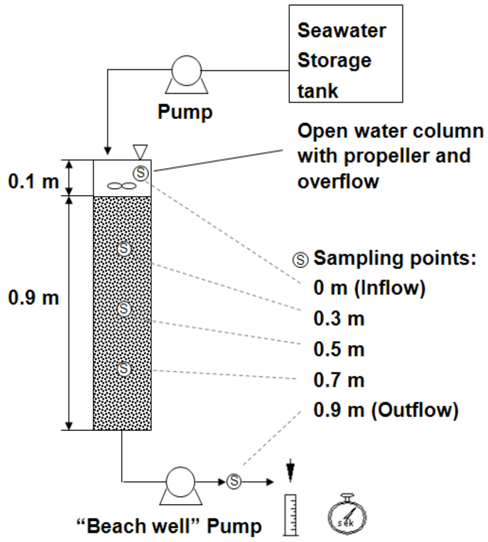

Figure 9. Experimental setup

The energy dispersive spectroscopy performed at 2 KV showed the coral sand's elemental composition to consist mainly of oxygen, calcium and carbon. More than 95 % of the grains were smaller than 1 mm and 90 % of the retained grains were in the range of 0.1 mm to 1 mm. The uniformity value was calculated to 2.2. The platy shaped coral sand had a measured hydraulic conductivity of 1.0E-04 m/s and a porosity of 41 %. To minimize wall effects, the sand was filled in wet and compacted in layers. After every compaction, water was pumped from the bottom in up-flow manner below the sandbed surface to remove entrapped air bubbles. The acrylic column was wrapped in opaque aluminium foil to prevent photodegradation and the growth of algae. At the inlet on top was a 0.1 m deep pump-fed open water column, equipped with an overflow to ensure a constant water level. This water column was constantly stirred at 20 rpm with a small propeller to prevent sedimentation and simulate wave movement. A clear clogging layer was not observed on the filterbed during the experiments nor did head loss affect the infiltration rate significantly. The water flow was regulated by a peristaltic pump installed at the column outlet. Water was drawn in a down-flow manner from the open water inlet through a 0.9 m long coral sand passage at constant room temperature of 20 – 21 °C. Three thin PE tubes with an inner diameter of 1.6 mm were placed at different depths inside the column to extract water samples with a syringe from 0.3 m, 0.5 m and 0.7 m below the sandbed. Water samples were also taken directly at the column inlet and outlet (PE tube). Flow rate was measured using a measuring cylinder and a stop watch. Water was analysed for parameters relevant to membrane fouling, such as TOC, turbidity and total nitrogen (TN) at low (0.4 m/d) and high (1.1 m/d) infiltration rates. TOC was analysed in duplicate as non-purgeable organic carbon (NPOC) together with TN in a Shimadzu TOC-V analyser with a TNM-1 total nitrogen detector. Turbidity was analysed using a 2100 N Turbidimeter (Hach) and nitrate using a Dionex DX-120 Ion Chromatograph. Dissolved oxygen, pH and electrical conductivity (EC) were measured using YSI probes in a flow-through cell. After a run-in phase of four weeks at the low infiltration rate and another week at the high infiltration rate, infiltration tests were run first with natural seawater at high and thereafter at low infiltration rates. Later, seawater was spiked with wastewater-derived DOC to simulate higher DOC, by adding filter-sterilized wastewater effluent from activated sludge treatment at the Honouliuli wastewater treatment plant at a ratio of 1:4. The seawater was collected weekly at Ala Moana Beach Park, located on Oahu's south shore in central Honolulu. The beach is man-made with coarse sand, protected by a reef and thus popular for swimming. Water was filled into photo resistant tanks at 0.5 m depth and stored in the laboratory at 4 °C.

Using natural seawater (nat. SW) at a low infiltration rate, the dissolved oxygen (DO) was completely consumed (to <0.2 mg/l) after 0.9 m filtration distance. As flow path length increased, the TOC concentration decreased linearly by 31 – 36 % from 0.98 – 1.02 mg/l to 0.67 mg/l at 0.9 m through biological metabolism as indicated by the strong oxygen depletion TN was in the range of 0.10 – 0.11 at 0 m and 0.09 – 0.11 mg/l at 0.9 m, indicating no significant change in concentration between in- and outflow. Turbidity was reduced by 47 – 67 % during 0.9 m sand filtration from 0.32 – 0.52 NTU to 0.16 – 0.17 NTU (Figure 10). Most of the turbidity-causing particles and colloids were already removed at 0.3 m into the sandbed. Longer flowpaths showed little further removal.

At high infiltration rates, dissolved oxygen was measured at 3 – 4 mg/l in the outflow, but TOC reduction was still in the range of 30 – 34 %. As TOC degradation remained unaffected by the travel time, it is assumed that most of the easily biodegradable fraction of TOC was degraded at both high and low infiltration rates. The lower dissolved oxygen values measured at the column outlet at low infiltration may be explained by the degradation of entrapped algae and organic matter within the coral sand, which is also subject to biological metabolism. Outflow turbidity was slightly higher in tests at low infiltration rates, but it was concluded that shear forces showed no effect on the removal efficiency as outflow turbidity was 0.13 – 0.14 NTU (Figure 10).

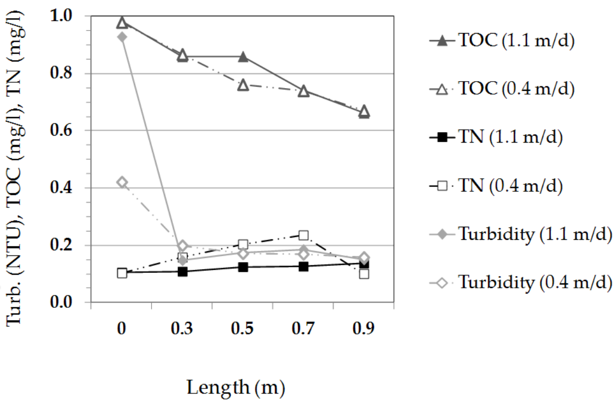

Figure 10. Turbidity, TOC and TN during filtration at high and low infiltration rate (average values, n=2-3)

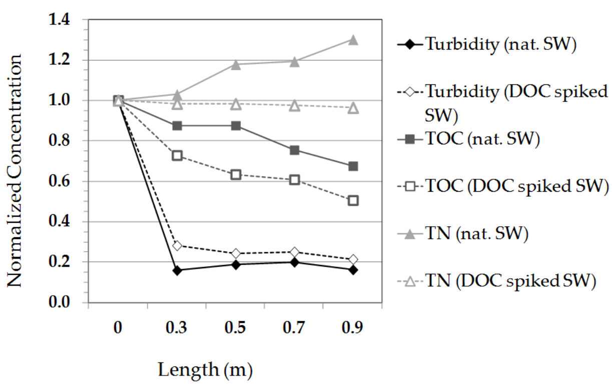

Figure 11. Turbidity, TOC and TN in natural and wastewater-spiked seawater at high infiltration rate (average values, n=2-3)

Beach well systems may be affected by wastewater inputs due to further development along coastlines and insufficient regulations. Thus, experiments were carried out with a mixture of seawater and domestic wastewater. Adding wastewater at a ratio of 1:4 lowered EC and DO from 49 to 41 mS/cm, and 8.4 to 6.6 mg/l, respectively. Nitrate increased from below the detection limit to 1.48 mg/l. Average TN and TOC were stepped up from 0.1 to 3.8 mg/l and 0.98 to 2.47 mg/l, respectively. Turbidity showed no effect from mixing.

Tests with wastewater-spiked seawater (DOC-spiked SW) were only conducted at a high infiltration rate. Nitrate concentration increased up to 4 mg/l at 0.9 m due to nitrification. Dissolved oxygen was measured below 0.2 mg/l in the outflow. Due to more easily available organic carbon, 47 – 52 % of the TOC was removed after 0.9 m beach sand filtration. The linear removal rate was up to four times higher than with natural seawater. TN was reduced slightly by 3 – 4 %. Turbidity was again removed to a value of 0.13 – 0.14, but above 0.1 NTU (Figure 11).

6. Conclusions

Through natural filtration, beach well abstraction can reduce BDOC and subsequent membrane fouling, and can even render pre-treatment unnecessary. According to the literature, SWRO plants on the Western Mediterranean Sea, the Gulf of Aqaba, North Pacific Ocean and the Red Sea utilizing beach wells show less bio- and organic fouling than conventional open seawater intakes. Studies have shown that beach sand filtration significantly reduces hydrophilic neutral substances such as polysaccharides and proteins with high molecular weight as well as AOC and DOC. Preliminary experimental results from column tests with coral beach sand from Hawaii show good reduction of the targeted parameters. In this study, tests indicate that the efficiency of the coral sand filterbed in removing turbidity and the biodegradable fraction of TOC was not affected by low and high infiltration rates. As in RBF, the highest removal of turbidity and TOC took place after infiltration in the upper sandbed. A flow path length of 0.3 m depth was sufficient to remove 70 to 92 % of the particles and colloids measured as turbidity in the seawater. Further filtration showed no effect and turbidity was not reduced below a value of 0.13 – 0.16 NTU. At both high and low infiltration rate, a flow path length of 0.9 m was sufficient to remove the easily biodegradable fraction of TOC and up to 50 % of the TOC in test with wastewater-spiked seawater at high infiltration rate and a temperature of 20 °C. Beach wells provide water with less turbidity, consistent water temperature, reduced dissolved organic content and higher biostability. However, beach sand filtration systems are limited in capacity by beach sand hydraulic conductivity and aquifer thickness. New beach well systems, such as HDD wells and artificial seabeds, have been designed to overcome hydrogeological limitations. However, further research is needed for a better understanding of how organic and bio-fouling can be effectively reduced by beach well abstraction and what are the design recommendations (e.g., filterbed depth, infiltration rate) for the cost effective design of beach well systems.

7. Acknowledgements

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