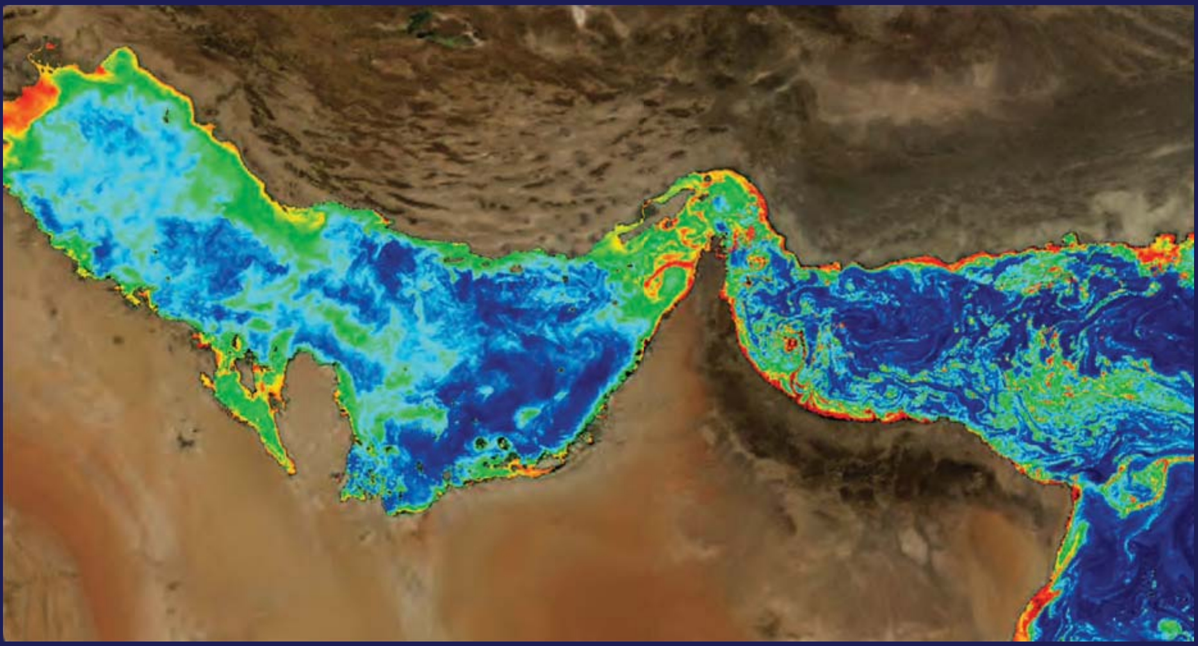
United Nations
Educational, Scientific and
Cultural Organization

Intergovernmental
Oceanographic
Commission

Manuals and Guides 78

Harmful Algal Blooms (HABs) and Desalination: A Guide to Impacts, Monitoring, and Management



Edited by:

Donald M. Anderson, Siobhan F.E. Boerlage, Mike B. Dixon

UNESCO

Manuals and Guides 78

Intergovernmental Oceanographic Commission

Harmful Algal Blooms (HABs) and Desalination: A Guide to Impacts, Monitoring and Management

Edited by:

Donald M. Anderson*
Biology Department, Woods Hole Oceanographic Institution
Woods Hole, MA 02543 USA

Siobhan F. E. Boerlage
Boerlage Consulting
Gold Coast, Queensland, Australia

Mike B. Dixon
MDD Consulting, Kensington
Calgary, Alberta, Canada

*Corresponding Author’s email: danderson@whoi.edu

UNESCO 2017

11 CASE HISTORIES FOR HARMFUL ALGAL BLOOMS IN DESALINATION

Siobhan F.E. Boerlage[1], Mike B. Dixon[2] and Donald M. Anderson[3]

[1] Boerlage Consulting, Gold Coast, Queensland, Australia
[2] MDD Consulting, Kensington, Calgary, Alberta, Canada
[3]Woods Hole Oceanographic Institution, Woods Hole, MA USA

11.1 INTRODUCTION

Algae have long been an issue impacting desalination plant operation in areas prone to algal blooms or where macroalgae (seaweeds) and detritus became dislodged from the seabed. Previously and still today, operators and designers may elect to turn down production or shut down SWRO plants, if contract obligations allow, when blooms are infrequent or of short duration. Alternatively, in areas subject to frequent and prolonged blooms, additional pretreatment such as conventional dissolved air flotation (DAF), hitherto designed for brackish water applications, began to be employed as early as 1995.

The unprecedented 2008/2009 bloom of *Cochlodinium polykrikoides* in the Gulf of Oman and the Gulf[1], brought algal blooms to the fore in the desalination industry. SWRO plant shutdowns were up to four months long as pretreatment processes struggled to remove the increased biomass and produce the required RO feedwater quality. Apart from a few exceptions, thermal desalination plants continued to operate without major issue throughout the bloom, as phytoplankton blooms generally pass through intake screens and thermal processes are very forgiving of source water quality. This was demonstrated at the Fujairah 1 hybrid desalination plant where the multi-stage flash (MSF) plant operated throughout the bloom while the adjacent SWRO plant was shut down.

---

[1] Here the Gulf refers to the shallow body of water bounded in the southwest by the Arabian Peninsula and Iran to the northeast. The Gulf is linked with the Arabian Sea by the Strait of Hormuz and the Gulf of Oman to the east and extends to the Shatt al-Arab river delta at its western end.

Globally, harmful algal blooms (HABs) similar to the 2008 bloom of *Cochlodinium polykrikoides* are increasing in frequency and severity (Anderson et al. 2012). Coupled with the increasing use of RO as the desalination technology of choice, HABs have become one of the major challenges facing the industry as RO membranes are extremely vulnerable to feedwater quality, making pre-treatment exceptionally important. Smooth operation is contingent on the selection of appropriate pretreatment processes upstream to remove organics, solids, colloids and other foulants from the RO feedwater. The 2008 Gulf HAB highlighted the limitations of conventional pretreatment based on ferric chloride coagulation and single stage dual media filtration (DMF) in removing algal biomass and organics. Ongoing research efforts to identify the algal organic matter (AOM) constituents responsible for membrane fouling and measurement of their removal in pretreatment intensified. To this end, the spike in AOM occurring during a bloom was found to comprise mainly of high molecular weight biopolymers (polysaccharides and proteins), which include sticky transparent exopolymer particles (TEP) (Myklestad 1995; Villacorte 2014). TEP have been shown to form microgels with a high hydraulic resistance and are increasingly recognized to promote biofouling of RO membranes (Villacorte 2014; Berman and Holenberg 2005; Li et al. 2015). With the increasing adoption of low pressure microfiltration (MF) and ultrafiltration (UF) membrane pretreatment, questions were raised as to their performance during algal bloom events and how they compared to conventional pretreatment in removal of AOM.

In preparing the Manual and to address some of the above questions, operators, researchers, and plant owners in the desalination industry were contacted as part of an informal survey and invited to contribute case studies related to their experience with algal blooms. As expected, it became clear that algal bloom issues were predominantly encountered in SWRO plants rather than those using thermal desalination. Twelve SWRO plants (Figure 11.1.1) at eleven different sites were in a position to share their experiences from a shortlist of 30 sites that may have experienced HAB issues.

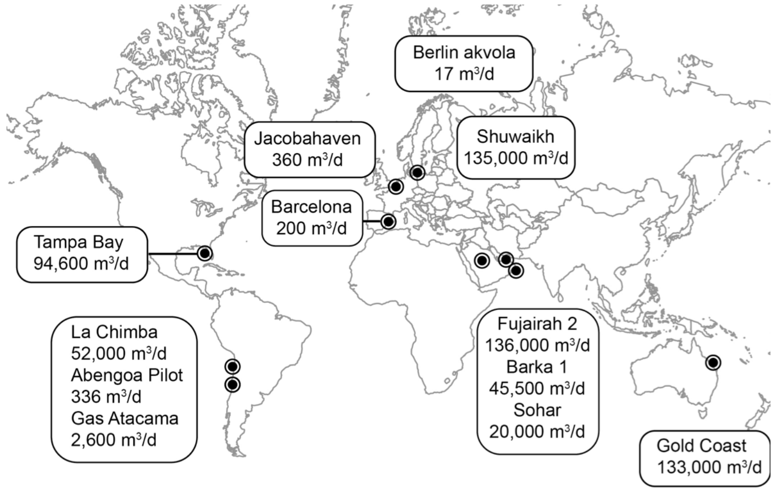


Figure 11.1.1. Location of the 12 plants presented in the case studies that have experienced algal blooms (two were at the same site).

Algal blooms, primarily phytoplankton, were reported in almost all geographic locations, in cold and warm seas over a range of salinities affecting municipal and industrial desalination plants. Notable areas affected include the warmer waters of the Gulf of Oman and the Gulf in the Middle East. Case studies include Sohar and Barka 1 in Oman, Fujairah 2 in UAE and the Shuwaikh plant located close to Kuwait's most important commercial port in the upper reaches of the Gulf where seawater quality is at its poorest. HABs are also commonly found in the cooler waters off the coast of Antofagasta in Northern Chile supplying industry and drinking water for towns in one of the driest areas of the world.

Key insights from the 12 case studies are summarized below in terms of impacts experienced, if any, in both conventional and advanced MF/UF membrane pretreatment plants during algal blooms. Commonly recommended measures implemented in the industry to combat algal blooms are discussed in relation to the case studies mitigation strategies, and lessons learned. This encompasses measures adopted during design and/or during plant operation, e.g. deep-water intakes (Gold Coast), and DAF (Fujairah 2, Shuwaikh) and/or direct MF/UF filtration (Jacobahaven, Sohar), or subsequently enacted in response to HAB events (La Chimba).

11.1.1 Algal-related impacts in desalination

HABs pose two main operational risks in desalination, namely safety of the drinking water produced (which relates to the toxicity of the bloom) and security of supply (Boerlage and Nada 2014). HABs are broadly classified as toxic or non-toxic. Toxic algal blooms produce potent toxins, causing illness or mortality in humans, fish, marine mammals, and other marine life through either the direct exposure to the toxin or ingestion of bioaccumulated toxin in higher trophic levels e.g. shellfish consumption. In desalination, marine algal toxins represent a potential health risk to the safety of desalinated drinking water if present in sufficiently high concentrations in the seawater and they breakthrough through the desalination process.

Non-toxic HABs can cause damage to ecosystems, fisheries resources, recreational areas, and commercial facilities such as desalination plants, sometimes because of the biomass of the accumulated algae, and in other cases due to the release of compounds that are not toxins (i.e., reactive oxygen species, polyunsaturated fatty acids, organic matter, mucilage) that can be lethal to marine animals or that can cause disruptions of other types. In desalination, these blooms represent an operational risk to plants, threatening water supply security through unplanned outages, and loss of production at any point in the process from blinding of intakes (less common) through to failure of pretreatment unit processes and/or the RO system itself. Such blooms can have massive financial impacts. Huge economic losses were reported, for example, at Oman's Sohar Industrial Port Area (SIPA), which supplies desalinated water and seawater cooling water to industrial customers. The non-toxic bloom of *Cochlodinium polykrikoides* in 2008/2009 resulted in an increase in the frequency of cleaning seawater intake screens from every 12 hours to every 4 hours and an inability to maintain the required free residual chlorine. The independent SWRO plant operated by the Sohar Refinery at SIPA shut down for four months and required 100% membrane replacement due to severe biofouling.

A myriad of HAB impacts in desalination were identified in the cases studies. Some are easily identified with most posing a risk to the security of desalinated water supply as in general, the causative species of the HAB, where identified, were non-toxic. Other impacts were more obscure and relate more to the perception that desalinated drinking water may be unsafe (e.g., malodorous) or even to the perceived environmental impacts of brine during an algal bloom event.

Perceived impacts associated with safety of drinking water may follow the decay of an algal bloom. In 2011, the La Chimba plant, supplying 60% of Antofagasta's drinking water, detected hydrogen sulfide at the seawater intake. The seawater, abstracted from a deep water intake, had become hypoxic (DO<0.5 mg/l) due to the decay of an intense bloom of *Prorocentrum micans* made worse by thermoclines that restricted mixing and movement of water in the bay. Under these conditions, sulfate reducing bacteria (SRB) flourished and hydrogen sulfide was generated. While the inhalation of hydrogen sulfide in air is well known to be extremely toxic, there are no data on the human health effects of ingesting water that contains hydrogen sulfide (NHMRC/NRMMC 2011). Instead, impacts are mainly related to the foul smell of rotting eggs, with hydrogen sulfide having a very low taste and odor threshold in water, estimated to be as low as 0.05 mg/l (WHO 2011). As a gas, hydrogen sulfide can readily pass through RO membranes resulting in customer complaints and/or the perception that water produced following a HAB is unsafe. Alternatively, oxidation of hydrogen sulfide could lead to elemental sulfur which has a detrimental effect on membranes. The plant owner therefore quickly enacted a raft of measures to remove H_2S from the product water.

Another atypical issue encountered during an algal bloom event was that a desalination plant was thought to be the cause of a dark plume in the seawater in an area renowned for its beaches and recreational fishing. A vast *Trichodesmium* bloom occurred in the area of the brine outlet (and intake) during commissioning of the Gold Coast plant which led a member of the public to complain to the local Environmental Protection Agency (EPA) of a dark plume emanating from the brine outlet. The bloom was, in fact, demonstrated to frequently occur naturally in the area (prior to the construction of the plant) and shown not to be entrained in the plant intake. If it was entrained, the solids associated with the high concentration of algal cells would be removed during residual treatment and not be returned to sea. Hence, no plume would be evident from the brine outfall. Nonetheless, this demonstrates potential community perception issues associated with algal bloom events in desalination.

The more typical algal-related issues in SWRO desalination arising from the high biomass and organics accompanying non-toxic HABs are well known in the desalination industry. High biomass blooms can increase suspended solids beyond design thresholds, overloading conventional granular media filters (GMF) and resulting in rapid filter clogging. If the coagulation dose becomes prohibitively high in response to a bloom, surface clogging of the media may occur, severely limiting filtration capacity. Downstream this may lead to more frequent cartridge filter replacement and cleaning of the RO membranes due to a higher iron residual and higher concentration of colloids and AOM remaining in the RO feedwater. At worst, plant production is lost due to frequent media backwashing and short filter runs, and conventional pretreatment may fail to produce water to meet RO guidelines. Plants are then forced to void warranties and continue operating or shut down to avoid the risk of irreversible RO membrane fouling. In the latter case, they may also incur cost penalties associated with loss of production. Conventional pretreatment was employed in 5 of the 12 case studies (Tampa Bay, Gold Coast, Barcelona, Atacama Plant 1, Fujairah 2). Shorter filter runs were observed for the diatomaceous earth filters at Tampa Bay during algal blooms, along with foaming. No negative impacts were observed in the gravity DMF at the Gold Coast plant as the deep water intake limited ingress of the most frequently occurring algal bloom. The same was true at Fujairah 2, which employs additional solids removal through an upstream DAF.

Similarly, HAB impacts are found in microfiltration or ultrafiltration which was the predominant pretreatment choice in the case studies. This involved a variety of membrane materials and pore sizes either in the pressurised inside-out or outside-in flow configuration. Here impacts were as expected and included blocking of strainers due to higher solids loading and increases in transmembrane pressure (TMP) in order to maintain a constant permeate flux as pretreatment membranes fouled. Backwashing and chemically enhanced backwashing (CEB) intervals were severely shortened in some cases and less effective than in non-bloom conditions, with a marked membrane permeability decrease over time. Additional cleaning-in-place (CIP) to recover initial permeability was required in some cases (Sohar, Barka 1, Antofagasta, Jacobahaven).

Biofouling of the SWRO membranes was noted at the Sohar plant during algal bloom events in 2013 (and earlier in 2008 at the Sohar Refinery SWRO plant as mentioned above), which uses direct MF membrane pretreatment without coagulation. Additional RO membrane cleaning was also required at the SWRO plant at Atacama using conventional pretreament but the nature of fouling was not identified. Pretreatment was effective during algal bloom events for most of the remaining case studies with no additional cleaning reported for the SWRO or fouling was not directly attributed to algal blooms. RO fouling is typically complex with more than one type of fouling occurring and may be the synergistic effect of operating conditions prior, during or after a bloom e.g. overdosing of ferric coagulants causing iron fouling along with biofouling during or following the termination of the bloom.

11.1.2 Algal bloom mitigation and lessons learned

11.1.2.1 Characterization of seawater quality and piloting

Ideally, prior to SWRO plant design, seawater quality is thoroughly characterized through a long-term monitoring study (see section 11.1.2.1.1 for parameters) to assist in selecting an intake site and pretreatment processes from which the plant footprint and layout can be estimated. This should be coupled to a review of historical records to determine factors that impact on water quality such as the frequency and severity of algal blooms. Hydrodynamic conditions at the intake area should also be considered, such as the presence of thermoclines or upwelling that may promote HABs. Monitoring methods and approaches are covered in detail in Chapters 3 and 5.

It should be noted that water quality can vary in a region or be strongly influenced by intake design. The importance of having data specific to a site cannot be understated, as highlighted by the Sohar case study in Oman. Sohar's SWRO plant based its design for a direct MF membrane pretreatment system on blooms with a maximum duration of one month once a year and on process data (e.g. MF flux) from a similar plant operating for 5 years located on the Duqum Coast of Oman. Instead of one month, the plant encountered a prolonged bloom of six months during plant commissioning and extremely poor water quality exacerbated by its shallow lagoon intake system. The plant experienced a multitude of issues including clogging of the intake screen, partially clogged self-cleaning strainers, high TMP on the MF system, biofouling of the SWRO, and ultimately loss of production and supply for downstream industrial users. Short-term mitigation measures to maintain supply included lowering MF flux and renting containerized MF-RO plants to compensate for the applied drop in production. A one-year feedwater characterization study for design was recommended following their experience.

Pilot plant trials are often employed in addition to, or instead of, a seawater quality assessment study and are a useful tool offering many benefits for process design optimization, leading to successful long term operation of the full scale plant. Ideally, MF/UF can be operated at high flux and without the addition of coagulant, thereby avoiding capital and operating costs associated with chemical storage, residual handling and treatment for coagulated solids. In practice, MF/UF cannot always achieve high fluxes during challenging water quality conditions such as HABs or storms where the solids and/or organic feedwater load increase. Piloting can therefore assist in determining whether solids removal by clarification or flotation is required prior to conventional or membrane pretreatment. Should no bloom occur during piloting, plants can be challenged through the addition of cultivated algae to the raw water (see section 11.5). Process parameters can also be optimized such as the fluxes that can be achieved on MF/UF with or without coagulation, efficacy of mechanical (hydraulic backwash, air scour) cleaning frequency and duration of CEB or CIP to maintain production targets (Sohar, Barka 1, Antofagasta, Jacobahaven). This information is often critical in preventing over-capitalization of pretreatment facilities if coagulation is incorporated for MF/UF pretreatment or upstream clarification or flotation. Moreover, these facilities may only be required for a short period each year. Alternatively, pretreatment requirements may be underestimated or key process parameters overly ambitious, potentially leading to loss of production and severe disruptions to drinking or industrial water supply.

Four of the case studies directly relate to piloting pretreatment options and process optimization during algal blooms; Abengoa, Jacobahaven, Barcelona, and the akvola pilots. Pilot or lab studies were also used to support pretreatment plant design for many of the full-scale plants reported in this paper. Sohar's rental containerized plant, following significant HAB events, acted as a pilot plant to determine long-term mitigation strategies so that the existing plant could be redesigned to operate through such prolonged algal blooms.

11.1.2.1.1 Water quality parameters for HAB monitoring in design and operation

Methods to measure AOM, its fouling constituents, and their impact on membrane fouling potential (organic, particulate and/or biofouling) are important to detect blooms and assess pretreatment efficiency. Monitoring efforts also need to continue following the collapse of an algal bloom. The succession of bacterial species which can thrive on decaying AOM may release organic matter extracellularly including TEP which can contribute to fouling.

Conventional water quality parameters typically included in monitoring programs to provide an indication of the increase in organics, solids, and fouling potential include: TOC, DOC, TSS, turbidity, SDI, and DO. Monitoring of the same parameters for process control during plant operation as during the design phase provides continuity so operational data can be compared with baseline data.

Although, the aforementioned parameters are not specific to algal blooms, changes may indicate their presence, e.g. increase in TSS (Abengoa pilot plant), or indirect impacts from HABs such as low DO following decomposition of a dense bloom (La Chimba plant). Despite the well-known limitations of the SDI (Schippers and Verdouw 1980; Kremen and Tanner 1998; Boerlage et al. 2000; Boerlage 2008), it has proven useful in detecting algal blooms at the intake compared to other parameters including turbidity and chlorophyll-*a* (determined via fluorescence). Elevated SDI at the intake corresponded to algal bloom events as seen at Fujairah 2, Barka 1, Sohar and Gas Atacama plants. Care should be taken however, in interpreting results. Often the SDI was measured at intervals not recommended by the ASTM standard, e.g. SDI_3 and even SDI_1. The SDI test was not designed to measure high fouling feedwater such as algal-laden seawater nor for UF permeate where UF have smaller pores than that of the SDI membrane. SDI results will underestimate the fouling potential of feedwater during a bloom as it does not capture small particles responsible for fouling including TEP precursors and the SDI is not linear with particle concentration. Moreover, when assessing process performance, SDI cannot be directly compared for different filtration intervals, e.g. SDI_5 for raw water and SDI_{15} after pretreatment, or when measured at different temperatures (Boerlage 2008).

Measuring TOC to detect AOM in the source seawater and for process control is generally unreliable. TOC (and DOC) measure bulk organic matter and therefore provide no information as to the composition or concentration of potential AOM foulants produced during an algal bloom. While TOC increases in the source seawater were found at Fujairah 2, Sohar, and Tampa Bay, this is not always true. Measuring TOC removal to assess pretreatment efficiency processes and as a process trigger is also inaccurate due to the difficulties in measuring low-level TOC residuals in saline process streams (as discussed in the Fujairah 2 case study).

SDI and TOC are often interpreted in conjunction with other parameters which directly identify the presence of algal species in the source water through algal cell identification and enumeration or an increase in algal productivity or advance warning through remote sensing. Algal counts were reported at 10 of the plants, but the dominant species were not always identified. Although cell counting can be automated using new biosensors if conducted on discrete samples at external laboratories, this can result in prohibitively long turnaround times and therefore cannot be used as an alert to trigger process adjustment, as discussed for Fujairah 2. Identification of the algal species, size, and toxicity is important for plant operation and process control, but must be done on discrete samples by experienced personnel. Published and online taxonomic guides listed in the Manual can be of great value, but trained personnel are needed to insure consistency through time.

Chlorophyll-*a* measurements were reported at 6 plants with La Chimba obtaining chlorophyll-*a* data from satellite images provided by NPOES and MODIS satellites. Results from chlorophyll-*a* data using fluorescence measurements at the seawater intake are not always a reliable indicator of the severity of a bloom nor are the instruments easy to maintain. The relationship between chlorophyll-*a* fluorescence and cell biomass is not constant across all phytoplankton species, nutritional conditions, and times of sampling. Some species have a low content of chlorophyll despite their size e.g. *Noctiluca scintillans* which ranges up to 2 mm in size. Other factors influencing chlorophyll-*a* include nutrients and light history, with limitations often resulting in lower chlorophyll-*a* content than the same cells under more favorable conditions. This may explain why chlorophyll-*a* readings were very low at Barka 1 (species not identified), yet operational issues were observed, while Tampa Bay (*Ceratium furca* and *Phaocystis*) and the Jacobahaven plant (*Phaeocystes, Chaetoceros*) reported much higher chlorophyll-*a* values at times of operational difficulties. Similarly, Fujairah 2 reported no particular trends in chlorophyll-*a* concentrations during a bloom.

Satellite-derived chlorophyll-*a* in conjunction with information on prevailing currents has been used as an early warning system by desalination plants to track algal blooms approaching plant intakes. La Chimba in Chile used the Bricker et al. (Bricker et al. 2003) eutrophication status classification based on chlorophyll-*a* levels from satellite images to assess the risk for algal blooms during the summer months. For the 2013 bloom, water in Antofagasta Bay was classed as hyper-eutrophication (chlorophyll-*a* > 60 µg/L).

Recently, more sophisticated tests have been developed to determine constituents of AOM which may better indicate the biofouling and particulate fouling potential of seawater and process streams during a bloom. Villacorte (2014) demonstrated that biopolymers and TEP can promote fouling of both pretreatment and SWRO membranes. Monitoring of biopolymer and TEP concentrations during a bloom would therefore be informative. Biopolymers can be determined by liquid chromatography - organic carbon detection (LC-OCD). LC-OCD fractionates natural organic matter (NOM), primarily by size and also by ion interaction and hydrophobic interaction. Fractions vary from larger biopolymers (> 20,000 Da) of which TEP is a component, to low molecular weight compounds (< 350 Da). In a LC-OCD chromatogram, a spike in biopolymers is observed during an algal bloom. Two methods have been developed to determine fractions of TEP in seawater (Villacorte 2014). $\mathrm{TEP}_{0.4\mu m}$ measures larger TEP (>0.4 µm) while TEP_{10kDa} includes both TEP and most of the smaller TEP precursors. TEP precursors dominate AOM during a bloom, therefore, applying both tests allow the differences in pretreatment removal efficiency for these algal-derived foulants to be distinguished (Villacorte 2014); however, the degree of difficulty and cost in determining them is correspondingly higher. As samples need to be sent to specialized laboratories, delays in obtaining the results mean these parameters cannot be employed to alert a plant of a bloom or to adjust process parameters during plant operation. Consequently, only a few plants used these tests. The Barcelona and Jacobahaven plants both used LC-OCD to examine the performance of pretreatment steps to remove biopolymers. $\mathrm{TEP}_{0.4\mu m}$ was also monitored for three years at the Jacobahaven plant and a correlation between TEP and fouling rates in the UF pretreatment system was observed.

A method to determine assimilable organic carbon (AOC) based on luminescence using *Vibrio harveyi* has also been developed to indicate the biofouling potential of the source seawater and process streams (Weinrich et al. 2011). The saline AOC test was trialed at the Tampa Bay plant to monitor pretreatment. High levels of AOC were measured in the source seawater during a bloom that further increased following chlorine dioxide prechlorination which may be due to oxidation of organic matter. The AOC was greatly reduced by bioactivity in the subsequent sand filtration step (LeChevallier 2014; Tampa Bay Case Study).

Finally, there are improved methods to measure particulate fouling which can be used during a bloom. The Modified Fouling Indices (MFI), developed to address the limitations of the SDI, comprise the MFI-0.45 (an ASTM standard) and the MFI-UF using ultrafiltration membranes (Schippers and Verdouw 1980; Boerlage et al. 2000; Salinas-Rodriguez 2011). The MFI-UF with smaller pore size membranes can measure UF permeate unlike the SDI and MFI-0.45. Both MFI tests are normalized to reference temperature, area and pressure values and can measure high fouling feedwater. Therefore, MFI can be compared and pretreatment efficiencies can be determined. When using a 10 kDa membrane in the MFI-UF test, a high correlation was found between MFI-UF and $\mathrm{TEP_{10kDa}}$, measurements (Villacorte 2014). This indicates the MFI-UF could be used to investigate the fouling potential of feedwater containing the smaller high fouling TEP precursors across a plant during a bloom. Of the twelve case studies, only the Jacobahaven plant employed the MFI-UF where it was used to measure pretreatment efficiency.

11.1.2.2 Intake depth and location

Careful selection of intake type, depth, and location, is often considered the first defense in preventing the entrainment of algal blooms into a plant coupled to a comprehensive investigation of seawater quality and site conditions as discussed above.

Subsurface intakes are one option to reduce the ingress of algal cells and associated AOM into a plant; however, subsurface intakes are not feasible for all sites and were not covered in the case studies, though chapter 6 covers intake designs in detail. Most large scale SWRO plants use an open ocean (or surface) intake. Abstracting water at depth is often promoted as a means to prevent entrainment of algae into desalination plants with open intakes. Indeed, the deep water (20 m water depth) intake option selected for the Gold Coast plant appears to be successful in providing good water quality and preventing the ingress of dense floating mats of *Trichodesmium erythraeum*, the most frequent algal bloom observed in that region. Limited ingress of *Colpomenia*, a macroalgae typically attached to rocks, has occurred. This is most likely not as a result of a bloom but through dislodgment with wind and waves breaking it into flakes which may then have become entrained into the intake. The success of deep water intakes depends on the bloom-forming species. Some are motile or display diel vertical migration so that they move within the water column and are not found solely within the surface, mixed layer. Indeed, they can be at the surface during the daytime, and at 10 or even 20 m depths at night. Moreover, the distribution of AOM may not reflect the distribution of algal cells in the water column, as AOM can be extracellular and detrital in form, sinking to the seabed or rising to the surface. Hence, a deep-water intake can assist in limiting ingress of some algal blooms, but is no guarantee in preventing all algae and AOM as seen in various SWRO desalination plants in Chile.

The La Chimba and Gas Atacama plants, located 50 km apart, abstract seawater from the sheltered bays of Moreno and Mejillones, respectively, using a deep (25 m) and shallow (5m) intake. Both plants entrain algae into the intake. Abengoa's pilot plant employed the La Chimba intake and measured a significant increase in algal concentration, suspended solids and organics during bloom events. TEP was found to increase five-fold to 3500 µg x-eq/L and suspended solids increased to 40 mg/L on average and up to 76 mg/L. The deep-water intake did not therefore prevent algal bloom and AOM from being entrained into the intake. Moreover, thermoclines in the Moreno Bay led to SRB and the generation of H_2S issues at the La Chimba plant as discussed above. Further up the coast, the shallow intake of the Gas Atacama is less likely to suffer from hypoxic events as at La Chimba, but directly from algae and AOM.

11.1.2.3 Chlorination

Chlorine lyses algal and bacterial cells and oxidizes high molecular weight organics into biodegradable low molecular weight compounds which are more easily metabolized by biofouling bacteria. Some of the organic compounds released or formed may adsorb onto MF/UF pretreatment membranes or pass through to the RO system, increasing fouling and biofouling of the RO membranes. Hence, the SWRO industry moved from continuous to shock dosing of chlorine. During an algal bloom, chlorination at the intake could be suspended to limit lysis of algal cells and release of fouling AOM and toxins (if it is a toxin-producing bloom).

The small Jacobahaven demonstration plant (360 m^3/d) avoided chlorination to prevent the formation of chlorination byproducts by pigging their intake lines (once every 2 weeks), which would be infeasible for large full scale plants. Yet, it still suffered from AOM fouling of the UF membranes. Although, the intake at the Fujairah 2 hybrid plant was switched from continuous to shock dosing during studies of HABs at the SWRO plant, it is difficult to show direct data from their case study to demonstrate that the plant reduced algal lysis. Shuwaikh, Gas Atacama and Gold Cost practice shock chlorination.

Some plants continue to practice continuous chlorination such as Barka 1 and Sohar. Sohar intends to change to shock chlorination, but has issues due to other co-located industries that require chlorinated seawater. La Chimba can continuously chlorinate, but doesn't use the system. At Tampa Bay, continuous chlorination is practiced at two locations; chlorine dioxide at the intake and hypochlorite prior to the coagulation mixing basins. A 65% increase in the AOC during algal blooms was found following disinfection with chlorine dioxide compared to the raw water at the plant intake. Increases in AOC have been observed following disinfection with chlorine dioxide (Haas et al. 2015). Increases in AOC may lead to increased biofouling potential and may be directly linked to HABs.

11.1.2.4 Dissolved air flotation

DAF is generally thought to be one of the leading approaches to mitigate algal-related issues in downstream processes. However, DAF can be an expensive addition to a plant if it is only required to remove algae and blooms are not severe or frequent. A disadvantage of operating DAF in bypass mode is that it needs to be brought online prior to the bloom, which is often difficult to time correctly. The advantage of DAF is that the algal cells will be gently lifted by air bubbles, minimizing damage to cells or release of AOM. Successful performance of DAF is contingent on optimized coagulation flocculation to promote attachment of algal cells to the micro-bubbles generated in DAF. In general, cell removal is higher for more dense blooms.

DAF was utilized in five of the twelve case studies, Shuwaikh, Fujairah 2, Gas Atacama, Barcelona and akvola. Two of these cases (Shuwaikh and Fujairah 2) require DAF for other problems besides HABs, such as very high turbidity, suspended solids, and hydrocarbons.

At Gas Atacama, a conventional DAF+DMF system ran side-by-side with a UF system. The DAF+DMF encountered significant operational issues: high coagulant dose (25 ppm), increased SWRO membrane cleaning and cartridge filter replacement, and eventually premature SWRO membrane replacement. The alternative system that employed UF did not require cartridge filter replacement or SWRO membrane cleaning even when challenged by HAB events; however, it should be noted that the DAF+DMF plant is approximately 20 years old and employs older designs for DAF and SWRO.

The Shuwaikh plant uses high rate Leopold Clari- DAF before autostrainers and UF (pressurized inside out). The DAF uses ferric chloride and sulfuric acid. The system maintained full capacity during a bloom after optimization of coagulant and acid dose. DAF pilot studies conducted on Antofagasta Bay reported in the Shuwaikh case study showed greater than 95% removal for varying species of algae.

At Fujairah 2, Spidflow® DAF is utilized in line with DMF. Ferric chloride average dose rate during blooms in 2011-2012 was < 20 ppm and in 2013 <15 ppm. Fujairah 2 has provision in the DAF for acid dosing, but this was only used in commissioning and has provision for polymer dosing, but this has never been used. A DAF pilot plant operated throughout the 2008/2009 *Cochlodinium* bloom and the full-scale plant operated through a 2013 bloom.

The Barcelona pilot operated a parallel trial of DAF followed by (i) conventional DMF or (ii) pressurized outside-in UF. The combination of DAF followed by UF gave superior removal of biopolymers (41%) compared to only 18% for DAF and conventional DMF pretreatment. The ferric chloride coagulant dose for the Barcelona DAF pilot study was low being 0-6 mg/L and acid and coagulant aid were not found to be crucial in optimizing DAF performance. Algal cell removal averaged at 75% and up to 87%.

11.1.2.5 Microfiltration/Ultrafiltration

Microfiltration and ultrafiltration were commonly used for treatment of algal rich water, with eight of the twelve plants employing advanced membrane pretreatment: Sohar, Barka 1, Shuwaikh, Gas Atacama, Abengoa pilot, Jacobahaven, Barcelona and akvola.

Due to the pore size of MF/UF membranes, cell removal is generally 99-100% and cells only pass the MF/UF through broken fibers (Dixon et al. 2011). Most of the plants employed ultrafiltration which will achieve a higher removal of AOM and particulates due to their smaller membrane pores (or MWCO rating) than microfiltration with larger pores. As fouling biopolymers and TEP precursors range upwards of 20,000 Da in molecular weight and a few nm in size, respectively, ultrafiltration membranes (with a typical MWCO of 100,000 – 150,000 Da) will not remove them completely. Coagulation, albeit at a lower dose than for DMF, is therefore practiced to remove dissolved AOM, improve removal of biopolymers and TEP, and the filterability of the cake deposited on UF membranes. Several of these plants used DAF in combination with UF in order to reduce the suspended solids and organics loading on the membranes: Shuwaikh, Barcelona and akvola. The akvola pilot plant is a single unit combined DAF+UF system employing ceramic membranes.

Several operating techniques to prevent hydraulically irreversible fouling are available to allow UF plants to continue operations during an algal bloom. The following were used in the case studies: reducing flux (4 plants), recirculating flow (1 plant), use of coagulation involving optimizing the dose or switching on coagulation in response to blooms (3 plants), decreasing backwashing intervals (2 plants), increased CEB frequency (5 plants) and CIP (3 plants). The specific actions taken at each plant to maintain membrane performance are described in more detail in the following paragraphs.

At the Sohar plant which employs direct MF filtration, immediate short-term mitigation measures included reducing the MF flux from 100 L/m^{2}h maximum to 60-73 L/m^{2}h. The operators also reduced backwash cycle time, increased CEB frequency, and optimized cleaning strategies using chlorine and caustic (twice/day) and acid cleans (every 3 days). Coagulation will be incorporated into pretreatment as part of long term bloom mitigation measures to improve removal of AOM.

At Barka 1, the plant experienced significant UF fouling yielding a permeability drop of 100 L/m^{2}hbar during light to moderate blooms. The plant maintained flux without coagulation by reducing the CEB design interval from 18 hours to 12-15 hours to delay the CIP to greater than once in 180 days. In the case of a more significant bloom, the plant could reduce flux or turn on coagulation.

The Gas Atacama UF plant maintained operation during blooms as coagulation is employed at the plant (maximum 2 ppm).

The Abengoa pilot plant experienced a rapid increase in TMP during their bloom and responded first by reducing the CEB interval from 30 to 7-8 hours, using hypochlorite and caustic for CEB cleaning, with the pH increased from 9 (normal pH) to 12 during blooms. Later, mitigation included reducing flux (16%), which allowed CEB to be conducted every 26 hours. Unlike most other UF plants, no coagulation was utilized. The UF membranes were operated with increased recirculation flow allowing scouring of the membrane. While the UF plant usually achieves 96% recovery, during the bloom, recovery dropped to 80% due to the reduction in flux while maintaining backwash frequency.

Jacobahaven (a demonstration plant) allowed for maximum flexibility in operation. Rapid fouling of UF coincided with high chlorophyll-*a*, TEP and algal counts. CEB decreased to every 6-12 hours while in non-bloom conditions, CEB was typically every 24 hours, and as infrequent as once every 2 weeks. Modification of the backwash interval gave limited improvement and increased backwash volume to 20%. Similarly, modification of CEB conditions and frequency was ineffective. Flux reduction did not yield a satisfactory CEB interval. Coagulation was effective but CEB remained ineffective during coagulation and HABs, requiring a CIP.

At Barcelona, no impacts were noted with algal cell counts up to 1.2 million/L. Both conventional and membrane pretreatment performed well; however, UF gave better performance with respect to SDI$_{15}$, turbidity, algal cell, and biopolymer removal.

11.1.2.6 Dual media filtration/Granular media filtration

While DMF is a common pretreatment practice, only four of the case studies employed DMF as part of their pretreatment. These were Fujairah 2, Gas Atacama, Barcelona and the Gold Coast. While DMF has been proven as an effective HAB removal method, giving between 20 and 90% removal in several cases (Gustalli et al. 2013), in this study little cell removal data was corroborated.

No negative impacts were observed in the gravity DMF at the Gold Coast plant as the deep water intake limited ingress of the most frequently occurring algal bloom. Hence, no cell removal data were recorded. Anecdotally, no increased DMF clogging was experienced during blooms with ferric sulfate (13 mg/L) coagulation and DMF. Similarly, no impacts were reported at Fujairah 2 and the Barcelona pilot plant, which employ additional solids removal through an upstream DAF.

At Barcelona cell removal with DMF was 74% and removal of biopolymers was 18% for DAF and DMF. As Barcelona was a side-by-side pilot plant, it showed DAF+UF cell removal (100%) was superior to DAF+DMF. Likewise, biopolymer removal was 41% versus 18%.

11.1.3 Summary

The twelve case studies present an array of mitigation strategies for operating in algal-rich seawater from around the globe including deep water intakes, DAF, conventional and advanced pretreatment with or without coagulation. A myriad of impacts, algal water quality monitoring and detection techniques and management practices are described in the case studies. In many cases, the observations collected from plant operations as part of the Manual development validate some of the key perceptions held by our industry about how to manage operations during HABs. For example:

- Careful, informed site analysis with a focus on the potential for different types of algal blooms can be a cost-effective strategy that minimizes future pretreatment needs;
- Long-term monitoring programs to characterize seawater quality should be conducted at the plant intake site. This should include a review of historical records examining the frequency and severity of algal blooms (if available);
- Piloting at site is recommended with challenge testing using cultivated algae if no blooms occur;
- Conventional parameters such as the SDI have proven useful in detecting blooms at an intake. Care needs to be taken with the SDI as it will underestimate the fouling potential of feedwater, especially during algal blooms;
- Parameters have been developed to monitor AOM constituents and the increase in (bio)fouling potential of seawater during a bloom e.g. biopolymer concentration by LC-OCD, TEP_{10kDa}, MFI-UF using a 10 kDa test membrane and the AOC luminescence test using *Vibrio harveyi*. These tests can be used to assess and optimize pretreatment during a bloom. While promising, the degree of difficulty and cost in determining them is correspondingly higher. As yet, these parameters cannot be employed to alert a plant to a bloom or to adjust process parameters during plant operation;
- Deep-water open ocean intakes may be successful in avoiding some bloom-forming species, but some species are motile or display diel vertical migration so that they move 10 m or more daily within the water column. Moreover, the distribution of AOM may not reflect the distribution of algal cells in the water column. Deep water intakes are thus not guaranteed to prevent the ingress of algae and AOM into a plant;
- Avoiding chlorination-dechlorination during a bloom will help to prevent downstream fouling as fouling AOM will be retained intercellularly along with toxins and less assimilable organic carbon is generated through oxidation of organic matter;
- Coagulation is important for all three pretreatments (DAF, UF, and DMF) and acts to remove AOM more effectively than these pretreatment processes alone. Less AOM in the pretreated water will help to alleviate SWRO fouling;
- DAF is a good choice for cell removal in areas predicted to experience heavy blooms, as it removes cells by floatation, minimizing cell rupture;
- DMF or UF alone can accomplish cell removal and some dissolved AOM (if coagulation is used for UF) for light algal blooms, but using a DAF upstream is prudent for heavy blooms; and
- The combination of DAF and UF is increasingly being applied in the industry, when applied in bypass mode, care needs to be taken to bring the DAF online in time.

11.1.4. References

Anderson, D. M., Cembella, A. D., and Hallegraeff, G. M. 2012. Progress in understanding harmful algal blooms: paradigm shifts and new technologies for research, monitoring, and management. *Annual Review of Marine Science* 4, 143-176.

Berman, T. and Holenberg, M. 2005. Don't fall foul of biofilm through high TEP levels. *Filtration and Separation* 42(4), 30-32.

Boerlage, S. F. E. 2008. Understanding the Silt Density Index and Modified Fouling Indices (MFI0.45 and MFI-UF). *Desalination and Water Reuse Quarterly* May –June, 12-21.

Boerlage, S. F. E, Kennedy, M., Aniye, M., Abogrean, E., El-Hodali, D., Tarawneh, Z., and Schippers, J. 2000. Modified Fouling Index - ultrafiltration to compare pretreatment processes of reverse osmosis feedwater. *Desalination* 131, 201-214.

Boerlage, S. F. E. and Nada N. 2014. Algal toxin removal in seawater desalination processes. In: *Proceedings of European Desalination Society*, Cyprus.

Bricker, S. B., Ferreira, J. G., and Simas, T. 2003. An integrated methodology for assessment of estuarine trophic status. *Ecological Modelling* 169(1), 39–60.

Dixon, M. B., Richard, Y., Ho, L., Chow, C. W. K., O'Neill, B. K., and Newcombe, G. 2011. A coagulation - powdered activated carbon - ultrafiltration multiple barrier approach for removing toxins from two Australian cyanobacterial blooms. *Journal of Hazardous Materials* 186(2-3), 1553-1559.

Gustalli, A., Simon, F. X., Penru, Y., de Kirchove, A, Llorens, J., and Baig, S. 2013. Comparison of DMF and UF pretreatments for particulate material and dissolved organic matter removal in SWRO desalination. *Desalination* 322, 144-150.

Haas, C. N., LeChevallier, M. W., and Weinrich, L. A. 2015. *Application of the Bioluminescent Saltwater Assimilable Organic Carbon Test as a Tool for Identifying and Reducing Reverse-Osmosis Membrane Fouling in Desalination.* Alexandria: Water Environment & Reuse Foundation. Project 11-07.

Kremen, S. S., and Tanner, M. 1998. Silt density indices (SDI), percent plugging factor (% PF): their relation to actual foulant deposition. *Desalination* 119(1), 259-262.

LeChevallier M. W. 2014. Measurement of biostability and impacts on water treatment in the US. In: *Microbial Growth in Drinking-Water Supplies Problems, Causes, Control and Research Needs.* IWA Publishing.

Li, S., Winters, H., Villacorte, L. O., Ekowati Y., Abdul-Hamid. E., Kennedy, M. D., and Amy, G. L. 2015. Compositional similarities and differences between Transparent Exopolymer Particles (TEP) from two marine bacteria and two marine algae: significance to surface biofouling. *Marine Chemistry* 174, 131–140.

Myklestad, S. M. 1995. Release of extracellular products by phytoplankton with special emphasis on polysaccharides. *Science of the Total Environment* 165, 155-164.

NHMRC/NRMMC. 2011. *Australian Drinking Water Guidelines Paper 6: National Water Quality Management Strategy*. Canberra: National Health and Medical Research Council / National Resource Management Ministerial Council.

Salinas-Rodriguez, S. G. 2011. Particulate and organic matter fouling of SWRO systems: characterization, modelling and applications. Doctoral dissertation, UNESCO-IHE/TUDelft, Delft.

Schippers, J. C. and Verdouw, J. 1980. The Modified Fouling Index, a method of determining the fouling characteristics of water. *Desalination* 32, 137-148.

Villacorte, L. O. 2014. Algal blooms and membrane-based desalination technology. CRC Press/Balkema, Leiden: 200 p.

Weinrich, L. A., Schneider, O. D., and LeChevallier, M. W. 2011. Bioluminescence-based method for measuring assimilable organic carbon in pretreatment water for reverse osmosis membrane desalination. *Applied and Environmental Microbiology* 77, 1148–1150.

WHO. 2011. *Guidelines for Drinking Water Quality, Fouth Edition*. Geneva: World Health Organization, 564 p.

11.2 FUJAIRAH 2, UNITED ARAB EMIRATES – EFFECTS OF HARMFUL ALGAL BLOOMS ON PLANT OPERATIONS IN 2008 AND 2013

Herve Faujour[1], Cyril de Vomecourt[1], and Jérôme Leparc[2]

[1]Veolia Middle East, Dubai, United Arab Emirates
[2]Veolia Recherche & Innovation, Maisons Laffitte, France

Figure 11.2.1. Location and aerial view of the Fujairah 2 hybrid plant in UAE. Photos: Veolia.

Table 11.2.1 Overview of Fujairah 2 SWRO plant.

Plant/Project Name	
Location	Fujairah (Qidfa)
Primary product water use	Municipal
Desalination Technology	Hybrid SWRO/MED, case study only covers SWRO as HAB did not affect MED plant
Total Production Capacity (m^3/d)	136,000 m^3/d for the SWRO (23%) 453,000m^3/d for the MED (77%)
SWRO recovery (%)	First pass approximately 41% Overall plant recovery 39%
Commissioning date	Official start of operation: Oct 2010
	Intake
Feedwater source	Oman Sea
Intake type	Open submerged intake – 3 risers
Intake description	500 – 600 m off shore, 10 m depth
Intake screening	Static and rotating drum screens
(shock) chlorination	Hypochlorite:
Strategy, dose rate	continuous dosing from 10/2010 to 12/2012 with additional shock dosing a few times per day from 01/2013 onwards, only shock dosing at intake risers
Online raw water monitoring	SDI, conductivity, temperature, pH, turbidity, and hydrocarbons
Discrete raw water analysis relevant to HABs	SDI, TOC, algal counts during presumed HABs, chlorophyll
	Pretreatment
Process description	Spidflow® DAF, Dual Media Gravity Filtration, 5 to 10 µm cartridge filtration
Chemical dosing	FeCl$_3$ Average dose rate in 2011-2012 was <20 ppm and in 2013 <15 ppm Provision in the DAF for acid dosing (but only used in commissioning) and for polymer dosing (never used)

	Feedwater design parameters	**Feedwater during blooms**
Temperature range (˚C)	22 to 33	22 to 33
Salinity range (TDS mg/L)	< 40,500	
Total Suspended Solids (mg/L)	4 to 6	10 to 30
SDI (%/min)	SDI$_3$ = 18 to 22	SDI$_3$ = 26 to 30
Turbidity (NTU)	0.2 to 0.3	0.5 to 1.0
Organic Matter	TOC < 1	TOC = 1.0 to 1.5
Algal cell count (cells/L)	2 to 4x10^5	Up to 10^6
Algal species (if known)	N/A	N/A
Chlorophyll-*a* or total chlorophyll (µg/L)	N/A	N/A
Additional water quality parameters for design or observed during algal bloom	N/A	N/A
	Desalination Design	**During bloom conditions**
Filter rates (DAF/DMF etc.) m/h	DAF up to 30	Same as normal design
UF flux (L/m^{2}h)	N/A	N/A
RO flux (L/m^{2}h)	Confidential	Same as normal design

N/A - not available

11.2.1 Introduction

High demographic growth in the United Arab Emirates (UAE) in recent years has resulted in a higher demand for drinking water and power. In order to satisfy the growing demand, the Fujairah 2 Independent Water and Power Plant (IWPP) was launched by the Emirate of Abu Dhabi for completion during 2010. The location of this new plant was immediately next to the existing Fujairah 1 IWPP in the Emirate of Fujairah on the Gulf of Oman (Figure 11.2.1).

Until recently, the Fujairah 2 IWPP was the largest hybrid desalination plant in the world with a combined net design capacity of 590,000 m^3/d linked to a power plant with a 2,000 MW/d net design capacity. Desalinated water is produced by a Seawater Reverse Osmosis (SWRO) plant and a Multi-Effect Distillation plant (MED).

In recent years, the unwelcome phenomenon of harmful algal blooms (HABs) have been experienced in the Gulf of Oman along the coasts of the UAE and Oman. Impacts had been devastating, particularly during a 2008/2009 HAB event which caused the shutdown of many SWRO plants due to the inability of conventional pretreatment processes to deal with the high concentrations of algae, and an associated increase in suspended solids and dissolved organics. The Fujairah pilot plant, which incorporated dissolved air flotation (DAF) as a pretreatment strategy, continued to operate during that bloom.

Effective pretreatment process performance is paramount for any SWRO plant, as feedwater quality needs to meet the generally stringent O&M contractual specification. Veolia meets the very stringent SWRO plant availability requirement of Fujairah 2 of 98%. In order to achieve such availability with challenging raw water quality, the Veolia SPIDFLOW® Dissolved Air Flotation process has been included in the pretreatment with the aim of mitigating algal blooms/red tide events in particular and ensuring a superior and highly consistent water quality.

11.2.2 Plant overview

11.2.2.1 SWRO desalination plant

A shared seawater intake supplies seawater to the power plant as well as the MED thermal and SWRO desalination plants with a common remineralization section where MED distillate and SWRO permeate are blended and remineralized. The Fujairah 2 RO plant process configuration comprises the SPIDFLOW® DAF units (16) with coagulation/flocculation, rapid gravity dual media filters (12), cartridge filtration (16), first pass Reverse Osmosis (10) and partial second pass Reverse Osmosis (2) with the second pass to achieve boron removal (Figure 11.2.2).

During the first five years of operation, two distinctly different intake chlorination strategies were employed. These had potential effects on general treatment process performance and water quality. During the first 27 months of operation, continuous intake chlorination was practiced plus an extra “shock-chlorination” every 6 – 8 hours, which could reach up to 2.5 mg/L. Since January 2013, shock or intermediate intake chlorination has been practiced at various frequencies and concentrations. Residual Cl_2 was monitored upstream of the RO, and when detected, was neutralized with sodium bisulfite (SBS) injection in the suction of the HP pump.

Provision was made for polymer and acid dosing to reach an optimum pH for coagulation, but experience from the five previous years showed that the efficiency of $FeCl_3$ alone is sufficient.

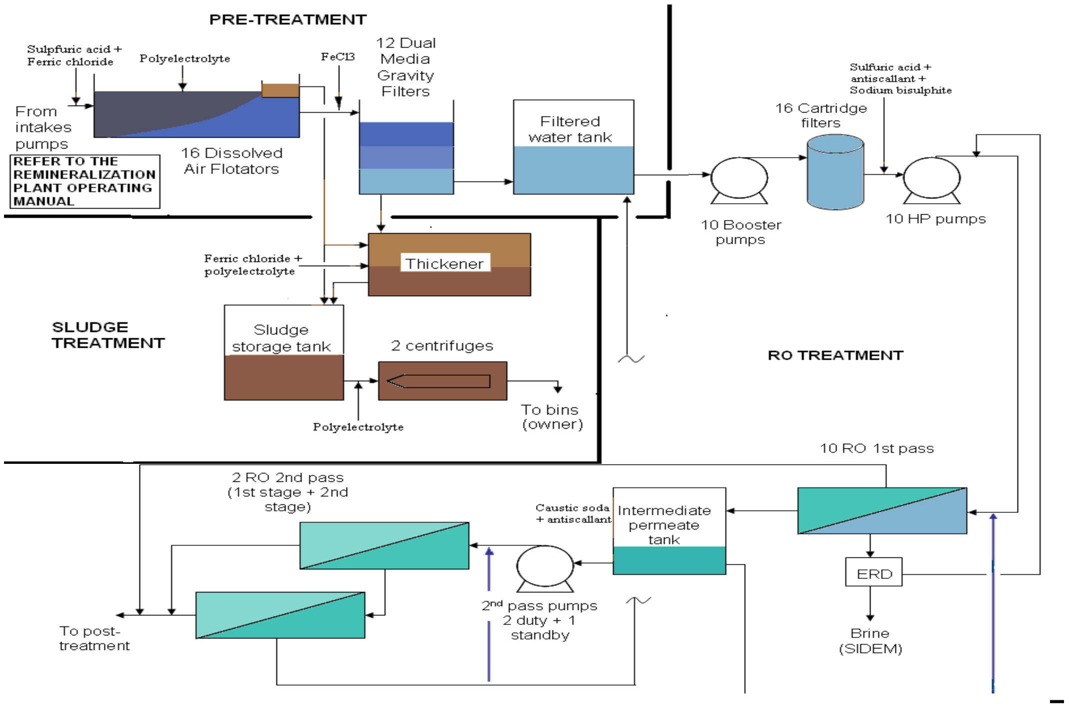


Figure 11.2.2. Process flow schematic for the SWRO desalination plant at Fujairah 2.

11.2.3 Inlet Water Monitoring

11.2.3.1 Summary of main feedwater quality excursion events since 2008

Poor seawater quality events during pilot plant operation (from 2008) and full scale plant operation (from 2010) are summarized in Table 11.2.2, highlighting the main parameters that characterized the event, along with the corresponding origin of the degradation. Two of these events were due to algal blooms (2008 and March 2011). The 2008 event was caused by *Cochlodinium polykrikoides*; the causative organism for the 2013 event is not known.

Despite degraded inlet seawater quality, the DAF was always able to maintain good water quality downstream of the dual media filter (DMF). The major red tide of 2008 was treated by the pilot plant only, without affecting the SDI_{15} after DMF (with higher $FeCl_3$ doses). Once the full-scale plant was operational, the DAF pilot was kept in operation in parallel to the main plant to investigate adjusting operating parameters on the pilot before applying them to the main plant. This approach confirmed that the results on the DAF were highly representative of the large-scale plant, which gives confidence that even very high intensity algal blooms similar to that of 2008 will not affect the RO performance when the inlet pretreatment includes a Spidflow® DAF.

The nature of the feedwater quality excursion is difficult to characterize in detail, and work is underway in collaboration with local research institutes such as MEDRC in Muscat to have more parameters analyzed when degradation is observed. This analysis will also be applied to normal operation to create background data for comparison to the excursions.

The nature of the poor water quality events was also interpreted in conjunction with remote satellite observations and on-site photographs (Figure 11.2.3), and through the description of the nature of the effects on the coastal industry. For instance, on the 18th of February 2009, the Khaleej Times quoted the following: *"**Red Tide Plaguing Fujairah, will continue to affect area**: The red tide that has been plaguing Fujairah's coastline since November last year will continue to affect the area for some more months".*

Table 11.2.2. Inventory of main feedwater quality excursion events at Fujairah 2 intake.

	Ref Value	2008	03/11	03/12	03/13	07/13	09/13	02/14	10/14
SDI_3 (inlet)	18-22	26-30	26.4	27.3	26-28	22	24.4	30	24-29
SDI_{15} (before RO)	3-3.5	5	4.8	5	5	No Impact	4.3	4.5	< 3.5
Turbidity (NTU)	0.2-0.3		0.5-0.8	0.6 ave 6.5 max	0.3 ave 29 max	0.2ave	2.9max	0.5 ave 1.5 peak	0.3 ave 13 max
TSS (ppm)	4-6	10-30	N/A	N/A	N/A	+10% in HC	N/A	20	1.5-9
Temp (°C) variability (D/N)	+/- 2C	N/A	normal	max around 16/3	more	No Impact	Start to increase	Normal	Normal
DMF clogging rate	N/A	N/A	x2	x3	N/A	No Impact	x2	N/A	N/A
DMF BW freq (h)	40-54	40	40	40 ave 17h min	26	No Impact	55 ave 42 min	N/A	N/A
Shore obs.	N/A	N/A	red patches	jellyfish	brown shore	oil patch	jellyfish	N/A	N/A
Satellite picture	N/A	N/A	N/A	N/A	visible	N/A	visible	N/A	N/A
Algae count (cells/L)	2-4x10^5	N/A	N/A	3-4x10^5	10^5-10^6	N/A	N/A	N/A	N/A
TEP (>0.45µm)	20-40µg/L	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Chl-*a* (µg/L)	0.02-0.06	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
TOC (ppm)	~1	N/A	N/A	N/A	1-1.5	N/A	N/A	N/A	N/A
Interpretation		**algal bloom**	**algal bloom**	**jelly fish**	**not known**	**oil spill**	**jelly fish**	**high turbidity**	**not known**

Note: ave, max and min refers to average, maximum and minimum values, respectively

Figure 11.2.3. Red tide of *Cochlodinium polykrikoides* on the coast of Fujairah during 2008/2009. Photo: D. Anderson.

On the 8th of March 2013, the Khaleej Times again reported another HAB in the same area (Kalba, 30 km south of Fujairah). *"The directorate [of SEWA, the Sharjah Electricity and Water Authority] had decided to stop the operation of the desalination plant for the safety of the residents in the region. He explained that SEWA regularly tests desalinated water to ensure that it meets required specifications. The operation will resume immediately after the red tides recede in the sea"*.

During the 2013 bloom period, a strong smell was present both outside and inside the plant. Water discoloration was clearly visible at the sea surface, especially close to the coast where the waves were yellow-orange. Fujairah 2 SWRO was not affected, as reported in the Water Desalination Report Volume 49 – Number 10, dated from the 11th of March 2013 in an interview with Erich Koenig, plant manager: *"I am not sure if we can call it red tide, because the visual signs were more yellowish green, although satellite* *images did also show red tide patches close to Oman", he said, adding: "Our process was stable with significant adjustment to our ferric chloride dose in order to satisfy coagulant demand and to ensure the effectiveness of our signature high-speed DAF system."*

11.2.3.2 Overview of SDI and turbidity of seawater

The trends in online SDI_3 and turbidity from January 2012 are shown in Figure 11.2.4. Spikes in both parameters were observed during the March 2013 algal bloom. SDI_3 and turbidity are not sufficient to entirely characterize all potential pollution events, but they remain the easiest parameters to monitor. Operational feedback for the monitoring of other parameters can be summarized as:

- **TOC:** TOC was not a reliable indicator to trigger adjustment of operational/process parameters. Interpretation of trends in TOC were also difficult due to the issues associated with accurately measuring TOC at low residual levels of 1 ppm with high salinity seawater.
- **Temperature:** This was an easy parameter to monitor, but a sharp change in temperature may not always signal that operational disturbance is expected.
- **Chlorophyll:** The laboratory analyzer did not show any particular trends, plus the low level of algal pigment makes local monitoring difficult. Furthermore, a HAB is not the only water quality excursion that needs a robust pretreatment, so adjustment of operating parameters may not be related only to chlorophyll.
- **Algal count:** Samples were sent to the USA several times for more accurate characterization, but the turn-around time was long, so this was used only for diagnosis rather than as an alert to trigger operational changes. Increase in the algal count was not sufficient to be relevant in March 2013.
- **Satellite data:** Imagery was used as a way to help the interpretation of the event rather than to adjust operating parameters;
- **Shore observation:** Some observations from shore may not be relevant to the plant intake due to the submergence of the intake, but it remains a pragmatic monitoring approach.
- **TEP:** Transparent Exopolymer Particles, associated with algal blooms could be monitored. As lab protocols are complex these were not set up locally. Long turn-around times for European laboratories make decision making based on laboratory data impractical.

11.2.4 Plant Performance

11.2.4.1 SDI monitoring

In combination, the pretreatment processes ensured the consistent delivery of exceptional water quality characterized by a SDI_{15} between 2 and 4 for the filtered water, even during the March 2013 algal bloom (Figure 11.2.5). A slight degradation of the RO feedwater SDI observed in 2013. It may be related to the modification of the pre-chlorination regime or to the optimization of the $FeCl_3$ dose, but the increase of SDI remains quite minor, in the range of 2.5 to 3.0, which is quite comparable to UF filtered water, showing that a robust combination of DAF with DMF with the injection of coagulant can achieve as good a result as UF, with the probable additional benefit of ability to take highly degraded seawater quality.

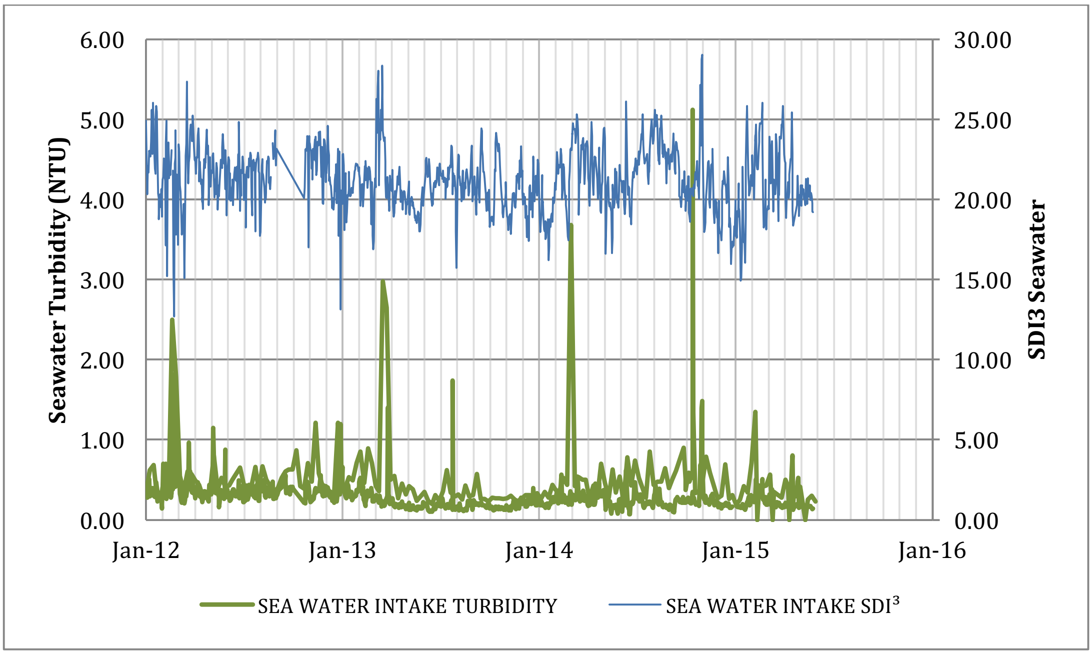


Figure 11.2.4. Online monitoring of inlet seawater turbidity and SDI_3 in January, 2012.

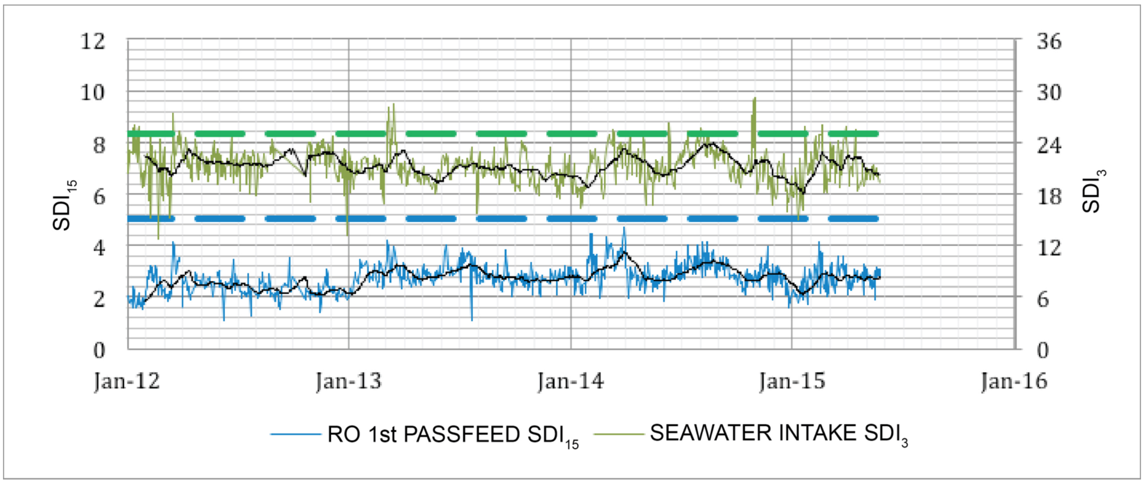


Figure 11.2.5. SDI_3 of the SWRO intake and SDI_{15} of the first pass RO feed in 2013.

Cartridge filtration, although not considered a treatment process, has also contributed to achieving well-polished feedwater for the RO membranes. In terms of SDI, the cartridge filters have generally reduced the SDI by 0.5 units.

11.2.4.2 Plant production and availability

As shown in Figure 11.2.6, the capacity of the plant was maintained at its highest requirement regardless of the quality of the raw feedwater during six poor water quality events experienced between 2008 and 2014. For example, during October 2014, SDI_3 at the inlet increased to 24 - 29, the cause of which was unknown, but the produced flow remained high and even exceeded the flow corresponding to when all skids including the standby (9 duty + 1 standby) were in operation.

A 98% availability (monitored as a cumulative value in the month of October every year) is a very stringent requirement, but over 5 years of operation, despite multiple HABs and other events, this has always been achieved.

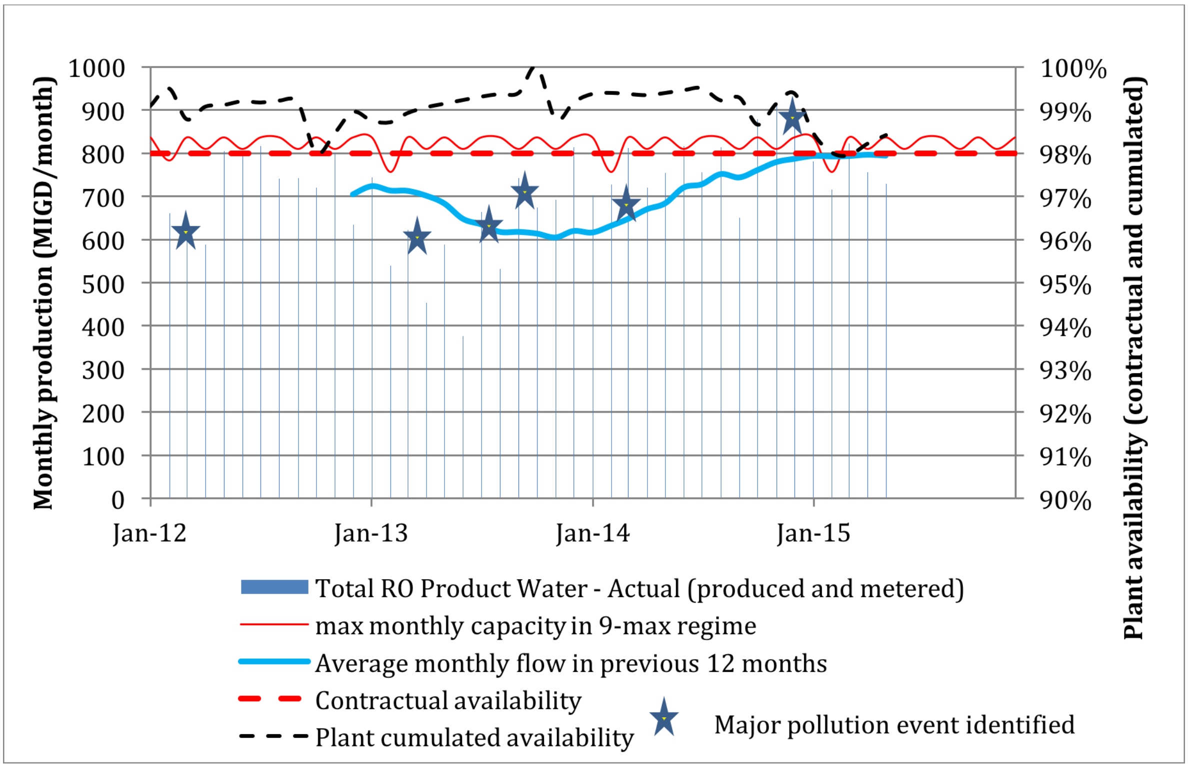


Figure 11.2.6. Water production and plant availability since 2011.

11.2.5 Conclusions

The pretreatment process combination of the Fujairah 2 SWRO Plant and optimized operations have allowed excellent performance of the SWRO plant. The plant has consistently met availability targets during challenging water quality events. This can be attributed to the success of the SPIDFLOW® DAF system that has proven to be a reliable and flexible treatment process under different water quality conditions, including moderate HABs.

In terms of additional cost of operation, the kWh needed for the Spidflow® DAF is in the range of 2% of the total plant consumption (excluding plant inlet and remineralization which are not in the scope of the Veolia O&M contract). While the $FeCl_3$ dose rate was kept high as a precaution during the first years of operation, it has been reduced to values that are comparable with the industry standard of SWRO plants that do not include a DAF.

RO membranes perform at their best when they are fed with excellent and consistent water quality. The overall result led to a contract performance far above the expectation of Veolia and the client.

11.3 SOHAR, OMAN – HARMFUL ALGAL BLOOM IMPACT ON MEMBRANE PRETREATMENT: CHALLENGES AND SOLUTIONS

Abdullah Said Al-Sadi[1] and Khurram Shahid[2]

[1]Majis Industrial Services, Sohar, Oman
[2] Water Solutions International Ltd, Gatwick, England

Figure 11.3.1. Map of the location of the Sohar desalination plant (top) and aerial view showing the combined intake channel and outlet for power and desalination plant (bottom).

Table 11.3.1. Overview of the Sohar SWRO desalination plant**.**

Maijs SWRO Plant		
Location	Sohar, Oman	
Primary product water use	Process and potable	
Desalination technology	MSF and SWRO	
Total production capacity (m^3/d)	150,000 MSF and 20,000 SWRO	
SWRO recovery (%)		
Commissioning date	September 2013	
	Intake	
Feedwater source	Gulf of Oman	
Intake type	Shallow intake channel	
Intake description	Lagoon of 4 m depth	
Intake screening	Chain raked bar screen (30 mm spacing); Travelling band screens (3 mm mesh size)	
(Shock) chlorination strategy, dose rate	Hypochlorite continuous dosing to provide a free chlorine residual between 0.4 to 0.8 mg/L	
Online raw water monitoring	Conductivity, temperature, pH, turbidity, hydrocarbon analyzer; residual chlorine, dissolved oxygen (DO)	
Discrete raw water analysis relevant to HABs	TOC, algal counts	
	Pretreatment	
Process description	100-µm self-cleaning strainers MF pressurized outside in	
	Feedwater design parameters	**Feedwater during bloom conditions**
Temperature range (˚C)	N/A	N/A
Salinity range (TDS mg/L)	N/A	N/A
Conductivity (mS/cm)	N/A	N/A
Total Suspended Solids (mg/L)	N/A	N/A
SDI (%/min)	5-15 SDI_5	SDI_5 unmeasurable; $SDI_{2.5}$ >35 100% of the time
Turbidity (NTU)	N/A	N/A
Organic Matter	TOC <3	5.8
TOC and COD mg/L	COD <20	56
Algal cell count (cells/L)	N/A	5.6 million
Algal species	N/A	*Gonyaulax polygramma*
Chlorophyll-*a* or total chlorophyll (µg/L)	N/A	N/A
	Desalination Design	**During bloom conditions**
MF flux (L/m^2h)	<100	<76
RO flux (L/m^2h)	16.6 (SWRO) and 36.5 (BWRO second pass)	

11.3.1 Introduction

The Oman Sohar Industrial Port Area (SIPA) is home to major petrochemical, iron and steel, methanol, and fertilizer plants, as well as three power stations. Since its inception in 2006 it has drawn some US$ 15 billion in investment and holds a strategic place in the future development of Oman. As the sole water services provider at SIPA, Majis Industrial Services (Majis) has a significant role in the economy of the Sultanate.

Majis provides seawater for cooling as well as high-quality desalinated water for process water applications, as well as potable water and wastewater collection, treatment, and re-use for irrigation. After the completion of its second seawater pumping station, the cooling water pumping facility with a capacity of almost 700,000 m^3/h will be one of the largest in the Middle East. Some of the industries at SIPA have their own treatment plants to produce process and boiler water using this seawater.

The plant comprises a 585MW combined-cycle, gas-fired power plant and a 170,000 m^3/d desalination plant located in the Sohar Industrial Port area in the North Al Batinah region of the Sultanate of Oman (Figure 11.3.1). The desalination plant comprises four conventional Multi Stage Flash (MSF) units and a SWRO system. The 20,000 m^3/d SWRO plant is unique in nature by using direct membrane filtration, not conventional pretreatment. The raw water originating from an open intake is pumped directly through the microfiltration (MF) membrane filtration system, then directly to the RO units without a break tank. The characteristics of the SWRO plant are given in Table 11.3.1.

HABs have been observed in the Sohar Region since 1970s, but presumably occurred long before that. Majis started its operations at SIPA in 2006-2007, and since 2008 has kept a record of algal bloom events. In 2008-2009 a severe red tide of *Cochlodinium polykrikoides* disrupted operations at SIPA resulting in huge economic loss. Sohar Refinery shut down its own SWRO plant and intake screens required cleaning every 4 hours instead of every 12. In 2011 and 2013 green algal blooms also impacted SIPA operations.

In September 2013, when the RO plant was ready for commissioning, the seawater conditions were very challenging with very high levels of $SDI_{2.5}$ >35, and high algal bloom cell concentrations > 5.8 million cells/L. This prolonged HAB event lasted almost six months during which the installations had to be commissioned, the feedwater consistently having the same high level of SDI.

11.3.2 System description

The screened and continuously chlorinated seawater is supplied from the Seawater Intake Pumping Station (SWIPS I). The SWIPS I has an open intake and the water comes from a shallow lagoon of 4 m depth which provides an ideal environment for algal blooms (Figure 11.3.1). The SWRO plant consists of MF pretreatment (with no coagulation or chemical injection prior) followed by five SWRO trains, each having a capacity of 4,000 m^3/d. Two trains are dedicated for process water and the other three for potable water. A diagram of the 20,000 m^3/d MF plant is provided in Figure 11.3.2. The microfiltration (MF) system uses Pall Microza UNA-620A, high crystalline PVDF Membranes, with < 0.1 µm pore size, and an outside-inside filtration mode. The first-pass SWRO system consists of a combination Hydranautics membrane, SWC5max/SWC6max at train 1 and 2 and SWC4max/SWC5max at train 3, 4 and 5. The second pass BWRO trains consist of ESPA2-LD/Hydranautics. The average membrane flux for the SWRO and BWRO systems is 16.6 L/m^2h and 36.5 L/m^2h, respectively.

The 20,000 m^3/d plant, was designed for standard seawater quality conditions where the duration of any red tide or algal bloom events were expected to last for two to a maximum of four weeks, once per year. The MF plant was designed to operate at a maximum flux of 100 L/m^{2}h. This flux has been demonstrated on a similar direct feed seawater installation that has been operating for 5 years in Ducum, Oman. While pre-commissioning the Majis 20,000 m^3/d plant, SDI$_5$ could not be measured as the SDI membrane filter completely blocked. These high levels continued and a few weeks later, a significant number of jellyfish affected the intake. These were up to 20 cm in size but due to their sheer numbers, organic matter penetrated some of the bar screens and this was not fully removed by the band screens. This high load partially clogged the downstream 100 µm self-cleaning strainers. The jellyfish attack was then rapidly followed by a HAB event consisting of unidentified fine green algae with an excessively large presence of the dinoflagellate *Gonyaulax polygramma* (Figure 11.3.3, Table 11.3.2).

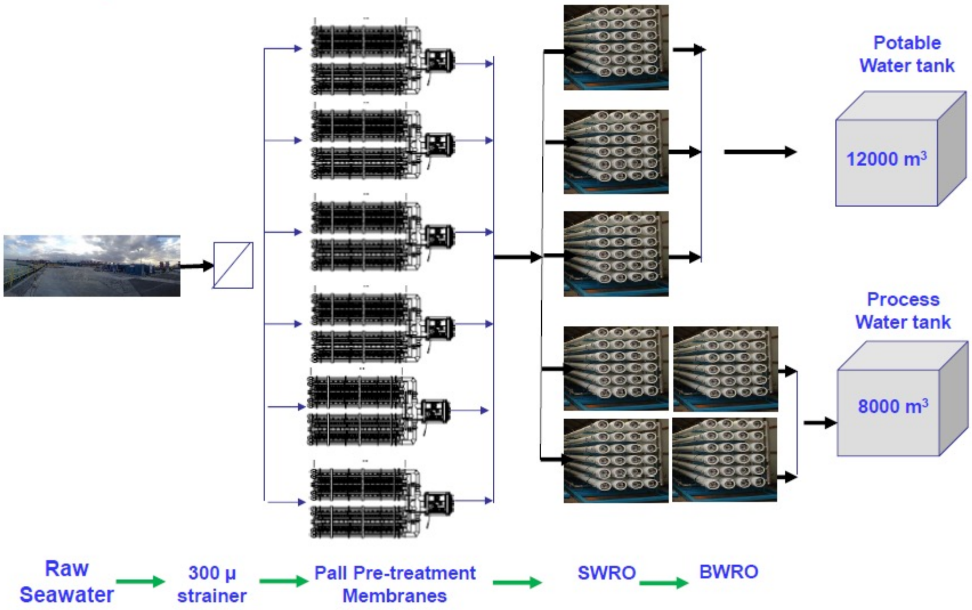


Figure 11.3.2. Process schematic for the Sohar SWRO desalination plant – the 100 µm screens first installed were replaced by a 300 µm strainers.

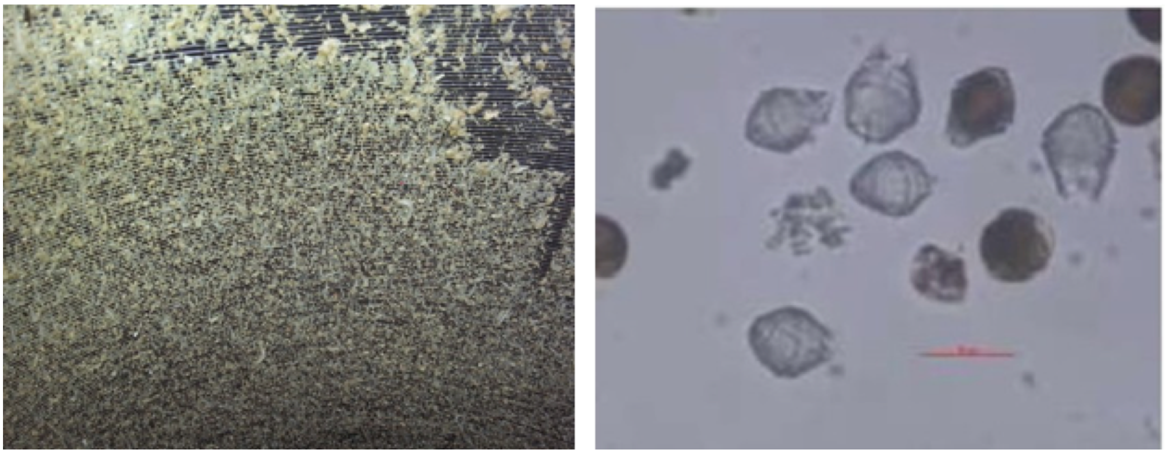


Figure 11.3.3. Clogged self-cleaning strainer during jellyfish and HAB event (left) and *Gonyaulax polygramma*, the dominant species during the 2013 HAB event (right).

Table 11.3.2 summarizes the biological analysis for samples taken from MF feed, filtrate, and backwash waste during the event. The direct impact of the massive changes in feedwater conditions are summarized below:

- Partially clogged self-cleaning strainers;
- High transmembrane pressure (TMP) on the MF units due to unexpected feedwater conditions; and
- Biofouling on the downstream SWRO units, due to the high level of dissolved organic carbon (DOC), that was not removed by the MF pretreatment.

Table 11.3.2 Algal cell counting and species identification of the MF feedwater, filtrate, and backwash water during a 2013 algal bloom event.

Phytoplankton Species	**MF Feed seawater**	**MF Backwash**	**MF Filtrate**
	cells/L	cells/L	cells/L
Cylindrotheca closterium	< 25,000	250,000	Absent
Pleurosigma normanii	< 25,000	250,000	Absent
Pleurosigma sp.	< 25,000	250,000	Absent
Ceratium furca	< 25,000	250,000	Absent
Dinophysis caudata	< 25,000	250,000	Absent
Gonyaulax polygramma	5,637,500	53,125,000	Absent
Prorocentrum sigmoides	37,500	375,000	Absent
Protoperidinium steinii	< 25,000	250,000	Absent
Total	**5,825,000**	**55,000,000**	**Absent**

11.3.3 Short-term mitigation measures

11.3.3.1 Intake

Short-term mitigation measures were urgently required to supply water during the 2013 event. Thus the backwash frequency of the intake screens was increased to minimize the chances of intake screen blockage, along with an increase in the chlorine dose. Change over to shock dose chlorination was considered as a long-term option.

11.3.3.2 Self-cleaning strainers

Due to repeated partial-to-complete clogging of the existing 100 µm self-cleaning strainers, the pressure drop across the strainers lead to insufficient pressure at the MF feed pump inlet and caused automatic shutdown of the pretreatment plant. Moreover, there was insufficient feed to the MF and the SWRO plant. The sticky nature of the jellyfish made it difficult-to-impossible to clean the strainers. Due to time limitations and the long procurement time needed for installing an alternative type of strainer, it was decided to take advantage of having robust MF modules downstream of the self-cleaning strainers, and temporarily replace the 100 µm mesh by a 300 µm mesh. In addition, the screen mesh material was changed to non-metallic instead of metallic, thereby facilitating the removal of sticky materials from the screen surface. Although, these measures helped in addressing the pressure drop issue on the strainers and allowed for continuous operation for the self-cleaning strainers, it transferred a greater solids load to the downstream MF units.

11.3.3.3 Microfiltration system

The high-crystalline outside-in PVDF membranes are known for their ability to handle difficult feedwater without the need for upstream conventional pretreatment. Although the outside-in filtration concept makes these modules more suitable for difficult water applications, the unexpected feed conditions in 2013 presented a challenge for the MF membranes, as it was originally sized at a flux of 100 L/m^{2}h, similar to another 5 year old installation on the Duqum coast of Oman. This plant operated for the majority of the time in normal seawater conditions. Majis therefore, invited the MF membrane supplier to revisit their design based on the new feedwater conditions and to come up with short-term and long-term mitigations to improve and sustain the MF performance.

Due to the high organic load, and the other parameters outside of the design envelope, it was decided to operate the MF plant at reduced capacity to allow for stable MF operation at reduced flux. Table 11.3.3 shows the original MF design flux and the applied reduced flux for the actual feed conditions.

Furthermore, Majis rented and installed additional 3,000 m^3/d containerized MF-RO units near the main plant to compensate for the applied drop in production and to allow the Pall team to pilot the best operational settings for the main plant under the new feedwater conditions using the same membranes.

Unlike the main plant, the new rental MF units could be sized based on actual water conditions. They thus offered Majis an opportunity to demonstrate the new design settings planned in the main plant for long-term operation. The rental MF containers were operated on the same setting and the same cleaning regime as adapted for the main plant during the short-term mitigations.

Table 11.3.3. Original MF design flux versus reduced flux.

Description	Unit	Original MF unit design	Short-term mitigation conditions
Daily feed to MF	m^3/d	51,600	42,000
Daily net filtrate to RO	m^3/d	48,347	38,737
Number of MF racks	Racks	7	7
Number of modules/rack	Modules/rack	84	84
Total installed membrane surface area	m^2	29,400	29,400
Flux condition when all racks in filtration (N)	L/m^{2}h	73	60
Flux condition at N-1	L/m^{2}h	85	70
Flux condition at N-2	L/m^{2}h	102	84

Operation at a reduced flux allowed for a lower permeability drop during the filtration cycle, and a lower frequency of cleans per day. It was necessary to revisit the cleaning regime considering the high level of organics and the high SDI values in the feedwater. The high crystalline outside-in PVDF membranes are known for their high chemical stability for chlorine and caustic. Given the poor nature of the feedwater (i.e., the high organic load) mixed with high concentrations of feedwater iron, it was important to apply skilled use of alkaline and acidic chemical cleaning regimes to achieve the right balance and to restore MF permeability. Table 11.3.4 summarizes the original cleaning plan and the changes made based on the feedwater conditions.

Table 11.3.4. Original MF cleaning versus modified cleaning based on feedwater conditions.

Description	**Original design**	**Short-term mitigation**
Filtration cycle time / backwash frequency	Every 30-40 minutes	Every 20-30 minutes
Number of EFM[1] cleanings per day	Once/day	Twice/day
Alkaline EFM regular cleaning	Chlorine	Chlorine + Caustic
Acid EFM cleaning frequency	Once every 5 days	Every 3 days
Acidic EFM cleaning	HCl	HCl/Citric
EFM cleaning process	From outside surface of the fibers	From outside/inside surface of the fibers

1. EFM = enhanced flux maintenance

11.3.3.4 Results of short-term mitigation measures

Figure 11.3.4 shows the MF performance before and after applying the short-term mitigation measures. Permeability started to improve once the plant's operational settings had been adjusted to suit the algal bloom conditions with the modified cleaning regime starting in early February. This change led to an immediate improvement in the permeability trend, with the modules recovering their normal permeability within two weeks. The acid EFMs used hydrochloric acid (HCl) to counter the effect of hardness scaling from seawater and were alternated with citric acid cleans to counter the impact of the iron fouling. Alkaline EFMs also used NaOH to counter the effects of the high algal concentration in the seawater feed.

The number of EFM cycles and the backwash frequency were increased during this period to control the permeability decline. Considering the long duration of the disruptions that were experienced, it was recommended to keep the flux < 85 L/m^2h to reduce chemical and energy consumption.

As per the normalized data, the differential pressure (DP) (Figure 11.3.5) started to increase in the SWRO trains in the middle of December when there was a significant change in seawater quality due to a green algal bloom. Such events are usually associated with increased amounts of organics in RO feedwater, and this was confirmed by TOC measurements. Since at least 50% of the TOC was in a dissolved state, it passed through the

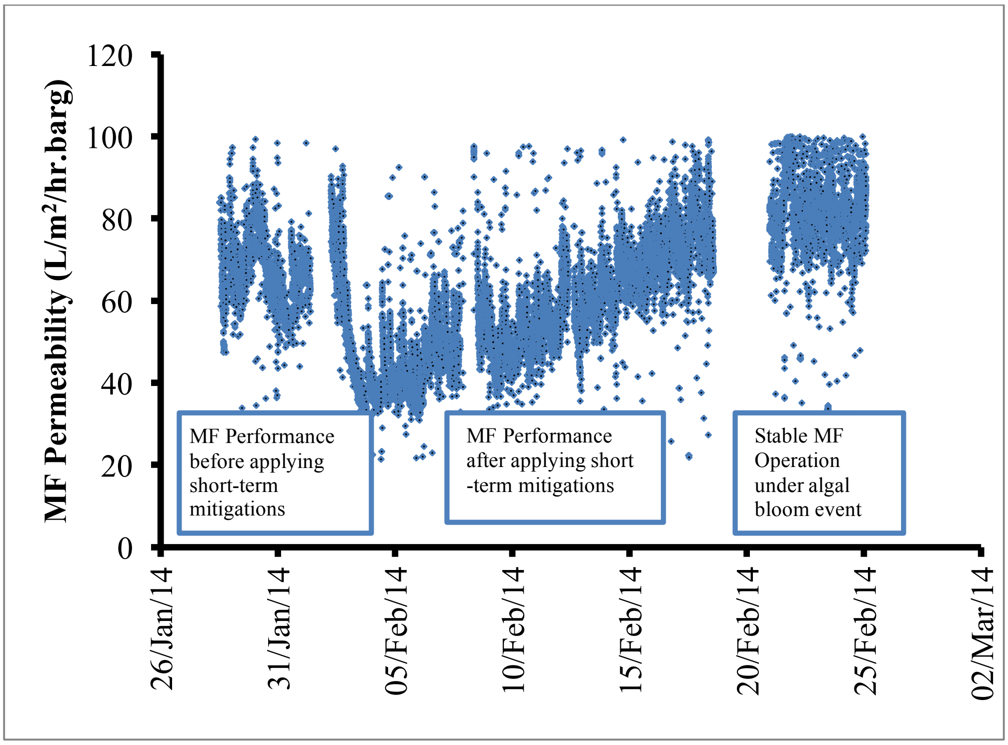


Figure 11.3.4. MF Performance before and after applying the short-term mitigation measures.

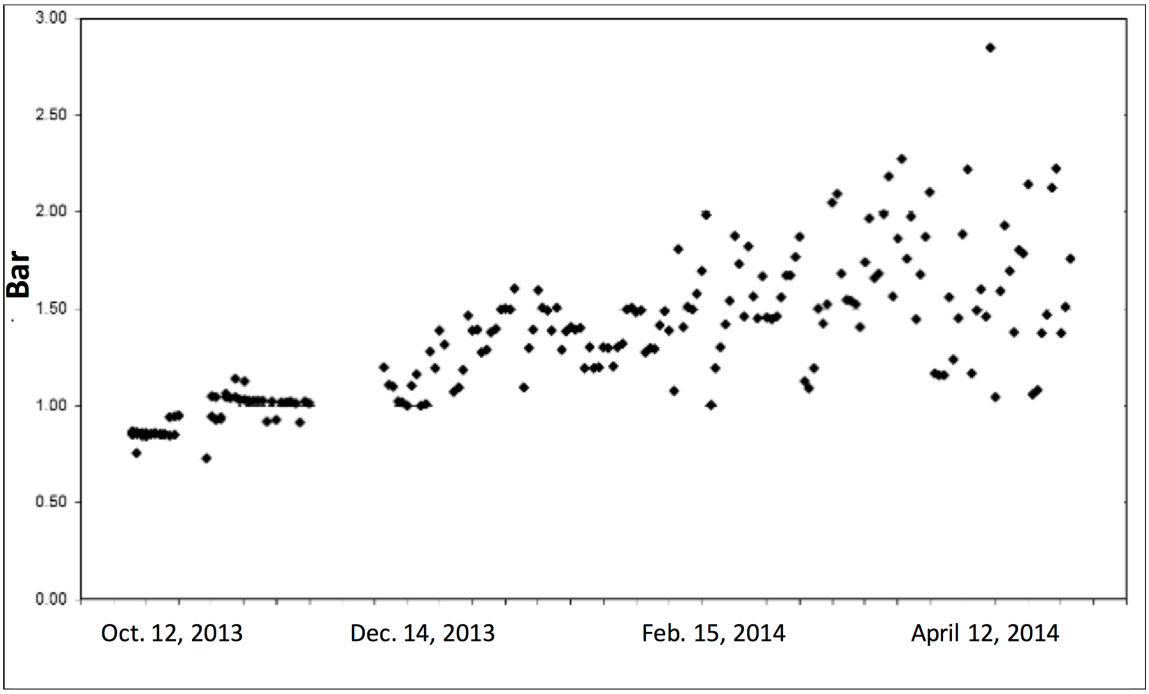


Figure 11.3.5. Normalized differential pressure during the period that short-term mitigation measures were adopted.

MF and reached the RO stage. Furthermore, the seawater intake is continuously chlorinated with a high chlorine concentration. The high dose of SMBS to de-chlorinate also has a negative impact on the RO membranes.

Chlorine, a strong oxidizing biocide, breaks down larger organic chains into smaller more assimilable organics, which are much easier for microorganisms to utilize as food. The combination of all these factors triggered biological fouling of the SWRO membranes. A cleaning regime with high pH and warm water flushing yielded positive results and DP were brought under control. This resulted in frequent RO cleaning cycles, which again detrimentally impacted the daily production rate of the plant. Overall the plant operator adapted a strategy to achieve optimal plant availability and to keep plant productivity up to 88%. In addition the SWRO was operated in a manner to control DP increases using frequent short cleaning followed by high pH solution and then hot water flushing. The short cleanings helped reduce downtime periods of the SWRO system to once per month.

11.3.3.5 Results of demonstration study

The short-term mitigation measures successfully led to stable operation for the self-cleaning strainers and the MF units. But, these measures were not sufficient to confirm long-term plant operation. When considering the seasonally, unstable seawater conditions, it was important to demonstrate the reduced MF flux for a longer time on actual pilot operation. It was also necessary to find a permanent solution for the DOC that passed through pretreatment and affected the downstream RO.

Therefore, a demonstration study was carried out on site using the rented containerized MF-RO units, with net RO capacity of 3,000 m^3/d near the main plant and sharing the same feed source. The objective was to demonstrate and confirm the reduced MF flux, to confirm the fiber status, and to select the optimum cleaning solutions that could fully recover the modules and achieve sustainable operation in the long term. Table 11.3.5 summarizes the MF container sizing parameters.

Table 11.3.5. MF-RO demonstration study sizing parameters.

Description	Unit	Original MF Units Design
Daily feed to MF container	m^3/day/container	4,225
Daily net filtrate from MF container	m^3/day/container	3,950
Number of MF racks/container	racks	2
Number of modules/rack	modules/rack	30
Total installed membrane surface area	m^2 / container	3000
Instantaneous feed flow/container	m^3/h	230
Constant operation flux	L/m^2h	76

Figure 11.3.6 shows the MF stable performance during 8 months of continuous operation. The containerized MF unit operation was stable and the permeability continuously

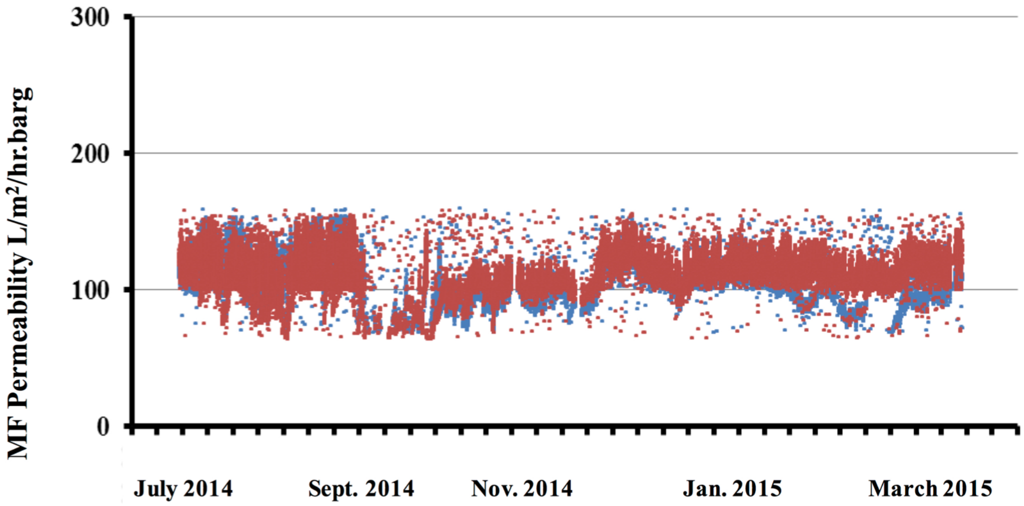


Figure 11.3.6. MF rack 1 and MF rack 2 Performance in the containerized MF unit.

maintained above 100 L/m^{2}h.bar, except for a few days during an algal bloom event that repeated again in September 2014.

11.3.4 Long-term mitigation measures

With a strategic view on the desalination business of Majis, it has been decided to replace continuous chlorination with shock chlorination. This will be challenging, as the Majis intake system serves various types of industries that are dependent on the chlorine level at their heat exchangers.

For the removal of DOC, it is important to use coagulation upstream of the MF system to remove dissolved organics that are currently fouling the RO membranes. Either a direct coagulation before the MF units will be applied in the existing plant, or during phase 2 of plant expansion, a common gravity filter stage with coagulation dose could be installed preceding the new RO system. This would be located upstream of the MF system to cover both phase 1 and phase 2.

The self-cleaning filters will be expanded by adding an extra two units, and the drum screens' pore size will be reduced back to 100 µm from 300 µm. This increase in the screen area will allow for continuous supply and the use of non-metallic parts instead of the metallic screens that have enhanced the removal of sticky materials from the screen surface.

Based on the research study, operation under a relaxed flux range of < 76 L/m^{2}h showed very stable operation for the MF containerised units. The same flux was used as the maximum MF flux for long term mitigation of poor feedwater in the main plant. Extra membrane surface area will be added to allow full production at the reduced flux. Table 11.3.6 summarizes design changes for long-term mitigation of algal blooms.

The frequency of HCl cleaning will be increased as will the use of citric acid in addition to HCl. Alkaline cleaning will use a mixture of chlorine and caustic soda (Table 11.3.7). The use of direct coagulation is one of the options proposed for removing dissolved organics.

Table 11.3.6. Planned design changes at Majis.

Description	Unit	Original MF unit design	Long-term mitigation
Daily feed to MF	m^3/d	51,600	58,500
Daily net filtrate to RO	m^3/d	48,347	54,800
Number of MF racks	Racks	7	9
Number of modules/rack	modules/rack	84	96
Total installed membrane surface area	m^2	29,400	43,200
Flux condition when all racks in filtration (N)	L/m^{2}h	73	56
Flux condition with N-1	L/m^{2}h	85	63
Flux condition with N-2	L/m^{2}h	102	72.5

Since the pretreatment system has been modified, the RO system performance is expected to improve. There is also a plan for reducing the flux rate on the SWRO from 16.6 L/m^{2}h to 14 L/m^{2}h by adding extra RO membranes. With the use of coagulation in front of the MF units, the majority of DOC should be removed, and this will further achieve better results in the RO system.

Table 11.3.7. Long-term operational settings for the MF system.

Description	Original design	Long-term mitigation
Filtration cycle time / backwash frequency	Every 30-40 minutes	Every 20-30 minutes
Number of EFM cleaning per day	Once/day	Twice/day
Alkaline EFM regular cleaning	Chlorine	Chlorine + Caustic
Number of EFM cleaning per day	Once/day	Twice/day
Acidic EFM cleaning	HCl	HCl/Citric
Acid EFM cleaning frequency	Once Every 5 days	Every 3 days
EFM Cleaning Process	From outside surface of the fibers	From outside/inside surface of the fibers

11.3.5 Conclusions

Although the raw water during commissioning was significantly poorer in quality than expected, it was possible with some modifications to start successfully and operate the 20,000 m^3/d plant at the Majis port of Sohar. Lessons learned from the various challenges faced during this phase of operation include:

- The open seawater intake with shallow depth, high silt concentration, and continuous chlorination is challenging enough, but when jellyfish and algal blooms also appear, raw water quality can deteriorate to the extent that normal operation becomes difficult. In those instances, a special operating regime needs to be adopted to enable the plant to operate with maximum output.
- Accurate and detailed feedwater analysis over a period of at least one year is required for the design, especially in the case of open intake installations liable to be affected by jellyfish and HABs.
- It is possible to apply direct membrane filtration in open intake installations challenged by high SDIs and prolonged algal bloom events without the need of conventional pretreatment if accurate feedwater analysis over a period of time is provided, and a combination of direct coagulation and membrane filtration are used as pretreatment.
- The membrane installation should always be designed to allow for the addition of extra modules, and space should be allocated for an additional rack to mitigate against a significant deterioration in the feedwater quality.
- The skilled use of alkaline and acid cleaning regimes can restore the permeability of the microfiltration membranes, even when challenged with unexpected feedwater conditions.
- Highly crystalline PVDF modules and the outside-in configuration are extremely robust and able to effectively operate in variable and unexpected seawater conditions.

11.4 BARKA 1, OMAN - THE IMPACT OF HARMFUL ALGAL BLOOMS ON THE PERFORMANCE STABILITY OF UF PRETREATMENT

Graeme K. Pearce[1]

[1]Membrane Consultancy, Reading, England

Figure 11.4.1. Location and aerial view of Barka 1 desalination plant in Oman.

Table 11.4.1. Overview of the Barka 1 desalination plant.

Plant/Project Name		
Location	Barka, Oman	
Primary product water use	Municipal	
Desalination Technology	UF-SWRO	
Total Production Capacity (m^3/d)	45,500	
SWRO recovery (%)	43%	
Commissioning date	February 2014	
Intake		
Feedwater source	Gulf of Oman	
Intake type	Shore intake via MSF cooling system of neighboring plant	
Intake description	Intake designed for MSF (1200m from shore, 500 m min 5 m depth)	
Intake screening	Intake screen (3 mm) designed for MSF	
Chlorination	Hypochlorite continuous dosing, at 0.1-0.2 mg/L residual	
Online raw water monitoring	Conductivity, temperature, pH, turbidity, residual chlorine	
Discrete raw water analysis relevant to HAB	TOC, Total N, chlorophyll-*a*	
Pretreatment		
Process description	Pressurized UF, inside-out with 300 µm pre-strainers Option for in-line Fe^{3+} coagulant dosing, but not used during 9-month operational period under review	
Feedwater design parameters		**Feedwater during bloom conditions**
Temperature range (˚C)	40 - 45	
Salinity range (TDS mg/L)	Approx. 40,000	
Conductivity (mS/cm)	Approx 55	
Total Suspended Solids (mg/L)	< 5	Unknown
$SDI_{2.5}$ (2.5 minute)	20 - 35	Light bloom: 35 – 40 Significant bloom: > 40
Turbidity (NTU)	Approx. 0.2	
Organic matter (mg/L)	Approx. 1 TOC	
Desalination Design		**During bloom conditions**
UF flux (L/m^2h)	65	65

11.4.1 Introduction

The original desalination and power plant at the industrial port city of Barka was based around a 91,000 m^3/d multi-stage flash (MSF) thermal desalination unit. Barka is located 60 km north east of Oman's capital, Muscat, and draws its feedwater from the Gulf of Oman as shown in Figure 11.4.1. In 2012, the plant operator, ACWA Power Barka won a contract from the government agency Oman Power and Water Procurement (OPWP) for expansion of the facility with a 45,500 m^3/d seawater RO (SWRO) unit. The contract to build this first phase expansion plant, subsequently referred to as Barka 1, was awarded to Abeinsa. The contractor, a wholly owned subsidiary of the Spanish EPC Abengoa, is experienced in UF-SWRO design and operation including with feedwater that are prone to algal bloom (Bernaola 2012). Commissioning for Barka 1 started in September 2013 with continuous operation in February 2014. In 2015, a second phase expansion for a further 57,000 m^3/d, known as Barka 2, was also brought online.

The Barka 1 plant uses an open intake seawater feed without any pretreatment by clarification or flotation. Before arriving at the RO desalination plant, the feedwater passes through the heat exchangers of a condensing system providing cooling water for the MSF facility. The plant has a provision for in-line coagulant dosing which was intended for periods of poor feedwater quality, but for the period of review in this case study, this dosing facility has not been used.

Details of the algal species at Barka during the period of this investigation were not determined directly. The HAB and red tide causing species commonly found in these areas are: *Noctiluca scintillans*, *Dinophysis* spp., *Gonyaulax* sp., *Trichodesmium* sp., and *Ceratium* spp. of which the dinoflagellate, *N. scintillans* is a major species that produces red tide blooms yearly (Thangaraja et al. 2007). More recently, 24 algal species have been identified in these waters (Al-Azri 2014) with relatively abundant concentrations of the dinoflagellates *Prorocentrum minimum* and *Cochlodinium polykrikoides* being reported for the first time.

The pretreatment system at Barka 1 utilizes Pentair-Xflow UF. The Xflow membranes are made from polyethersulfone (PES) and have a nominal 0.02 µm pore size rating. The membranes operate with an inside-out feed flow configuration, with four 1.5 m elements mounted in a 6 m horizontal pressure vessel.

This case study focuses on the performance stability of the UF system during a 9-month period which took place 5 months after continuous operation commenced in February 2014. This ensured that initial conditioning of the membrane was completed and effective chemical cleaning procedures were established. The period under review started in July 2014 and finished in April 2015 and was assessed through the monitoring of permeability trends for three months at the start of the review period and comparing these trends with the three months at the end of the period.

11.4.2 Plant overview

A simplified block flow diagram for the Barka 1 desalination plant is shown in Figure 11.4.2. The seawater feed is taken from an open intake 1200m from shore at a depth of 5 m below the lowest tide level. Following 3-mm screens, the seawater is used as cooling water for the neighboring MSF desalination plant, which increases the temperature by 9 ºC. The feedwater is chlorinated with a 2 ppm free chlorine dose prior to the MSF, but by the time it reaches the membrane units, the chlorine residual has reduced to around 0.2 ppm. The desalination plant feedwater is filtered by 300 µm strainers before passing through the eight UF units. There is an option for in-line coagulant dosing, but this was not employed during the nine-month period of evaluation described in this case study. The UF is connected directly to the RO without a balance tank. The RO high-pressure pumps feed three RO trains that normally operate continuously at a constant flux.

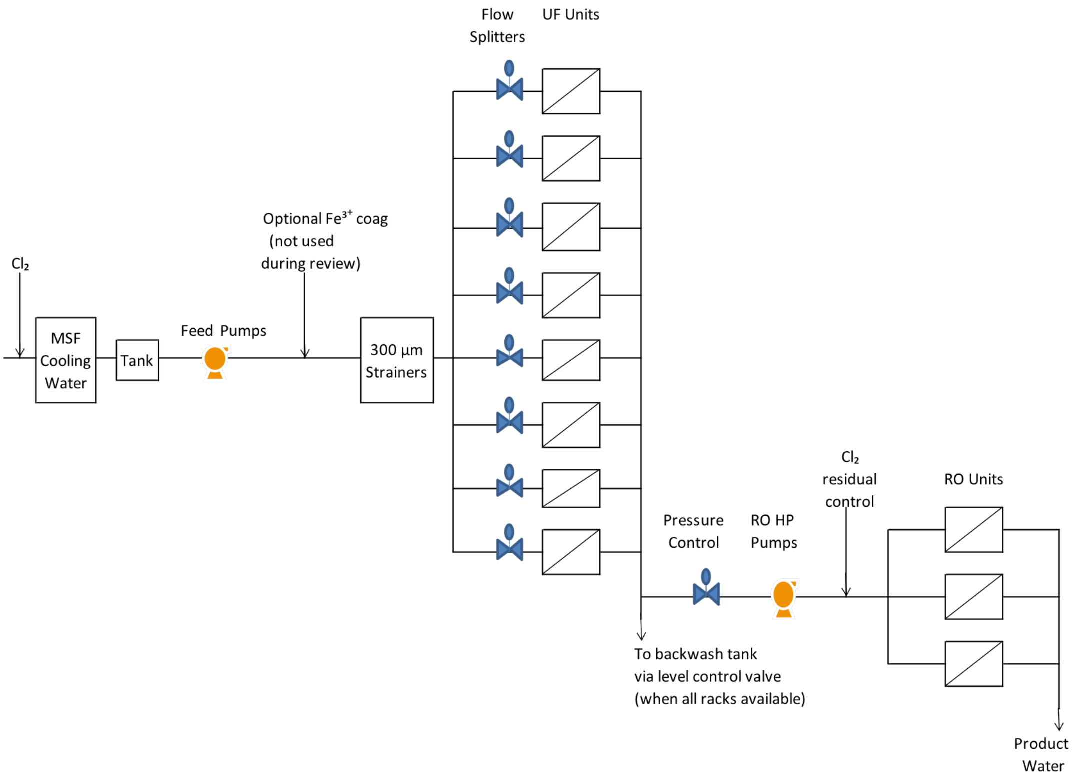


Figure 11.4.2. Simplified block flow diagram showing feed and product flows for the Barka I SWRO desalination plant.

Essential details for the Barka 1 desalination plant are summarized in Table 11.4.1 with details of location, intake, and pretreatment design as well as a description of the feedwater quality. Note that the feedwater from the MSF cooling system is continuously chlorinated with de-chlorination prior to the SWRO. Algae is frequently experienced in this feedwater, but the blooms have not been too severe to date.

11.4.3 UF System Design

11.4.3.1 Membranes

The Barka UF pretreatment system utilizes the Pentair-Xflow Xiga 55, which has a membrane area of 55 m² for each element. The plant is arranged in eight units. Each unit has 46 housings that hold 4 elements per housing, thus there are 184 elements per unit with a total membrane area of 10,120 m². The total membrane area for the whole plant is 80,960 m². There are two vacant places on each of the units, so that a total of 48 housings per unit could be used if production capacity needed to be expanded allowing a 4.3% increase in membrane area.

The housing for the Xiga 55 element has a 9 inch (225 mm) nominal bore. Prior to 2012, most Pentair-Xflow systems were based on the 8 inch (200 mm) Xiga 40 element. The Xiga 55 still uses a central filtrate collector, but has bypass channels on the outer circumference rather than around the central collection pipe. The additional diameter combined with the different filtrate collection arrangement has enabled a significantly higher membrane area to be obtained from a single element, even though the dimensions of the membrane fiber are identical (internal diameter, 0.8 mm, external diameter, 1.3 mm).

11.4.3.2 In-line design

The UF is connected directly to the RO in a direct-coupled design that eliminates the break tank between UF and RO systems. Pentair-Xflow is a strong proponent of the in-line UF-RO system design, especially for large scale seawater duties. The control system provides a constant inlet pressure to the RO feed pump at approximately 2 bar. Eliminating the RO feedwater tank reduces space and cost for the system and saves energy. Of arguably greater significance, the intermediate tank can promote biofouling, and so by eliminating it from the flowsheet, the operational stability of the RO can be improved and chemical cleaning frequency reduced (Pearce 2013; Knops 2014).

In-line designs need to employ a significant number of units to ensure that flow can be kept reasonably constant. In order to minimize fouling it is preferable to keep flux variation within 10% of the average if possible (+/- 15% maximum), or alternatively the average flux should be reduced by a few percent (Pearce 2015). In the Barka 1 design, the flux selected is moderate and the flux variation for the in-line design has been optimized such that the variation falls within the 10-15% guideline. Accelerated fouling would therefore not be expected, and as will be seen from the results review in section 11.3.4, has not been observed.

11.4.3.3 Flux

For a plant without flux variation, it would be expected that 70 L/m^{2}h would be a suitable design flux for the Pentair-Xflow membrane on seawater from the Gulf based on comparison with other plants. The Barka 1 plant has been designed to operate at an average UF flux of around 65 L/m^{2}h, but with a modest degree of flux variation. Flux varies during the filtration cycle (time between backwash) between 60 and 70 L/m^{2}h, with occasional short-lived excursions down to 55 L/m^{2}h and up to 75 L/m^{2}h. Fine-tuning the process cycle has minimized the flux variation. At the design flux, the filtration cycle time is approximately 50 minutes, but this cycle time may extend at lower flux.

When a unit is taken off-line for backwash, the remaining units increase their flow in proportion causing an increase of flux over the average for when all 8 units are available, that is, from around 62 L/m^{2}h with 8 units in filtration, to about 70 L/m^{2}h when one unit is in backwash. The filtration cycle takes about one minute. At the same time, some filtrate is taken from the manifold to replenish the backwash tank. The replenishment rate has been optimized to ensure that there is no adverse effect on flux variation.

11.4.3.4 Temperature correction

Warm feedwater temperatures increase clean water permeability. For example, an elevation of 9 ^{o}C above ambient should increase permeability by 30%. Furthermore, the elevated temperatures would reduce lumen length pressure drop as well as pressure drop in the shell, resulting in improved hydrodynamic efficiency of the module. The benefit at 70 L/m^{2}h would, however, be minimal since hydrodynamic stress at this moderate flux is relatively low.

Furthermore, the benefit of elevated temperature for a real feedwater is observed to be significantly less than the 30% permeability improvement indicated above. For seawater from the Gulf, fluxes are determined as much by the concentration of particles in the lumen as by the permeability across the membrane. Any increase in flux would increase the particle concentration in the lumen and at the membrane surface thereby increasing the fouling rate. Thus in these circumstances, elevated temperature would have no significant benefit. This assumption is reinforced by the practical observation that there does not appear to be a benefit from high temperature operation for other power plant cooling water desalination systems.

11.4.4 UF system performance

11.4.4.1 Expected permeability

A typical Pentair-Xflow membrane has a permeability of 400-500 L/m^{2}h.bar during early operation on a surface water feed at 20°C (for example during take-over testing). Generally, the membrane would stabilize after the first month at 300-400 L/m^{2}h.bar, depending on feedwater quality, and this would be expected to represent an initial baseline.

Seawater feeds may have lower permeabilities than for surface waters at the same temperature since the viscosity and density are both higher. Permeability is also strongly affected by foulants and the adsorption of organics, especially algae and algal derivatives. A higher temperature would decrease viscosity, which would give an increase in permeability.

For the Gulf water feedwater at Barka, taking account of the effects described above, it would be expected that the baseline permeability after the initial operating period should be around 350-400 L/m^{2}h.bar, depending on local feedwater quality characteristics. Permeability reported in subsequent sections shows that the Barka 1 plant has been able to achieve the expected permeability level.

11.4.4.2 Use of chemical cleaning to maintain permeability

Performance stability is maintained by conducting a chemical enhanced backwash (CEB) on a regular basis. Under normal circumstances with good quality feedwater, the CEB would be scheduled once every 23 or 24 backwash cycles, equivalent to an interval of around 18 hours between consecutive CEB's (which is the period referred to in this review as a CEB cycle). If feedwater quality deteriorates, for example due to an algal bloom, or permeability drops for some other reason, the CEB is performed more frequently, perhaps after 12 or 15 hours. The change of CEB frequency is initiated manually.

If there is a long-term deterioration in CEB, a Clean-In-Place (CIP) is performed. The CIP is more effective than CEB since the contact time is longer and the chemicals may be recirculated. The longer CIP downtime would mean that recovery and hence output would be reduced if conducted too frequently, so it is beneficial to make the interval between CIP as long as possible with a target of at least 6 months. It is therefore important for the CEB to recover a high proportion of the permeability lost during the course of a CEB cycle.

360 CEB cycles have been performed in the period of this review. The following time periods have been evaluated which used the full design flux at a consistent level:

1. Period 1: CEB cycles 8 to 119 during 10 July to 7 October 2014; and
2. Period 2: CEB cycles 201 to 360 during 1 January to 27 April 2015

Prior to cycle 8, flux varied. No data were evaluated for cycles 120 to 200 in the last quarter of 2014, but the plant appeared to operate in a stable fashion at this time. The starting permeability at the beginning of Period 2 was fully satisfactory and in line with expectations for this type of operational plant with membranes in good condition.

The analysis focuses on the performance of unit 7 since this unit was found to have average performance, although, variation between units was found to be almost negligible.

11.4.4.3 Permeability trends during period 1

Figure 11.4.3 shows the permeability trend data for Period 1, CEB cycles 8 to 119, together with the CEB cycle time on the right-hand axis.

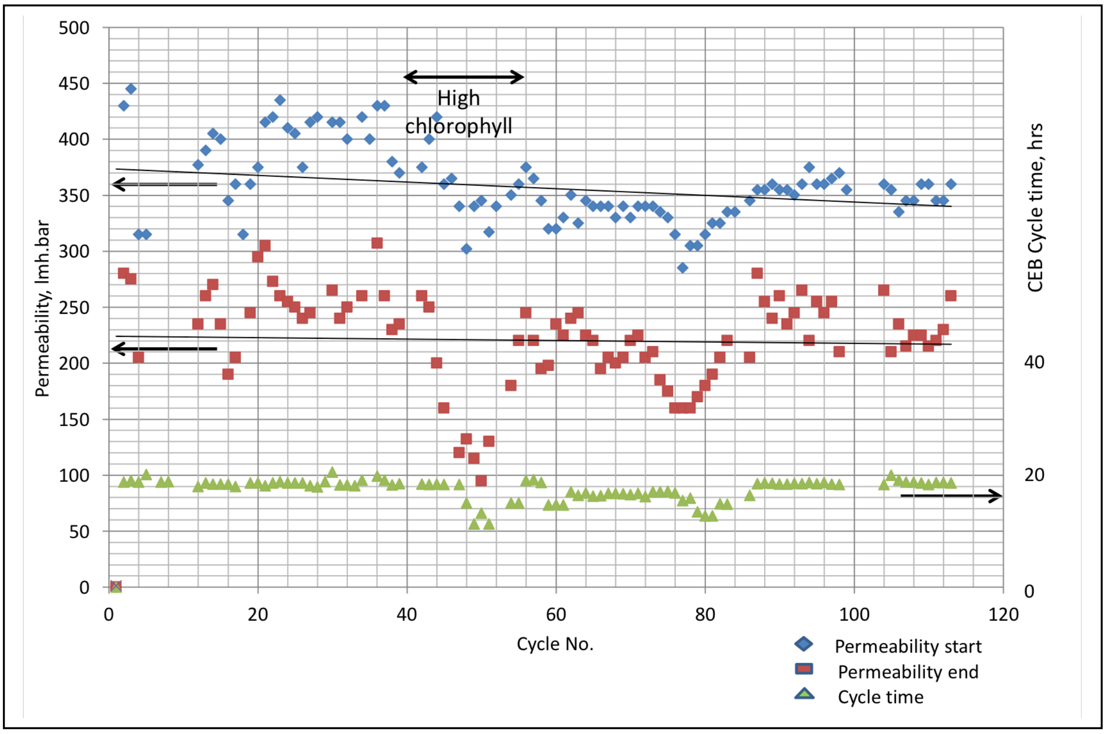


Figure 11.4.3. Permeability at start and end of CEB cycle for cycles 8-119

The chart shows the loss of permeability during the course of a CEB cycle was significant at around 100-150 L/m^{2}h.bar, and that the CEB was reasonably effective at recovering the permeability (Figure 11.4.3). The CEB was not fully effective, and there was a gradual loss of permeability with time. The loss reduced slightly in the later cycles and showed a response to external factors.

At the beginning of CEB cycle 8, the initial permeability was fully satisfactory. The chart shows the trend lines for start and end permeability. The two trend lines gradually converge, indicating that the rate of fouling was falling, and this issue will be discussed in more detail below. The slope can be used to predict the requirement for CIP and quantify the CIP interval and this will be discussed below.

For a given flux, permeability is affected by the following control variables:

- Filtration cycle time
- CEB interval
- Feedwater quality

The loss of permeability in a single filtration cycle was approximately 5 L/m^{2}h.bar per cycle. A series of 24 cycles would therefore lead to a permeability loss of approximately 120 L/m^{2}h.bar. In reviewing the data, there has not been an opportunity to examine the effect of changing the filtration cycle time, since this value is linked to the flux, and only increased if the flux reduced. It is possible that the rate of fouling could be reduced slightly by reducing the filtration cycle time from the standard interval of 50 minutes. This action would not be recommended, since recovery would fall significantly. The first of the three parameters is therefore not a control variable as far as the operator is concerned.

The second factor listed is the interval between CEB. Although normally set at one CEB every 23 or 24 backwash cycles (equivalent to a time interval of 18 hours), the interval can be reduced as shown by the green triangles in Figure 11.4.3.

The final operational factor affecting performance is the feedwater quality. The main parameter that appears to correlate with permeability is the chlorophyll concentration. Typical concentrations vary between 0.02 and 0.04 µg/L, but minor excursions to 0.1 µg/L do not appear to cause the UF system any problems and appear to indicate a normal non-problematic seawater quality. A moderate algal bloom event between cycles 40 and 60 (mid to late August 2014) had a significant effect on permeability, but the plant managed to maintain flux and recovered without any intervention other than a reduction in the CEB cycle time. For a more significant algal bloom, it might be necessary to reduce flux or possibly consider coagulant dosing.

Figure 11.4.3 shows that increasing CEB frequency from once in 18 hours to once in 15 hours or 12 hours during a period of high algae between cycles 40 and 60 enabled the plant to cope with the challenging conditions. Although permeability dropped during this period by around 100 L/m^{2}h.bar, the plant recovered without having to reduce the flux. Permeability then recovered to a level only marginally below the original level once feedwater quality returned to normal conditions.

Note that the CEB cycle time remained slightly below the original level between cycles 60 and 80, which appeared to arrest the rate of decline slightly. The situation was made more complicated by the fact that there was a sticking valve on unit 7 at around cycle 75, that is, during the 2nd week of September. The result of this was that CEB was not fully effective during this period and permeability temporarily declined. After the problem was resolved, the plant returned to previous levels without any further intervention, again underlining the fact that the operational regime was sufficiently robust for performance to recover after a minor upset.

11.4.4.4 Permeability Trends after One Year of Operation

Figure 11.4.4 shows permeability trends for cycles 201 to 360. The figure shows that the starting permeability in cycle 201 was similar to the starting permeability at cycle 119, thus the gradual decline discussed in the previous section had been arrested. The difference between the start and end permeability from cycle 201 onwards is normally around 100 L/m^{2}h.bar or just over which is similar to or slightly less than in cycle 119.

The initial permeability did not decline further between cycles 119 and 201 because of the use of a slightly shorter CEB cycle time, i.e., CEB frequency increased. Shortening CEB cycle time reduces the loss of permeability in the course of a CEB cycle. For cycles from 201 onwards, CEB cycle time was 12 - 15 hours as opposed to 18 hours previously. The higher frequency was implemented in response to the poor feedwater quality from an algal bloom that began in December and continued for much of January through April. Increasing CEB frequency made the start permeability more stable. This has the effect of lengthening the CIP interval and will be quantified in section 11.4.4.7.

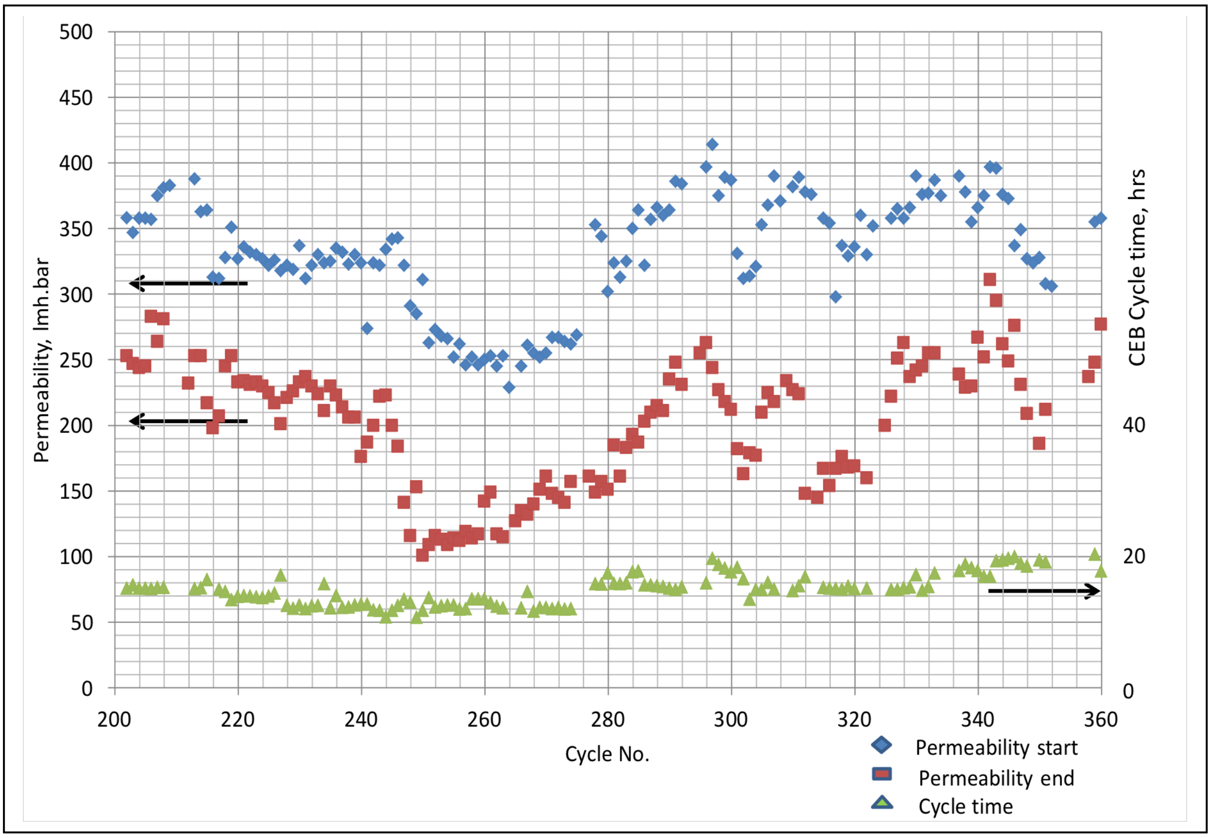


Figure 11.4.4. Permeability at start and end of CEB cycle for cycles 201-360.

11.4.4.5 Analysis of CEB Cycle Time

Figure 11.4.5 shows the effectiveness of the CEB at recovering permeability. Between cycles 8 and 119 there was a steady drop in the recovery obtained, and that drop can be used to predict the required CIP interval. It would be possible to improve recovery by changing the procedure or the frequency of the CEB. Procedural changes would include the following:

- increasing the concentration of the chemicals used;
- increasing the contact time;
- changing the chemicals used; and
- changing the order in which the CEB's were performed and chemicals utilized in the CEB procedures

The other changes that could be considered for improving the effectiveness of chemical cleaning and might be practical for a CIP procedure are:

- introducing flow-through or recirculation to improve mass transfer (due to replenishment of spent chemical at the foulant location); and
- warming the chemicals (only applicable in cold climates and not relevant at Barka)

These changes would depend on whether they could be accommodated by the system design.

A simpler alternative to changing the CEB procedure is to increase the CEB frequency, and the effectiveness of this approach is demonstrated in Figure 11.4.6 for CEB cycles 201 to 360. Whereas the average CEB cycle time was 18 hours in Figure 11.4.5, the cycle time in Figure 11.4.6 was reduced to 12 or 15 hours up until cycle 320. The consequence of this was that permeability recovery steadily improved despite the fact that feedwater quality was

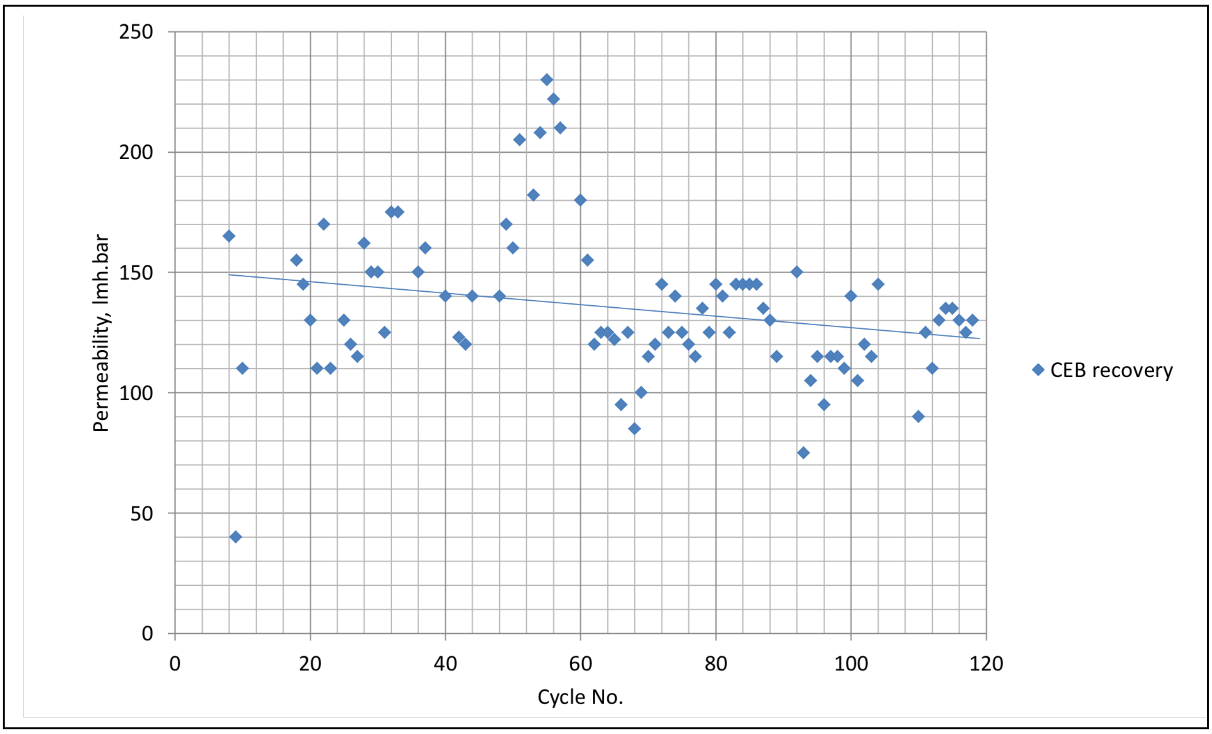


Figure 11.4.5. Permeability recovery by CEB; cycles 8-119 (CEB cycle mainly 18 hours)

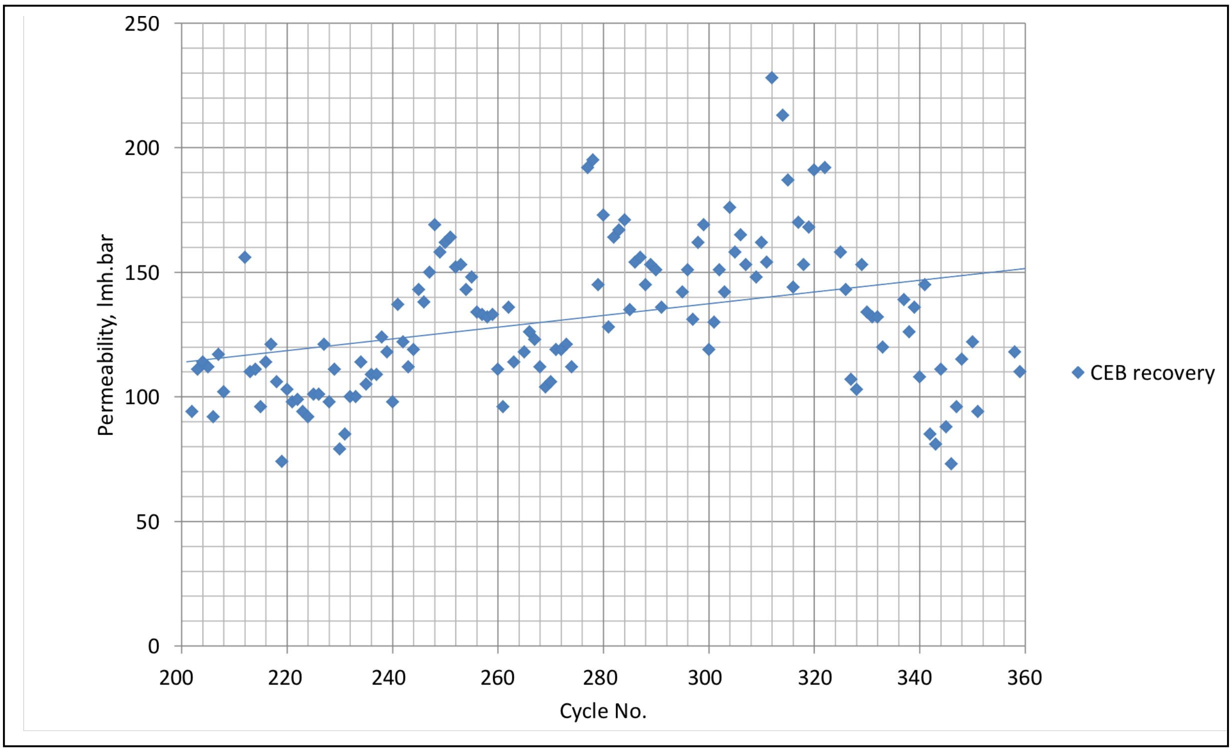


Figure 11.4.6 Permeability recovery by CEB; Cycles 201-360 (CEB cycle mainly 12-15 hours)

poorer. Early in April, the CEB interval was increased to the original level of 18 hours, resulting in a sharp drop off in recovery. The problem was exacerbated due to a second sticking valve incident which made CEB completely ineffective for 3 or 4 cycles between cycle 356-358 on 22nd to 24th April 2015. The strong downward trend was already well established by this time, so the sticking valve did not appear to initiate the problem of permeability drop off.

11.4.4.6 Fouling Rate Trends

Figure 11.4.7 shows the fouling rate trend for cycles 8 to 119. The fouling rate is calculated by dividing the permeability loss in units of L/m^{2}h.bar in the course of a CEB cycle by the CEB cycle time in hours. Data are also shown for the first 7 cycles in which the lower and variable flux gave rise to a lower fouling rate. After an effective CIP at the end of June, fouling rates after cycle 8 between July and October were steady and slightly decreasing, apart from the period of poor feedwater quality (high algae) in the third week of August (corresponding to CEB cycles 40 to 60).

The fouling rate during CEB cycles 201 to 360 is shown in Figure 11.4.8. In general, the fouling rates during this period were higher than those previously. Whereas in period 1, one algal bloom happened in the third week of August between cycles 40 and 60, Figure 11.4.8 shows that there were multiple occasions in period 2 when chlorophyll spiked higher. There was one extended event from 13 January to 9 February (cycles 220 to 260) and there were four other shorter episodes between late February and early April. The chart shows that the fouling rate increased during the first episode, and stayed at a relatively high level through the beginning of April. This sustained poor feedwater quality did not cause operational stability problems however, since the CEB cycle time was shortened throughout this period.

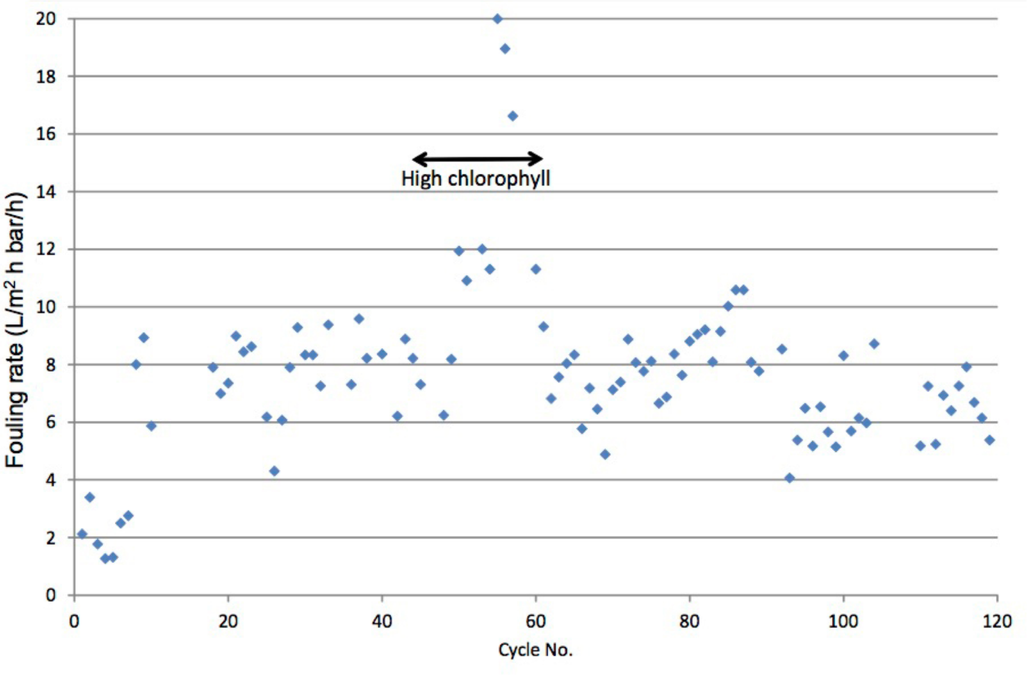


Figure 11.4.7. Fouling rate vs CEB cycle number for Cycles 1 to 119.

As of October, regular measurements of the SDI were taken and these are shown on the chart as well. Note that the values used by the operator were not the conventional 15-minute SDI, and for simplicity the reported chart values in Figure 11.4.8 have been adjusted to show the relative trend rather than the absolute values of SDI$_{2.5}$. For very high fouling feeds, the operator used an SDI$_1$ measure at one minute. The operator's SDI was 20 times the value on the chart axis, that is, normally falling between 30 and 40 units for SDI$_{2.5}$ and up to 90 for SDI$_1$.

High SDI was observed sporadically after 13 January (cycle 220) and for a sustained period in early February when the algal bloom was at its most intense (cycles 250-260). After that, high SDI was observed occasionally at times corresponding to the high chlorophyll measurements. Many high SDI measurements were made during mid-late March (cycles 310-340), but these were interspersed with lower SDI measurements, suggesting that the algal bloom was light, or at least not sustained. SDI is useful as an indicator of high algal concentrations, but the correlation is only partial, since other factors influence SDI values.

The fouling rate fell during April after cycle 340 due to the improvement of feedwater quality and extension of the CEB cycle. Notwithstanding, as shown in this review, the frequency of CEB was not sufficient to maintain the permeability during this period, which led to a significant drop off in permeability (Figure 11.4.4).

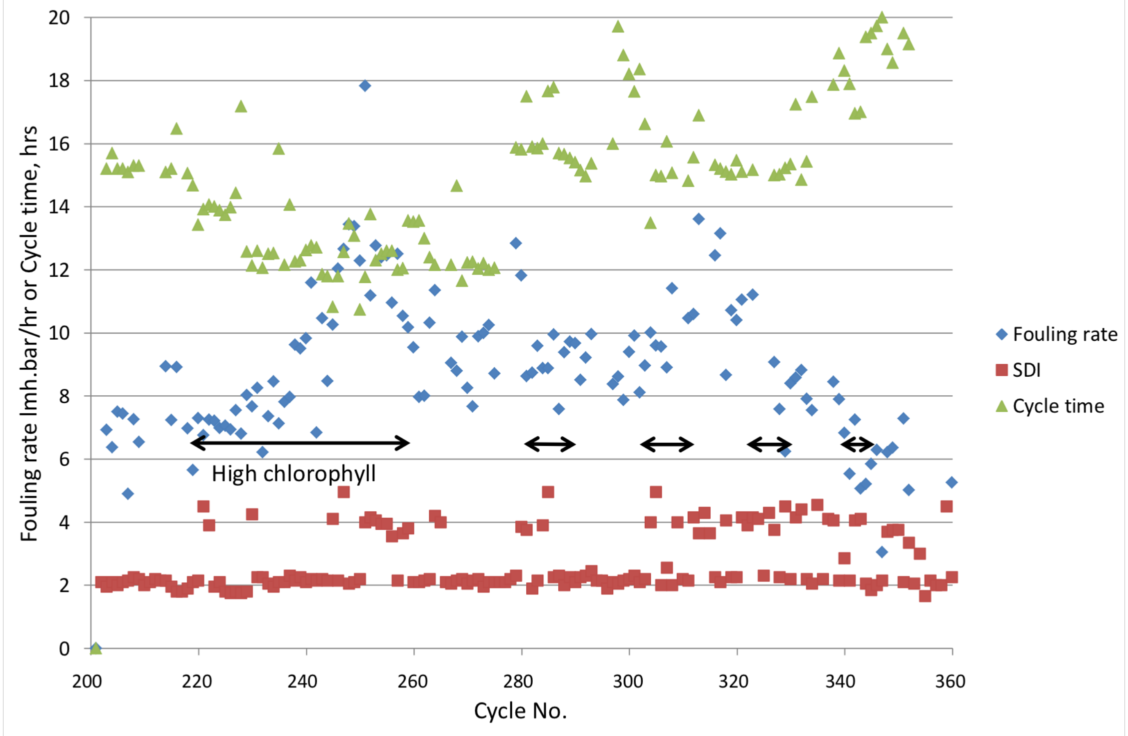


Figure 11.4.8. Fouling rate, SDI and CEB cycle time for cycles 201 to 360 (Note – SDI values indicate a relative trend of $SDI_{2.5}$ values and are not SDI_{15} values).

11.4.4.7 Projected CIP Interval

Figure 11.4.3 shows that after a CIP, the permeability at the start of a CEB cycle can be expected to be 350-400 $L/m^2h.bar$. With an 18-hour interval between CEB, as was applied for most of the time between cycles 8 and 119, the slope of the line of best fit through the data shows a decline in permeability of around 30 L/m^2hbar over 100 cycles or 1800 hours (74 days). This is a rate of decline of 0.4 $L/m^2hbar/day$.

Figure 11.4.3 also shows that the loss of permeability in the course of a CEB cycle is around 100 to 150 L/m^2hbar between the start and end of each CEB cycle (the difference between the two lines of best fit). The difference is slightly greater when the membrane is cleaner and less towards the end of the cycle.

If we take it that just prior to a CIP, we should expect the permeability loss to be towards the lower end of this range, say 100-125 L/m^{2}h.bar, we can use this value to predict the allowable decline in the starting permeability. An idealized chart is reproduced in Figure 11.4.9 using the typical permeabilities discussed. The chart shows that for an 18-hour CEB cycle, the projected CIP interval would be 6 months. This would mean that after 6 months of operation and prior to a CIP, the worst-case permeability would be 150-200 L/m^{2}hbar (assuming the permeability is measured at the end of the CEB cycle).

It should be noted that this analysis assumes that swift action is taken during a light to moderate algal bloom to reduce the CEB interval first to 15 hours, and then to 12 hours if necessary, and this shortened interval in maintained until the starting permeability has fully recovered to its pre-bloom level.

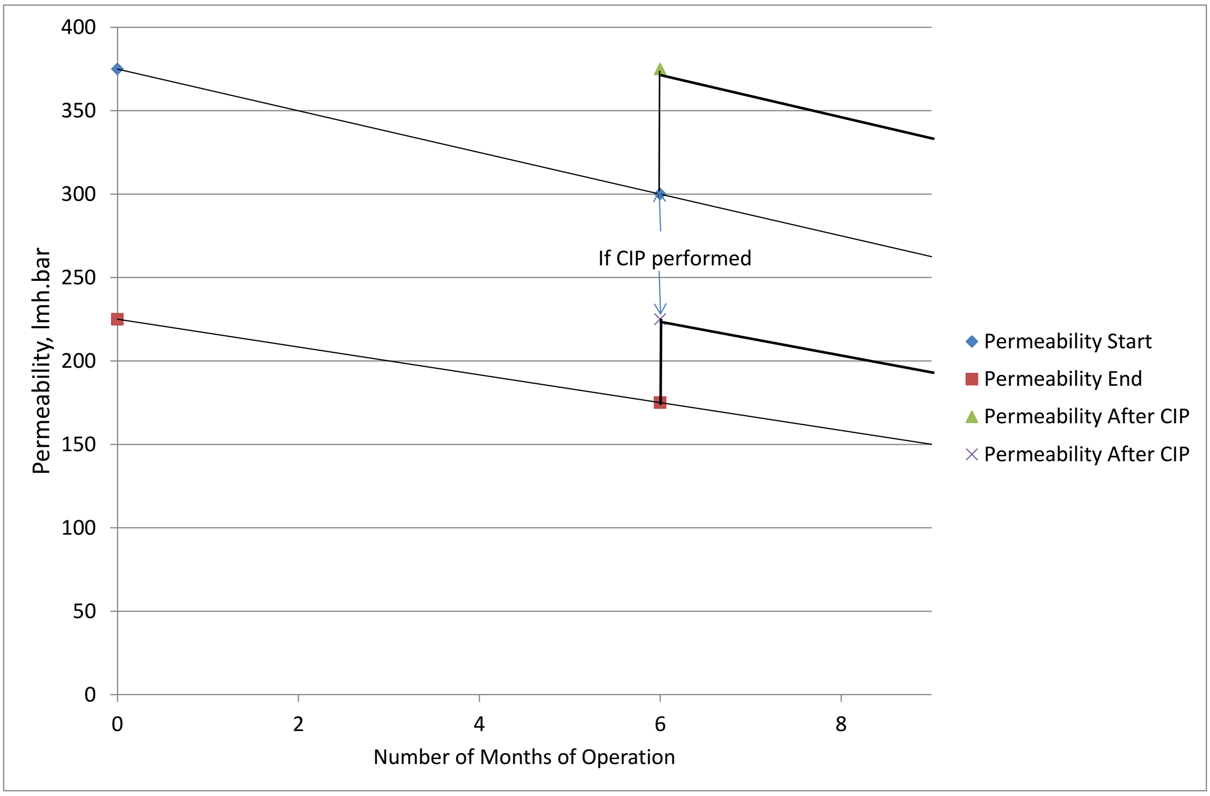


Figure 11.4.9 Projected CIP interval for an 18 hour CEB cycle.

The permeability trends for cycles 201-360 show that shortening the CEB cycle to 15 hours for extended periods would extend the interval between CIP beyond 12 months, especially without feedwater quality excursions or equipment failure. Figure 11.4.4 showed that the long-term permeability could be maintained at this frequency even during light algal events and the system could easily recover itself during moderate algal events without flux reduction.

Plant experience that has shown a 6 month CIP interval was achieved for unit 7 with the June CIP being followed by a CIP in early February. Allowing for short shutdowns, unit 7 has achieved just over 6 months of operation at full flux in line with this expectation. The experience of chemical use on unit 7 has shown that it is better to manage permeability expectations by slightly increasing CEB frequency and reducing the use of CIP.

The analysis has not determined the effect of a severe algal bloom, since none occurred during the period of evaluation. Projecting the expected performance based on behavior during moderate algal bloom events indicates that a stepwise reduction of flux may be necessary during very poor feedwater quality. For example, an initial reduction of flux to 80% of the design level (to 52 L/m^{2}h), accompanied by an immediate reduction of the CEB interval to 12 hours would probably accommodate most situations. A further set of reductions may be necessary if the algal bloom is dense and sustained.

Another option would be to use coagulant during significantly poor feedwater quality episodes including high algal cell concentrations. This has not been found to be necessary with the feedwater quality experienced to date.

11.4.5 Conclusions

- The permeability of Pentair-Xflow membranes for the seawater duty at Barka 1 was expected to be at least 350-400 L/m^{2}h.bar after cleaning by CIP; actual permeabilities observed after the CIP in June 2014 were found to be in the acceptable range;
- The average flux since July has been consistently around 65 L/m^{2}h with an acceptable level of variation through the cycle (normally +/- 5 L/m^{2}h and nearly always within +/- 10 L/m^{2}h), i.e. a maximum variation of around 15%;
- The fouling rate is significant but it is well controlled by CEB to ensure long term stability of the permeability;
- Occasional high fouling periods have been observed and these can be linked with the occurrence of moderate to high chlorophyll in the feedwater due to algal blooms, which is also shown by an increase in $SDI_{2.5}$ (>35 units);
- Plant operation without coagulation is stable and maintainable in the long term with a CIP interval of $\geq$ 180 days and a CEB interval of 18 hours, provided that the CEB interval is reduced to 15 or 12 hours during light or moderate algal blooms; the plant has also been able to cope with algal blooms at this level without intervention (apart from CEB cycle reduction) or reduction of flux;
- Under normal feedwater conditions and using an 18 hour CEB interval, the required CIP frequency would be $\geq$ 180 days to ensure that the average end permeability was $\geq$ 175 L/m^{2}h.bar; this should enable a CIP to work effectively to restore a high starting permeability (note that CIP intervals at the plant have been > 180 days);
- A more severe and sustained algal bloom may require a reduction of flux (for example by 20%); use of coagulant during such an episode could be an alternative;
- If the CEB interval were to be reduced from 18 to 15 hours for normal conditions, this would have the effect of significantly extending the CIP interval well beyond 6 months (e.g. $\geq$ 12 months), and would ensure that permeabilities were steady and stable with a significantly higher average permeability and hence lower pressure requirement;
- With a 15 hour CEB interval, the plant would have much better resilience in handling algal blooms or occasional equipment failure

11.4.6 References

Al-Azri, A. R. 2014. Expansion of harmful algal blooms in the coastal water of Oman, and potential threat to desalination plants. In: *Proceedings of the Harmful Algal Blooms Conference*, Mucat, Oman.

Bernaola, F. 2012. Red Tide Event Prevention and Influence on Desalinated Water Production Cost, *Expert Workshop Red Tide and HABs: Impact on Desalination Plants, Muscat –Sultanate of Oman*.

Knops, F. N. M. 2014. Reducing SWRO life cycle costs by direct coupling of UF and SWRO Systems. In: *Proceedings European Desalination Society Conference*, Limmasol, Cyprus.

Pearce, G. K. 2013. The Potential Advantages of Direct Coupled UF System Designs for Bio-Fouling Control in Pre-treatment of Seawater RO Systems. In: *Proceedings International Desalination Association Conference*, Tianjin, China.

Pearce, G. K. 2015. How Much Flux Variation Can We Allow in UF System Design; Striking the Right Balance between Performance Stability and Cost Minimization. In: *Proceedings American Membrane Technology Association Membrane Technology Conference*, Orlando, Florida, USA.

Thangaraja, M., Al-Aisry, A., and Al-Kharusi, L. 2007. Harmful algal blooms and their impacts in the middle and outer ROPME sea area. *International Journal of Oceans and Oceanography* 2(1), 85-98.

11.5 SHUWAIKH, KUWAIT – HARMFUL ALGAL BLOOM CELL REMOVAL USING DISSOLVED AIR FLOTATION: PILOT AND LABORATORY STUDIES

Robert Wiley[1], Mike Dixon[2] and Siobhan F. E. Boerlage[3]

[1]Leopold, a Xylem Brand, Zelienople, PA, USA
[2]MDD Consulting, Kensington, Calagry, Alberta, Canada
[3] Boerlage Consulting, Gold Coast, Queensland, Australia

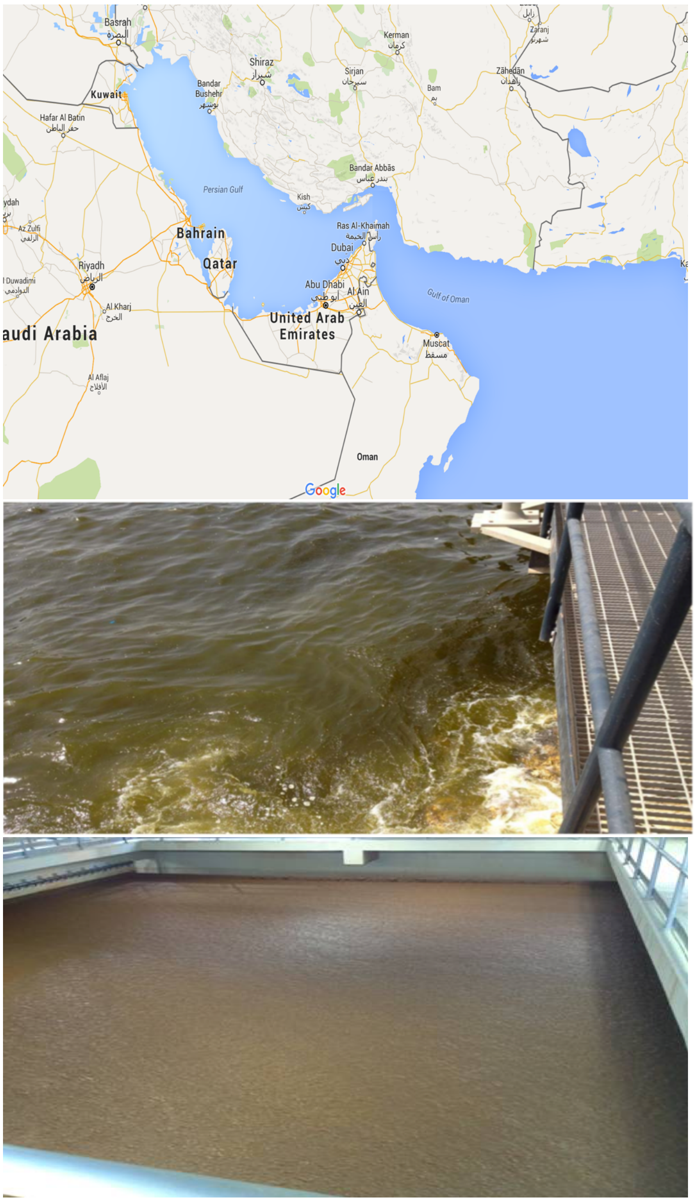


Figure 11.5.1. Location of the Shuwaikh, SWRO Plant in Kuwait (top). Algal (species unidentified) bloom near intake (middle). DAF Float during the bloom (bottom).

Table 11.5.1. Overview of Shuwaikh plant.

Plant/Project Name		
Location	Shuwaikh, Kuwait	
Primary product water use	Municipal	
Desalination Technology	SWRO	
Total Production Capacity (m^3/d)	SWRO 135,000	
SWRO recovery (%)	42%	
Commissioning date	October 2011	
Intake		
Feedwater source	The Gulf	
Intake type	Open near shore intake	
Intake description	Intake depth 3 m, 200 m from shore, 5 mm coarse screening grill aperture	
Intake screening	Travelling band screens	
Shock chlorination Strategy, dose rate	Shock chlorination utilized. Dose unknown.	
Online raw water monitoring	Conductivity, temperature, pH, turbidity, dissolved oxygen hydrocarbon analyzer.	
Discrete raw water analysis relevant to HABs	DOC, TOC	
Pretreatment		
Process description	DAF, autostrainers, UF (pressurized inside out), UF direct coupling to RO (no cartridge filtration)	
Chemical dosing	Ferric chloride, Sulfuric acid	
Feedwater design parameters		**Feedwater during bloom conditions**
Temperature range (˚C)	20-35	
Salinity range (TDS mg/L)	42,000	
Conductivity (mS/cm)		
Total Suspended Solids (mg/L)	5-43 (average 14.5)	17
SDI		
Turbidity (NTU)	1-55 (average 5.2)	>30
Organic Matter TOC/DOC (mg/L), TEP, biopolymers etc.		
Algal cell count (cells/L)		Unknown
Algal species		Unknown
Chlorophyll–*a* (µg/L)		
Desalination Design	**During bloom conditions**	
DAF Loading Rate (m/h)	22	
UF flux (L/m^2h)	80	
RO flux (L/m^2h)	15	

11.5.1 Shuwaikh plant

DAF has been used by the majority of countries in the Gulf Region for all new SWRO projects that utilize open intake systems. The application of the DAF process on seawater, however, is still in its infancy. The Shuwaikh Seawater Reverse Osmosis (SWRO) Desalination Plant, which was built for the Kuwait Ministry of Electricity and Water (MEW) incorporates the Leopold Clari-DAF® System followed by pressurized inside-out ultrafiltration (UF) for pretreatment. The pretreatment capacity is 350,000 m^3/day with a SWRO output of 136,000 m^3/d. Figure 11.5.2 shows a model of a typical Clari-DAF System as used at the Shuwaikh, Kuwait SWRO Plant.

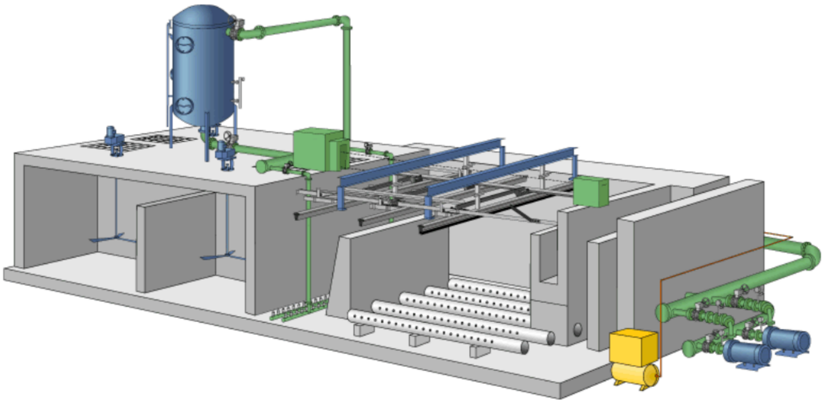


Figure 11.5.2. Model of typical Clari-DAF system as used at the Shuwaikh, Kuwait SWRO plant.

The plant is located directly next to the Port of Shuwaikh, which accommodates the majority of Kuwaiti shipping. Seawater in the region is warm, highly saline, laden with organics and polluted due to port activities with occasional harmful algal blooms (HABs) known to occur. Therefore, a robust pretreatment system was designed (Figure 11.5.3) with the intention of protecting the downstream UF and RO from potential contamination (Figure 11.5.4). The small footprint of the site necessitated a high-rate pretreatment system capable of dealing with any contamination associated with the shipping traffic, such as oil, grease, and suspended solids removal due to the shallow, near-shore intake.

The DAF was designed with in-line static mixing for the ferric chloride and sulfuric acid dosing. It incorporates two stages of flocculation with total flocculation time of 13.2 minutes at design flow. To generate the bubbles, a vertical packed tower saturator is utilized with 10% of the design flow being recycled and saturated at pressure of 5.5 bar within the saturator. The DAF basin hydraulic loading rate is designed at 22 m/h and utilizes hydraulic desludging for removal of the generated solids.

The plant was commissioned in October of 2011 and at that time was the world's largest SWRO plant using dissolved air flotation and pressurized inside-out ultrafiltration (UF) as pretreatment.

While, this area of the Gulf does not have a history of severe, recurring HAB events, occasional blooms have occurred. In the context of this case study, during plant operation in May, 2012 and once again in April, 2014 a localized bloom near the port occurred (Figure 11.5.5). Turbidities of >30 NTU were seen in the source water, and total suspended solids (TSS) increased up to 17 mg/L in May 2012 indicating a rather substantial bloom, as seen in Figure 11.5.6. DAF reduced the turbidity and TSS to less than 3 NTU and 11 mg/L, respectively (Im et al. 2012). These blooms came on without warning, but most likely exhausted the nutrients needed to support the algal growth quite quickly, and lasted for approximately 10 days.

Minor changes were made to the plant's chemistry to accommodate this increase in organic loading. This included increasing the coagulant feed from an average of 4 mg/L of ferric chloride to 12 mg/L as well as decreasing the coagulated pH with a sulfuric acid dose of 40 mg/L during the bloom. In addition, the chemically enhanced backwash (CEB) frequency of the UF system was increased. With these changes the DAF and UF pretreatment system provided high-quality seawater feed with the SDI_{15} consistently less than 3.0 at all times to the SWRO system. The Shuwaikh plant was therefore, able to maintain capacity throughout the duration of the bloom allowing for the uninterrupted supply of potable water to the residents.

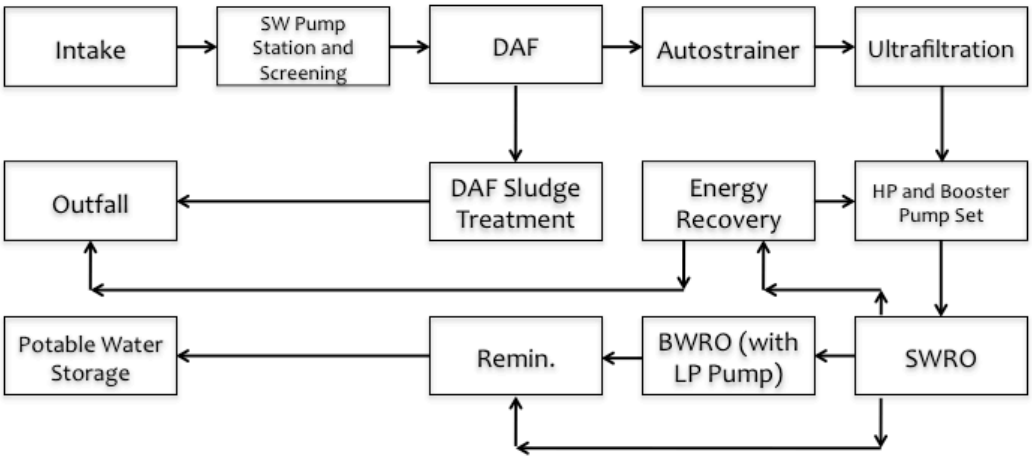


Figure 11.5.3. Process flow diagram for Shuwaikh. (HP = High Pressure, LP = Low Pressure).

Figure 11.5.4. Shipping traffic passing by the Shuwaikh intake (pictured at left), heading into the Shuwaikh Port (left and out of frame).

Figure 11.5.5. Seawater conditions during the algal bloom (top) showing the condition of the seawater close to shore (intake pipe at right of image); bottom shows a close-up of the green-brown hue produced by the algae.

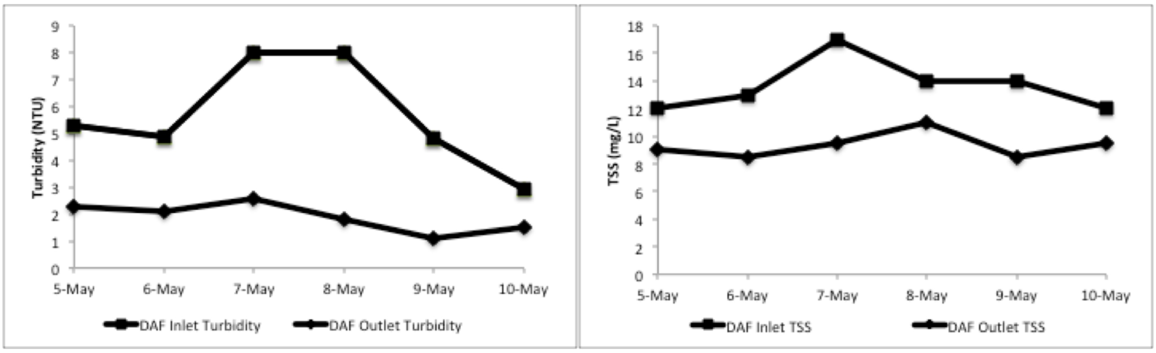


Figure 11.5.6. DAF Performance in HAB conditions from May 5 to May 10 2012 (data from Im et al. 2012).

The thick floating blanket formed in the DAF cell during a bloom is shown in Figure 11.5.7. The DAF process performed well during the blooms in Shuwaikh, but the severity of the bloom, type and concentration of algae, and the percent algal removal from the system were not determined.

Figure 11.5.7. Floc blanket on the surface of the DAF unit.

As an example of the UF performance, the operating data from one UF skid is shown before, during and after the algal bloom event (May 5-10, 2012) in Figure 11.5.8 (http://xflow.pentair.com/en/case-studies/shuwaikh, 2016). The top line shows in membrane permeability over time. The bottom line shows development of transmembrane pressure (TMP) of the UF unit. The UF performance data confirms that the UF skids operated during the bloom event, which allowed continuous operation of the SWRO desalination plant.

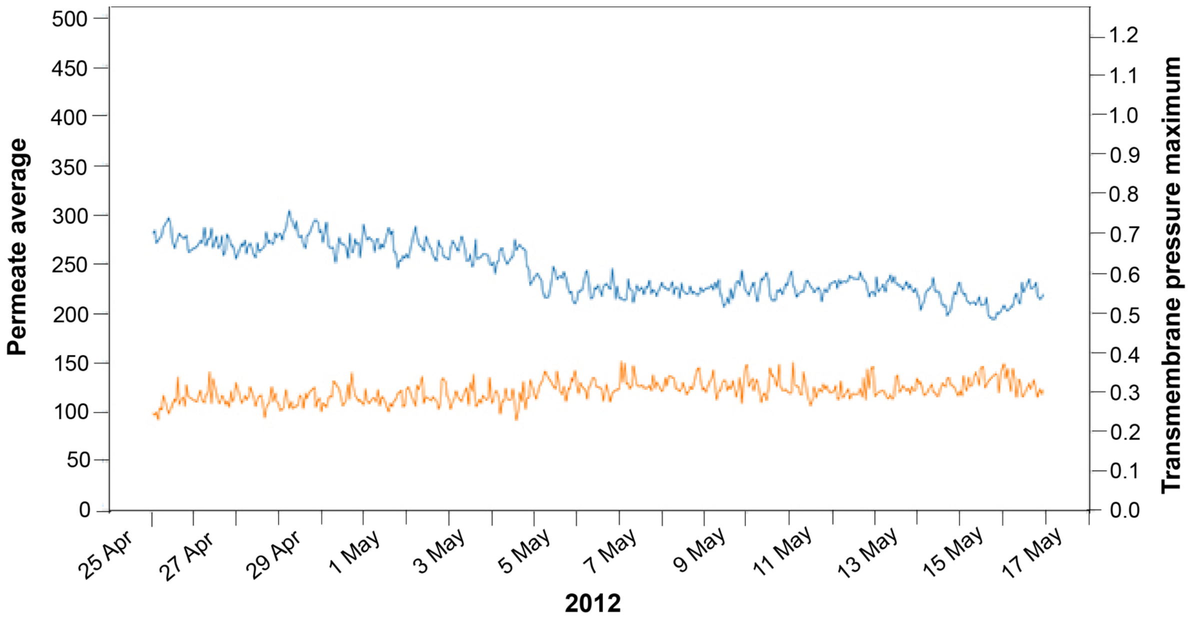


Figure 11.5.8. UF permeability (top line) and transmembrane pressure (bottom line) during a bloom in May 2012. Figure modified from: http://xflow.pentair.com/en/case-studies/shuwaikh.

11.5.2 Laboratory and Pilot Scale DAF Testing

To confirm the performance of the full-scale DAF system during a HAB event, multiple HAB species were cultivated at Woods Hole Oceanographic Institution for DAF bench scale testing. These species included *Cochlodinium polykrikoides*, the algal species that caused the 2008 - 2009 bloom in the Gulf. Different coagulation techniques were investigated to help lower the high charge-neutralization demand of the algal cells. The most promising techniques found to date are oxidation with sodium hypochlorite (typically less than 1 mg/L) and adjustment of the pH prior to coagulation. These techniques lowered the coagulant demand while improving cell removal by a few percentage points. Following laboratory bench tests, the process was tested on a naturally occurring *Cochlodinium* bloom in Buzzards Bay, MA in 2011 (14,000 cells/mL), with over 99% of the algae removed with the DAF process.

The most interesting pilot study conducted to date was a simulated algal challenge test conducted for the Fujairah I expansion in Fujairah, UAE. To demonstrate the effectiveness of the DAF design which now feeds the existing Fujairah I filtration system and the ongoing expansion of the plant, a pilot study with up to 100,000 cells/mL in the source water was required as part of the contract. To accomplish this test with an algal concentration approximately 4-5 times that present in the 2008- 2009 Gulf bloom, a cultivated alga was utilized. The DAF pilot consistently removed over 95% of the algal cells and at times exceeded 99% removal, as seen in Figure 11.5.9. The DAF pilot was followed by a gravity media filtration pilot which utilized the current Fujairah I plant's media profile. Interestingly when the algae was introduced to the DAF system, the downstream filtration system Silt Density Index (SDI) actually improved and filter head loss accumulation decreased. This is most likely due to the algae acting as a sweep floc to incorporate colloidal material in the source water.

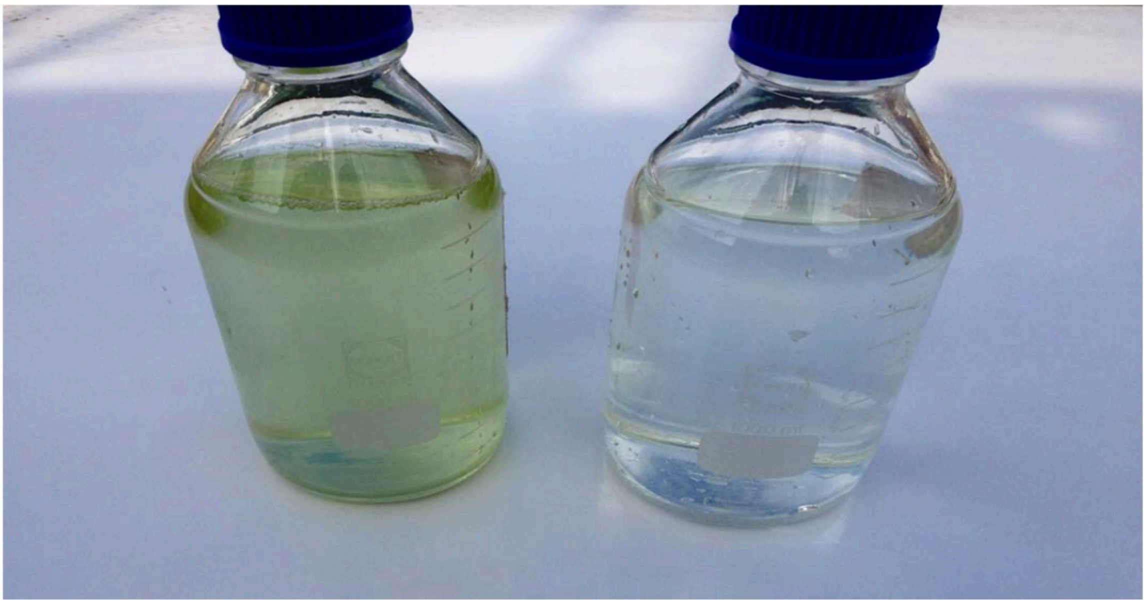


Figure 11.5.9. Samples of feedwater (left) and DAF-treated water (right) from the challenge test at the Fujairah I pilot plant using cultured algae.

Several pilots have also been conducted on naturally occurring blooms including a pilot at the University of Texas Marine Science Institute at Port Aransas, Texas during a bloom of *Karenia brevis*. Also a pilot study was conducted in Antofagasta Bay in Chile which experiences a prolonged HAB event yearly, lasting at times up to 3 to 4 months due to the bay's currents which serve to feed nutrients to the algae continually over the summer months. This prolonged bloom tends to support the growth of many algal species. The results from each of the pilot tests on the different species of algae all showed greater than 95% removal, suggesting that DAF would be equally effective on differing strains of algae and should be considered a robust process for pretreatment around the world when an uninterrupted supply from open intake systems needs to be assured.

11.5.3 Conclusions

DAF effectively removed cells during a HAB bloom in Kuwait, producing a stable and dense floc blanket and effectively removed elevated levels of TSS and turbidity. The UF performed well during the bloom, with no TMP spikes during this period. After optimization of the ferric chloride dose, the DAF and UF pretreatment system provided high-quality seawater feed with the SDI_{15} consistently less than 3.0 at all times to the SWRO system.

The DAF-UF pretreatment system at the Shuwaikh Desalination Plant provided a very stable and effective system for providing RO feedwater during a HAB bloom. The DAF system has also been tested and its effectiveness demonstrated through pilot studies on multiple other HAB species in the laboratory and the field.

11.5.4 References

Im, J., Park, K., and Yim, W. 2012. Doosan as Pioneer in Supplying and Operating Large-scale RO Desalination Plant at Shuwaikh on Coast of Kuwait. In: *Proceedings of the International Water Association World Water Congress & Exhibition*, Busan, South Korea.

11.6 LA CHIMBA, ANTOFAGASTA, CHILE – OXYGEN DEPLETION AND HYDROGEN SULFIDE GAS MITIGATION DUE TO HARMFUL ALGAL BLOOMS

Walter Cerda Acuña[1], Carlos Jorquera Gonzalez[1], and Victor Gutierrez Aqueveque[1]

[1]Aguas Antofagasta, Anofagasta, Chile

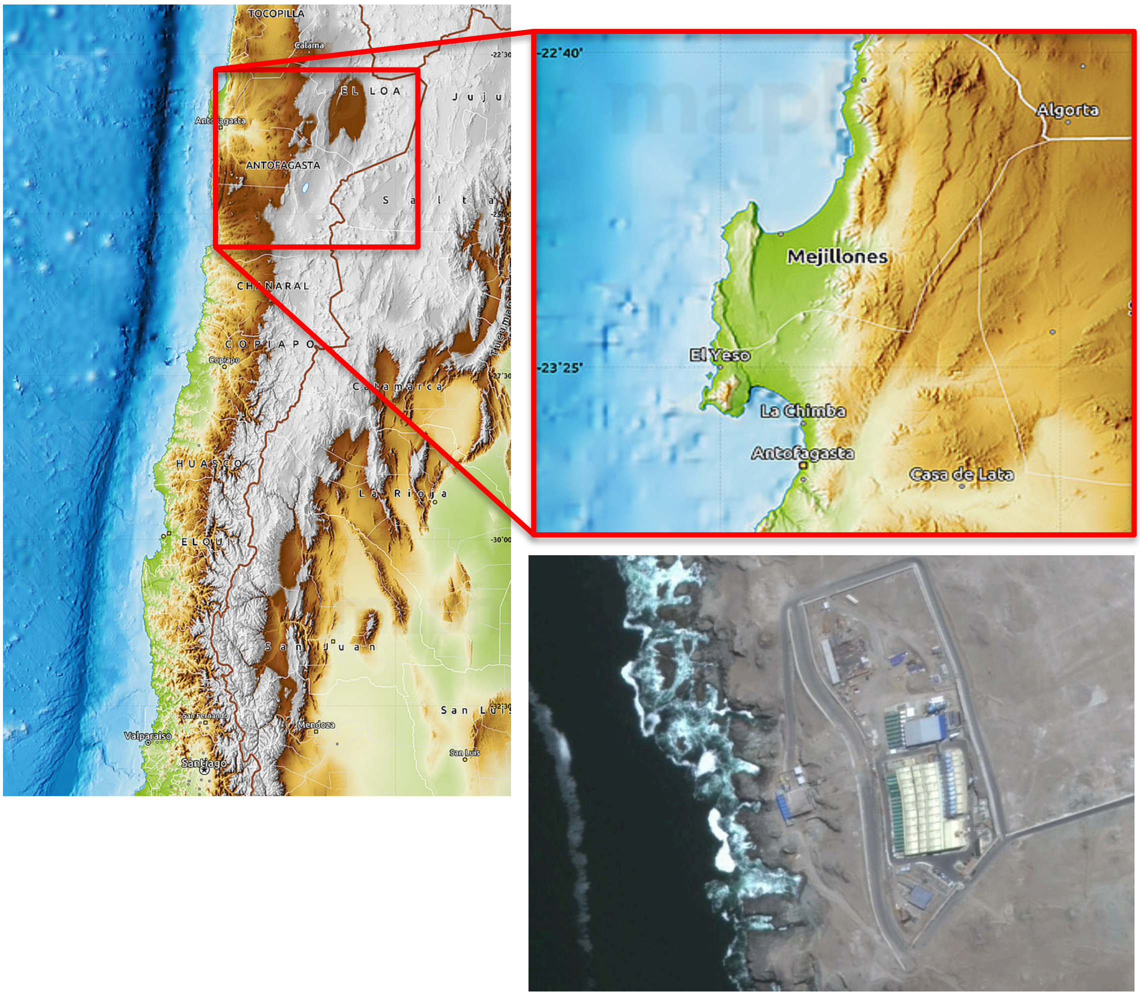


Figure 11.6.1. Left and top right - Geographic location of the La Chimba desalination plant. Photo: maphill.com Prepared by F.Knops. Bottom right – Aerial view of the La Chimba desalination plant. Photo: Google Earth.

Table 11.6.1. Overview of La Chimba desalination plant.

Plant/Project Name		
Location	La Chimba, Antofagasta, Chile	
Primary product water use	Municipal	
Desalination Technology	SWRO	
Total Production Capacity (m^3/d)	52,000	
SWRO recovery (%)	52	
Commissioning date	2002-2003	
	Intake	
Feedwater source	Pacific Ocean, Moreno Bay	
Intake type	Deep water intake	
Intake description	Intake depth: 25 m, distance from shore: 400 m	
Intake screening	Offshore open intake with 8 screens of 1 m^2 protected with trellised boxes of fiber-reinforced plastic	
Chlorination Strategy, dose rate	Continuous chlorination installed but not used	
Online raw water monitoring	Conductivity, temperature, pH, turbidity, dissolved oxygen (DO), ORP	
Discrete raw water analysis relevant to HABs	Chlorophyll-*a*, algal counts, DO, pH and ORP	
	Pretreatment	
Process description	Pressure multimedia filtration, 5 µm cartridge filtration	
Chemical dosing	1ppm antiscalant; sulfuric acid to pH 5 for sulfate reducing bacteria control	
Feedwater design parameters		**Feedwater during bloom conditions**
Temperature range (˚C)	14 – 19	14
Salinity range (TDS mg/L)	36,000	36,000
Conductivity (mS/cm)	53.0	52.8
Total Suspended Solids (mg/L)	6.0	unknown
SDI (15 minute interval)(%/min)	5.0	unknown
Turbidity (NTU)	<1	unknown
Organic Matter TOC/DOC (mg/L), TEP, biopolymers etc.		
Algal cell count (cells/L)	unknown	11.3 Million
Algal species	*Prorocentrum micans*	
Chlorophyll-*a* (µg/L)	23	65-109
Additional relevant water quality parameters		Low DO (0.5 - 2mg/L), H_2S 50mg/L max
Desalination Design		**During bloom conditions**
DMF Filter rate m/h	7.6	7.6
RO flux (L/m^2h)	11.6	11.6

11.6.1 Introduction

"Red tide" or harmful algal bloom (HAB) phenomena are a recurrent issue off the coasts of Antofagasta, Chile, due to blooms of phytoplankton that, depending upon environmental conditions, can vary in severity. The presence of phytoplankton in coastal waters can originate from fluctuations in essential nutrients (nitrate, phosphate, and silicate) as a result of surface runoff and/or coastal hydrographic phenomena and wind conditions.

Depending upon the species present in the algal bloom, these effects can be quite varied, from innocuous to lethal. On some occasions, the high rates of nutrients and phytoplankton biomass produced during these blooms greatly exceeds the natural capacity of the marine environment to assimilate the phytoplankton growth, generating conditions of eutrophication. Under this condition, the degradation of the organic material causes a reduction in dissolved oxygen levels, resulting in the generation of noxious gases, such as methane and hydrogen sulfide.

Given the geographic conditions of the location of the La Chimba Desalination Plant, it is regularly affected by the presence of HABs. From 1964 to 1999, 41 algal bloom events were recorded in the area known as Moreno Bay. On 23 occasions, the cause was the dinoflagellate *Prorocentrum micans*, the same species that was dominant in a major bloom in March 2011. Figure 11.6.2 presents a historical series of cell counts in the Bay of Antofagasta from 1970. Notable among these events is the bloom of March of 2011 with a peak cell density of over 11 million cells/L, five times greater than the maximum historical level recorded in prior years.

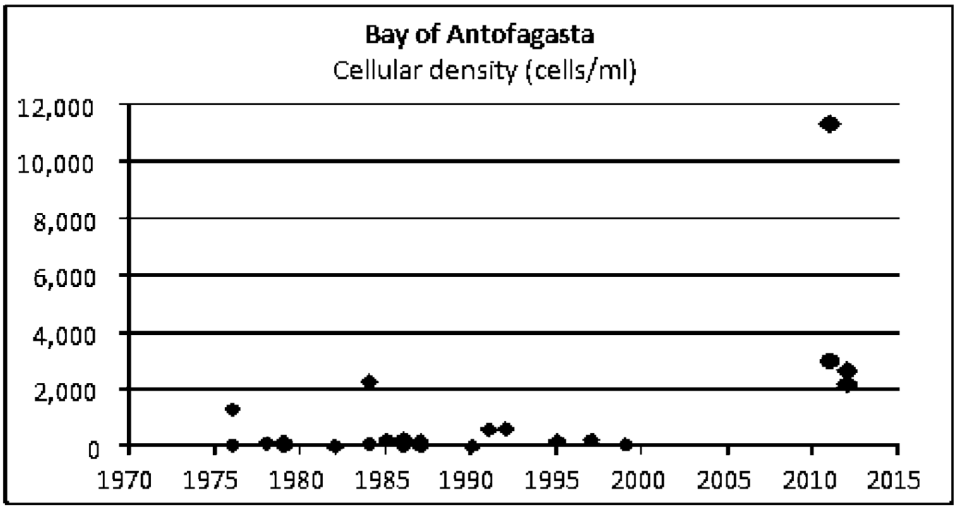


Figure 11.6.2. Algal blooms between 1970 and 2012 in the Bay of Antofagasta.

11.6.2 Presence of hydrogen sulfide gas in a desalination plant

The presence of hydrogen sulfide (H_2S) gas in a seawater desalination plant is uncommon. More typically, information in the literature related to hydrogen sulfide generation in SWRO plants is as a result of overdosing sodium metabisulfite to neutralize chlorine added in the pretreatment. Sodium metabisulfite not only neutralizes the chlorine, but also, due to its excess, reduces oxygen levels and therefore generates ideal conditions for the appearance of sulfate-reducing bacteria (SRB).

There is little information related to desalination plants where hydrogen sulfide gas is naturally present, as during very intense algal blooms; some plants may elect to cease operations until the algal bloom activity is reduced.

11.6.2.1 Generation of hydrogen sulfide gas in the seawater

In the presence of very intense algal blooms, with water retained in the bay and the presence of a thermocline that impedes mixing and oxygenation of seawater, the appearance of sulfate reducing bacteria is quite likely. Oxygenation of the water is limited and the death and decomposition of organic matter leads to hypoxic (<0.5 mg/l DO) and even anoxic (absence of DO) conditions in the deepest zones, which favors the proliferation of SRB, a group of totally anaerobic organisms that use the sulfate ion (SO_4^{2-}) as an electron receptor in their energy metabolism. They are distributed in sulfate-rich anoxic sediments, such as marine sediments. In marine ecosystems, a good part of the metabolic activity occurs in the oxic/anoxic interface and also in the deeper and anoxic zones of the sediment. This process is illustrated in Figure 11.6.3.

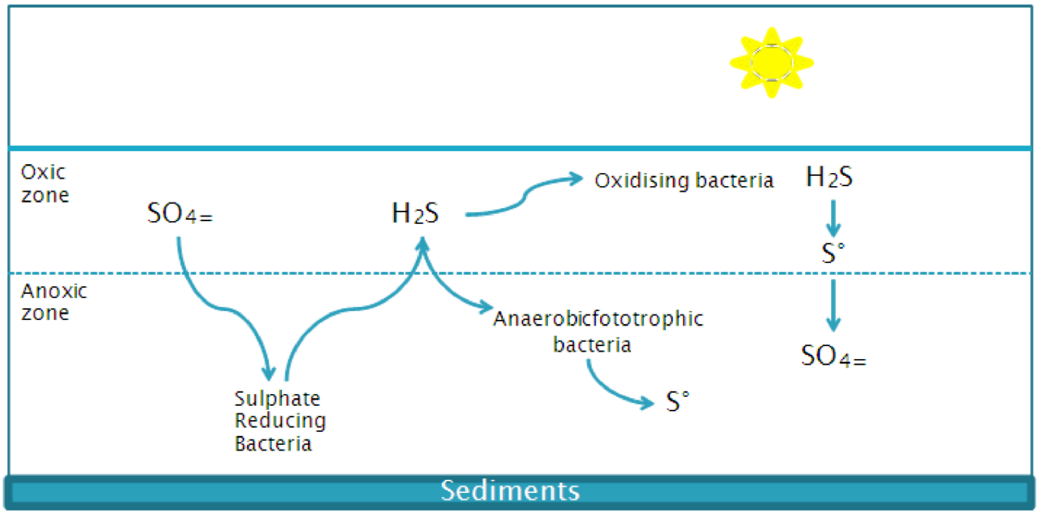


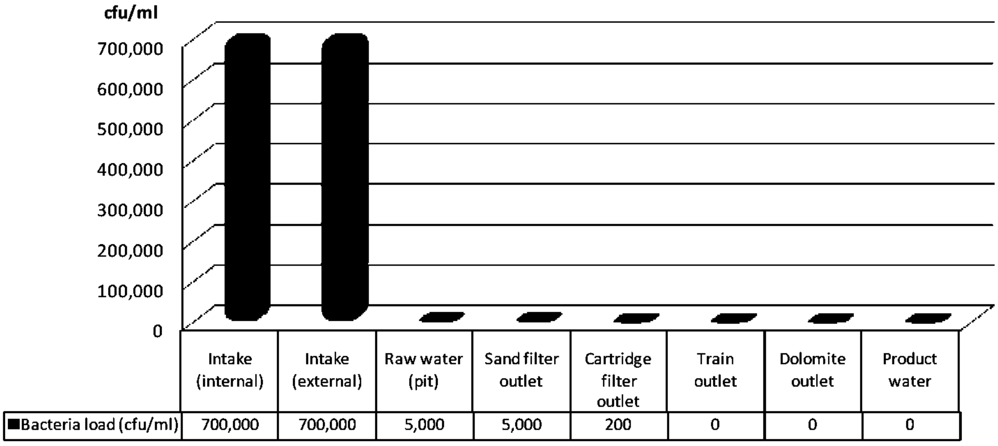
Figure 11.6.3. Diagram of sulfate reducing bacteria metabolism.

11.6.2.2 Hydrogen sulfide gas in La Chimba desalination plant

Figure 11.6.4 shows the counts of SRB in all unit processes of La Chimba during the algal bloom in March 2011. The seawater intake had the highest concentration of SRB (700,000 CFU/mL), which strongly contrasts with the 5000 CFU/mL at the sand filters and no presence of SRB in the RO stage. The difference between internal (inside the intake tower) and external intake (outside the intake tower, or surrounding ocean) is noted in Figure 11.6.4 to demonstrate that the bacterial concentration originates in the ocean as opposed to inside the intake tower due to poor maintenance. This indicates that there was no operational problem, but rather the problem originated from external sources in the Bay of Antofagasta.

11.6.3 Operation of La Chimba Plant in the presence of hydrogen sulfide gas

At first it was thought that the appearance of hydrogen sulfide gas in the plant was caused by an operating problem or by local contamination. The count of SRB demonstrated that the origin of the problem was the source seawater (seawater intake). Notwithstanding the origin of the phenomenon, and given that this desalination plant supplies 60% of the potable water for the city of Antofagasta, Aguas Antofagasta, who owns and operates the plant, had to implement a quick and effective solution that would eliminate the hydrogen sulfide gas present in the potable water.



	Intake (internal)	Intake (external)	Raw water (pit)	Sand filter outlet	Cartridge filter outlet	Train outlet	Dolomite outlet	Product water
■Bacteria load (cfu/ml)	700,000	700,000	5,000	5,000	200	0	0	0

Figure 11.6.4. Presence of SRB in the La Chimba intake and desalination plant processes, March 2011. CFU: Colony Forming Unit.

Potential strategies to eliminate hydrogen sulfide gas present in the source seawater can be classed as aerobic and anaerobic solutions. There are three aerobic solutions:

- Elimination of H_2S by degassing at the entry to the plant;
- Precipitation of sulfides to sulfates and decantation; and
- Oxidation of sulfur derivatives and decantation

The aerobic alternatives are risky due to the probability that elemental sulfur is generated by exposure to oxidizing agents, such as dissolved oxygen or chlorine. This elemental sulfur can then reach the membranes to cause damage and thus a loss of salt rejection. Therefore, the alternative anaerobic solution was pursued whereby pretreatment was maintained under anaerobic conditions, with no contact with oxygen or other oxidants (Fethi 2003). A system was implemented that enabled maintenance of the presence of sulfur as dissolved sulfuric acid through the SWRO process and eliminating it in the final stage with a stripping system and through the controlled addition of chlorine. This solution involved the following:

1. Installation of dissolved oxygen sensors in the seawater intake pit for early detection of conditions that could favor the presence of H_2S in the seawater;
2. Addition of H_2SO_4 to reduce the pH of the seawater, to stabilize the H_2S present, and eliminate the probability of generation of H_2S in the plant pretreatment;
3. Installation of H_2S sensors on the outlet from the dolomite post-treatment filters, product water tank access hatch and distribution of potable water;
4. Implementation of stripping with air in the product water tank, so as to displace the H_2S present in the product water;
5. Direct dose of sodium hypochlorite in the product water tank to eliminate traces of H_2S by oxidation to sulfate; and
6. Contingency procedure to operate in seawater conditions with a low level of dissolved oxygen.

In the following diagram (Figure 11.6.5), existing water quality variables measured in the designed plant line are; ORP, CE, Cl, pH and TS, while new variables incorporated are labeled as $^*H_2S$ and $^*O_2$. The intervention points for eliminating the sulfuric acid were the hypochlorite (hypo) and air added to the potable water storage tank.

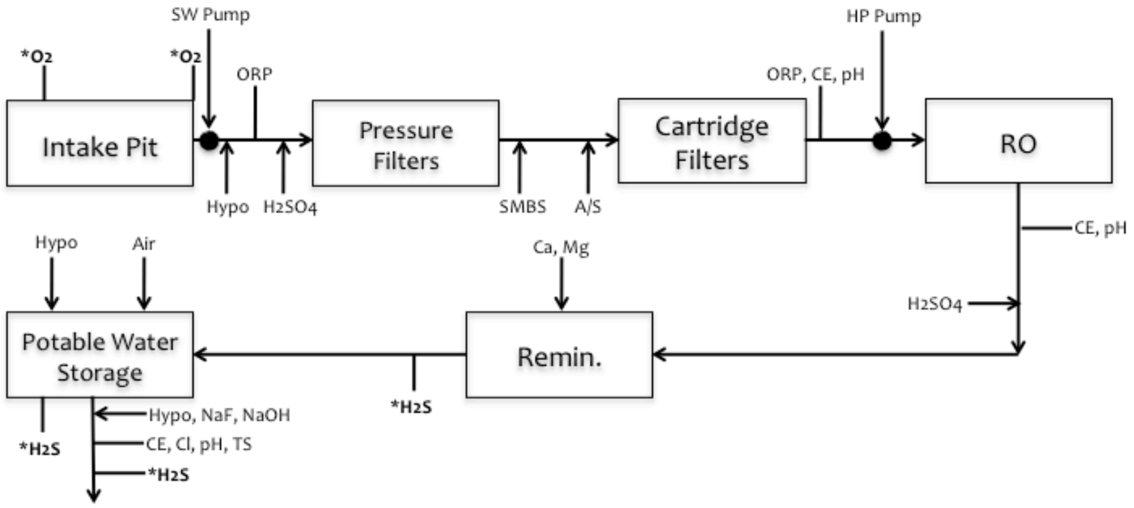


Figure 11.6.5. Diagram of operation during H_2S events in La Chimba desalination plant (CE = Conductivity; ORP = oxidation and reduction potential; Cl = Free Chlorine; TS = total dissolved solids).

11.6.3.1 Analysis and discussion of the application of the anaerobic method

The application of the anaerobic method to eliminate hydrogen sulfide gas is examined in the following sections. The measures adopted, from the implementation of the dissolved oxygen measurement systems, portable hydrogen sulfide gas sensors and the installation of aeration in the product water tank, were very effective. The traces of hydrogen sulfide gas in the potable water were almost completely eliminated. Nonetheless, despite the very low concentration of hydrogen sulfide (< 0.3 mg/L) it produced an unpleasant smell.

11.6.3.2 Water quality during 2011 bloom

Dissolved oxygen levels during the 2011 bloom are presented in Figure 11.6.6 where it was observed that the seawater tank was hypoxic and even very close to anoxic. During this period, the levels of hydrogen sulfide gas concentrations eliminated from the product water tank reached a maximum level of 50 mg/L (Figure 11.6.7). Nonetheless, the anaerobic alternative was highly efficient and the presence of hydrogen sulfide gas was not detected at any time in the transmission of potable water to the tanks in the city of Antofagasta.

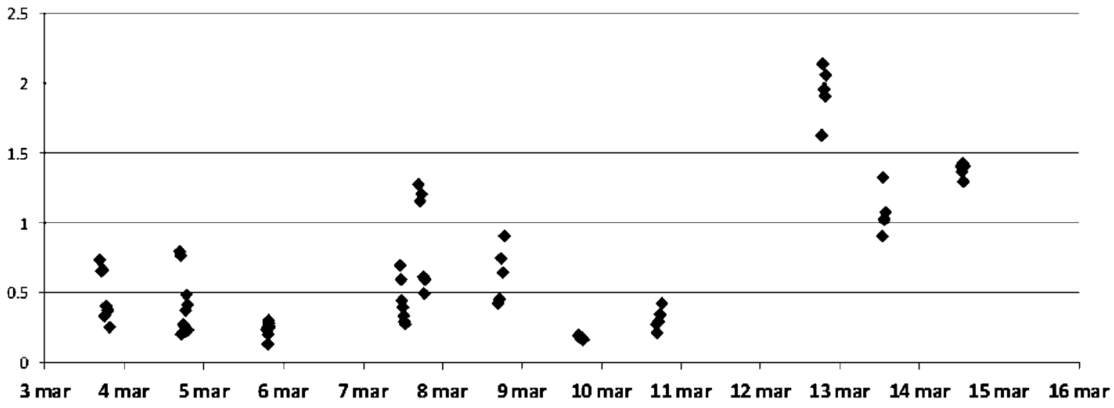


Figure 11.6.6. Concentration of dissolved oxygen (ppm, y-axis) in the seawater tank, March 2011.

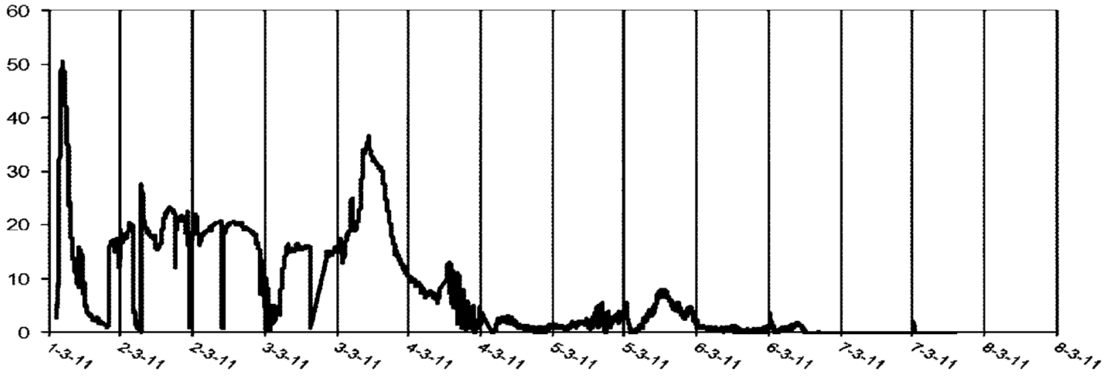


Figure 11.6.7. Concentration of H_2S (ppm, y-axis) extracted from product water tank.

11.6.3.3 Prevention strategy

The strategy implemented to prevent and/or mitigate the effects of atypical phenomena seen in the coastal area of the city of Antofagasta in March 2011 has two complementary aspects:

- Early prevention (discussed below) and
- Mitigation

Early prevention aspects can indicate the presence of conditions that generate the presence of sulfate-reducing bacteria in seawater and/or minimize the probability of their appearance during operations. The following were implemented:

- Seawater dissolved oxygen sensors;
- Monitoring of SRB bacteria during the summer months (December to March);
- Satellite monitoring of chlorophyll concentration and eutrophication status based on chlorophyll (Bricker et al. 2003) during summer months (Figure 11.6.8);
- Monitoring of pH, temperature, dissolved oxygen and redox potential of the water column in the seawater abstraction zone during summer;
- Dredging of the seawater suction pond twice per year;
- Dredging the seawater intake tower every two years; and
- Continuous inline dosing of sulfuric acid in the pretreatment during summer to reduce the pH to levels where SRB cannot survive.

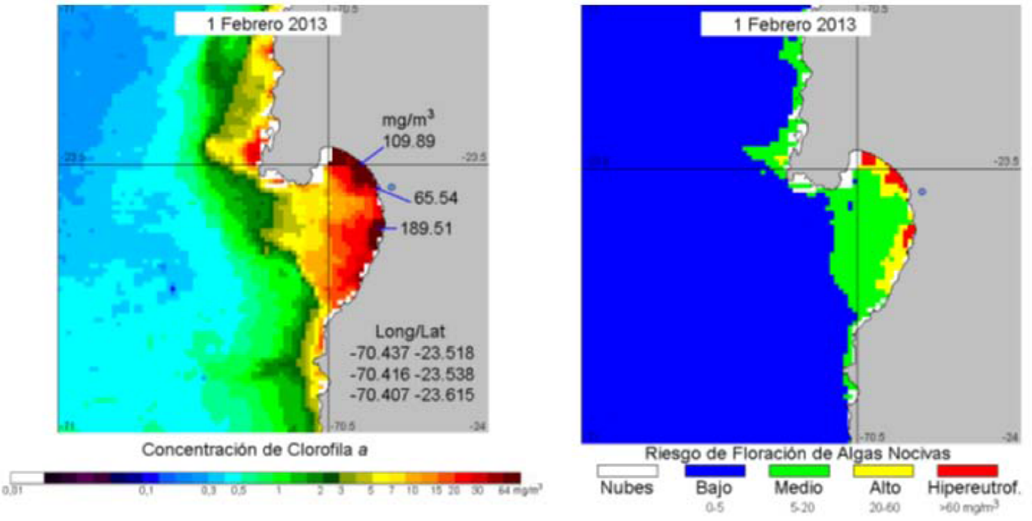


Figure 11.6.8. Satellite image of chlorophyll (left) and the risk of algal blooms based on eutrophication status (right), 1 February 2013. Low eutrophication (Bajo): ≤ 5 ppb; Medium eutrophication (Medio): > 5 ppb and ≤ 20 ppb; High eutrophication (Alto):> 20 ppb and ≤ 60 ppb; Hyper eutrophication (Hipereutrof):> 60 ppb.

In terms of mitigation, when dissolved oxygen concentrations <2 mg/L are detected, operational procedures are activated based on the anaerobic solution described above, with additional actions that minimize the production of H_2S gas. These actions are as follows:

- Dosing sulfuric acid prior to the multimedia filters to lower pH to 4 - 5. Growth of SRB bacteria is prevented in multimedia and cartridge filters and/or RO membranes;
- Activate the aeration system in the product water tank to strip out H_2S; and
- Dosing sodium hypochlorite directly to the product water tank, transforming the traces of H_2S into sulfates.

Additional actions:

- Permanently washing the multimedia filters (even when the pressure differential is low) to remove biological matter and reduce the probability of its decomposition;
- Change out of filter cartridges when differential pressure is >0.7 kg/cm^2;
- Maintain a minimum level of water in the product water tank, equivalent to 90% of its total capacity, so the reaction of the H_2S with air is effective;
- Monitoring of pH, odor and dissolved oxygen in all stages of the process, to detect, the sources of generation of H_2S gas (if possible); and
- Hourly monitoring of the product water quality for pH, residual chlorine, turbidity, odor (by observation), taste and H_2S.

11.6.4 Conclusions

- Red tide is a recurrent phenomenon on the coast of Antofagasta; however, the episode in March 2011 was the most intense recorded to date, leading to a major problem with hypoxia and H_2S gas.
- The anaerobic solution described above was successful. During the bloom, DO in the seawater was at hypoxic levels until mid-March 2011, with the presence of H_2S, but La Chimba was able to operate with no impacts on potable water quality.
- The measures adopted, from the implementation of DO measurement systems, portable H_2S gas sensors, and the installation of aeration in the product water tank were effective. Other actions included dosing sulfuric acid prior to the multimedia filters to lower pH, and dosing sodium hypochlorite directly to the product water tank.
- The presence of H_2S in seawater is an exceptional event; nevertheless, desalination plants that supply potable water to cities can have effective operating systems under these conditions.
- As it is very likely that this phenomenon will occur again, Aguas Antofagasta desalination plants have been equipped with instrumentation in anticipation of the presence of H_2S in the source intake water.
- Monitoring of phytoplankton communities, bacteria, and the determination of chlorophyll in the seawater, especially in periods when red tides appear, are good approaches to detect the appearance of conditions that could favor the proliferation of sulfate reducing bacteria and thereby provide an early warning of this phenomenon.

11.6.5 References

Bricker, S. B., Ferreira, J. G., and Simas, T. 2003. An integrated methodology for assessment of estuarine trophic status. *Ecological Modelling* 169(1), 39–60.

Fethi, K. 2003. The 15,000 m^3/d RO Djerba Plant: Desalination of Brackish Water with a High Hydrogen Sulfide Concentration. In: *Proceedings of the International Desalination Association World Congress*, The Bahamas.

11.7 MEJILLONES, CHILE – OPERATION OF THE ULTRAFILTRATION SYSTEM DURING HARMFUL ALGAL BLOOMS AT THE GAS ATACAMA SWRO PLANT

Frans Knops[1] and Alejandro Sturnilio[2]

[1]X-FlowBV/Pentair Water Process Technology BV, Enschede, the Netherlands
[2]RWL Water Unitek, Mar del Plata, Argentina

Figure 11.7.1. Intake to the Gas Atacama SWRO Plant (top left and bottom) and the algal bloom discussed in this case study. Bloom photo: Aquacien Consultoria Maritima.

Table 11.7.1. Overview of Gas Atacama desalination plant.

Plant/Project Name		
Location	Mejillones, Chile	
Primary product water use	Industrial (boiler feed to power plant, NOx reduction)	
Desalination technology	SWRO first pass, BWRO second pass, CEDI (polishing)	
Total production capacity (m^3/d)	1,200 m^3/d (plant #1), DAF and media filters 2,600m^3/d (plant #2), UF pretreatment	
SWRO recovery (%)	50%	
Commissioning date	1995 (plant #1), 2010 (plant #2)	
	Intake	
Feedwater source	Pacific Ocean	
Intake type	Open intake (existing, shared with intake of power plant)	
Intake description	Intake 5 m below sea level, 3 m above ocean floor	
Intake screening	unknown	
(shock) chlorination	Hypochlorite shock dosing 3 mg/l (frequency unknown)	
Online raw water monitoring	TDS (measured as conductivity), turbidity, temperature	
Discrete raw water analysis	pH, dissolved oxygen	
	Pretreatment (plant #2)	
Process description	Automatic backwashable screens (200 µm), UF (pressurized, inside-out filtration mode), cartridge filtration (5 µm)	
Chemical dosing	UF feed coagulant – $FeCl_3$ (max 2 ppm as Fe), UF cleaning chemicals (NaOCl, H_2SO_4, NaOH), SWRO antiscalant (5 ppm), SWRO $Na_2H_2SO_5$ (5 mg/L)	
Feedwater design parameters		**Feedwater during bloom conditions**
Temperature range (˚C)	11 – 22	18 – 20
Salinity range (TDS mg/L)	33,000	No change
pH	7.6 – 8.8	No change
DO (at 20 m depth)	1.8 – 5.4 mg/L (24 – 71%)	No change
DO (at 5 m depth)	6.7 – 10.4 mg/L (92 – 148%)	No change
Total suspended solids (mg/l)	-	-
SDI (%/min)	-	$SDI_5 > 18$
Turbidity (NTU)	10	35
Organic Matter TOC/DOC (mg/L)	-	-
Algal cell count (cells/L)	~25,000	400,000 – 1,300,000
Algal species	*Leptocylindrus danicus* (Diatom)	*Leptocylindrus danicus* *Prorocentrum graciles*
Chlorophyll-*a* (µg/L)	< 20	40 – 120
Additional relevant parameters	ORP 140 – 220 mV	ORP 20 – 75 mV
Desalination Design		**Bloom conditions**
Filter rates	N/A	N/A
UF flux (L/m^2h)	75	75
RO flux (L/m^2h)	-	-

11.7.1 Introduction

Gas Atacama operates a combined-cycle thermal power plant in Mejillones, Chile (see location map Figure 11.7.1), with an installed capacity of 780 MW. The plant uses seawater as its only source of water. Two SWRO plants, with their corresponding pre- and post-treatment, are installed in parallel and are operated simultaneously. Each of the two plants uses different pretreatment technologies, so a comparison can be made between them.

The existing cooling water intake for the power plant is an open intake, without any treatment. The flow of water used for cooling is much higher than the flow needed to feed the desalination plants. As the intake was capable of handling this additional flow, using the existing cooling water intake was therefore considered the most viable option.

The source water is characterized by seasonal variations in turbidity; during autumn and winter it ranges from 1 to 5 NTU, while during spring and summer, the range increases from 3 to 35 NTU. Water temperature ranges widely from 11 to 22°C, resulting in a significant variation in SWRO operating pressure between winter and summer. It also affects the microbiological conditions of seawater. Another important issue is the occasional presence of algal blooms, responsible for SWRO biofouling on the membrane surface that can require frequent chemical cleaning. Such algal blooms occur one to three times per year with durations of up to a week. As the power plant uses SWRO desalination as the sole source of water, a robust pretreatment process is required that can reliably operate through algal bloom events with minimal down time to ensure high plant availability.

Plant 1

Installed in 1995, Plant 1 produces 50 m^3/h of demineralized water reaching a conductivity of less than 0.1 μS/cm. The main stages are:

- Dissolved Air Flotation (DAF) with upfront coagulation;
- Pressurized depth filters;
- Seawater Reverse Osmosis with Pelton Turbine energy recovery;
- Cation ion exchange;
- Forced draft degasifier;
- Anion ion exchange; and
- Mix Bed ion exchange

Plant 2

Installed in 2010 by Unitek (now RWL Water), Plant 2 produces 108 m^3/h (0.7 MGD) of demineralized water reaching a conductivity of less than 0.1 μS/cm. The main steps are:

- In line coagulation with $FeCl_3$;
- Ultrafiltration (UF) (Figure 11.7.2);
- SWRO shown in (Figure 11.7.2) with ERI pressure exchanger (not visible);
- Brackish Water Reverse Osmosis (BWRO); and
- Continuous Electrodeionization (CEDI)

Note: UF backwash waste and SWRO brine are blended and discharged to the ocean without further treatment. BWRO and CEDI concentrate streams are recycled to SWRO inlet.

Figure 11.7.2. Ultrafiltration (left) and SWRO (right) trains at the Gas Atacama Plant.

11.7.2 Water quality

Only limited water quality information (turbidity, temperature, and TDS) is available, as the plant operators do not monitor raw water on a regular basis. A nearby facility (Aguas de Antofagasta) at Antofagasta conducted an extensive study of seawater quality in Antofagasta during a HAB event in January/February 2013, measuring chlorophyll-*a*, dissolved oxygen, pH, algal cell counts, Secchi depth, and ORP at 0, 5, 10, 15 and 20 m depths, (Atacama Agua y Tecnología Ltda. 5^{o}, 9^{o} and 11^{o}, 2013). The monitoring program covered the coast line approximately 40 km to the north and to the south of Antofagasta. The distance from Antofagasta to Mejillones is 50 km, and both Mejillones and Antofagasta are located in sheltered bays. Therefore the results obtained are considered representative for the conditions in Mejillones.

Although, the algal bloom event occurred in the Southern Hemisphere summer season, with elevated seawater temperatures (18–20 ^{o}C), there was no direct relationship between seawater temperature and algal counts. The level of dissolved oxygen varied between 1.8 and 5.4 mg/L (24–71%) at 20 m depth and 6.7 and 10.4 mg/L (92–148%) at 5 m water depth.

No anoxic conditions were observed, but the level of eutrophication and the presence of *Prorocentrum graciles* suggests that anoxic conditions might occur during other HAB events as this species has been known to deplete nutrients and cause anoxia (Cassis et al. 2012). pH varied from 8.0 to 8.9 at the seawater surface and from 7.6 to 8.0 at 20 m depth. Typically it was 0.5 to 1 unit lower at 20 m depth, compared to the surface. One observation (on 27 December 2012) showed no variation (pH 8.0 for the entire water column).

Satellite images of chlorophyll-*a* data were provided by NPOES and MODIS satellites processed with SeaDAS 6.3 software (Figure 11.7.3). Four images of chlorophyll-*a* were collected every week for 2 ½ months to monitor chlorophyll-*a*. The following classification based on chlorophyll-*a* concentration was used (based on Bricker et al. 2003) to assess the risk for algal blooms:

- Low eutrophication: ≤ 5 ppb
- Medium eutrophication: > 5 ppb and ≤ 20 ppb
- High eutrophication: > 20 ppb and ≤ 60 ppb
- Hyper eutrophication: > 60 ppb

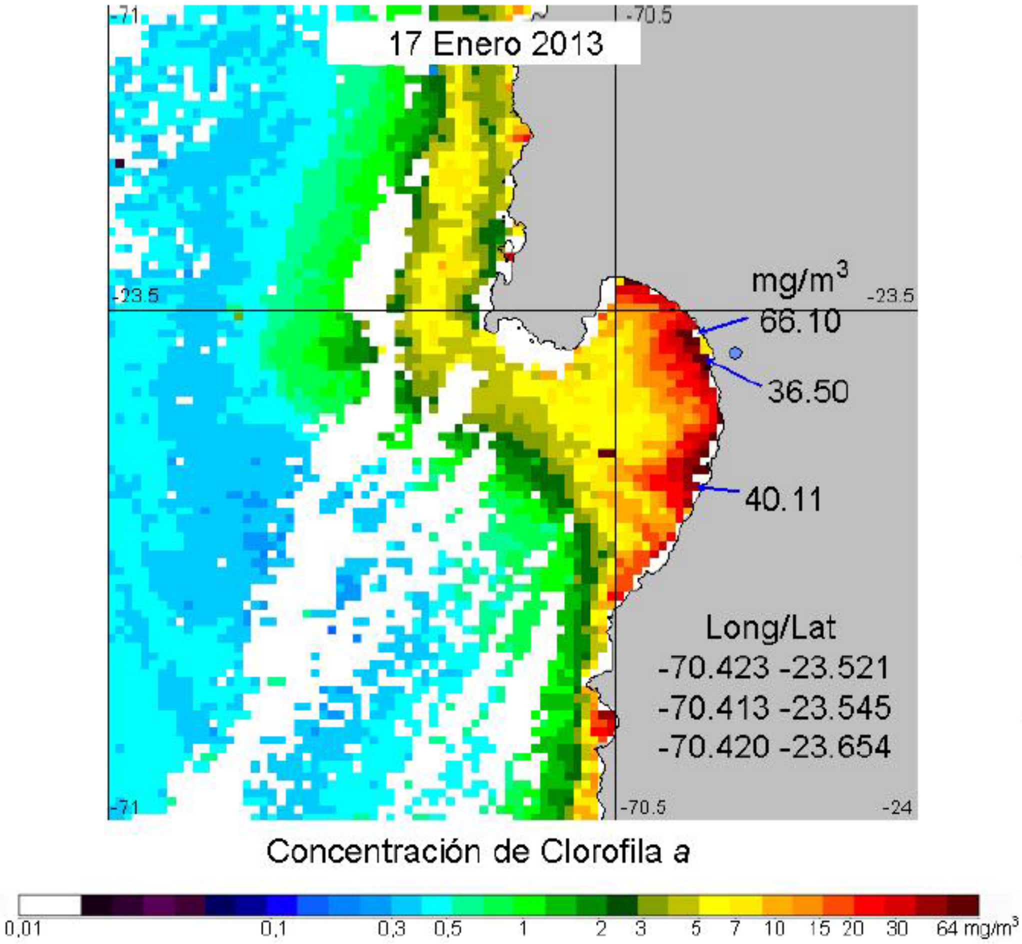


Figure 11.7.3. Satellite image with chlorophyll-*a* concentration on 17th of January 2013 adjacent to La Chimba.

Figure 11.7.4 gives a time series of the chlorophyll-*a* concentration during this period. Three individual readings were averaged to a single value. Background chlorophyll-*a* concentrations preceding and following the chlorophyll-*a* spike (up to 120 µg/l) during the bloom were typically around 10 - 40 µg/L, which is higher than the initial design envelope (See Table 11.7.1). From January 14 to around the 4 February, chlorophyll-*a* levels were in the high- to hyper-eutrophic zones.

Seawater samples were taken during this study and phytoplankton counted on three separate occasions: 14 January 2013, 14 February 2013 and 28 February 2013 (Figure 11.7.5). On 14 January, the algae count was 1.3 million cells/L with the highest count close to the sea surface (at 1 m depth) and only 11,000 cells/L at 15 m depth. One dinoflagellate species accounted for 99.8% of the bloom at that time (*Prorocentrum gracile*s). On 14 February, the total algal count was 417,000 cells/L at 1 m depth and 160,000 cells/L at 15 m depth. One diatom species (*Leptocylindrus danicus*) accounted for 99% of the population at that time. The dinoflagellate that had previously been observed had almost completely disappeared, accounting for only 0.2% of total count. Characteristics of these two species are summarized in Appendix 1. Both are not known to produce toxins and are relatively large, especially *Leptocylindrus danicus,* which forms long chains. Hence, intact cells should be well removed by both pretreatment systems. The pore size of the UF membranes (25 nm) is two to three orders of magnitude smaller than the typical size of the algae. The equivalent pore size of the media filters would be less than one order of magnitude smaller than the size of the algal cells, but still adequate.

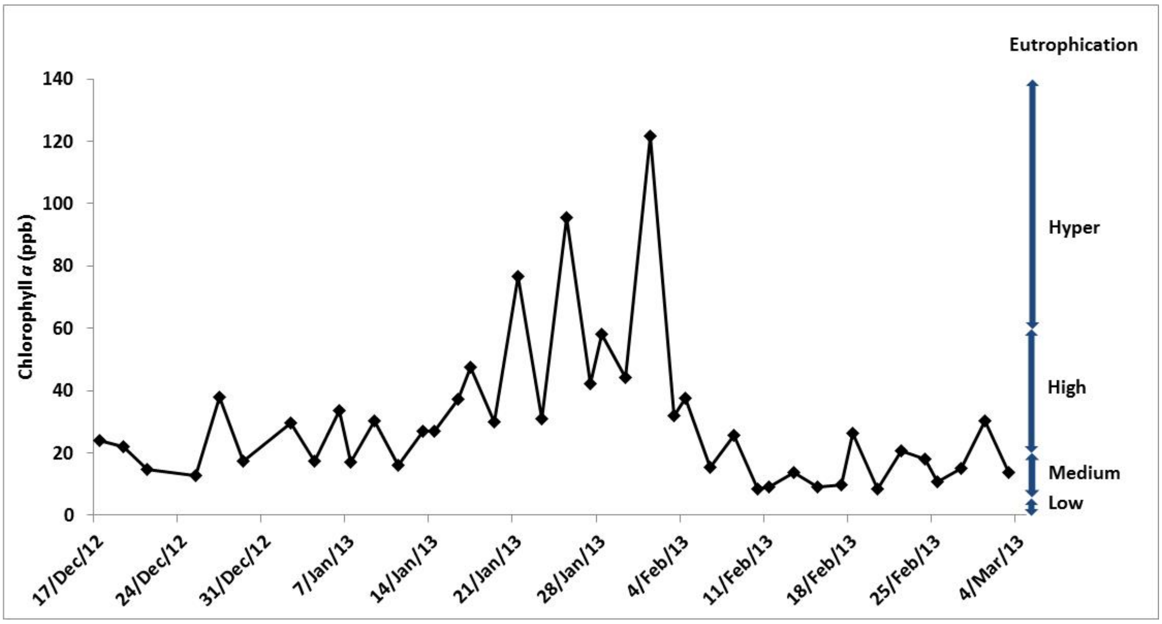


Figure 11.7.4. Average chlorophyll-*a* concentration measured from satellite data measured at La Chimba during the summer bloom in January – February 2013 and associated eutrophication classification.

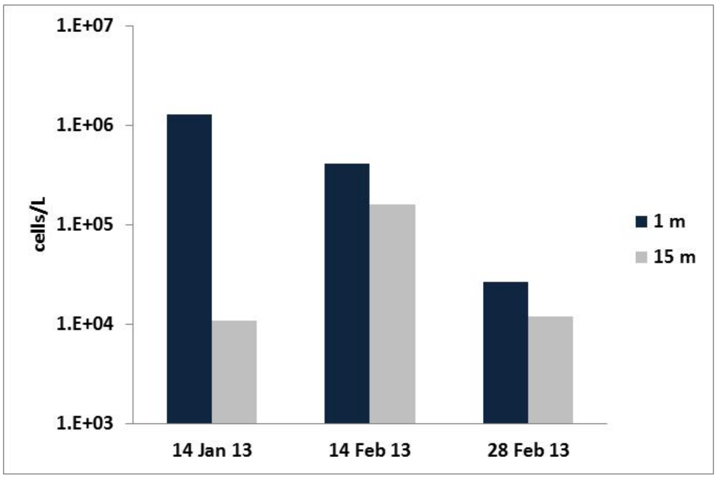


Figure 11.7.5. Algal cell counts at various depths in January and February 2013.

On 28 February the total algal count was 27,000 cells/L at 1 m depth and 12,000 cells/L at 15 m. The most abundant species was again *Leptocylindrus danicus*, but the population was more diverse, with the most abundant species only accounting for 80% of the total count. Figure 11.7.5 provides a graphic overview of sampling results.

The chlorophyll-*a* measurements suggest that an algal bloom started on or around 21 January and ended on or around 4 February. Seawater sampling showed elevated algae counts immediately prior to (14 January) and after the bloom event (14 February). Unfortunately no samples were taken during the period of highest chlorophyll-*a*. Extrapolating the data, it can be estimated that algal counts may have reached a maximum of 2 to 5 million cells/L at 1 m depth during the peak of the bloom.

During the same period, transparency and oxidation-reduction potential (ORP) were monitored as well. Transparency was monitored by means of a Secchi disk. ORP was averaged from 5 individual samples: 0, 5, 10 15 and 20 m depth. Both data are plotted in Figure 11.7.6 along with chlorophyll-*a*. Transparency is a good indicator for seawater turbidity. Bricker et al. (2003) employs the following classification for turbidity:

High turbidity	Secchi disk depth < 1 m
Medium turbidity	Secchi disk depth ≥ 1 m and ≤ 3 m
Low turbidity	Secchi disk depth > 3 m

Turbidity (as measured by Secchi depth) showed a good correlation with chlorophyll-*a* concentration at the start of the HAB event (around 15 January; Figure 11.7.6). After the decrease in chlorophyll-*a* (10 February), however, it took another 7 – 10 days for the Secchi transparency to reach a value of more than 2 m. This suggests that the end of the HAB event resulted in a further water deterioration due to release of organics from decaying algae.

The ORP value monitored on 4 January was 29 mV (Figure 11.7.6). This value appeared to be an anomaly, but was confirmed by multiple samples. Apart from this data point, there is a good relationship between transparency and ORP. A drop in ORP indicates that oxygen concentration is being reduced (assuming no other oxidant or reducing agent is present in the water). Hence, it was concluded that ORP may be a good indicator for the occurrence of HAB events.

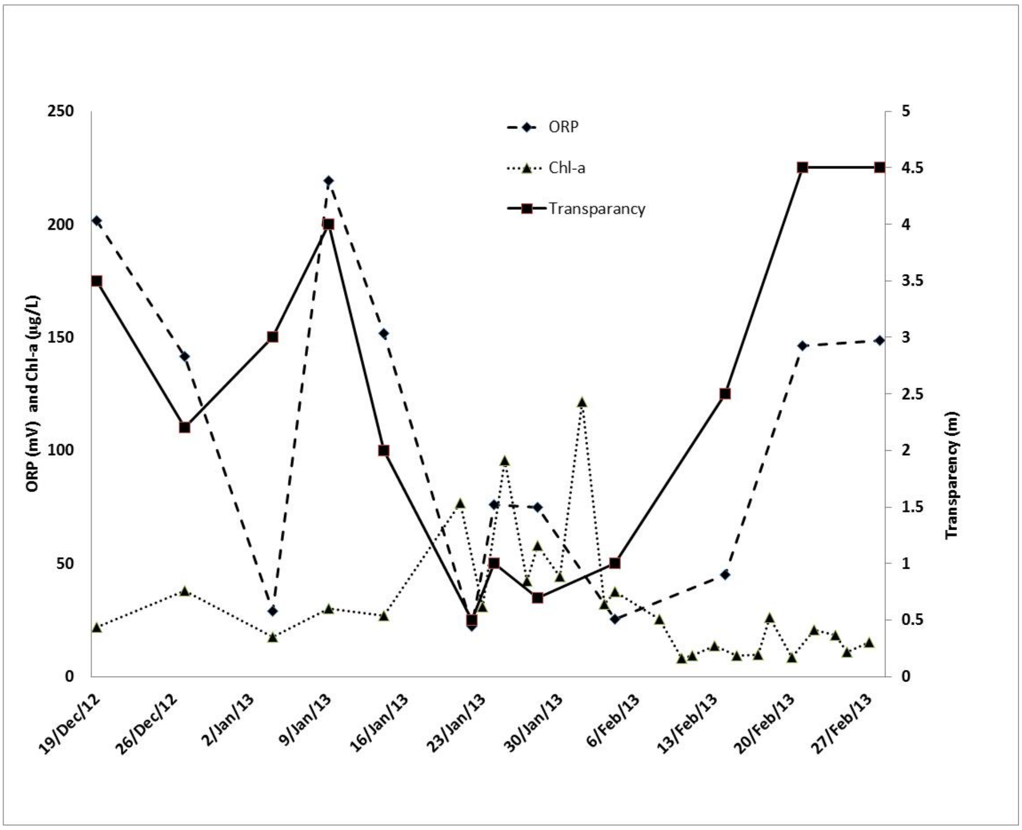


Figure 11.7.6. ORP, Chlorophyll-a and seawater transparency (Secchi disk depth) measured at La Chimba during the summer bloom in January – February 2013.

11.7.3 Operational data

The following data (Table 11.7.2) were provided by the end user of the plants (Knops et al. 2012; Vasini et al. 2013). No detailed plant operating settings were provided. Both plants were operating at design capacity during all periods. HAB events in the older plant (SWRO #1) were managed by additional SWRO cleanings and cartridge filter replacements. It should be noted that SWRO Plant 1 is approximately 20 years old, and employs older designs for DAF and SWRO. Up to 25 ppm of coagulant was required to keep the DAF system operational.

In contrast, SWRO plant #2 did not require additional cleaning or cartridge filter replacements. The ultrafiltration system in that plant provided sufficient pretreatment during the algal blooms to enable trouble free operation of the SWRO system. A maximum of 2 ppm coagulant was used directly in front of the UF system.

Table 11.7.2. SWRO plant design and operating parameters.

	SWRO Plant 1	**SWRO Plant 2**
Pretreatment	DAF, media filters and 5 µm cartridge filters	200 µm strainers, pressurized UF and 5 µm cartridge filters
Coagulant dose	25 ppm $FeCl_3$ in front of DAF	1 – 2 ppm $FeCl_3$ in front of UF
Cartridge filter replacement	15 – 30 days during winter Once every 4 days during summer	No filters replaced in 2 years
SWRO replacement frequency	165% over 5 years of operation, approximately 30% per year.	0% over 2 year's operation
SWRO cleaning frequency	Once per month during winter 15 – 30 days during summer	No cleaning performed in 2 years

11.7.4 Conclusions

- Satellite data providing chlorophyll-*a* concentrations were very useful, and indicated that an algal bloom event occurred over approximately two weeks, from 21 January 2013 to the 5 February 2013.
- This bloom was confirmed by seawater sampling that documented elevated cell counts immediately prior to (14 January) and after the event (14 February). Unfortunately no samples were taken during the period of highest chlorophyll-*a* concentration. Total algal counts are estimated to have reached a maximum of 2 – 5,000,000 cells/L during the peak of the bloom.
- Secchi disctransparency and ORP measurements showed a good correlation with chlorophyll-*a* and cell count levels, and confirmed the occurrence of an algal bloom event and a deterioration in water quality after the bloom due to decay of the algae.
- The bloom event consisted of two separate periods in which different species of algae dominated. Initially *Prorocentrum graciles* (a dinoflagelate) dominated. Within four weeks this species was completely replaced by *Leptocylindrus danicus* (a diatom).
- During the blooms, a single species prevailed whereas, during periods of low and medium eutrophication, the algal population was more diverse.
- Two SWRO systems were operating on a common intake system. These two systems had different pretreatment designs (DAF plus media filtration versus ultrafiltration) and allowed for a comparison of pretreatment under identical operating conditions.
- Both SWRO systems operated at design capacity during the algal bloom events.
- The SWRO system that employs conventional pretreatment (DAF plus media filters) did encounter significant operational issues: high coagulant dose, increased SWRO

membrane cleaning and cartridge filter replacement and eventually premature SWRO membrane replacement. 12% of SWRO membranes were replaced within 18 months of operation.

- The alternative system that employed UF did not require cartridge filter replacement or SWRO membrane cleaning even when challenged by HAB events. During the first two years of operation, no SWRO membranes had to be replaced. The lower mechanical stress and chemical exposure suggest that extended SWRO lifetime can be achieved.

11.7.5 References

Atacama Agua y Tecnología Ltda. 2013. Programa de vigilancia ambiental preventivo Comunidades fitoplanctónicas, Período estival 2012 – 2013, sector aducción de agua de mar Planta Desaladora la Chimba, Antofagasta, 5º , 9º, 11º Monitoreo semanal.

Bricker, S. B., Ferreira, J. G., and Simas, T. 2003. An integrated methodology for assessment of estuarine trophic status. *Ecological Modelling* 169(1), 39-60.

Cassis, D. et al. Phyto'pedia., 2012. http://www.eos.ubc.ca/research/phytoplankton/index.html accessed 1 September 2015.

Knops, F., Kahne, E., Garcia de la Mata, M., and Mendoza Fajardo, C. 2012. Seawater Desalination of the Chilean Coast for Water Supply to the Mining Industry. In: *Proceedings of the Water in Mining Conference*, Santiago, Chile.

Vasini, V., Garcia de la Mata, M., and Sturniolo, A. 2013. Two full-scale desal plants operating side-by-side: results and comparison of conventional vs new technology. In: *Proceedings of the International Desalination Association World Congress on Desalination and Water Reuse*, Tianjin, China.

11.8 ANTOFAGASTA, CHILE - ABENGOA WATER MICRO/ULTRAFILTRATION PRETREATMENT PILOT PLANT

Francisco Javier Bernaola[1], Israel Amores[1], Miguel Ramón[1], Raquel Serrano[1],
and Juan Arévalo[1]

[1]Abengoa, Spain

Figure 11.8.1. Aerial photo of pilot plant area at La Chimba Antofagasta (top). Photo: Google Earth). Intake area of the pilot plant (bottom). Photo: Abengoa.

Table 11.8.1. Overview of the Abengoa Water multimembrane pilot plant.

Plant/Project Name	**Multimembrane - Antofagasta**	
Location	Antofagasta (Chile)	
Primary product water use	Municipal	
Desalination Technology	MF / UF pretreatment	
Total Production Capacity (m^3/d)	336	
Commissioning date	May 2013	
Intake		
Feedwater source	Pacific Ocean	
Intake type	Shore intake-submerged bar screen	
Intake description	Intake depth: 25 m, distance from shore: 400 m	
Treatment		
Process description	Prefilter strainer plus two parallel membrane systems one MF and UF both pressurized with outside-in configuration	
Chemical dosing	No chemicals added	
Feedwater design parameters		
Temperature range (˚C)	17-20 ºC	
pH	7.5-8.5	
Turbidity (NTU)	0.4-4	
Organic Matter TEP *µg* xanthan-eq/*L*	3500 Measured once during the algal bloom	
Algal cell count (cells/L)	~up to 1.2 x10^6	
Algal species	*Pseudo-nitzschia delicatissima* *Ceratium fusus*	
Chlorophyll-*a* (µg/L)	≤ 50	
Treatment Design (*)	**During normal conditions**	**During bloom conditions**
UF flux (L/m^2h)	76	64
MF flux (L/m^2h)	83	70

(*) Different fluxes as both MF and UF systems were designed to operate maintaining the same pressure.

11.8.1 Introduction

Low-pressure membranes are an emerging technology as a pretreatment option in seawater desalination processes using reverse osmosis. Many advantages can be obtained when microfiltration (MF) or ultrafiltration (UF) membranes are used instead of conventional pretreatment such as:

- Positive barrier to particulates and pathogens;
- Lower operating costs due to significantly reduced RO membrane fouling and cleaning frequency;
- Lower chemical requirement and extended RO membrane life;
- Reliable production of high quality RO feedwater regardless of raw water turbidity;
- Higher RO membrane flux; and
- Smaller footprint for both RO and pretreatment systems resulting in lower capital costs.

It remains necessary to evaluate the performance of membrane pretreatment when faced with challenging feedwater conditions such as algal bloom events, when the seawater composition changes drastically.

The Chilean coast suffers red tides frequently and at the same time desalination plants are increasingly being installed along the coast to solve water scarcity problems, providing a water source to the cities and mines, mainly in the north, one of the driest deserts in the world. Therefore, Abengoa Water conducted a pilot study in the Bay of Antofagasta, in northern Chile, in which various MF and UF membrane technologies, processes and configurations were tested as pretreatment for the seawater reverse osmosis (SWRO) installation.

The MF and UF membranes both operated under pressure from a feed pump mainly in the outside-in configuration whereby, feedwater is pushed through the membrane pores from the shell side into the lumen of the hollow fibers. In the first stage of the pilot plant, one module was tested in the inside-out configuration. During mechanical cleaning, reverse flow was used, and air could also be introduced into the membrane modules in order to create turbulence along the membrane surface to increase the efficiency of cleaning if required. Rising air bubbles scour and clean the surface of the membrane fibers, maximizing membrane cleaning to restore flux.

To assess the quality and capacity of membrane fouling with this feedwater, Abengoa developed new measurement indexes, the AMFI[1] and AMI[2], and measured new parameters, including, among others, the content of TEP (Transparent Exopolymer Particles) - gelatinous particles composed mainly of negatively charged polysaccharides that are very sticky and can dramatically clog filters and membranes (see Chapter 2 and Appendix 3).

The multi-membrane Abengoa Water MF/UF pilot plant is shown in Figure 11.8.2 with a block diagram of the pilot plant given in Figure 11.8.3. The configuration allowed collection of operational as well as analytical data to evaluate the performance of different membranes tested at the same time and treating the same water. This is a very robust system as it was designed to treat seawater of varying quality with different types of membranes. The pilot plant is designed to work at the same time with two different modules, but both modules must be working either in outside-in or inside-out filtration mode.

Figure 11.8.2. Multi-membrane pilot plant.

---

[1] AMFI is based on the MFI procedure but simplified to allow automatic measurement.

[2] AMI is a procedure using a hollow fiber membrane at lab scale to evaluate clogging capacity.

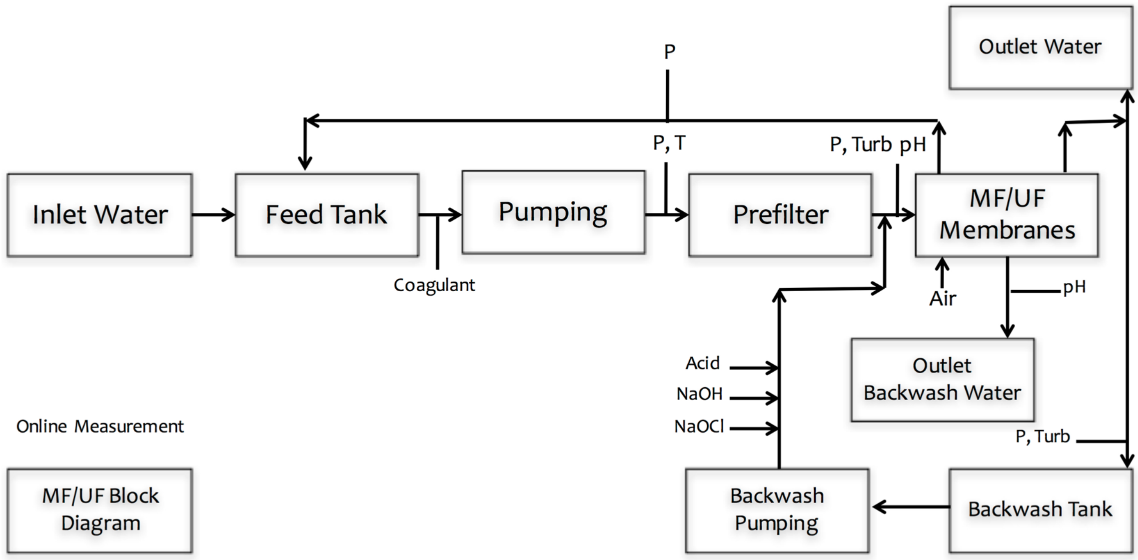


Figure 11.8.3. Process schematic for the Abengoa multi-membrane pilot plant operating in Antofagasta.

The objectives of the Antofagasta pilot study were to demonstrate the feasibility of UF/MF for SWRO pretreatment during normal feedwater conditions and algal bloom events and to optimise the following operational parameters:

- UF/MF flux;
- UF/MF backwash frequency and parameters;
- chemical cleaning frequency and duration; and
- cleaning efficiency and procedures

The trials were carried out in two stages. In the first, five different membrane modules were tested in the rig with various pore sizes and material (summarized in Table 11.8.2) in order to identify membranes for further long term testing in the second stage. In Figure 11.8.4, the behavior of different modules is shown along with AFF, a clogging index, showing the fouling kinetic of each membrane. No direct relationship was found between membrane pore size and clogging capacity. Therefore, clogging capacity is more likely to be related to membrane manufacture and the affinity of the membrane for the contaminant, for example membrane hydrophilicity. Membranes P0046 and P0035 were selected based on their lower AFF value (fouling capacity at different flux) as shown in Figure 11.8.4 and a AMFI below a maximum value that was considered acceptable in an RO pretreatment plant).

Table 11.8.2. Characteristics of MF and UF membranes used in the first stage of the pilot study.

Module Number	Material	Pore Size (µm)	Flow mode	Pressure decay test (PDT) (mbar/min)
F1223	PVDF reinforced	0.02	Outside-In	1.4
P0033	PVDF	0.03	Outside-In	0.9
P0035	PVDF	0.1	Outside-In	2.1
P0046	PVDF	0.02	Outside-In	1.2
P0047	PESM	0.02	Inside-Out	1.1

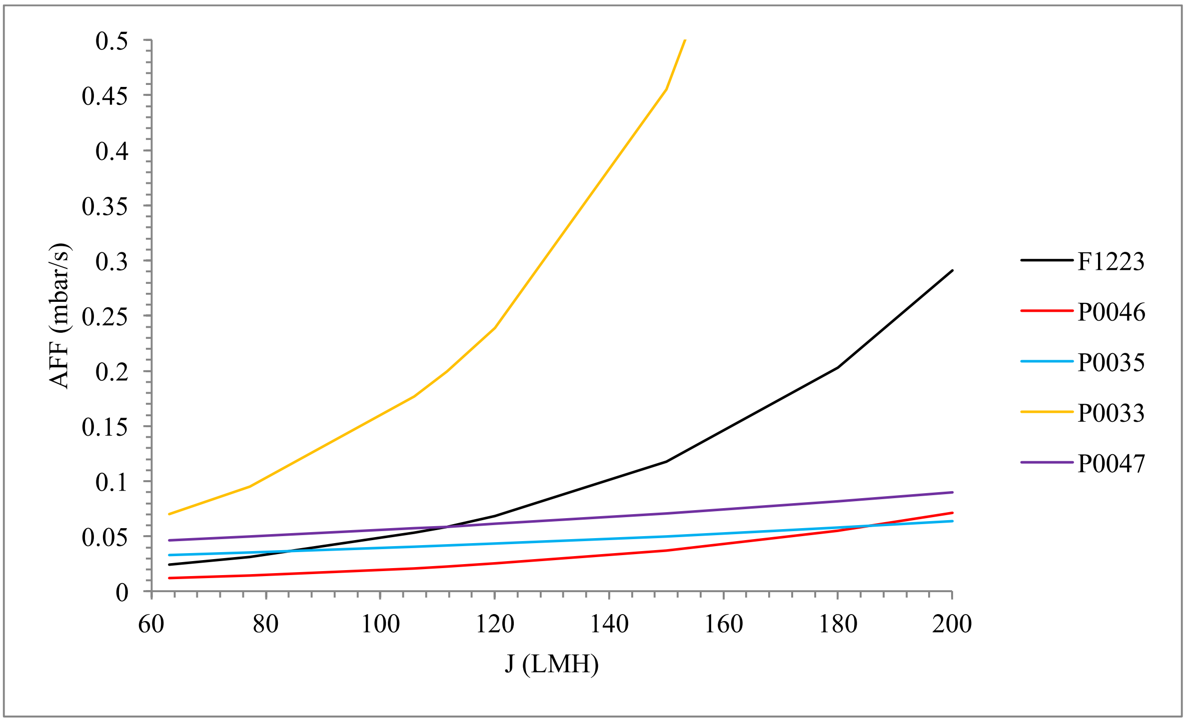


Figure 11.8.4. AFF Index obtained for the MF and UF membranes used in the first stage of the pilot plant study. P0046 and P0035 membranes were selected for the second stage of the study.

In the second stage of the study, the pilot plant, was equipped with two commercial modules and operated in parallel at the same AFF value, so that each module had its own specific operating flux.

11.8.2 Results

The pilot plant achieved excellent results testing different MF/UF technologies for normal seawater quality through comprehensive monitoring of the operating conditions of the system, the frequency of chemical cleaning, resulting in high filtrate quality, high flow and good membrane fouling management. A recovery of 96% was achieved.

The pilot plant also faced challenging situations where algal bloom counts reached 1.2 x10^6 cells/L. During this time the rate of membrane fouling grew exponentially compared to the usual rate, necessitating modification of plant operating conditions. The frequency of cleaning was also increased. It was possible to maintain stable control of the process during the bloom without plant shutdowns and without the addition of chemical reagents such as coagulants, so that chemical consumption was minimized. Disposal of coagulant residuals was avoided, decreasing the environmental impact of the process while achieving high quality feedwater for SWRO.

The pilot plant faced some algal bloom issues in the warm periods of the year (December - March), when the cell counts increased from a background level of ~ 6 x 10^3 to > 1.2 x 10^6 cells/L measured at the intake basin (Figure 11.8.5). TEP concentrations were found to increase from ~ 700 µg xeq/L to 3500 µg x-eq/L during this period.

Based on the concentration of chlorophyll-*a*, the eutrophication status and the risk of algal blooms was classified as medium/high (Bricker et al. (2003); Gas Atacama case study). The two most abundant species in the blooms were *Pseudo-nitzschia delicatissima* (diatom) and *Ceratium fusus* (dinoflagellate), both are non-toxic, but can foul membranes.

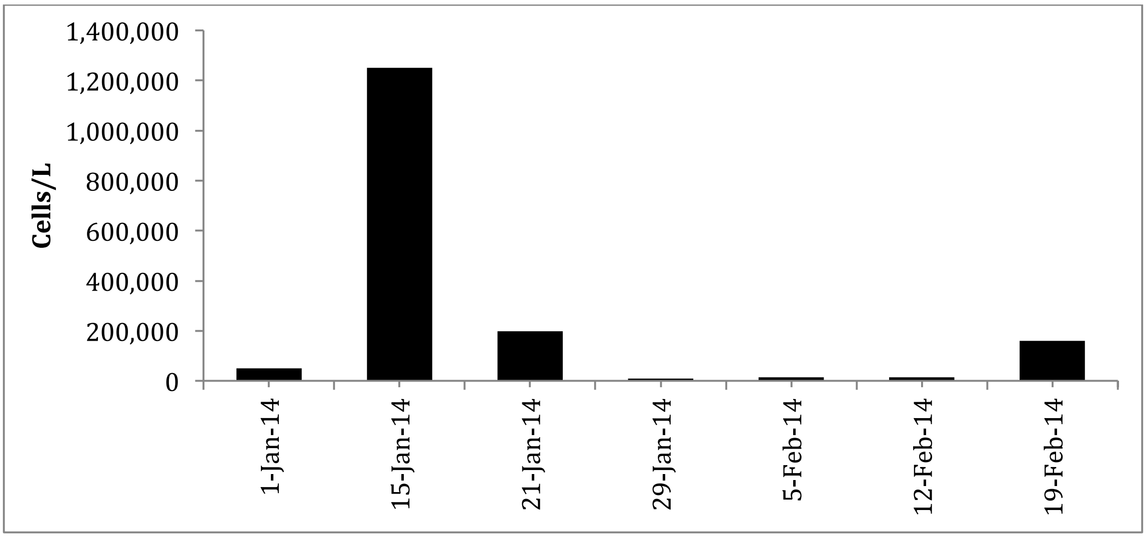


Figure 11.8.5. Total cell counts in the multi-membrane pilot plant feedwater showing an increase during an algal bloom.

The presence of these microscopic algae caused problems in filtration performance as the suspended solids concentration increased due to the high cell numbers and organic compounds (TEP) associated with the bloom. This resulted in a rapid two-fold increase in transmembrane pressure. TSS measured in this period increased from 6 – 8 ppm during non-bloom periods up to an average value of 40 ppm, with a peak of 76 ppm during the bloom, measured downstream of the pre-filter.

Figure 11.8.6 shows how the membrane fouling kinetics significantly increased during the time that algal blooms were more frequent, that is during the summer months with higher temperature in the southern hemisphere.

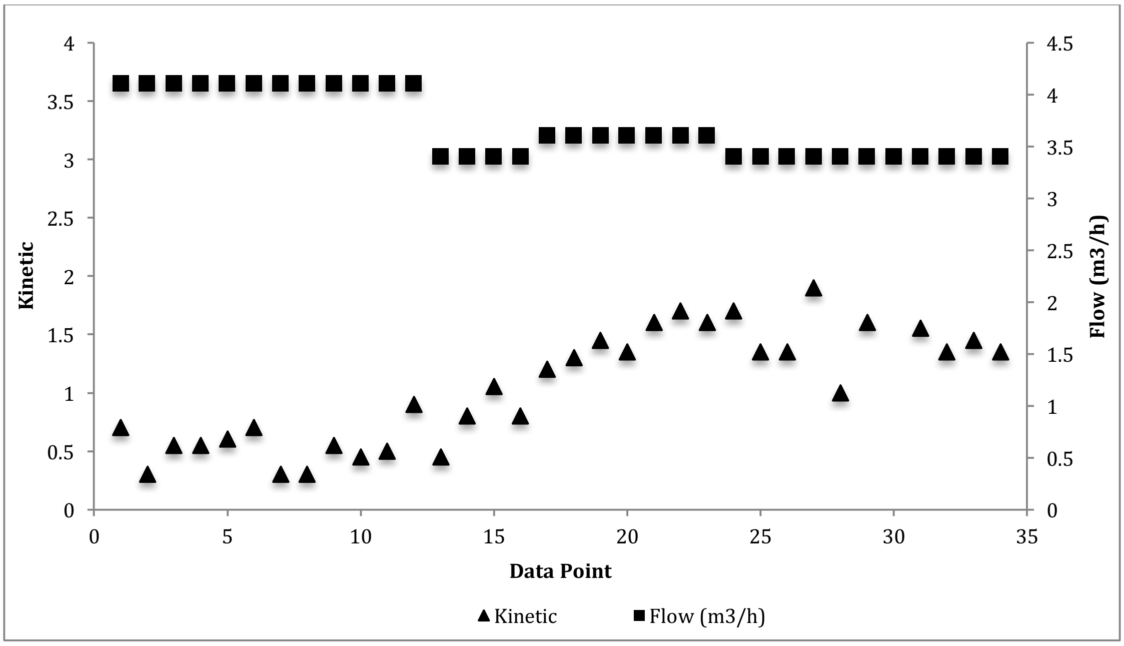


Figure 11.8.6. Membrane fouling kinetic during the 2014 algal bloom event. Data points were taken at uneven times and 34 data points were taken between early November 2013 to mid-March 2014.

This increase in transmembrane pressure made it impossible to operate the installation under the normal operating conditions. Therefore it was necessary to adapt the process to the feedwater quality changes during the bloom. To allow for continued membrane operation during the algal bloom it was necessary to adjust the flux, filtration mode and cleaning frequency as described further below.

It was necessary to reduce the flux by 16% on average to return the fouling kinetics to its initial value, where the fouling was controlled and the permeability restored using mechanical cleaning or simple backwashing.

The increase in suspended solids concentration measured in bloom periods also made it necessary to adapt the filtration process. In normal conditions the UF operated in dead-end mode with all the seawater pumped across the membrane. During bloom events the water composition was more complex and the higher suspended solids made it more attractive to operate in cross flow, where part of the water pumped scours the outside membrane surface and removes the excess of solids off the membrane. In this case, a 10% recirculation ratio was used. While operating in cross flow mode may require more energy, the average pressure was less and any increase in energy consumption would be more related to the loss of recovery than from recirculation.

Finally, the frequency of chemical enhanced backwash (CEB) was greatly increased during algal blooms. The increase in TSS and a much more complex aqueous seawater matrix made more frequent cleaning necessary. The initial plant configuration was fixed with a CEB period of 30 hours, but during the bloom event and prior to changing flux the CEB period was reduced down to 7-8 hours (Figure 11.8.7). Following the optimization of flux during bloom conditions the CEB was set to 26 hours to achieve stable operation.

The CEB and clean in place (CIP) were carried out with the same chemicals and concentration, but the duration for each procedure was different. CIP comprised of a chlor-alkali phase followed by an acid phase.

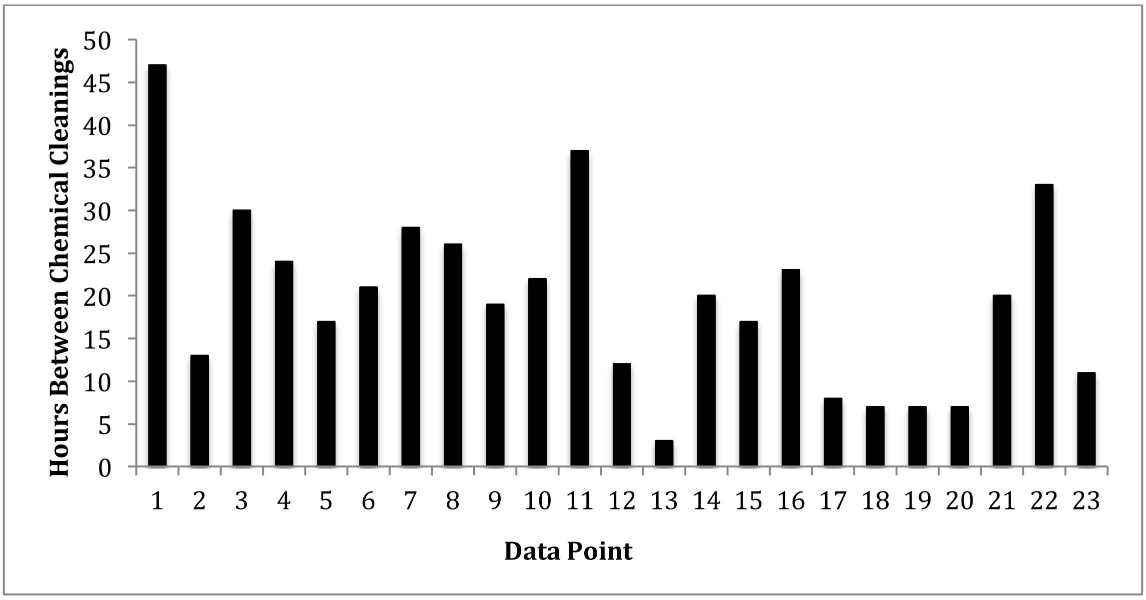


Figure 11.8.7. The duration between chemical cleaning (CEB) during normal feedwater conditions and during the algal bloom. Data points were taken between early November 2013 and late February 2014 on 23 occasions. From data point 21, both hypochlorite and sodium hydroxide were used during the CEB.

The increased cleaning frequency resulted in much higher operational costs, due to the higher chemical consumption. To lower the chemical consumption during algal blooms, the pH value of the chemical cleaning solution was increased to values around 12 compared to 9 during normal operation. This resulted in chemical cleaning restoring UF recovery to 94%.

11.8.3 Conclusions

- Based on the concentration of chlorophyll-*a*, the phytoplankton bloom experienced at the pilot plant can be classified as medium/high, using the classifications of Bricker et al. (2003).
- The pilot plant initially tested inside-out UF membranes but thereafter tested outside-in. Conclusions therefore relate to outside-in membranes.
- The pilot plant achieved an average recovery of 96% in normal conditions when no algal blooms were present. During events, recovery decreased to 85% due to the reduction in flux when keeping the same mechanical cleaning configuration (backflush flow rate and time and frequency used). Therefore, more water required disposal and less filtered water was produced.
- To decrease the kinetics of membrane fouling, the optimal choice was to reduce flux before shortening the cycle time and switching to recirculation mode. When the plant was operated in recirculation mode, membrane fouling did not steadily increase until a cleaning was required. Instead, fouling increased asymptotically until it reached a value at which it stabilized and remained constant, or increased very slowly. This allowed membrane chemical maintenance to extend to every 20 - 24 hours, enough for stable operating conditions.
- The most effective cleaning was with an elevated pH of 12 using chlor-alkali in the chemical cleaning stage. This achieved up to 94% flux restoration for these types of membranes versus 40% obtained by cleaning at pH 9.
- The pilot plant was operated in recirculation mode during the algal bloom; however, no chemicals (for example, coagulant) were added to the feedwater to improve solids and organics removal, thereby reducing operating costs.

11.8.4 References

Bricker, S. B., Ferreira, J. G. and Simas, T. 2003. An integrated methodology for assessment of estuarine trophic status. *Ecological Modelling* 169, 39-60.

11.9 TAMPA BAY, FLORIDA (USA) – NON-TOXIC ALGAL BLOOMS AND OPERATION OF THE SWRO PLANT DETAILING MONITORING PROGRAM FOR BLOOMS

Lauren Weinrich[1]

[1]American Water, Voorhees, NJ, USA

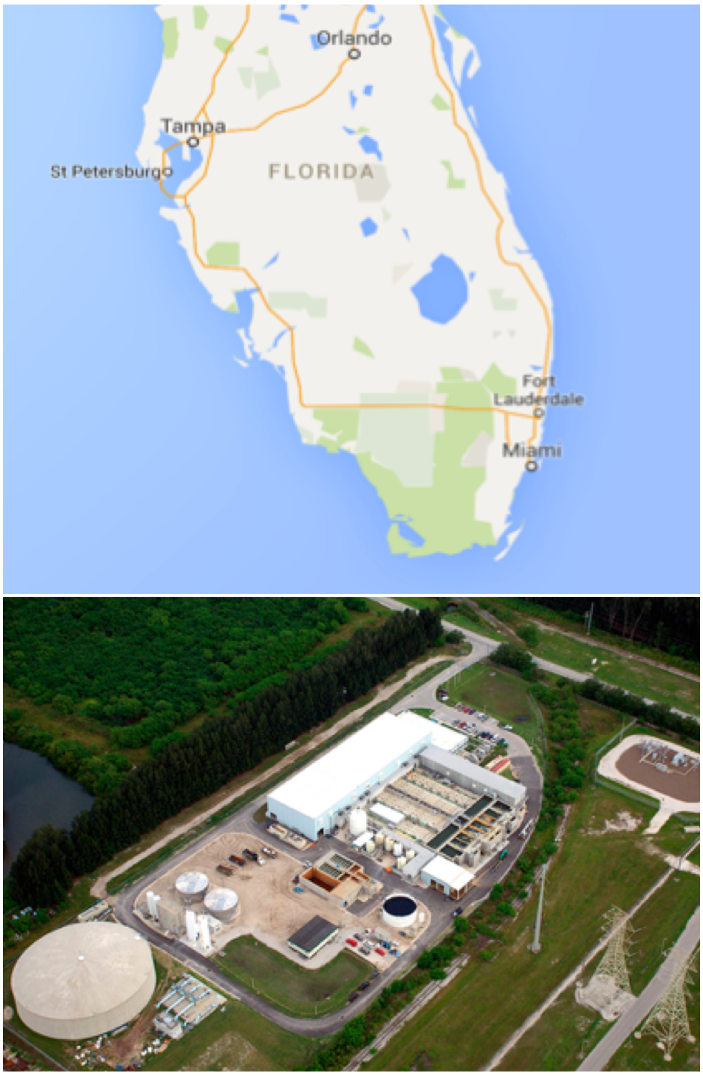


Figure 11.9.1. Location of the Tampa Bay Seawater Desalination Plant (top) and aerial view (bottom; Accessed on 11 Nov. 2016 http://www.acciona.us/projects/water/desalination-plants/tampa-bay-desalination-plant/).

Table 11.9.1. Overview of Tampa Bay seawater desalination plant.

Plant/Project Name	**Tampa Bay Seawater Desalination Plant**	
Location	Gibsonton, Florida, U.S.A.	
Primary product water use	Municipal	
Desalination Technology	SWRO	
Total Production Capacity (m^3/d)	94,635	
SWRO recovery (%)	60% (additional recovery up to 73-75% is achieved for the plant from recirculating pretreatment supernatant)	
Max. Feed RO Temp. (°C)	40	
Commissioning date	2008 (Final acceptance test passed 2010)	
Intake		
Feedwater source	Tampa Bay	
Intake type	Cooling outflow from co-located power plant, mixed with bay water when needed to meet temperature requirements.	
Intake description	Outfall canal from power plant (power plant uses open intake canal system).	
Intake screening	Plant intake uses 0.5 mm fine mesh for reducing impingement and entrainment.	
(shock) chlorination Strategy, dose rate	Chlorine dioxide is dosed at the intake continuously between 0.5 – 1.1 mg/L. Sodium hypochlorite is fed continuously prior to the coagulation mixing basins.	
Online raw water monitoring	Conductivity, temperature, pH, turbidity, dissolved oxygen	
Discrete raw water analysis relevant to HAB		
Pretreatment		
Process description	Upflow, deep bed sand filters, diatomaceous earth (precoat) filtration, cartridge filtration (5µm)	
Chemical dosing	Chlorine dioxide at the intake. Ferric chloride, sodium hypochlorite, and sulfuric acid (for pH adjustment) are dosed prior to the rapid mix basins. Sodium bisulfite is added after the cartridge filters.	
Feedwater design parameters		**Feedwater during bloom conditions**
Temperature range (˚C)	15.5 – 40	36 - 38
Salinity range (TDS mg/L)	25,000 – 31,000	29,000
Conductivity (mS/cm)	37 – 43	N/A
Total Suspended Solids (mg/L)	10 - 30	37
SDI$_{15}$	6 – 6.5 SF effluent 2.8 – 4.0 DE effluent 2.5 – 3.5 CF effluent	N/A
Turbidity (NTU)	1 – 3 Seawater	2 - 5
Organic Matter	TOC 1 – 12 mg/L AOC 60 – 260 µg acetate C per L	TOC 5 – 7.6 mg/L AOC 230 – 490 µg acetate C per L

Table 11.9.1 *(Continued)*

Feedwater design parameters		**Feedwater during bloom conditions**
Algal cell count (cells/L)		
Algal species		*Ceratium furca* (red-tide) *Phaeocystis* (foaming)
Chlorophyll-*a* (µg/L)		9.6
Additional relevant water quality parameters for design or observed spikes during algal bloom	DO 4 – 9 mg/L Tot. N 0.4 mg/L	Tot. N 2 mg/L
Desalination Design		**During bloom conditions**
Sand filter	2.4 – 12.2 m/h	N/A
Diatomaceous earth	24.4 – 97.7 m/h	N/A
RO flux (L/m^{2}h)	23.3	N/A

Terms:

AOC	assimilable organic carbon
CF	cartridge filter
DE	diatomaceous Earth (Precoat)
DO	dissolved oxygen
N	nitrogen
SF	sand filter
TOC	total organic carbon

11.9.1 Introduction

The Tampa Bay Seawater Desalination Plant (TBSDP) is located in Gibsonton, Florida on the south shore of Apollo Beach on Hillsborough Bay (Figure 11.9.1). TBSDP can produce up to 94,635 m^3/d and supplies 10% of the drinking water to the region. Tampa Bay Water owns the plant and the joint venture American Water – Acciona Agua is responsible for water production. TBSDP is co-located with a coal-fired power plant and receives feedwater from either the plant's cooling loop or, if the cooling water exceeds the temperature limits of the membranes, bay water can be mixed with the cooling water. Pretreatment comprises upflow deep bed sand filters, diatomaceous earth (DE) (precoat) filtration and cartridge filtration (Figure 11.9.2). There are seven reverse osmosis treatment trains. Since the plant went online, TBSDP has not experienced a toxic harmful algal bloom (HAB). Non-toxic micro-algae contributed to periodic operational challenges within the pretreatment process, described in the following case study.

11.9.2 Periodic performance issues

Plant personnel observed operational problems and recorded adverse water quality events during late 2009. In order to track the severity of intermittent yet recurring issues, staff assigned a grade to both the water event and the loss of membrane performance on a scale of 0 – 3 (3 being the most severe). From September to December 2009, there were seven events classified as level 3 that lasted between one and nine days. Other problems associated with the level 3 events included reduced production capacity, foaming in the pretreatment basins (Figures 11.9.3 and 11.9.4), and shortened diatomaceous earth filter run times.

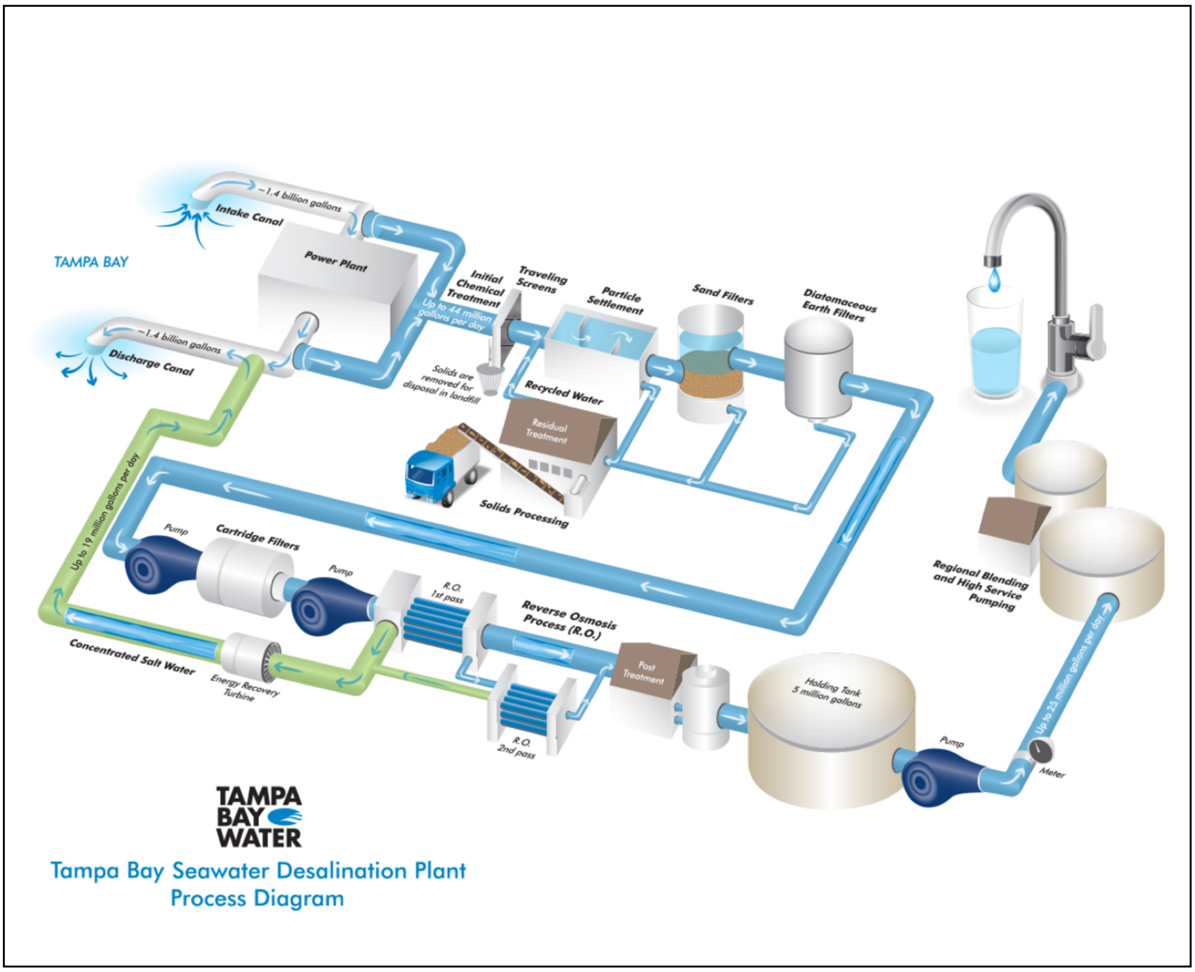


Figure 11.9.2. Process flow diagram of Tampa Bay Seawater Desalination Plant. Photo: http://www.tampabaywater.org/Portals/0/desal-fact-sheet.pdf. Accessed May 01, 2017).

Figure 11.9.3. Normal pretreatment basin appearance (Voutchkov 2009).

Figure 11.9.4. Foaming observed in the rapid mix basins during pretreatment at TBSDP. Source: Voutchkov (2009).

After a particular episode of shortened DE filter run time and foaming in the rapid mix basins in late September 2009, microscopic analysis of source seawater, sand filter and DE filter backwash was conducted. The algal species *Ceratium furca* and *Phaeocystis* spp. were present in the source seawater in October, between the initial event in September and another level 3 episode in November (Voutchkov 2009). The presence of algae in the sand and DE filter backwash waters suggest that algae were not retained by the sand filters and passed through to the DE filters, thereby blinding the DE filters and causing shorter DE filter run times. Other causes of the adverse event were considered, such as an increase in alluvial organic matter from the nearby Alafia River, changes in salinity and calcium concentration, or other intermittent issues from the co-located TECO power plant. Total organic carbon (TOC) measured in the raw seawater during the performance issue on September 30, 2009 was 7.6 mg/L (Owen 2015, pers.comm., 21 July), which was in the upper range of the fluctuations that TBSDP experiences and commensurate with increased algal activity. Averages determined from a study in 2015 found that TOC ranged from 5.5 to 6 mg/L (Haas et al. 2015).

During the November event, samples were collected for assimilable organic carbon (AOC) and TOC from the raw seawater, after initial chemical pretreatment, after the settling basins and before sand filters, after sand filters, after diatomaceous earth filters and the RO feed. AOC ranged from 230 – 490 µg acetate C per L; average AOC in the raw water was 360 ± 180 µg acetate C per L over three days (Figure 11.9.5). The pretreatment sample was collected after chlorine dioxide dosing and ranged from 190 – 760 µg acetate C per L over the three days of monitoring, and averaged 440 ± 290 µg acetate C per L. AOC was 65% higher in the pretreatment location (following disinfection with chlorine dioxide) compared to the raw water. Oxidation of organic matter or sheared algal cells from turbulent discharge at the power plant may have caused the increase in AOC during the pretreatment stage. Increases in AOC have been observed following disinfection with chlorine dioxide (Haas et

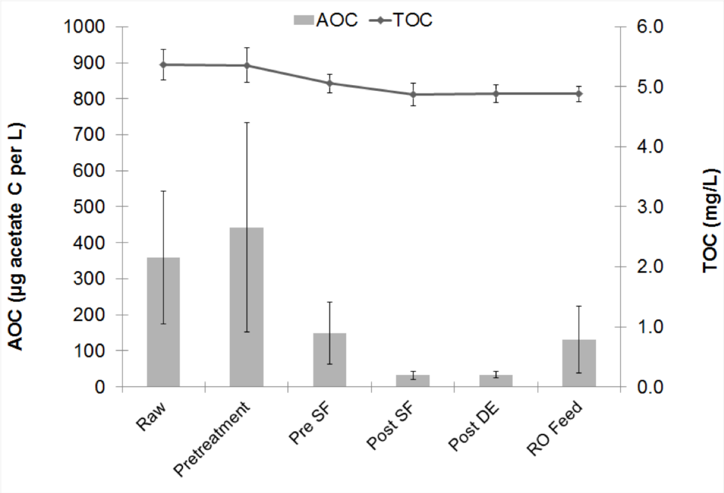


Figure 11.9.5. AOC and TOC at TBSDP during periodic operational issues in November 2009 thought to result from a non-toxic HAB. Pretreatment refers to post-chlorine dioxide addition. SF = sand filter (after $FeCl_3$ coagulation), DE = diatomaceous earth filter. Error bars represent standard deviations of samples collected over three days.

al. 2015; see also Chapter 9). While the actual cause of the operational challenges was not confirmed to have exclusively resulted from an algal bloom, increases in AOC may lead to increased biofouling potential which is an important consideration for seawater RO plants worldwide.

Biological and organic RO fouling are the most common fouling issues at TBSDP. Recent studies have shown that although the levels of organic carbon at the intake are generally high and variable, the treatment process impacts the biodegradable fraction. Intake AOC levels ranged from 60 – 260 µg acetate C per L in recent studies (Schneider et al. 2012; Haas et al. 2015) and were often reduced after filtration. AOC levels increased in the RO feed following chemical addition of sodium bisulfite for reducing ORP. The presence of AOC greater than 30 µg acetate C per L has been correlated to increased RO biofouling potential (ich et al. 2016; Haas et al. 2015).

11.9.3 Algal bloom monitoring and HAB strategy

Monitoring for HAB in Tampa Bay is conducted by the Florida Fish and Wildlife Conservation Commission for protection of human health, ecosystems, recreation, tourism, and aquaculture. The most common HAB species in the region, *Karenia brevis,* produces brevetoxin, with outbreaks occurring nearly every year along the coast and is monitored at numerous stations around Florida, with results reported through the website http://myfwc.com/REDTIDESTATUS. TBSDP personnel regularly monitor the website for updates on occurrence of algal blooms in the area (Martorell Cebrian 2015). HABs and biotoxin occurrence affect recreation and potentially desalination treatment processes.

Studies in southern California have suggested potential desalination plant concern associated with marine algal biotoxins that include domoic acid, saxitoxin, brevetoxin, okadaic acid, and yessotoxin (Caron et al. 2010; see Chapter 2). Tampa Bay, however, has not had a major event since 2005. In 2014 a *K. brevis* HAB occurred north of Tampa Bay between Franklin and Citrus counties in the Gulf of Mexico. Algal blooms caused by other species have occurred in Old Tampa Bay (the northwest arm of Tampa Bay) since 2008 but did not impact TBSDP, which is between Tampa Bay and Hillsborough Bay (Figure 11.9.6).

Watershed and water quality management are the focus of numerous projects to improve water quality and reduce nutrient loading in Old Tampa Bay. Despite the lack of HAB occurrence at TBSDP, monitoring for increased algal growth in water near the intake is important for maintaining effective treatment, avoiding adverse effects, and maintaining historical records for establishing patterns of water quality changes. There would be tangible benefits if a monitoring program were also in place for organic carbon, chlorophyll-*a* and other algal constituents, nutrients, particle size and abundance for evaluating water quality trends and to track changes and make adjustments to preempt adverse effects of algal blooms.

If toxic HABs occur, the plant would opt to shut down (Owen 2015). The water portfolio for the region currently ensures that the majority of the drinking water supply is from other freshwater sources. The desalination plant can provide 10% of the Tampa Bay Water supply. Operations staff would monitor intake online water quality parameters such as turbidity and pH and work with state and local authorities to conduct additional analyses to decide when the plant could be started and brought back online.

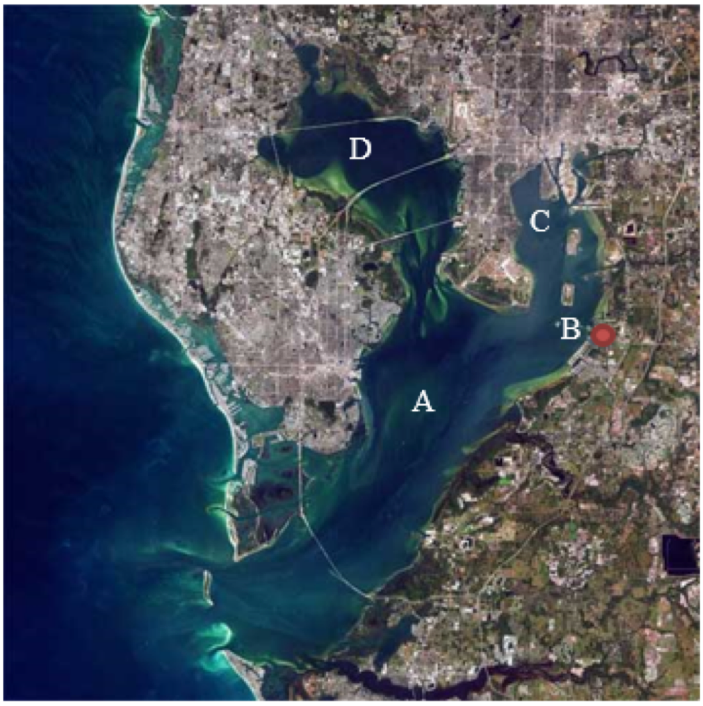


Figure 11.9.6. Satellite photo of Tampa Bay (A); Tampa Bay Seawater Desalination Plant (TBSDP) (B); Hillsborough Bay (C); and Old Tampa Bay (D).

11.9.4 Conclusions

With a diverse water supply portfolio, Tampa Bay Water has been able to meet supply demands from other resources when adverse water quality events (e.g., non-toxic algal blooms) affected production capacity. In the events described above that caused foaming in the rapid mix basins and shortened filter runs, TBSDP staff worked to define the severity of events and track their occurrence over time. When the events occurred, staff had to adapt treatment to the limitations caused by the event and the result was a decline in plant production. To date, there have been no toxic HABs and TBSDP continues to monitor for the occurrence of HABs using information provided by the Florida Fish and Wildlife Conservation Commission. If a toxic HAB occurred and threatened the water quality of the intake supply, then TBSDP would stop processing seawater and shut down the plant. Taking these necessary precautions is critical for avoiding health risks, as Tampa Bay Water would supply safe drinking water using other sources in their water supply portfolio.

11.9.5 References

Caron, D. A., Garneau, M. È., Seubert, E., Howard, M. D., Darjany, L., Schnetzer, A., Cetinić, I., Filteau, G., Lauri, P., Jones, B., and Trussell, S. 2010. Harmful algae and their potential impacts on desalination operations off southern California. *Water Research* 44(2), 385-416.

Haas, C. N., LeChevallier, M. W., and Weinrich, L. A. 2015. Application of the Bioluminescent Saltwater Assimilable Organic Carbon Test as a Tool for Identifying and Reducing Reverse-Osmosis Membrane Fouling in Desalination. *Water Environment & Reuse Foundation*. Project 11-07.

Martorell Cebrián, A. 2015. Personal Communication, July 2015.

Owen, C. 2015. Personal Communication, June 2015.

Schneider, O. D., Weinrich, L. A., Giraldo, E., Kennedy, M., and Salinas, S. 2012. Investigation of Organic Matter Removal in Saline Waters by Pretreatment. *Water Research Foundation*. Project 4280.

Voutchkov, N. 2009. Initial biofouling analysis. *Water Globe Consulting Tech. Memo*. Proj. No. 0007-2009-0001 on Nov. 5, 2009.

Weinrich, L., LeChevallier, M. and Haas, C. N. 2016. Contribution of assimilable organic carbon to biological fouling in seawater reverse osmosis membrane treatment. *Water Research* 101, 203-213.

11.10 JACOBAHAVEN, THE NETHERLANDS – ULTRAFILTRATION FOR SWRO PRETREATMENT: A DEMONSTRATION PLANT

Rinnert Schurer[1,2], Loreen O. Villacorte[2,3], Jan C. Schippers[2] and Maria D. Kennedy[2]

[1] Evides Water Company, Rotterdam, the Netherlands
[2] UNESCO-IHE Institute for Water Education, Delft, the Netherlands
[3]GRUNDFOS Holding A/S, Bjerringbro, Denmark (current affiliation)

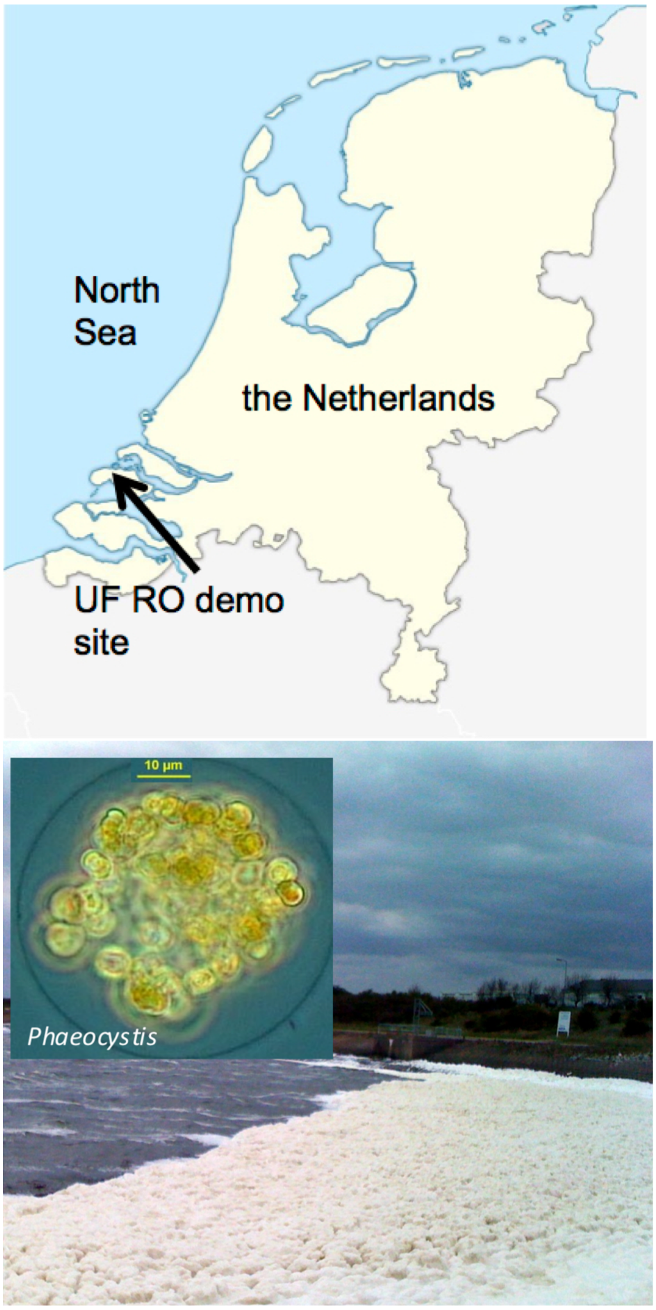


Figure 11.10.1. Location of the UF RO demonstration site in the Netherlands (top). Algal foam at demonstration plant intake site (bottom); inset – *Phaeocystis* colony. Photos: D. J. Patterson and R. A. Andersen; A. Al-Hadidi.

Table 11.10.1. Overview of Jacobahaven UF-SWRO demonstration plant.

Plant/Project Name	**Evides Desalination Demoplant Jacobahaven**
Location	Jacobahaven, Oosterschelde Estuary, the Netherlands
Primary product water use	Pilot for drinking water and/or industrial water production
Desalination technology	SWRO first pass and BWRO second pass
Total production capacity (m^3/d)	360 (output)
Operational period	January 2009 to July 2012 (decommissioned)
Intake	
Feedwater source	North Sea / Oosterschelde. Subject to tidal currents and sediments of the nearby tidal flats
Intake type	Open intake
Intake description	2 parallel open pipes DN150 mm, submerged 4 m below water surface into a rapid-flowing tidal current; coarse screening (aperture unknown); 10 mm-perforated secondary screen in intake pump suction
UF pre-screening	50-µm microstrainer, automatic backwash (purpose: retention of mussel seed)
(Shock) Chlorination strategy, dose rate	Not practiced, intake pipe was pigged regularly in summer
Online raw water monitoring	Conductivity, temperature, pH, turbidity
Discrete raw water analysis relevant to HABs	TOC, algal cell counts and identification, chlorophyll-*a*, TEP (Transparent Exopolymer Particles)
Pretreatment	
Process description	In-line coagulation (seasonally optional); pressurized inside-out dead-end UF; cartridge filter 10 µm; SWRO; BWRO (seasonally optional for boron removal); remineralization
Chemical dosing	UF in-line coagulation (seasonally optional, initially PAC, later superseded by ferric, 0.5 – 1.0 mg/L); SWRO pH control (HCl, to pH 7.2, later omitted, no antiscalant dose); BWRO pH control (NaOH, to pH > 9.5); Remineralization CO_2 (~ 100 mg/L) and $CaCO_3$ (100 mg/L)

Feedwater design parameters	**Conditions outside algal bloom**	**Conditions during algal bloom**
Temperature range (˚C)	2 – 25	~ 9 – 15 (Spring)
Salinity range (TDS mg/L)	29,000 – 35,000	(unaltered)
Conductivity (mS/cm)	45 – 50 at 25 °C	(unaltered)
Total suspended solids (mg/L)	<1 - ~ 100 (avg: 35)	(unaltered)
SDI (5, 10 or 15 minute interval)(%/min)	No data available	SDI_{15} >5 (see Al-Hadidi, 2012)
Turbidity (FTU)	5 – avg. 15 – 50 (shut down, peaks up to 100)	(unaltered)
Organic Matter TOC/DOC (mg/L), TEP, biopolymers	DOC 1.2 – 1.8; TOC 1.5 – 2.2	DOC: unaltered; TOC: 3.0

Table 11.10.1 *(Continued)*

Feedwater design parameters	**Conditions outside algal bloom**	**Conditions during algal bloom**
Algal cell count (cells/L)	100 – 300	$0.5 \times 10^6 - 12 \times 10^6$ (peak)
Algal species	Centric diatoms	*Phaeocystis, Chaetoceros*
Chlorophyll-*a* (µg/L)	1 – 5	~ 15 -20 (peak)
Additional relevant water quality parameters	pH: 7.9 – 8.1 ortho-P: 0.04 mg/L DO: 8 – 11 (avg.) – 18 mg/L $TEP_{0.4\mu m}$: <0.05 mg X_{eq}/L	pH: 8.5 ortho-P: < 0.01 mg/L (same, possibly due to intake turbulence) $TEP_{0.4\mu m}$: 0.05 - 0.74 mg X_{eq}/L
Desalination design	**Conditions outside algal Bloom**	**Conditions during algal Bloom**
UF type	150 kDa MWCO, Pentair	(unaltered)
UF flux (L/m^{2}h)	55 – 90, without coagulation	55, with coagulation activated
UF backwash	Backwash interval 45 – 90 min. Backwash flux 250 L/m^{2}h for 45 seconds	Backwash interval 45 (30) min. Other settings unaltered
UF feedwater pH	6.6 if pH correction deployed, otherwise 7.4 to 8.1 - 8.4 (ambient)	~7.6 for Fe-coagulation, ~6.6 for Al-coagulation
UF coagulation	No coagulant dosed	0.5 – 1.5 mg/L Fe inline coagulation for UF
UF CEB	CEB initiated when TMP (at 20 °C) had increased to 0.30 bar NaOH pH 9.4, NaClO 200-400 ppm, HCl pH 2, soaking time 10 – 20 min.	Omitted during coagulation, as not effective Same protocol, but less effective (as described in the text)
UF CIP	Only practiced after or during coagulation, otherwise no need	Solution of 1% ascorbic acid and 0.4 % oxalic acid, soaking time 12 – 48 h. No temperature control
UF wastewater handling	Direct discharge to sea, as no UF-coagulation was practiced outside algal bloom	Buffering, secondary coagulation and clarification, clarified water discharged to sea
other wastewater handling	Discharge to sea, combined with strainer backwash water, SWRO and BWRO brine and UF waste water	Discharge to sea, combined with strainer backwash water, SWRO and BWRO brine and clarified UF waste water
SWRO flux (L/m^{2}h)	13.4	13.4
SWRO recovery (%)	40	40
BWRO recovery (%)	90	90

11.10.1 Introduction

Evides Waterbedrijf, the South-Western Netherlands water supply company providing municipal drinking water, industrial water, as well as wastewater treatment services, owned and operated a UF-RO (Ultrafiltration – Reverse Osmosis) desalination plant on the Oosterschelde for demonstration and research purposes between 2009 and 2012. The overall aim of the project was to study desalination as one of the alternatives to the water resources already used by Evides (i.e., fresh surface water, ground water and infiltrated water), in the framework of the company's efforts to safeguard water supply in the long term with respect to climate change. The desalination research was conducted under locally relevant conditions regarding water quality (seasonally variable) and temperature (seasonally low). The characteristics of the plant are given in Table 11.10.1.

As the site featured an open intake, and raw water quality was variable, conditions were challenging for the downstream treatment processes. A major characteristic in this respect was the occurrence of seasonal algal blooms, which impacted the UF pretreatment in terms of fouling, necessitating the temporary application of in-line coagulation. To guide plant operation and design, a major objective was to gain an understanding of the following topics relative to the ultrafiltration pretreatment:

- Seasonal variation in raw water quality, especially of parameters associated with algal blooms, expected to be relevant for the strainer and UF treatment steps such as algal presence, associated algogenic organic components and nutrients;
- Impact of algal bloom-related raw water quality variations on UF permeability performance i.e., fouling, and its maintenance by means of hydraulic backwash, chemically enhanced backwash (CEB), and application of coagulant;
- Resultant UF permeate quality and SWRO membrane permeability.

During the plant's operation, ample data were collected; several scientific institutes conducted or participated in research at the site. A valuable dataset, experience, and lessons learned have therefore been acquired[1]. The dissemination of this material by means of the current Case Study aims to contribute to the ongoing improvement of operating standards in the desalination industry.

11.10.2 Feedwater intake

The demonstration plant feedwater was drawn from the Oosterschelde water body, close to the southern landfall of the identically-named storm surge barrier (Figure 11.10.2). This feed can be regarded as North Sea water in terms of salinity, temperature, and organic and inorganic constituents. Due to its geographical position, seasonal temperature variations were applicable.

The intake was located at a site featuring highly turbulent conditions caused by tidal currents, hence stratification was absent. During stormy weather, severe turbidity peaks occurred, due to mobilization of sediments from the tidal flats in the Oosterschelde water body. If turbidity exceeded 50-75 FTU for more than several hours, the limited capacity of the strainer forced a plant shut down, which occurred two to four times a year.

A specific characteristic of the feedwater was the recurrence of seasonal algal blooms in Spring (April-May) every year, as described in Section 11.10.5. For further feedwater data, see Table 11.10.1.

---

[1] For further literature specific for the current Case Study, the reader is also referred to Al-Hadidi et al. (2012); Villacorte (2014); Tabatabai (2014) and Schurer et al. (2012, 2013).

Figure 11.10.2. Intake location at arrow, Oosterschelde storm surge barrier (structure in center) Photo: Pinterest.

No intake chlorination was conducted, contrary to common practice. The main reasons were to preclude the formation of chlorination by-products (trihalomethanes) and to safeguard SWRO membranes from chlorine degradation. Although clogging by barnacles and shells did occur in the (multiple) intake structures during summer, this could be controlled satisfactorily by regular (2-weekly) pigging due to the relatively small-scale system.

11.10.3 Process line-up

The plant comprised process stages depicted by the block diagram in Figure 11.10.3 and further specified in Table 11.10.1. Figure 11.10.4 presents images of the main UF and RO equipment, respectively.

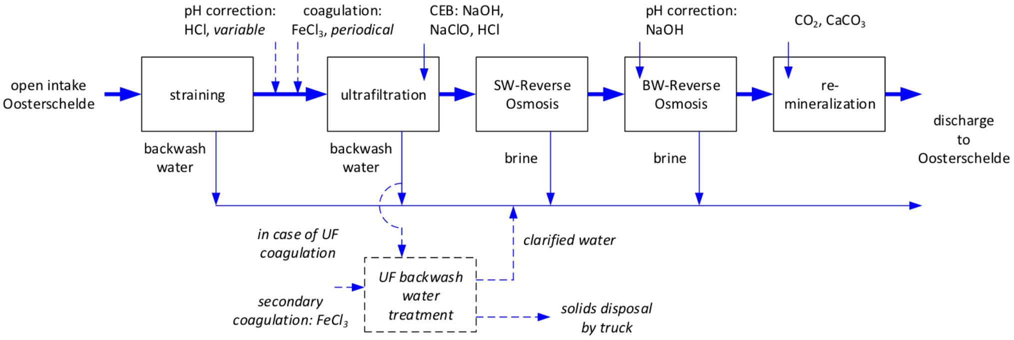


Figure 11.10.3. Treatment process block diagram for the SWRO Jacobahaven demonstration plant.

Figure 11.10.4. Demonstration plant ultrafiltration (left) and SWRO (the 5 pressure vessels on the left of the right hand image) and BWRO (the 3 pressure vessels on the right side of the skid).

11.10.4 Occurrence of algal blooms

During the four years of site operation, algal blooms recurred every spring, from mid-April onwards. Such events are common in this section of the North Sea (Janse et al. 1996). As the blooms always commenced at the same time of the year, it is speculated that favorable daylight length and seasonal temperatures were contributing factors in bloom development. Typically, blooms developed in a short period (2-4 weeks) in spring and subsequently declined after several months in summer. The severity of the blooms varied, ranging from peak levels of 12 million cells/L to a relatively subdued bloom in 2012 at 2 million cells/L (which could possibly be attributed to the cold and stormy weather conditions in that particular year).

Algal speciation varied from year to year. Diatoms were generally present during each bloom (*Chaetoceros, Thalassiosira*), whereas *Phaeocystis* or *Chrysochromulina* prevailed only in some years (2010 and 2010 and 2011, respectively) during the four years of monitoring (Evides data). Example images of these species are given in Appendix 1. The prevalence of *Phaeocystis* caused noticeable foam formation as shown in Figures 11.10.1 and 11.10.5.

Figure 11.10.5 Foam formation at the intake site during *Phaeocystis* bloom occurrence.

11.10.4.1 Associated raw water quality parameters

During algal blooms, levels of chlorophyll-a (Figure 11.10.6) and algal counts (Table 11.10.1) correspondingly spiked up to 20 µg/L and 10,000/mL, respectively. Interestingly, a measurable elevation of the pH (~0.5 pH above average) occurred during the algal bloom periods. In contrast, no deviation in dissolved oxygen was noted, possibly because of the highly turbulent conditions at the raw water intake site.

Also, in associated research work, the presence of $TEP_{0.4\mu m}$ was measured. $TEP_{0.4\mu m}$ levels fluctuated in rather close unison with chlorophyll-*a* levels, increasing 20 to 60-fold at the algal bloom peak (Villacorte 2014; Schurer et al. 2012), as shown in Section 11.10.6 – (Impact on UF). More data on TEP measurements are presented in Chapters 2 and 5 and the methods for TEP measurement are outlined in Appendix 4.

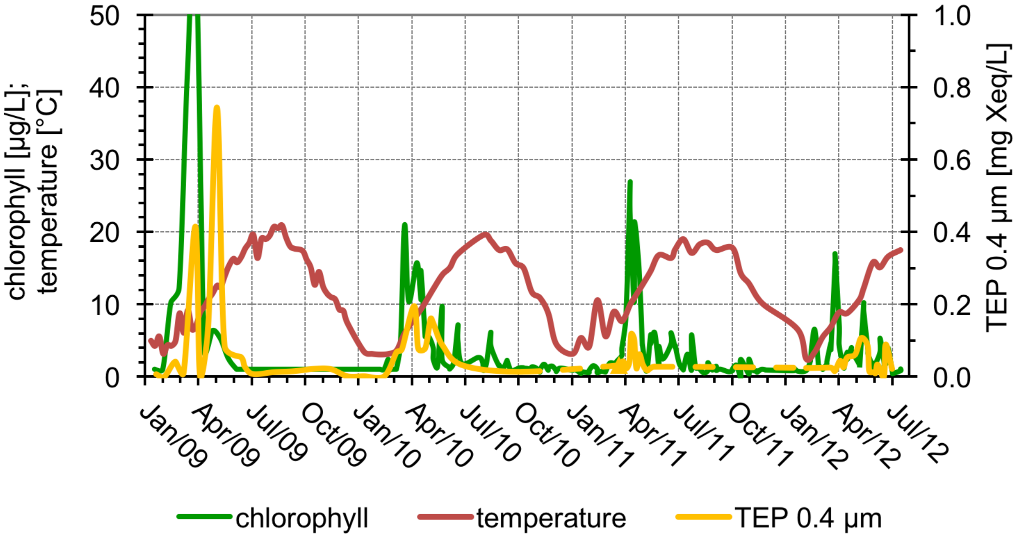


Figure 11.10.6. Seasonal patterns of raw water temperature and algal-boom related parameters (chlorophyll, $TEP_{0.4\mu m}$).

11.10.5 Impact of harmful algal blooms on microstraining

During algal blooms, a significant increase in the clogging rate of the 50-µm strainer was observed, manifested as a backwash interval reduction to 5 minutes from 0.5 – 1.5 hours for non-bloom conditions at identical turbidity. The overall plant production capacity remained unaffected as the required strained water output could still be met.

11.10.6 Impact on Ultrafiltration (UF)

11.10.6.1 General overview of seasonal fouling pattern

A set of UF transmembrane pressure (TMP) profiles as typically encountered over the seasons is depicted by Figure 11.10.7. Here, the TMP is normalized to 20 °C by inclusion of a correction factor according to the temperature-dependency of the viscosity of water.

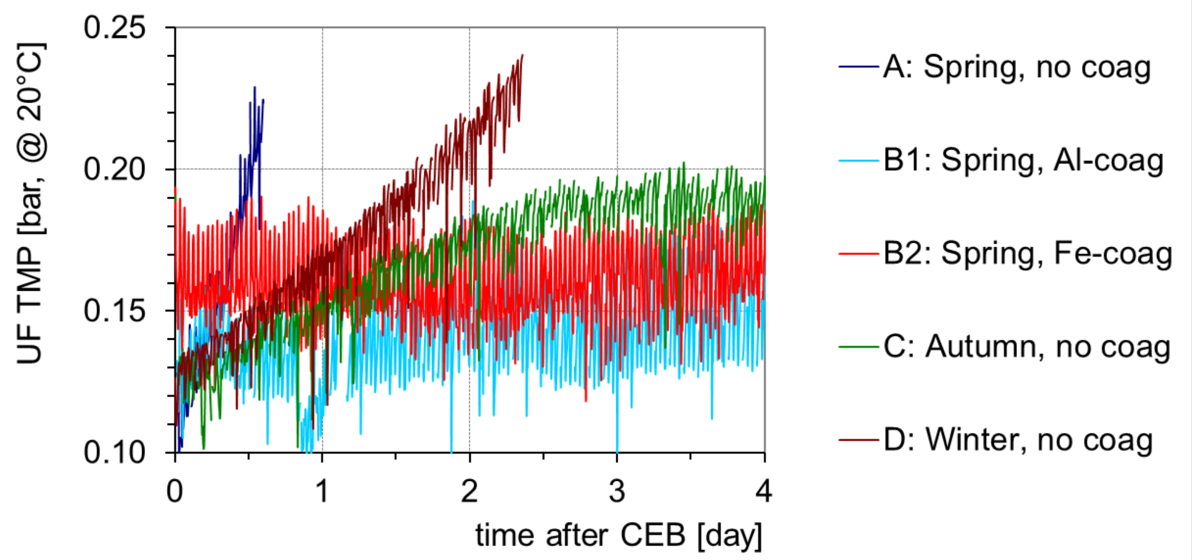


Figure 11.10.7. Typical seasonal UF fouling patterns. TMP is normalized to 20°C and at 55 L/m^{2}h.

Typically, a CEB (Chemically Enhanced Backwash) was initiated once the TMP had increased to 0.30 bar (temperature-corrected and at the default flux of 55 L/m^{2}h), instead of fixed time or volume intervals. As the applied membranes were of a high-permeability type, equivalent permeability ranged from 180 – 200 L/m^{2}hbar just before CEB, and 300 – 500 L/m^{2}h bar after CEB.

As is evident from Figure 11.10.7, a remarkable seasonal variation occurred in the UF fouling pattern, ranging from a comparatively slow increase and eventual stabilization of the TMP in Winter and Autumn (curves D, respectively C) to a steep increase in Spring (curve A).

The fouling behavior of the UF throughout the research period is depicted in Figure 11.10.8. In this graph, the UF fouling rate is expressed as the (temperature-corrected) TMP increment incurred between two successive CEB's, divided by the elapsed time. TMP just after CEB ranged generally between 0.12 - 0.15 bar. The fouling rates are shown for both UF operation with coagulation, which was typically around April-July, and without coagulation for the remainder of the year, as is further elaborated in the next paragraphs. A fouling rate of 0.25 – 0.3 bar/day was considered to be an upper practical limit in terms of CEB interval (< 12 h) and hence UF water loss for the operating conditions applicable in this case study.

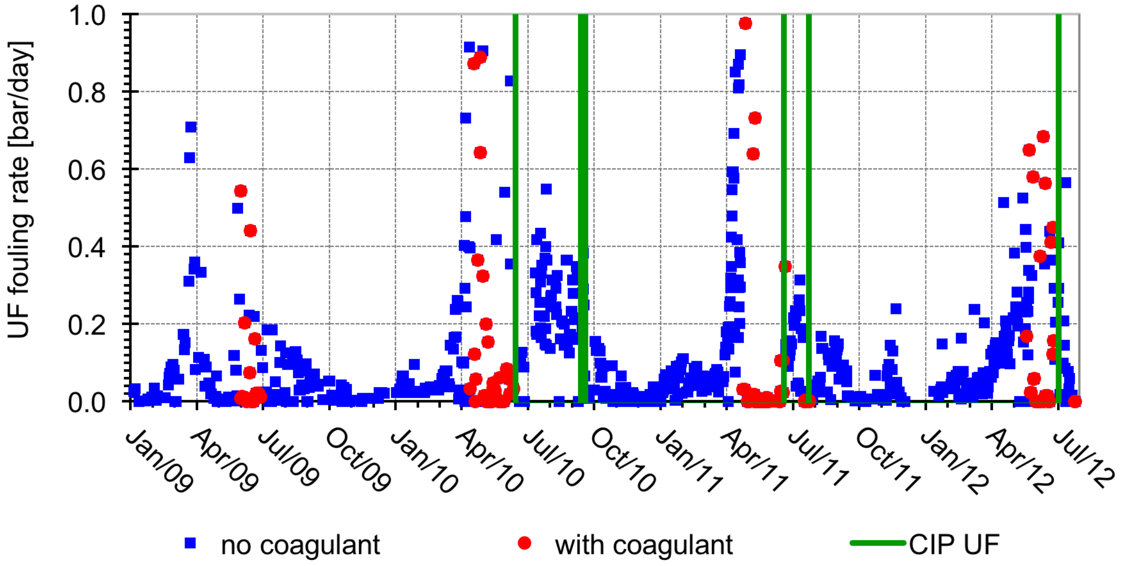


Figure 11.10.8. Seasonal pattern in UF fouling rate, for periods without respectively with coagulation deployed. Also, CIP's are indicated.

11.10.6.2 UF operation during algal bloom: fouling

As highlighted by a comparison of Figures 11.10.7 and 11.10.8, algal blooms had a significant impact on the fouling rate of the ultrafiltration system, as the occasions of high fouling rate coincided with the elevated levels of chlorophyll-*a*, $TEP_{0.4\mu m}$ and algal counts (the latter is not shown). Typically, the UF fouling rate accelerated in a 2 - 4 week period in April to such an extent that CEB intervals declined to less than 12 or even 6 hours. In this fouling regime, unaltered operation was no longer practical due to UF downtime and water loss which eventually led to a shortfall in the net permeate output, as no redundancy in UF production capacity was installed in the plant.

In the first instance, operators attempted to control the aforementioned bloom-related UF fouling by adaptation of the hydraulic backwash regime, that is, extension of backwash duration and shortening of backwash intervals from 45 to 25 minutes. Only a marginal reduction in UF fouling was achieved which was outweighed by the associated increase in backwash water losses (20%). Furthermore, intensified CEB (prolonged soaking, increased concentrations) proved unable to compensate for the rapid fouling, whereas a frequent CEB execution (e.g., more than 1-2 times daily) implied excessive UF production loss due to downtime and CEB water losses. Hence, extended regimes of hydraulic backwash or CEB were not capable of countering the increase in UF fouling. Similarly, lowering of the flux to 30 L/m^2h still did not yield a feasible CEB interval (and would have meant an uneconomically oversized UF system for the non-bloom periods).

11.10.6.3 UF operation during algal bloom: coagulation

As modifications of backwash, CEB and flux proved unable to adequately control UF fouling during algal blooms, coagulation was seasonally implemented. In the first year of operation (2009), aluminum (~0.5 mg/L Al) coagulant was applied at pH 6.6, but although effective to counter UF fouling, it proved detrimental to RO operation due to aluminum silicate scaling, and hence was abandoned in favor of ferric coagulant.

Ferric doses ranging from 0.5 to 1.5 mg Fe/L proved generally capable of controlling UF fouling during the algal bloom, as shown by curves B1 and B2 in Figure 11.10.7. During Fe coagulation, a pH of 7.6 was maintained. In some cases, the coagulant became less effective for UF fouling control, for which no clear reason was found. At such times, the dose was increased. Eventually, cleaning-in-place (CIP) was required to restore permeability, as further elaborated in Section 11.10.6.4.

Coagulation efficacy was improved by relocating the dosing point, which was originally sited in the UF feed tank, to the UF feed pump suction side, thereby creating a better defined hydrodynamic regime for the rapid mixing of the coagulant. This resulted in longer periods of stable UF operation. During coagulation, the UF was always operated at the default flux of 60 L/m^{2}h. Hence, it is not known whether a higher flux would have been feasible.

Although it was relatively clear when to commence the UF coagulation (that is, at UF fouling rate exceeding ~ 0.25 – 0.30 bar/day), it was less obvious when to actually terminate the coagulation. In general, cessation of Fe-dosing after the algal bloom had apparently passed (as indicated by chlorophyll-*a* levels) still resulted in a rapid permeability decline. Only after conducting a CIP (see Section 11.10.6.4), a situation with only moderate fouling without coagulation dosing was re-established.

11.10.6.4 UF operation during algal bloom: CEB and CIP

An important observation was that the regular CEB was no longer effective during periods of Fe-coagulation. UF permeability was only restored by conducting a CIP, where a mixture of ascorbic acid (1%) and oxalic acid (0.3 %) proved adequate. Other chemicals (for example, citric acid), or omission of either ascorbic or oxalic acid, were not effective in recuperation of permeability. Although not explicitly tested, the CIP appeared to be more effective at higher temperatures for example in mid-summer when compared to during May. Each algal bloom period necessitated 1 or 2 such CIPs. For one such CIP, the liquid was analyzed for metallic composition, as shown in Table 11.10.2. Unfortunately, quantification of organic foulant release by a CIP was not feasible due to the high carbon content of the CIP medium itself.

Table 11.10.2. Metallic compounds released by CIP, as g/m^2 membrane area.

Metal	Membrane area	Comments
Fe	0.3 g/m^2	Likely originating from the coagulant
Al	0.2 g/m^2	Possibly immobilized clay particles
Mn	not detectable	Potential UF foulant, originating as trace compound in Fe-coagulant

11.10.6.5 UF operation outside algal blooms

Outside of algal blooms, from July till April, the UF fouling rate was low, allowing CEB intervals ranging from 24 hours up to a week or even or even a fortnight. No coagulation was deployed, as there was no need since fouling rates were low. Increasing the filtration cycle duration from 45 min (default value) to 60 and even 90 min proved to be possible without incurrence of noticeable acceleration in fouling (see Figure 11.10.9), thereby reducing UF backwash water loss from 10 % to < 5 %. The backwash duration utilized (hence backwash volume) proved to be sufficient, as a more prolonged backwash did not establish further permeability recuperation. Furthermore, filtration fluxes could be increased up to 90 L/m^2 h without excessively raising the fouling rate (Figure 11.10.10), but this was only utilized for intermittent trials as there was no use for the surplus UF permeate.

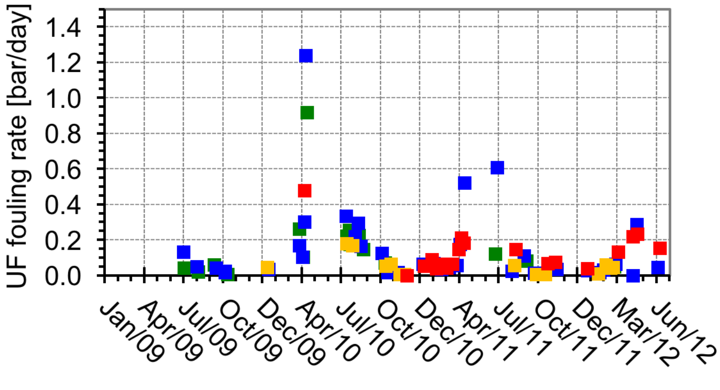


Figure 11.10.9. UF fouling rate outside algal bloom, and without coagulation, for various backwash intervals at the default 55 L/m^{2}h flux.

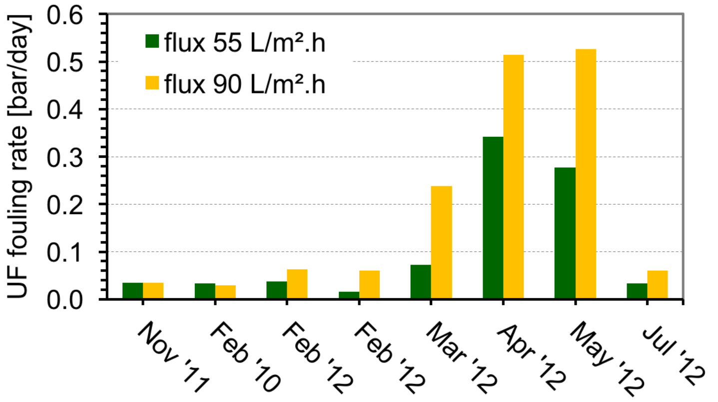


Figure 11.10.10. UF fouling rate outside algal bloom, and without coagulation, for 55 and 90 L/m^{2}h flux.

UF feedwater pH was initially kept at 6.6 outside application of coagulant, but this pH correction was discontinued after 2009 as no obvious need was apparent, the RO being in a non-scaling regime due to the relatively low recovery of 40%. In the subsequent period, pH was varied between 6.6, 7.4 and ambient (~8.1 – 8.4), but no significant effect on UF fouling was observed. Turbidity, even at elevated levels during storm events, did not affect UF permeability.

11.10.6.6 UF wastewater handling

Outside of algal bloom periods, the spent UF backwash water was discharged directly into the Oosterschelde as it did not contain additional chemicals. During periods of coagulation, the spent wastewater was conveyed to the plants integrated wastewater treatment, which consisted of secondary coagulation (ferric, 5–10 mg/L Fe dose) and a combined flocculator / lamellae clarifier. The produced sludge was thickened and stored in a tank, and eventually disposed of by truck, due to the relatively small sludge quantities involved. The clarified wastewater was generally discharged back into the Oosterschelde, as the risk of additional UF fouling by inadvertent reintroduction of algal biopolymers and/or excess unsettled coagulated material was considered not to outweigh the water intake savings, the latter being quite limited in absolute sense. In a few short-term trials runs where clarified water was purposely recirculated to the UF feed, no immediate effect on UF fouling was noticed.

11.10.6.7 Alternative UF backwashing by SWRO concentrate

As the SWRO concentrate did not have scaling properties due to the relatively low applied recovery (40%), it was theoretically possible to use this for UF backwash water. Several trial runs were achieved, where indeed no increase in the UF fouling rate was encountered compared to the regular backwash with UF permeate. Hence, UF backwash with RO concentrate appeared feasible. This was not tested extensively during the more critical period of algal bloom, where accumulation of algogenic organic compounds in the SWRO concentrate is a potential issue.

11.10.6.8 UF permeate quality and membrane integrity

Selected UF permeate quality data are presented by Table 11.10.3. Appropriate RO feedwater quality standards were met. Furthermore, UF integrity testing revealed that UF fiber breakage amounted to < 0.06 % over a period of 3.5 years of nearly continuous operation under periodically challenging conditions, attesting to the resilience of UF pretreatment in the retention of particulate and biomass matter in conjunction with the upstream-positioned microstrainer.

Table 11.10.3. UF permeate quality data and reductions.

Parameter	**Result**
Turbidity	< 0.05 FTU
Particle count	reduction > 3.6 log for particles ≥ 0.5 µm
SDI_{15}	< 2 (Al-Hadidi et al. 2012)
Fe during coagulation	< 0.05 µg/L (detection limit)
Biopolymer (LC-OCD)	~50 % reduction (Salinas Rodríguez 2011; Villacorte 2014)
$TEP_{0.4\mu m}$	< 0.01 mg X_{eq}/L (detection limit), equivalent reduction > 90% (Appendix 4; Villacorte 2014).

11.10.6.9 Further data on UF foulant levels

During an algal bloom period in May 2013, various parameters relevant to HABs were monitored at the same Oosterschelde site. Since operation of the demo-site UF unit was discontinued in July 2012, samples for the UF feed and UF permeate were collected from a smaller pilot UF unit (1” module) with similar membrane properties and operational settings as in the previous demo-site unit. On this occasion, the raw water recorded algal density was 6.25 x 10^6 cells/L and the chlorophyll-*a* concentration was 10.6 µg/L. Table 11.10.4 shows the comparison of the different parameters and their reduction over the pretreatment processes.

Table 11.10.4. Measured parameters for raw water, strained water and UF permeate during the 2013 algal bloom. Data from Villacorte et al. 2014.

Sampling point	**MFI-UF_{10kDa} s/L^2**	**$TEP_{0.4\ \mu m}$ (mg X_{eq}/L)**	**$TEP_{10\ kDa}$ (mg X_{eq}/L)**	**DOC mg C/L**	**Bio-polymers mg C/L**	**SUVA L/(mg.m)**
Raw water	16000	0.079	1.49	1.61	0.34	2.38
After strainer	9200	0.075	0.78	1.55	0.32	2.52
UF permeate*	1200	0.001	0.44	1.25	0.10	3.02

* The sample for UF permeate was collected from a 1” module size pilot system operated with the same feedwater, membrane type and hydraulic settings as the previous demonstration plant.

The strainer showed significant reduction of MFI-UF_{10kDa} and TEP_{10kDa} but no significant reduction of other parameters was observed. The UF demonstrated remarkable reduction in MFI-UF_{10kDa}, TEP_{10kDa}, $TEP_{0.4\mu m}$ and biopolymers. DOC was only slightly reduced mainly because the low molecular weight (<1 kDa) organic substances such as humic substances, building blocks, organic acids and organic neutrals, comprising about 80% of the DOC, are poorly removed by UF by nature of the UF MWCO (150 kDa). The increase in SUVA (UV_{254nm}/DOC) was due to the reductions in DOC and relatively unchanged UV absorbance over the pretreatment processes. UV absorbance was attributed to the aromatic compounds such as humics, which were poorly removed in the pretreatment processes.

11.10.7 Operational characteristics of downstream Reverse Osmosis (RO)

During the experimental period, SWRO fouling was assessed by relative MTC (Mass Transfer Coefficient) as a measure of permeability and NPD (Normalized Pressure Drop) to indicate spacer fouling. Figure 11.10.11 presents their respective behavior throughout the research period.

At the first spring season of SWRO operation, an initial sudden permeability decline was associated with the original application of aluminum coagulant (Gallego et al. 2007; Gabelich et al. 2005), which was thereafter abandoned. In the subsequent three years of SWRO operation, RO permeability declined by approximately 20%. No clear relation (e.g. a sudden concomitant permeability decline) with algal blooms was observed, although autopsies indicated the presence of some biopolymeric organic deposition. CIP's by caustic and acid restored permeability only marginally. Iron deposits present (see Figure 11.10.12) could be removed by CIP. Mineral scaling (e.g. calcium carbonate) was absent, as attested by autopsies and as expected with the practiced regime of (low) recovery and pH control.

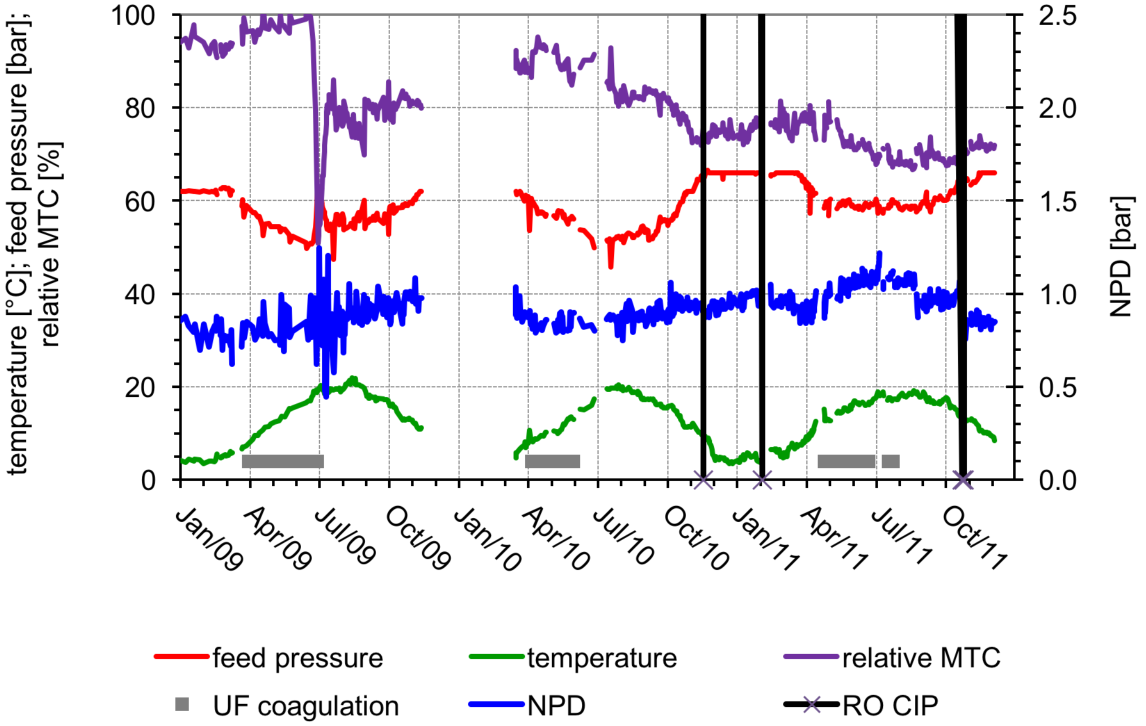


Figure 11.10.11. SWRO performance throughout the research period as feed pressure and relative MTC (initial = 100%), NPD. Periods where coagulation was deployed are indicated. Between December 2009 and March 2010, the RO was out of operation for mechanical reasons.

Normalized spacer head loss was continuously low throughout the trial period, indicative of the absence of biofouling and particulate fouling and thereby confirming the beneficial potential of UF as RO pretreatment in this respect. This was corroborated with the results of membrane autopsies (see Figure 11.10.12) whereby the maximum ATP (Adenosine Tri-Phosphate) concentration (< 50 pg/cm^2) measured at the lead element was substantially lower than the biofouling threshold (> 1000 pg ATP/cm^2) reported by Vrouwenvelder et al. (2008).

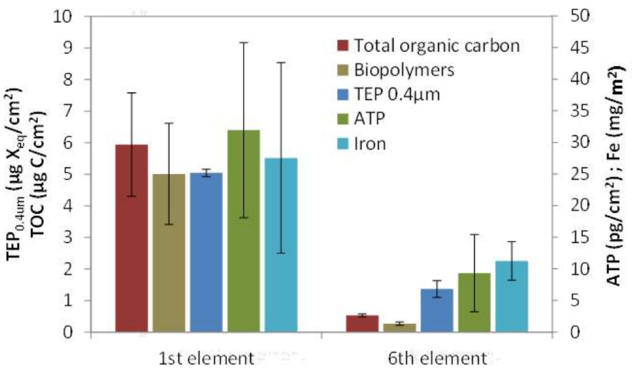


Figure 11.10.12. Concentrations of iron, ATP and some organic constituents per surface area of autopsied RO membranes. The autopsies were conducted in December 2009 for the lead and last RO elements of the SWRO train (adapted from Villacorte et al. 2014).

Biopolymers and TEPs were also observed mainly in the lead element. Salt passage remained continuously < 0.5 % (measured as conductivity), being in line with the SWRO specifications (not shown further).

11.10.8 Conclusions

Seasonal algal blooms encountered at the North Sea test site posed challenging conditions to the UF pretreatment i.e., severe UF fouling. This could be controlled by in-line coagulation. Nevertheless, algal bloom events essentially governed the overall UF design in terms of size and auxiliary equipment, as the algal-related UF fouling capped the UF flux and necessitated the inclusion of additional coagulation and wastewater treatment facilities.

Multiple issues were identified that merit further research based on the experience gained from the UF-RO demo-plant study in Jacobahaven. These pertain to the use of UF for SWRO pretreatment for feedwater prone to algal blooms.

- During the plant design phase, scenario studies should be included regarding algal-related UF fouling, taking into account the estimated UF fluxes attainable and equipment cost and space required for coagulant storage and dosing, wastewater treatment and sludge handling facilities. Since feedwater properties may fluctuate seasonally and can significantly impact UF layout and operation, as highlighted above, local advance piloting is recommended to establish an optimal plant lay-out.
- For a relatively large UF plant that experiences challenging feedwater properties, (semi-) continuous parallel operation of a small-scale UF unit for optimization purposes may be a worthwhile consideration. This especially pertains to optimizing coagulation: duration of coagulation required, dose and applied filtration fluxes in relation to algae-related fouling without coagulation.
- Understanding of local and seasonal presence of algal-bloom related compounds (biopolymers, polysaccharides, TEP) is important for UF operation, as these impact UF fouling.
- For plants where recirculation of treated UF backwash wastewater into the seawater intake is considered, verification of presence or rather absence of residual algogenic foulants in the returned (clarified) UF wastewater water is a worthwhile provision, in order to assess risk for accelerated UF fouling by these recirculated compounds.
- Further optimization in establishing a more effective CEB during coagulation is worthwhile to further enhance process robustness and possibly limit the need for the more cumbersome CIP’s. The cause for the observed decline in CEB efficacy was not studied in detail in the current study, though a relation with iron compounds seems plausible. Conservation of UF permeability may be attempted by e.g. dose of citric acid during backwash rather than as CEB or CIP, and a further improvement of the exact configuration (hydrodynamic regime, contact time) of the coagulant introduction into the main water flow.

- Although it was not directly studied, UF CIP efficacy appeared to be enhanced by elevated ambient temperature, suggesting that a temperature-controlled CIP system could be worthwhile to shorten system downtime.
- Further study of the exact cause of the decline in SWRO MTC is recommended, by conducting more extensive membrane autopsies specifically aimed at determining the presence and identification of organic compounds.

11.10.10 References

Al-Hadidi, A. M. M., Kemperman, A. J. B., Schurer, R., Schippers, J. C., Wessling, M., and van der Meer, W. G. J. 2012. Using SDI, SDI+ and MFI to evaluate fouling in a UF/RO desalination plant. *Desalination* 285, 153-162.

Gabelich, C. J., Chen, W. R., Yun, T. I., and Coffey, B. M. 2005. The role of dissolved aluminum in silica chemistry for membrane processes. *Desalination* 180(1-3), 307-319.

Gallego, M. S. and Darton, M. E. G. 2007. Simple laboratory techniques improve the operation of RO pretreatment systems. In: *Proceedings of the International Desalination Association World Congress, Maspalomas, Gran Canaria*, Spain.

Janse, I., Van Rijssel, M., Gottschal, J. C., Lancelot, C., and Gieskes, W. W. 1996. Carbohydrates in the North Sea during spring blooms of *Phaeocystis*: a specific fingerprint. *Aquatic Microbial Ecology* 10(1), 97-103.

Salinas Rodriguez, S. G. 2011. Particulate and Organic matter fouling of seawater reverse osmosis systems. Thesis Dissertation, UNESCO-IHE / TU Delft PhD Thesis, CRC Press.

Schurer, R., Janssen, A., Villacorte, L., and Kennedy, M. 2012. Performance of ultrafiltration and coagulation in an UF-RO seawater desalination demonstration plant. *Desalination and Water Treatment* 42(1-3), 57-64.

Schurer, R., Tabatabai, A., Villacorte, L., Schippers, J. C., and Kennedy, M. D. 2013. Three years operational experience with ultrafiltration as SWRO pre-treatment during algal bloom. *Desalination and Water Treatment* 51(4-6), 1034-1042.

Tabatabai, S. A. A. 2014. *Coagulation and Ultrafiltration in Seawater Reverse Osmosis Pretreatment.* Dissertation, Unesco-IHE / TU Delft.

Villacorte, L. O. 2014. Algal Blooms and Membrane Based Desalination Technology. Thesis Dissertation, Unesco-IHE / TU Delft.

Vrouwenvelder, J. S., Manolarakis, S. A., Van der Hoek, J. P., Van Paassen, J. A. M., Van der Meer, W. G. J., Van Agtmaal, J. M. C., Prummel, H. D. M., Kruithof, J. C., and Van Loosdrecht, M. C. M. 2008. Quantitative biofouling diagnosis in full scale nanofiltration and reverse osmosis installations. *Water Research* 42(19), 4856-4868.

11.11 BARCELONA, SPAIN – SWRO DEMONSTRATION PLANT: DAF/DMF VERSUS DAF/UF

Joan Llorens[1], Andrea R. Guastalli[1] and Sylvie Baig[2]

[1] University of Barcelona, Barcelona, Spain
[2] Degrémont SA, Rueil-Malmaison Cedex, France

Figure 11.11.1. Location of the Barcelona seawater desalination pilot plant, the open intake and the Llobregat River discharge. Photos: Google Earth and Wikimedia Commons).

Table 11.11.1. Overview of Barcelona SWRO demonstration plant.

Plant/Project Name	**Barcelona Pilot Plant**
Location	Southern shore of Barcelona, Spain
Primary product water use	Municipal drinking water
Desalination technology	SWRO
Total Production Capacity (m^3/d)	200 of desalinated water (with a pretreatment capacity of 750)
Recovery (%)	45
Operational period	May 2007 to April 2010
Intake	
Feedwater source	Mediterranean Sea
Intake type	Open intake
Intake description	1.2 km offshore at a depth of 12 m
Online raw water monitoring	Conductivity, turbidity, pH, temperature
Discrete raw water analysis relevant to HAB	TOC, Algal count, SDI
Pretreatment	
Process description	Flotation (DAF) + Filtration (DMF) or DAF + 400 µm pre-screens + Ultrafiltration (UF)
Chemical dosing (as $FeCl_3$)	DAF pilot is a rapid flotation using ferric chloride as a coagulant (0-6 mg/L)
Feedwater design parameters	**Mean ± SD (maximum value due to degradation or "green" algal blooms)**
Temperature (^oC)	19 ± 4 (27.8)
pH	8.2 ± 0.1 (8.4)
Conductivity (mS/cm)	56 ± 1 (60)
TDS (g/L)	36 ± 2 (-)
Turbidity (NTU)	1.7 ± 0.8 (63)
TSS (mg/L)	6 ± 3 (117)
SDI $_{75\%}$ (%/min)	20 ± 10 (> 50)
TBC (cells/mL)	$7 \times 10^5 \pm 3 \times 10^5$ (1×10^6)
Algae count (cells/L)	332,000 ± 302,000 (1,254,000)
Absorbance 254nm (1/m)	0.7 ± 0.2 (1.6)
DOC (mg C/L)	0.9 ± 0.1 (1.1)

11.11.1 Introduction

A SWRO desalination pilot plant was operated to provide important information for the development of a large-scale desalination plant in the coastal area of Barcelona. An assessment of raw water quality considered all parameters that could have a capital or operational impact on pretreatment and/or the SWRO membrane process such as turbidity, suspended solids, algal blooms, and organic carbon.

Two pretreatment strategies, dual-media filtration (DMF) and ultrafiltration (UF), running in parallel to reduce the particulate material and natural organic matter (NOM) from

Mediterranean seawater were studied and compared.[1] Figure 11.11.1 above shows an aerial view of the Demonstration Pilot Plant location at Barcelona.

11.11.1.1 Feedwater

Barcelona's desalination pilot plant had an open intake, located 1.2 km offshore at a depth of 12 m in the Barcelona area of El Prat de Llobregat, Spain. The raw water quality was monitored on line and extensively analyzed for 21 months from June 2007 to March 2009.

Annual analysis of the raw water demonstrated that the open-intake water was generally of an excellent quality, with turbidity lower than 4 NTU for 90% of the year. Occasional divergences in quality were mostly related to severe weather events in which the open intake was simultaneously affected by the adjacent Llobregat River discharge and wave turbulence at sea which caused the high TSS (refer Table 11.11.1).

The algal count in seawater averaged 130,000 cells/L for 65 % of the year and increased almost tenfold, reaching peaks of more than 1,200,000 cells/L during spring and summer blooms.

11.11.1.2 Process Line-up

The first level of pre-treatment was a dissolved air flotation unit (DAF). The DAF (25 m/h average) had three main zones: coagulation, flocculation (11 minutes average) and flotation with ferric chloride used as coagulant. The water then flowed along two different treatment pathways, as shown in Figure 11.11.2. In the first pathway, additional coagulant could be added to the seawater prior to a dual-media filter (DMF) unit with a 0.55 m layer of anthracite (0.95mm size) and 0.45 m layer of sand (0.28 mm size), which operated in down-flow mode at 14 m/h. DMF was designed to reduce turbidity and the presence of colloids in the water by physical straining. In the second parallel pathway, seawater was passed through 400 µm pre-screens and then a pressurized outside-in UF hollow fibre membrane (PVDF; 0.02 µm nominal pore size). The UF permeate was then passed through 5 µm security cartridge filters and fed through a RO module (thin film composite membrane operating at 14 L/m^{2}h and 45% recovery).

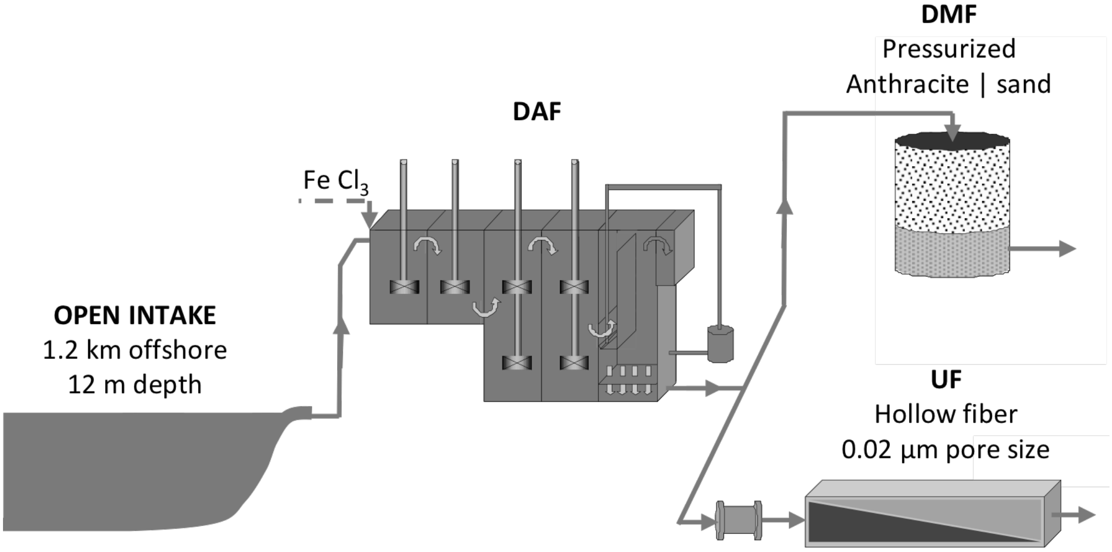


Figure 11.11.2. Schematic representation of the Barcelona pilot plant pretreatment scheme.

---

[1] Further literature regarding the current case study can be obtained from Guastalli et al. (2013); Simon et al. (2013); Sanz et al. (2007).

11.11.2 Occurrence of algal blooms

The initiation of blooms in the pilot plant feedwater and subsequent death of algal cells were found to correlate with the increase and decrease of temperature and sunlight in the seawater, starting in March and ending in July (peaking in late June). This period is referred to as the "green season". During the "green season", the high phytoplankton productivity maintains algal concentrations around 600,000 cells/L with occasional short blooms being observed, leading to concentration peaks greater than 1,200,000 cells/L (see Table 11.11.2). Between August and February, algal cells have a low activity and the average concentration remained around 130,000 cells/L.

Table 11.11.2. Algal count (cells/L) measured in the raw seawater seasonally for the Barcelona SWRO pilot plant from June 2007 to March 2009.

	Minimum	**Maximum**	**Average**	**Standard dev.**
Bloom (March-July)	215,000	1,254,000	**575,000**	290,000
No bloom (August-February)	13,000	282,000	**126,000**	53,000

11.11.3 HAB-associated water quality parameters

11.11.3.1 Temperature

Temperature variations can affect salt passage in RO membranes and hence, product water quality. It is therefore an important design parameter for desalination facilities. There is also a close relationship between temperature and microorganism reproduction rates and seawater temperature has also been related to the occurrence of algal blooms at the pilot plant. Raw seawater temperature ranged from 11.7 to 27.8 ^{o}C with an average of 19.2 ^{o}C. As can be seen in Figure 11.11.3, the maximum temperature occurs in July-August (summer) whereas the minimum occurs in January-February (winter).

11.11.3.2 Algal count

The algal counts found, regardless of the period, are low compared to the concentrations detected in other seas. Nonetheless, the pretreatment should consider effects due to the possible maximum load of algae. Measurement of algal count over the extended period of 21 months allowed the detection of a sudden algal bloom followed by a five month "green season" when the algal count was high and stable between March and July.

Algal counts above 200,000 cells/L (defined as an algal bloom for the purposes of this study) corresponded to 30% of the time. As can be seen in Figure 11.11.3, an algal bloom started in mid-February when minimum temperatures were reached and continued during increasing seawater temperatures. Algal blooms remained until the temperature reached average summer values in July (approximately 22 ^{o}C). The rest of the year, corresponding to 70% of the samples taken, the value observed was less than 200,000 cells/L.

11.11.3.3 Turbidity and SDI

Storm and rain events, prevalent in winter, had the greatest impact in deteriorating water quality and gave rise to elevated $SDI_{75\%}$. Generally, apart from these events, water quality was good, with raw seawater turbidity showing little variability with values below 4 NTU for over the 90% of the samples including algal bloom events. SDI was measured as $SDI_{75\%}$ following the method in Mosset et al. (2008).

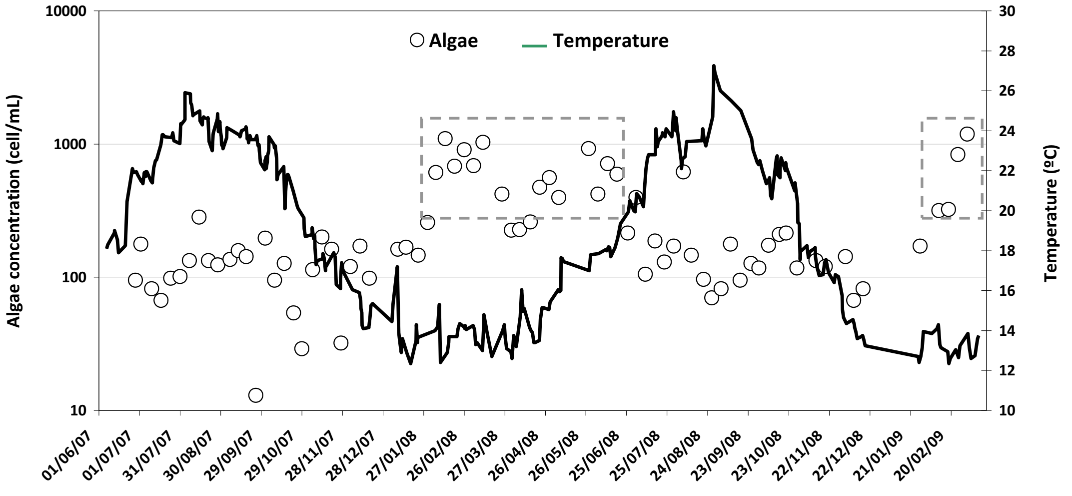


Figure 11.11.3. Algal count (points) and measured temperature (line) in pilot plant raw seawater. Dashed squares show algal bloom events.

Almost 60% of the $SDI_{75\%}$ measured in summer samples were below 21%/min. The occurrence of high $SDI_{75\%}$ values in summer that raised the $SDI_{75\%}$ over 20%/min occurred simultaneously with the completion of the algal bloom and occasional turbidity spikes (see Figure 11.11.4). Hence, degradation of algae in water could be responsible for the high $SDI_{75\%}$ values observed in summer.

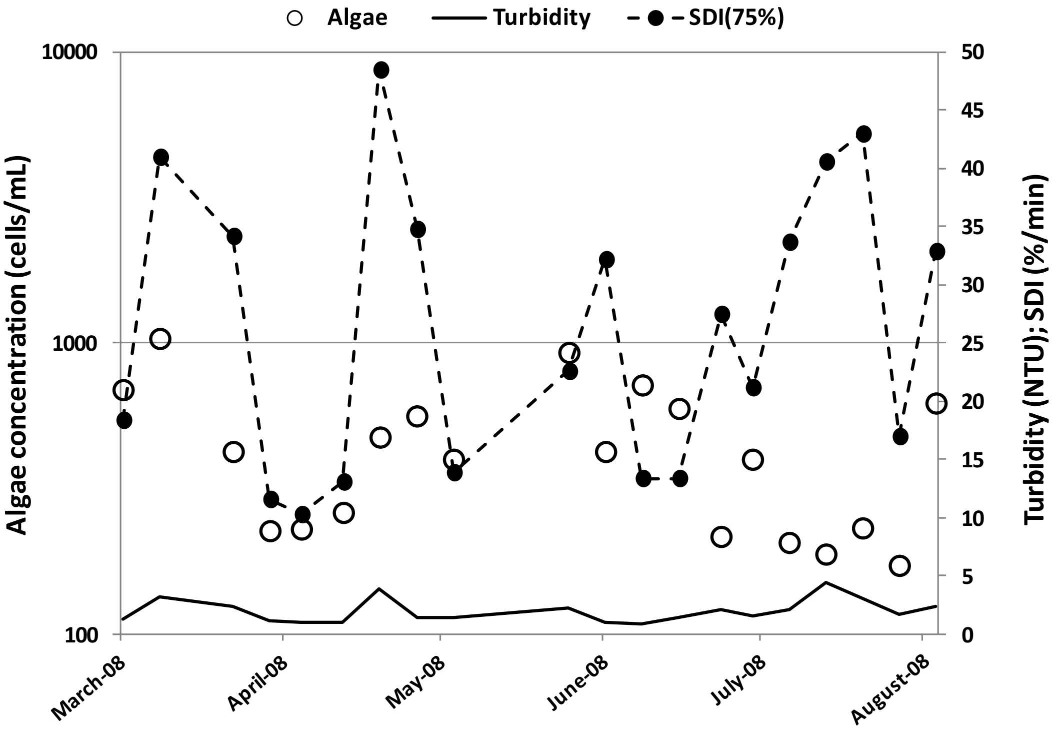


Figure 11.11.4. Algal count (points), turbidity (line) and $SDI_{75\%}$ (dashed line) in raw seawater during a HAB between March and April 2008 at the Barcelona pilot plant intake.

11.11.4 Impact on Pretreatment Processes

Results from pilot operation demonstrate the specific performance of each pretreatment process technology (see Table 11.11.3 for comparison). For more information on the operation of each pilot, see Guastalli et al. (2013).

Table 11.11.3. Quality of seawater treated by DAF followed by either DMF or UF. Removals are based on the raw seawater (RSW) quality.

		DAF			**DMF**			**UF**		
	Units	**Average**	**SD**	**% Removal**	**Average**	**SD**	**% Removal**	**Average**	**SD**	**% Removal**
Temperature	°C	**18**	4	-	**18**	4	-	**18**	3	-
pH	-	**8.0**	0.1	-	**8.2**	0.1	-	**8.2**	0.1	-
Conductivity	mS /cm	**56**	1	-	**57.6**	0.4	-	**57.5**	0.3	-
Turbidity	NTU	**1.5**	0.9	38%	**0.1**	0.02	96%	**0.06**	0.02	98%
TSS	mg/L	**3**	2	58%	**N.D.**[a]	-	-	**N.D.**[a]	-	-
SDI[b]	% /min	**12**	4	42%	**2**	1	90%	**1**	1	95%
TBC	Cells/ mL	**6 x10^5**	3 x10^5	16%	**3 x10^5**	2 x10^5	57%	**7 x10^2**	4 x10^2	99.9%
Algal Count	cells /mL	**81**	89	75%	**87**	72	74%	**3**	1	99%

[a] N.D. Not Detected

[b] The SDI method used was SDI$_{75\%}$ for FW, and SDI$_{15min}$ for DMF and UF waters. TBC = total bacterial counts, SD = standard deviation.

11.11.4.1 DAF

Optimization of the coagulant dose (0 to 6 mg/L as $FeCl_3$) was specific to the feedwater quality. The use of acid and coagulant aid was not found to be crucial for the optimal operation of DAF. During algal blooms, DAF fulfilled its purpose by successfully removing up to 87% (and 75% on average) of the algal content confirming the benefits of using this technology when algal blooms events are present.

11.11.4.2 UF

Excellent water quality was obtained by ultrafiltration with no coagulant addition, with high removal of algae and bacteria. Algal removal by UF increased to 99% on both DAF treated water and raw water, SDI$_{15}$ was low (1%/min) and turbidity averaged 0.06 NTU (see Table 11.11.3). Pressurized UF maintained high and stable permeability in direct seawater filtration at high fluxes (approximately 100 L/m^{2}h at 20 ºC). Filtration cycles were up to 35 minutes. Successful UF performance was due to the high efficiency of the chemical cleaning protocols that involved tangential circulation and alternating hypochlorite and citric acid cleaning in place. Backwash conditions were both air/water and only water.

11.11.4.3 DMF

The dual media filter (sand and anthracite) incorporated all additional equipment for air and water filter backwash, in the same conditions as full scale. Similar filtered water quality as UF was observed over a wide range of filtration feed velocities (11-19 m/h), post-coagulant doses (1-3 ppm as $FeCl_3$) and seawater conditions (normal turbidity, high turbidity, and adverse climatic events), such that the average SDI$_{15}$ values were typically between 2.0 and

2.8 %/min, turbidity was generally less than 0.13 NTU, algal rejection was 74% on average, and no residual iron was detected.

11.11.5 Removal of natural organic matter by LC-OCD

An important aspect of the pilot plant project was characterization of Natural Organic Matter (NOM) and understanding of the performance of different pretreatment options on NOM removal prior to the SWRO membranes. Liquid chromatography with organic carbon detection (LC-OCD) was used for the fractionation of the organic carbon into biopolymers (> 10 kDa), humic substances (humics and building blocks, 0.3-10 kDa) and low molecular weight compounds (LMW acids and neutrals, < 0.3 kDa).

The program was implemented over a period of 8 months mainly in winter (from July 2009 to March 2010) and organic carbon was monitored across the SWRO treatment line periodically. LC-OCD chromatograms are shown in Figure 11.11.5. Raw seawater was mainly composed of 47% of low molecular weight organics (LMW), 47% of humic substances and 6% of biopolymers.

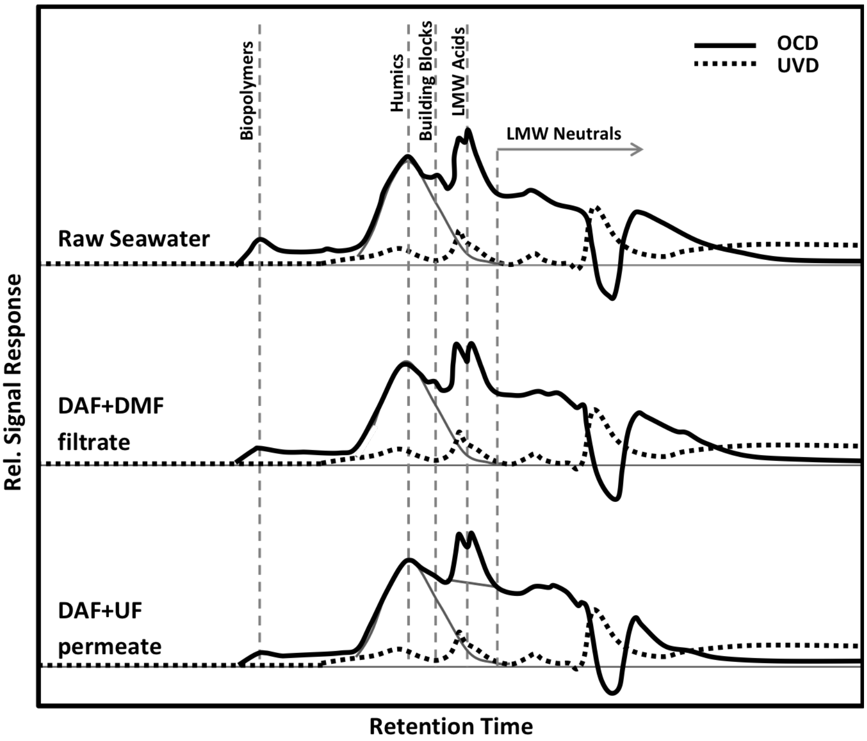


Figure 11.11.5. LC-OCD chromatograms of raw and seawater treated by DAF followed by DMF or UF at the Barcelona pilot plant.

The main fraction rejected after DAF + UF was biopolymers (41% removal). Removal of this fraction is relevant since biopolymers contain transparent exopolymer particles (TEP). TEP are highly sticky and accumulate on membranes that potentially induce fouling in membranes by providing favorable conditions for biofilm formation. Humic substances and LMW were only removed in UF permeate to a small extent, with an 8% and 6% rejection, respectively.

The combined effect of DAF + DMF eliminates 18% of biopolymers; the other fractions were practically not removed.

11.11.6 Conclusion

Algal counts increased in March and declined in July. Maximum algal cell counts of approximately 1,200,000 cells/L were observed.

Compared to conventional DMF, the UF showed excellent performance with good quality and stable permeate. During dense algal blooms, UF yielded almost 100% removal of algal cells. This value and other results highlight an important advantage of the UF with respect to the DMF.

Acknowledgment: The authors are grateful to CDTI (Spain) through the project CENIT-Sostaqua (CEN20071039).

11.11.7 References

Guastalli, A. R., Simon, F. X., Penru, Y., de Kerchove, A., Llorens, J., and Baig, S. 2013. Comparison of DMF and UF pretreatments for particulate material and dissolved organic matter removal in SWRO desalination, *Desalination* 322, 144-150.

Mosset, A., Bonnelye, V., Petry, M., and Sanz, M. A. 2008. The sensitivity of SDI analysis: from RO feedwater to raw water. *Desalination* 222, 17-23.

Sanz, M. A., Cremer, G., Beltran, F., Bonnelye, V., and Del Campo, I. 2007. Barcelona: 200,000 m^3/day of Potable Water coming from Mediterranean Sea. In: *Proceedings of the International Desalination Association World Congress*, Maspalomas, Gran Canaria, Spain.

Simon, F. X., Penru, Y., Guastalli, A. R., Esplugas, S., Llorens, J., and Baig, S. 2013. NOM characterization by LC-OCD in a SWRO desalination line. *Desalination and Water Treatment* 51, 1776-1780.

11.12 GOLD COAST, QUEENSLAND, AUSTRALIA - DEEP WATER INTAKE LIMITS *TRICHODESMIUM* INGRESS

Dianne L. Turner[1], Siobhan F. E. Boerlage[2] and Scott Murphy[1]

[1]Veoila Australia and New Zealand, Gold Cost, Australia
[2]Boerlage Consulting, Gold Coast, Australia

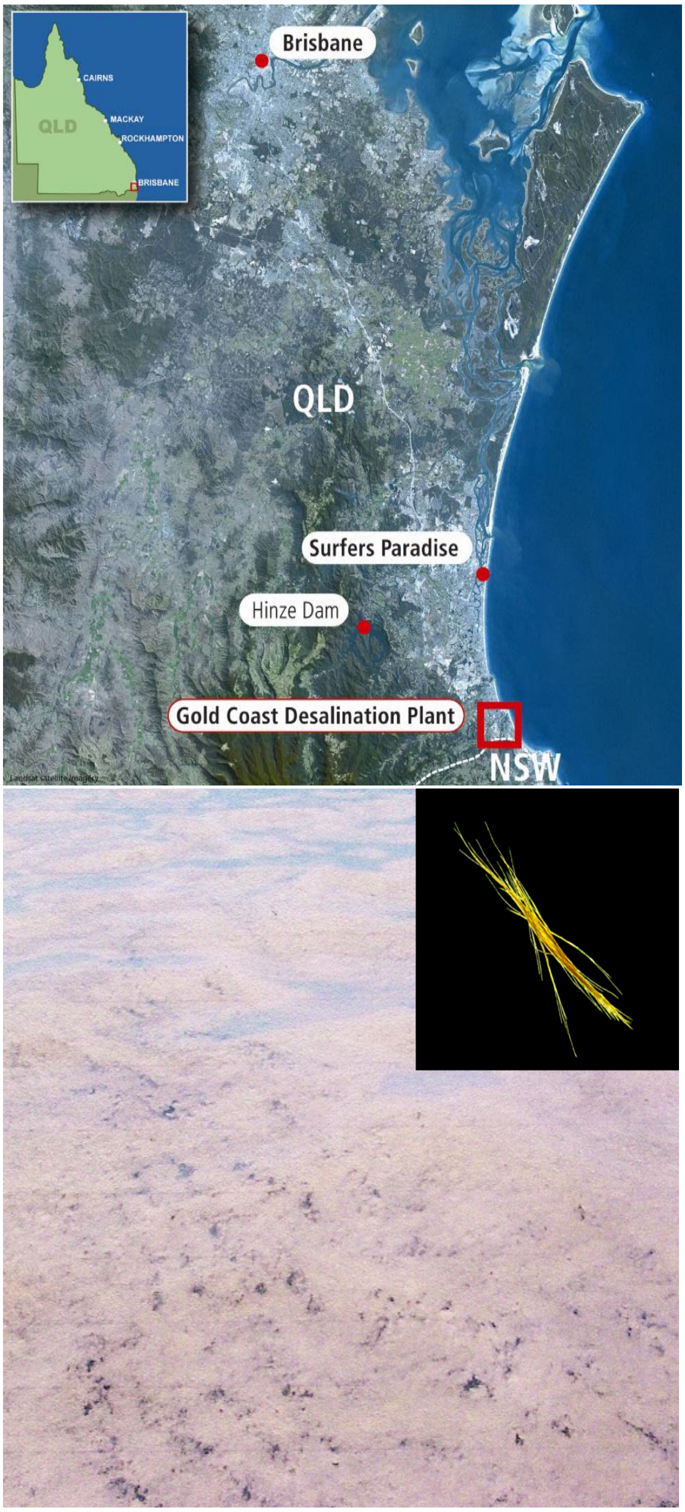


Figure 11.12.1. Location of Gold Coast Desalination Plant in Queensland (top). *Trichodesmium erythraeum* bloom off shore at intake (bottom). Insert - colony of *Trichodesmium erythraeum* cells – photo: WHOI.

Table 11.12.1. Overview of the Gold Coast SWRO desalination plant.

Plant/Project Name	**Gold Coast Desalination Plant (GCDP)**
Location	Tugun, South East Queensland, Australia
Primary product water use	Municipal
Desalination Technology	SWRO first pass (SWC5) and BWRO second pass ESPA2+
Total Production Capacity (m^3/d)	133,000
RO recovery	SWRO 45%, BWRO membrane 85%
Commissioning date	February 2009
Intake	
Feedwater source	South Pacific ocean – Coral Sea
Intake type	Deep water intake
Intake description	Tunneled intake 1.5 km offshore at 20 m depth. Coarse screen (2 m high) on intake riser with 140 mm maximum aperture bars.
Intake screening	3 mm variable speed drum screens.
(shock) chlorination Strategy, dose rate	Sodium hypochlorite is dosed at 3-5 mg/L for 2 hours daily
Online raw water monitoring	Conductivity, temperature, pH, turbidity, hydrocarbon analyzer, total chlorine, oxygen reduction potential(ORP)
Discrete raw water analysis relevant to HAB	TOC, Total N, Total P, Ammonia, TSS, SDI_3
Pretreatment	
Process description (Including UF prescreens, cartridge filters etc.)	Ferric sulfate coagulant is injected at second static mixer followed by flocculation and gravity DMF consisting of both sand and Australian filter coal. 5 µm cartridge filtration prior to SWRO.
Chemical dosing (acid, coagulants, polymers)	13 mg/L Ferric sulfate for coagulation. Antiscalant is dosed at 1.7mg/L for first pass and 2 mg/L for second pass RO to prevent membrane scaling. NaOH is dosed at the second pass for pH control of 10 for boron removal.

Feedwater design parameters		**Feedwater during bloom conditions**	
		(Event 2)	**(Event 3)**
Temperature range (˚C)	17 to 28	20.8-23.6	21.5
Salinity range (TDS mg/L)	34,000 to 39,000	Unaltered	Unaltered
Conductivity (mS/cm)	50.0 to 53.0	Unaltered	Unaltered
Total Suspended Solids (mg/L)	<10	0.5-7	0.2
SDI_3	N/A	8.3 - 29.1	26.4
Turbidity (NTU)	8	0.1 – 1.8	0.7
Organic Matter			
TOC (mg/L)	< 4	N/A	N/A
Algal cell count (cells/L)	N/A	20×10^6 to 24×10^7	N/A
Algal species		*Trichodesmium erythraeum*	
Chlorophyll-*a* (µg/L)	N/A	N/A	N/A

Table 11.12.1 *(Continued)*

Feedwater design parameters		Feedwater during bloom conditions (Event 2)	(Event 3)
TN mg/L	N/A	N/A	N/A
TP (mg/L)	N/A	N/A	N/A
Ammonia (mg/L)	0.2	N/A	N/A
Desalination Design		**During bloom conditions**	
DMF Filter rates (m/h)	< 8	Unaltered	Unaltered
SWRO flux (L/m^2h)	<16	N/A	12.9

11.12.1 Introduction

In response to an unprecedented drought, the Queensland Government developed a strategy for South East Queensland (SEQ), to ensure reliable water supply for the next 50 years. The strategy comprised a regional Water Grid which linked dams, water treatment plants and water storages, allowing the transport of water from surplus areas to water deficit areas (Cannesson 2009). In addition, a key component of that strategy was the construction of the 133,000 m^3/d Gold Coast Desalination Plant (GCDP). Due to the drought risk posed to the reliability of regional water supplies, the GCDP plant was critical to maintaining supplies of potable water and design and construction were fast tracked.

The GCDP was the first large-scale seawater desalination plant on Australia's eastern seaboard (commissioned in February 2009) and is located in Tugun adjacent to an international airport, approximately 20 km south of the iconic Surfers Paradise and close to the border with New South Wales (Figure 11.12.1). The plant abstracts seawater from the pristine embayment of Kirra-Tugun in the Coral Sea that is renowned for fishing, swimming and surfing. The plant was designed and constructed by the GCD Alliance comprising Seqwater, Veolia Water Australia, John Holland, with sub Alliance partners; Sinclair Knight Merz and Cardno and is now operated and maintained by Veolia Water Australia.

Prior to construction, a Seawater Quality Assessment Study was commissioned in November 2005 at the three proposed desalination plant intake sites for the GCDP extending from Tugun (the selected site) at the southern end of the Gold Coast to 40 km further in the north (Boerlage 2006). The study provided water quality data for the GCDP design envelope and information on factors that would impact seawater quality to assist in selecting and designing pretreatment. Marine algal blooms identified in the report that could occur in the SEQ region included *Trichodesmium, Lyngbya majuscula, Colopomenia sinuosa* (cornflake weed), various brown macroalgae and *Anaulus autralis.* A marine cyanobacterium *Trichodesmium* was identified as the most frequently occurring species throughout the Gold Coast, typically commencing from late spring to early summer and lasting from four to ten days followed by *Colopomenia sinuosa* which occurs sporadically every few years.

Trichodesmium, first described by the English explorer, Captain James Cook in Australian waters (Beaglehole 1955), is commonly found along the Queensland coast, particularly in the warmer North tropical regions, the sub-tropical seawater of the Gold Coast and also along the NSW coastline. It is a ubiquitous genus with blooms also found in the Gulf and other oceans. Surface blooms of *Trichodesmium* can be extensive with some covering on the order of 100,000 m^2 (Sudek et al. 2006; Mckinna 2015). Under stagnant conditions, *T. erythraeum* can release a clear organic compound that changes the bloom's color from rust brown to green and hence the blooms are commonly mistaken as oil slicks. In addition, the bloom can release a purple photosynthetic pigment so that the water appears pink; the Red Sea is so named due to the presence of *Trichodesmium* blooms and coloration of the water. Decaying blooms of *Trichodesmium* spp. may lead to anoxic conditions and mortality and/or an unpleasant fishy smell may be associated with the blooms.

To avoid operational issues at the GCDP, design measures were incorporated to minimize the ingress of algae including *Trichodesmium* into the seawater intake and growth of algae during pretreatment as discussed herein.

11.12.2 Seawater intake

Design of the seawater intake (and outfall) was challenging as the plant site is located within the highly developed Gold Coast tourist coastal strip with white sandy beaches and is highly visible from landing aircraft at the adjacent airport. Various intake options were therefore considered which would limit community and environmental impacts while delivering high-quality seawater. The Neodren technology for subsurface intakes was investigated as it was recognized that this may reduce pretreatment capital and operating costs due to "prefiltration" of the intake water through sand at a rate similar to slow sand filtration, reducing algal issues, turbidity, SDI and TSS. Following a Multi Criteria Assessment, a deep-water intake option comprising an on-shore shaft, tunnel and riser at sea was found to be the most feasible and preferred solution when considering factors such as cost, risk, scheduled delivery window, environmental impact, community disruption, visual amenity, and water quality. An additional factor was that the design had to be capable of meeting the 100 year design life. This was the first time that tunneling had been used for the intake (and outfall) for a large-scale SWRO desalination plant anywhere in the world (Burch and Murphy 2008).

The tunnel intake length was finalized to ensure that seabed infrastructure was clear of the active beach zone and at a depth to provide water with an acceptable quality. Twin tunnels (2.8m internal diameter) were constructed for the intake and outfall, approximately 1.5 km off shore and 2.2 km from the plant (see Figure 11.12.2). Design aspects were incorporated to minimize the ingress of sand, macroalgae (seaweed), algae and marine fauna into the intake. The intake riser, at 22 m depth was fitted with a vertical coarse bar screen which abstracts seawater 6 m above the seabed to limit the entrainment of sand and benthic organisms through the screens (see Figure 11.12.3). The riser was also located in an area devoid of seaweed, based on marine surveys prior to construction. At the top of the intake riser, a dome was fitted to convert vertical intake flows to horizontal flows to reduce marine entrainment. Similarly, the intake flow velocity was designed to operate at 0.05 m/s at the bar screen to reduce the impingement and entrainment of marine flora (including algae) and fauna (Cannesson et al. 2009).

The intake riser was located approximately 250 m away from the outfall diffuser. Modelling was conducted to ensure the brine diffuser achieved high brine exit velocities and dilution and to determine the footprint of the mixing zone. The intake depth and location took into account modelling results to prevent recirculation of the brine and any seawater constituents back into the intake. including dissolved algal organic matter concentrated in the brine. Diffuser performance was later validated during plant commissioning and operation (Boerlage and Gordon 2011).

11.12.3 Treatment process overview

The GCDP is required to produce 45.6 million m^3/year at 94% availability. It has a modular design, allowing it to operate at 33, 66 or 100% of its maximum capacity to enable the plant to respond to dam levels and demand. An overview of the treatment process is presented in

Figure 11.12.2. Self-elevating platform over intake during construction with the GCDP in the background (left) and Surfers Paradise (right).

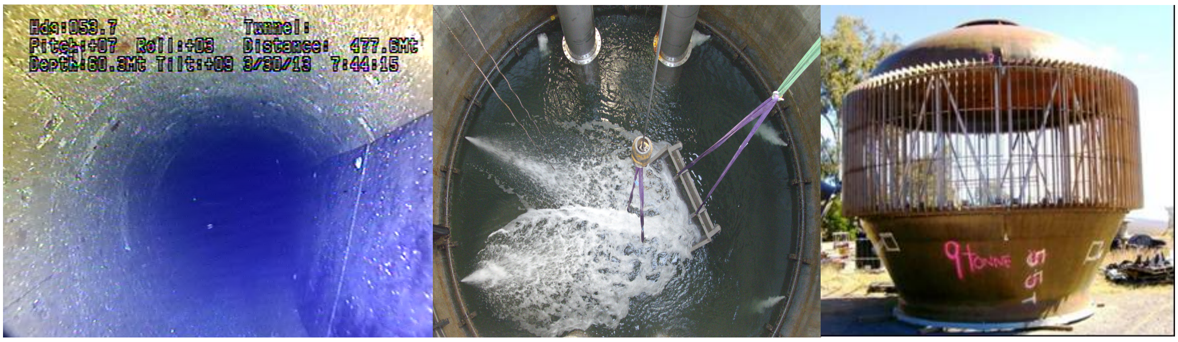


Figure 11.12.3. Intake tunnel (left), intake shaft with intake pumps (middle) and the intake coarse screen prior to installation (right).

Figure 11.12.4. The seawater flows by gravity through the intake tunnel to the plant that is intermittently chlorinated, typically once a day to limit marine growth. Following fine screening (3 mm rotating screens), the seawater undergoes conventional pretreatment with optional pH correction with sulfuric acid, coagulation by the addition of ferric sulfate and a cationic polymer, followed by flocculation and gravity dual media filtration (DMF) which will remove intact algal cells, some organics and suspended solids. The DMF and the filtered seawater tank were enclosed in buildings to prevent sunlight stimulation of algal growth.

Antiscalant is added to the filtered seawater before final filtration through 5 µm cartridge filters prior to the RO system, which comprises two passes. The first pass is operated with split permeate extraction. The high-quality front-end permeate is directly transferred to remineralization while the rear permeate is desalinated in a second pass. The blended permeate is remineralized by addition of carbon dioxide and lime water, dosed with sodium hypochlorite, and fluoridated.

Backwash from the DMF is treated in the residuals treatment section of the plant by lamella thickeners and centrifugation. Solids are transferred to a landfill and the treated water returned to sea with the RO brine through a purpose-built diffuser. Hence, particulate and solid algal matter that may be entrained during a bloom will not be returned to sea.

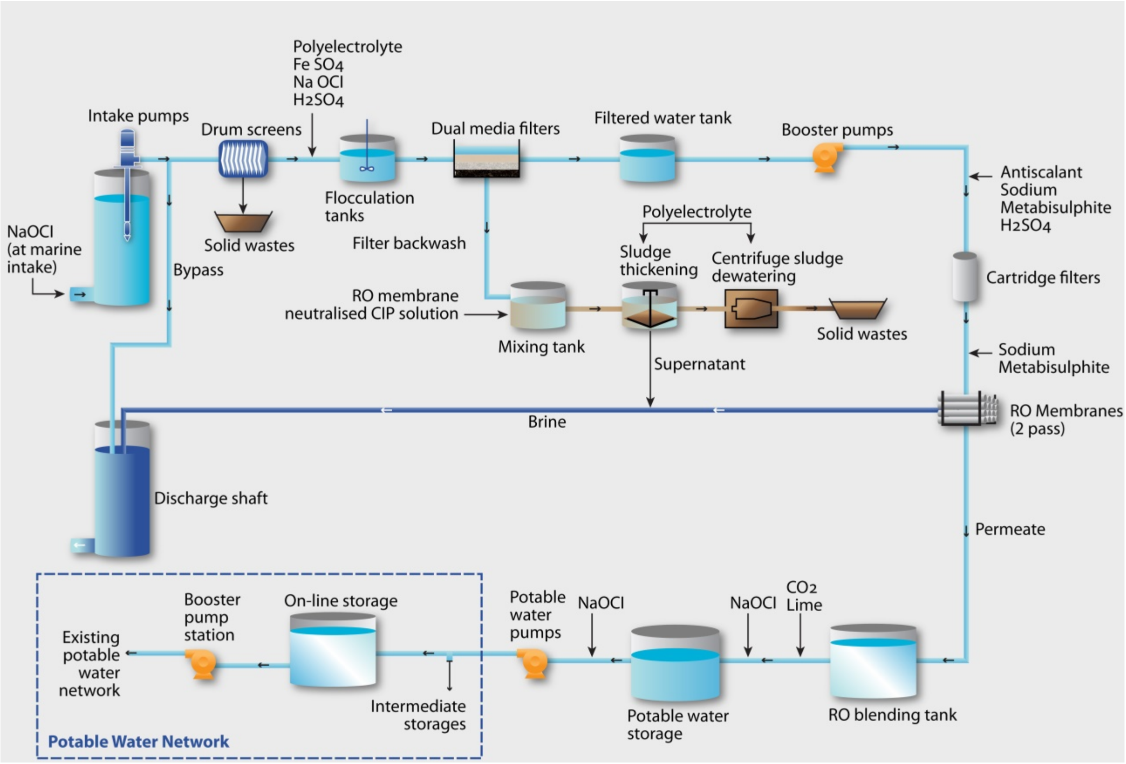


Figure 11.12.4. GDCP process schematic for desalination and residual treatment (Burch and Murphy 2008).

11.12.4 Algal bloom events

11.12.4.1 Event 1 (January 2008)

During plant construction, a dense algal bloom was observed at the surface of the seawater in late January (22nd – 23rd, 2008) during monthly boat surveys. The bloom was extensive, covering both the desalination plant intake and outlet areas. Similar, more extensive blooms were observed a year earlier in January 2007, extending up to Surfers Paradise during marine monitoring surveys. On both occasions, a sample of the dense brown algae was taken which colored the seawater a profuse pink color following storage. This indicated the bloom was caused by *Trichodesmium*, as a quick test for this species is to shake a sample of the bloom and let stand for several hours after which the water will turn pink/purple due to pigments dissolving (pers. comm. A. Negri). In the case of the 2008 event, the sample was sent for analysis and the dominant species was indeed confirmed as the filamentous blue green cyanobacteria *Trichodesmium erythraeum*, which was expected from the seawater quality assessment study.

The prior weather conditions experienced in the Kirra-Tugun embayment were favorable for an algal bloom, with heavy rainfall (4th, 5th and 11th of January) and flooding of the Tweed River (5km to the south) bringing high nutrients with it, followed by clear weather, calm seas and high summer temperatures (Boerlage 2008). The nutrient input due to high rainfall was not likely to be the driver for the bloom as *Trichodesmium erythraeum* is well known as a nitrogen fixing organism (e.g., capable of taking dissolved nitrogen gas from the water) thriving in nutrient poor tropical- sub tropical waters with temperatures > 20 ˚C. Instead the combination of rough marine conditions followed by calm winds and warm water temperatures most likely stimulated the bloom, as such conditions are known to increase the growth and accumulation of *Trichodesmium*. Typically, *Trichodesmium* algal cells are barely visible to the naked eye and spread throughout the water column. Under such favorable conditions the single filamentous algal cells can aggregate in strings and clumps to form colonies of up to 200 cells (0.5 to 3 mm in size). As the cells age, they become positively buoyant and begin to float like sawdust on the surface, forming extensive blooms described as mats or rafts (Negri et al. 2004). This is what was observed on the Gold Coast in 2007 and 2008 (Figure 11.12.5).

As the GCDP was still being constructed, no impacts on desalination plant operation could be investigated.

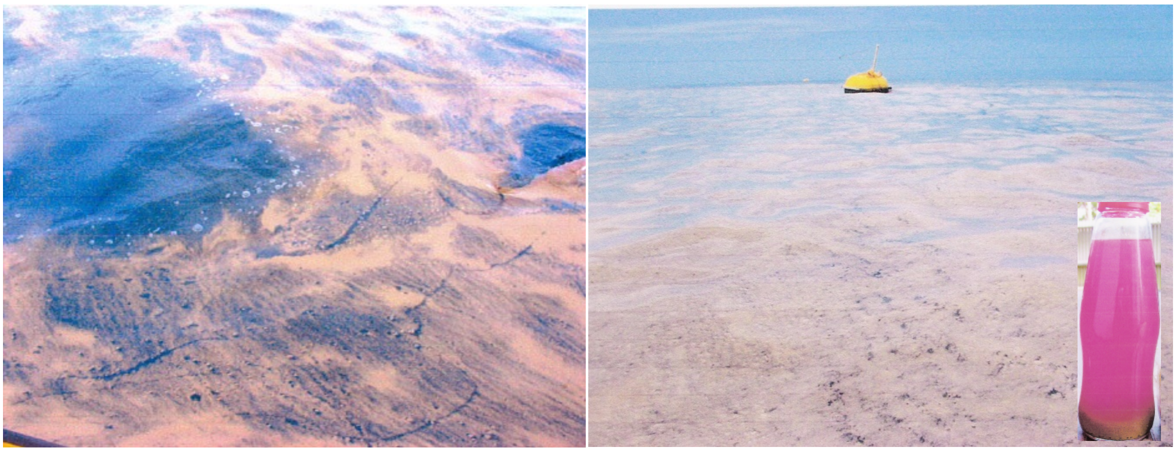


Figure 11.12.5. Algal blooms observed in January 2007 (left) and 2008 at the GCDP seawater intake and outfall (right). Inset - coloration of seawater sample (2008 bloom) of the photosynthetic pigment – phycoerythrin produced by *Trichodesmium* (Boerlage 2008).

11.12.4.2 Event 2 (January to February 2009)

Another bloom similar to that previously observed in 2007 and 2008 was seen the following summer in late January to mid-February 2009 during monthly boat surveys when the GCDP was being commissioned. Rafts of the bloom were estimated to cover several hundred meters. A member of the public suggested it emanated from the plant brine outlet. Surface water samples collected on two occasions were again an intense pink color and the bloom was confirmed by laboratory analysis to be a natural bloom event caused by *Trichodesmium erythraeum.* The bloom was dense with viable cell counts ranging from 238 million cells/L in January reducing ten-fold to 20 million cells/L in mid-February. If indeed an algal bloom were significantly entrained in the deep-water intake, the solids associated with the high concentration of algal cells would be removed during residual treatment and not be returned to sea. The brine diffuser was designed and proven to achieve a high dilution with a minimum footprint (Boerlage and Gordon 2011). Hence, no plume would be evident from the brine outfall.

As the intake is 1.5 km off shore, visible inspection of the intake area is not possible from the plant and therefore the exact date for the dissipation of the bloom is not known. As a result, all water quality data for February 2009 was examined. At the time of this bloom event, the plant was mainly operating at 33% capacity with no significant impacts observed on raw seawater quality, operation of the DMF filters, cartridge filters or RO feedwater quality. No spikes in SDI_3 (Figure 11.12.6), or TSS were observed for late January – early February and all parameters were within the design envelope with the exception of TOC that was 1mg/L above design on one occasion (shown in Table 11.12.2). The maximum SDI_{15} value observed in the DMF filtrate occurred in early February as a one-off measurement and was still within guarantee values. This may be attributable to limited ingress of the algal bloom due to the deep-water intake. While *Trichodesmium* species are generally regarded as "floaters" literature suggests they may sink during die-off. Some algal cells might then be entrained into the intake resulting in the higher SDI_3 values observed for late February (>25). Nevertheless, no impacts on plant operation were observed.

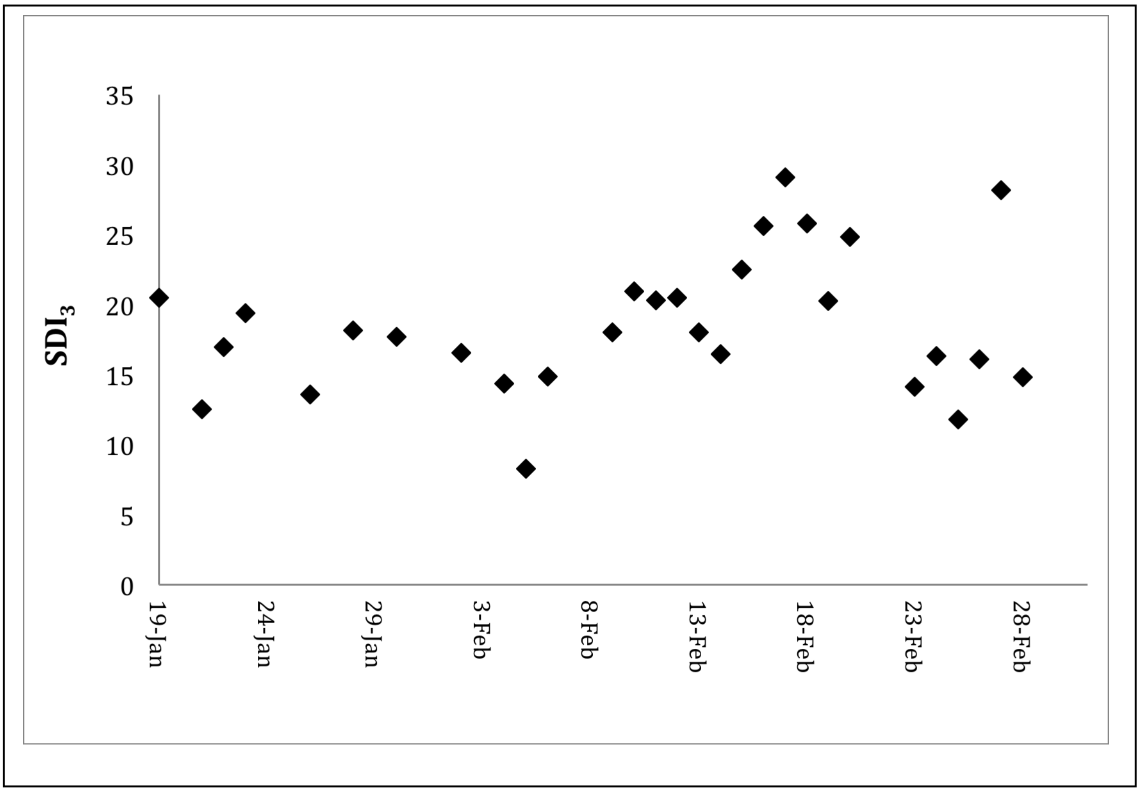


Figure 11.12.6. Raw water SDI_3 measured at the seawater intake during plant commissioning in January – February 2009.

Table 11.12.2. Intake and filtered seawater quality (following dual media filtration) during a February 2009 bloom event.

Algal Bloom Event 2	Data	Intake seawater					Filtered seawater
		SDI_3	Temperature °C	Turbidity NTU	TSS mg/L	TOC mg/L	SDI_{15}
1st February – 28th 2009	Minimum	8.3	20.8	0.1	0.5	0.5	1.1
	Maximum	29.1	26.9	1.8	7	5.0	4.0
	Average	19.0	23.6	0.7	2.53	1.65	2.8

11.12.4.3 Event 3 (November 2012)

The City of Gold Coast reported that algal blooms were observed in coastal areas on Monday, 5th November 2012, identified as *Trichodesmium* from water quality testing by the City Council. No cell counts were available. The bloom was reported to extend south of Surfers Paradise down to Coolangatta, an area that incorporates the seawater intake abstraction site.

Raw seawater quality data for October, the month preceding the bloom, and for November when the bloom occurred are presented in Table 11.12.3. SDI_3 and turbidity are plotted in Figure 11.12.7. Higher SDI_3 and turbidity values were generally found in October. No noticeable increase in SDI_3 (21.6), turbidity (0.639 NTU) and TSS (1.6 mg/L) were observed on November 5th, the date corresponding to the bloom report by the City Council. Nor was there any impact on plant operation. The plant was operating on the 5th of November at the desired 33% capacity. The clean-bed head loss was stable for all filters, just under 2.5kPa on average for the month of November 2012 indicating no fouling/clogging of the DMF.

Similarly to Event 2, all seawater and RO feedwater quality parameters were within the design envelope and RO membrane guarantee values (Table 11.12.4), respectively. While limited nutrient data were available, no increases in total nitrogen were observed from that observed in marine environmental monitoring studies.

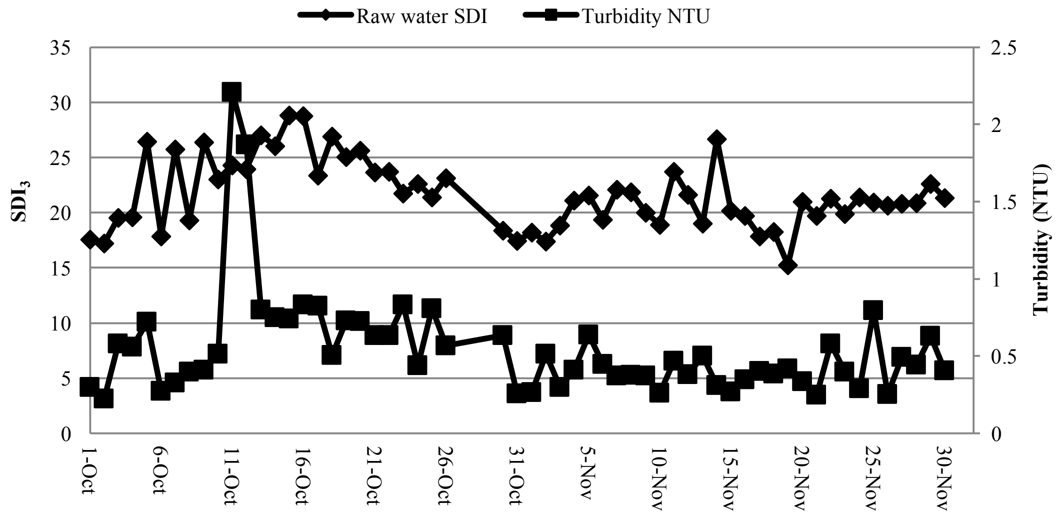


Figure 11.12.7. Raw seawater quality in October and November 2012 during which a *Trichodesmium* bloom was reported by the Gold Coast City Council on November 5th.

Table 11.12.3. Intake seawater quality data for October and November 2012.

Algal Event 3	Date	Data statistics	SDI_3	Temp °C	Turbidity NTU	TSS mg/L	Total Nitrogen mg/L	Ammonia mg/L
5 Nov. 2012	Oct. 2012	Min	17.2	19.4	0.225	0.2	N/A	N/A
		Average	23.0	21.6	0.698	1.84	N/A	N/A
		Max	28.8	24.0	2.21	5.2	0.09	0.079
	Nov. 2012	Min	15.2	20.9	0.249	0.2	<0.05	N/A
		Average	20.4	22.9	0.411	1.16	<0.05	N/A
		max	26.6	24.5	0.795	3	<0.05	0.015

Table 11.12.4. Monthly RO feedwater quality before and after algal event in November 2012.

Algal event Dates	Water quality month date	Data statistics	SDI_{15}	Turbidity NTU	TOC mg/L
5 November 2012	October 2012	Min	2.21	0.01	1
		Average	2.95	0.045	1
		Max	3.69	0.135	1
	November 2012	Min	2.13	0.01	1
		Average	2.57	0.025	1
		Max	3.51	0.05	1

11.12.5 Long-term plant operation

The GCDP plant has been in operation for more than seven years, with anecdotal reports of *Trichodesmium* blooms similar to algal events 1-3 described above occurring during the summer months when conditions are expected to promote blooms. In the absence of any observed impacts at the plant, algal blooms are likely to be unreported as the intake is 2.5 km from the plant and algae are not specifically monitored for by the GCDP.

Blooms of another marine algal species, *Colpomenia sinuosa*, have been detected sporadically, once in 2010 and again in 2014, through an increase in the mass of intake screenings. In the latter case, this resulted in the unusually high mass of screenings (approximately 400 kg). *Colpomenia sinuosa*, a globe-shaped brown macroalga, is much larger than *Trichodesmium,* ranging in size from 1 to 3 mm and up to 10 mm. It is found in intertidal areas growing on rocks or other algae. *Colpomenia sinuosa* is typically in the attached form, it becomes dislodged with wind and waves breaking into flakes and may then have become entrained into the intake.

In general, the depth of the intake and pretreatment design is believed to have largely mitigated algal bloom impacts, especially surface *Trichodesmium* blooms with limited ingress of *Colpomenia*. Water quality associated with algal blooms does not appear to have deteriorated - SDI_3, TSS and TOC were within the range observed throughout the year. No operational issues were observed at the plant such as increased DMF clogging. No sudden increases in RO operating pressures due to biofilm or adsorptive organic fouling have been observed associated with the potential increase in organics from an algal bloom entrained at the seawater intake.

Membrane autopsies and the low cleaning frequency of the RO trains further support the contention that no organic fouling or significant biofouling has occurred during plant operation. Autopsies of a cartridge filter, first and second pass RO membranes in May of 2009 following algal event 2 showed no evidence of organic deposits or fouling with only minor inorganic deposits. Similar autopsies were conducted in August 2009, March 2010, August 2010 and April 2013. In general, visual inspection of lead membranes showed that the level of fouling was very light with only minor biofilm deposits present. The loss of ignition results indicated that the organics on the membrane were low.

Only limited CIP cleans of RO membranes have been carried out, which is attributed to the effectiveness of pretreatment coupled to good raw water quality. Clean in place have not been conducted in response to any fouling issues but rather as a trial run on a limited number of RO trains or as preventative cleans.

11.12.6 Conclusions

Trichodesmium, the most frequent bloom-forming species in the region, occurred prior to operation of the GCDP and continues to occur during the summer months as a result of marine and meteorological conditions that promote the growth of this genus. Dense surface blooms have been extensive, covering the seawater intake and brine discharge area with a density of up to 238 million cells/L. Occasional blooms of *Colpomenia* have also occurred.

The deep water (20 m water depth) intake option selected for the GCDP appears to be successful in providing good water quality and preventing the ingress of *Trichodesmium,* which typically floats at the surface with limited ingress of *Colpomenia*. No increase in raw water TOC, TSS, SDI_3 have been observed as a result of blooms. Membrane autopsies also show no organic or biofilm fouling due to the potential increase in organics associated with such dense blooms.

11.12.7 References

Beaglehole, J. C. 1955. *The Journals of Captain James Cook on His Voyages of Discovery. I. The Voyage of the Endeavour* 1768–1771. Cambridge: Cambridge University Press.

Boerlage, S. F. E. 2006. Seawater quality investigation at proposed desalination intake sites Consultancy Report.

Boerlage, S. F. E. 2008. Identification of marine algal bloom, Gold Coast Desalination Alliance, Internal Memo.

Boerlage, S. and Gordon, H. 2011. Assessing diffuser performance and discharge footprint for the Gold Coast Desalination Plant. In: *Proceedings of IDA World Congress, Perth, Western Australia*.

Burch, R. and Murphy, S. 2008. Twin intake/outfall tunnels save space and environment. *IDA Journal of Desalination and Water Reuse* 18(2), 22-28.

Cannesson, N., Johnstone, P. M., Mitchell, M. A., and Boerlage, S. F. 2009. Minimizing community, environmental, and marine impacts at the Gold Coast Desalination Plant. *IDA Journal of Desalination and Water Reuse* 1(1), 74-87.

Negri, A. P., Bunter, O., Jones, B., and Llewellyn, L. 2004. Effects of the bloom-forming alga *Trichodesmium erythraeum* on the pearl oyster *Pinctada maxima*. *Aquaculture* 232(1), 91-102.

McKinna, L .I. 2015. Three decades of ocean-color remote-sensing *Trichodesmium* spp. in the World's oceans: a review. *Progress in Oceanography* 131, 177-199.

Sudek, S., Haygood, M. G., Youssef, D. T., and Schmidt, E. W. 2006. Structure of trichamide, a cyclic peptide from the bloom-forming cyanobacterium *Trichodesmium erythraeum*, predicted from the genome sequence. *Applied and Environmental Microbiology* 72(6), 4382-4387.

11.13 BERLIN, GERMANY – AKVOLA: AN INTEGRATED DAF-UF PILOT

[1]Johanna Ludwig[1] and Matan Beery

[1]akvola Technologies, Berlin, Germany

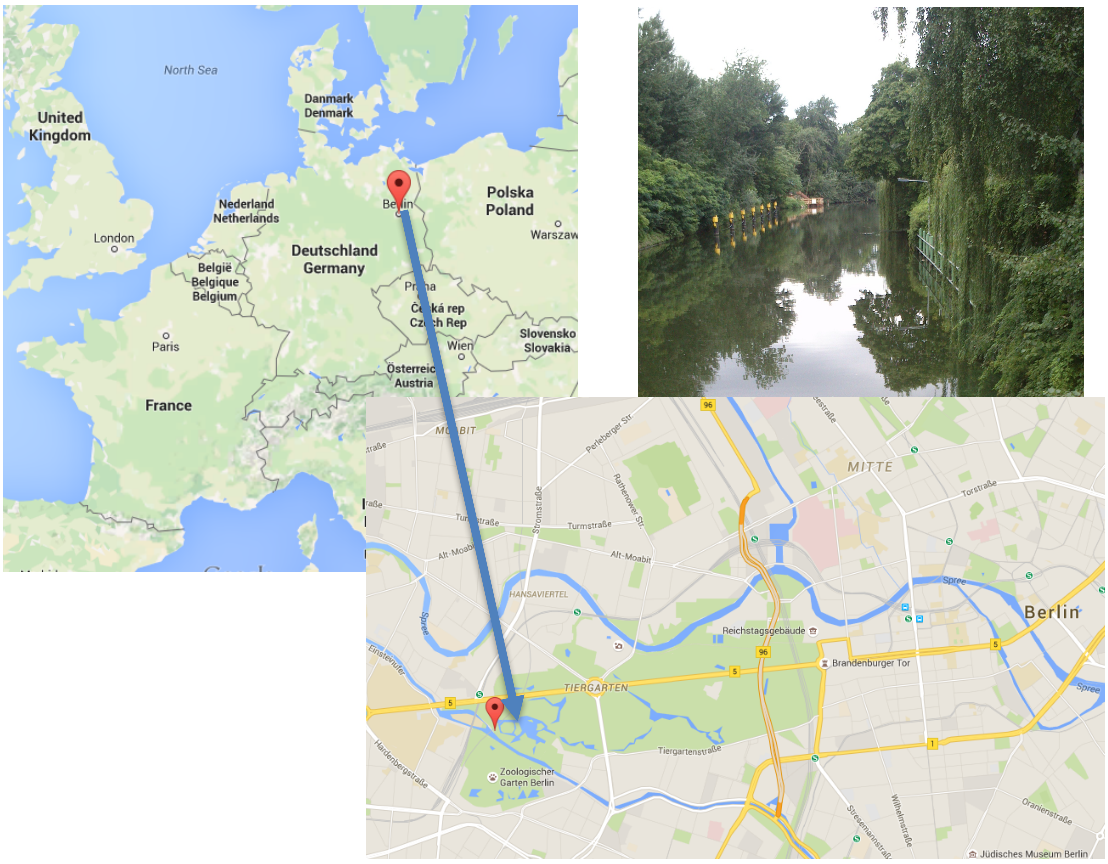


Figure 11.13.1. Pilot plant location at Landwehrkanal Berlin.

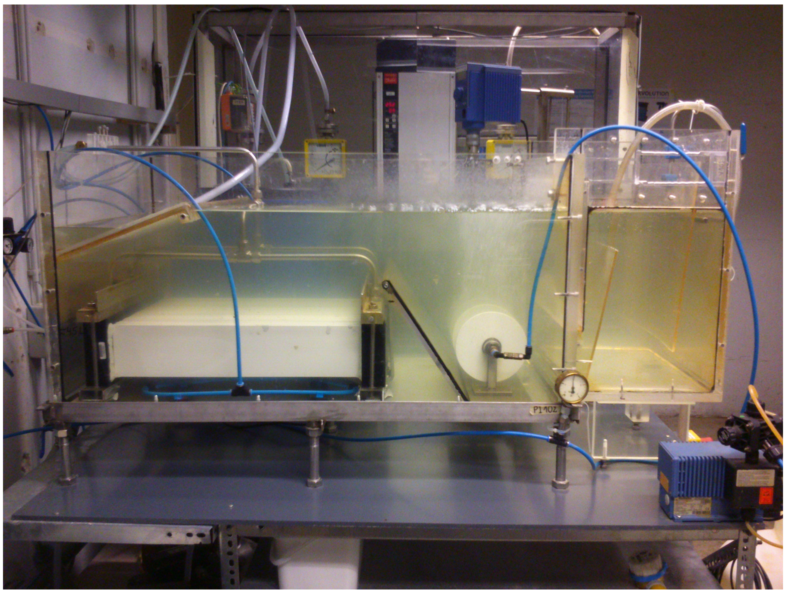


Figure 11.13.2. Pilot plant at Landwehrkanal Berlin.

Table 11.13.1. Overview of the akvola Technologies' pilot plant.

Plant/Project Name	**akvoFloat pilot at Berlin City River**
Location	City River (Landwehrkanal), Berlin, Germany
Total Production Capacity (m^3/d)	15-17
Commissioning date	January 2013
Intake	
Feedwater source	Surface Water (River: Landwehrkanal), Berlin
Intake type	Surface intake
Intake description	Intake depth 0.5-1 m, distance from shore 2 m
Intake screening	15 mm mesh
Discrete raw water analysis relevant to HABs	TOC, turbidity, algae cell count, temperature, pH
Pretreatment	
Process description	300 µm automatic strainer, coagulation-flocculation, flotation and MF/UF (submerged out-in)
Chemical dosing	Coagulant $FeCl_3$ 8-12 mg/l as Fe; Polyacrylamide 0.1 mg/l

Feedwater design parameters		**Feedwater during bloom conditions**	**Annual avg. feedwater conditions**
Temperature range (˚C)	5-25	14-21	0.2-25
Salinity range (TDS mg/L)	490-550	490-505	410-526
Conductivity (mS/cm)	660-830*	732-753	612-785
Total suspended solids (mg/L)	1.7-12*	5.5-12	1.7-12
SDI			
Turbidity (NTU)	1.5-7.5	2.1-7.5	
Organic matter	7.8-10.8 (TOC)	8.6-10.2 (TOC)	
Algal cell count (cells/L)	6.4 - 56 million*	30 - 56 million	6.4 - 56 million
Algal species	Blue-green algae (60-95%), Diatoms (3-37%) Main species: _Pseudanabaena limnetica, Anabaena planctonica, Aphanizomenon flos-aquae, Aphanizomenon issatschenkoi_*	Blue-green algae (82-95%), Diatoms (3-8%),	Blue-green algae (60-95%), Diatoms (3-37%) Main species: _Pseudanabaena limnetica, Anabaena planctonica, Aphanizomenon flos-aquae, Aphanizomenon issatschenkoi_*

Table 11.13.1 *(Continued)*

Feedwater design parameters		**Feedwater during bloom conditions**	**Annual avg. feedwater conditions**
Chlorophyll-*a* (µg/L)	2-18*	7-18	< 2 - 18
Additional relevant water quality parameters for design or observed spikes during algal bloom e.g. low DO at intake, H_2S, ammonia	3-11 mg/L DO*, 0.09-0.27 mg/L TP*	5-7 mg/L DO, 0.2-0.27 mg/L TP	3-15 mg/L DO, 0.06-0.27 mg/L TP

Desalination Design		**During bloom conditions**
Filter rates (DAF) m/h	0.8-10 m/h (including both flotation and filtration area)	0.8 m/h (not optimized)
UF flux (L/m^2h)	107-167	146-158

*Data measured by third party: Berlin's Senate Department for Urban Development and the Environment (Department VIII E 24 Integrative Ecology)

11.13.1 Introduction

Originally developed for SWRO pretreatment as a reliable and energy efficient technology, akvoFloat was first piloted at a freshwater river. The pilot results are valid for seawater as well, as laboratory studies have shown flotation bubbles to be 5-10% smaller (and thus more efficient) in saltwater than in freshwater. Seawater application requires corrosion resistant materials for all parts, but the overall performance of akvoFloat in terms of separation and efficiency will be similar or better. (See Chapter 9 for a detailed comparison on DAF conditions in fresh water *vs* seawater).

Specializing in the treatment of hard-to-treat waters in the industrial, commercial and municipal sectors, akvola Technologies is a water technology company with a focus in oil-water separation and suspended solids removal for applications such as SWRO pretreatment. In 2013, pilot tests of the akvoFloat technology, comprising a hybrid flotation-filtration process using ceramic membranes in both steps, were conducted using Berlin's city river water at 0.5-0.7 m^3/h. The goal was to determine the optimal operating conditions giving a constantly low transmembrane pressure of the MF/UF membrane. An algal bloom occurs every summer at the river. More information can be found in Hög et al. (2015) and Beery et al. (2014).

11.13.1.1 Feedwater

In the pilot plant, water from the Berlin city river, Landwehrkanal (a branch of the river Spree), was treated during summer to autumn 2013. The period was characterized by fluctuating levels of total organic carbon (TOC), turbidity and temperature (Figure 11.13.3). The slow flow (10 cm/s) of the river and low depth (2 m) promotes occasional algal blooms in summer. Furthermore, the canal is used to relieve the sewage system during heavy rain events. Phytoplankton counts close to the water inlet are given in Figure 11.13.4, using data provided by Berlin Senate Department for Urban Development and the Environment (Department VIII E 24 Integrative Ecology). An algal bloom was declared when the phytoplankton concentration was higher than 30 million cells/L (Aug-Oct.), see Figure 11.13.4 and the image in Figure 11.13.5.

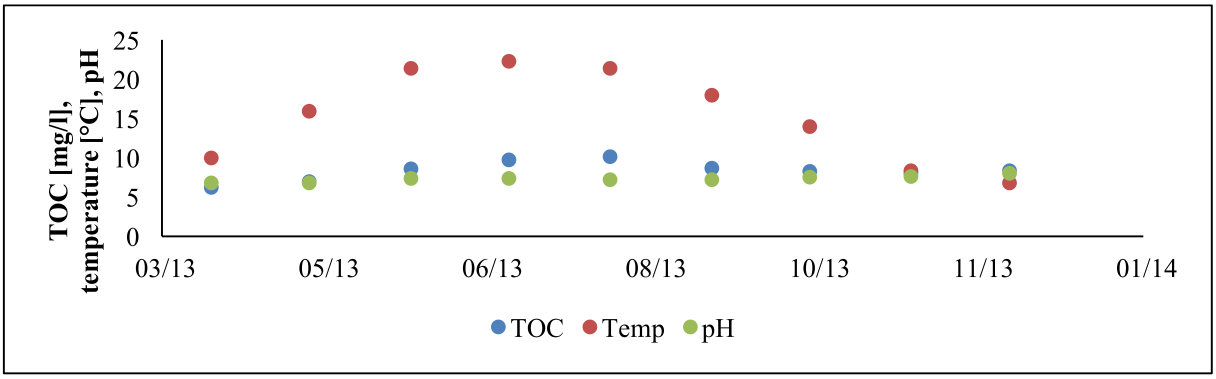


Figure 11.13.3. Average TOC, pH and temperature during pilot plant testing.

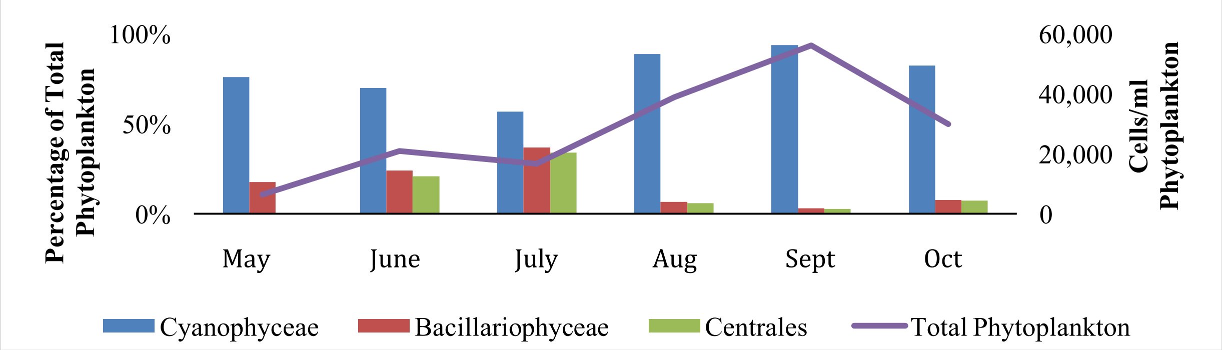


Figure 11.13.4. Algal cell count close to the water inlet, data provided by the Berlin Senate Department for Urban Development and the Environment (Department VIII E 24 Integrative Ecology).

11.13.2 Process Description

The akvoFloat process is a hybrid of flotation and membrane filtration with inline coagulation/flocculation (iron (III) chloride). The production of micro-bubbles for flotation is achieved by a bubble generator, composed of ceramic diffusor disks, giving 50-100 µm bubble size. A ceramic MF/UF membrane is submerged in the flotation tank operating at constant flux. The membrane is backwashed with permeate which simultaneously removes the float layer hydraulically over a weir. Backwashes typically had a two-minute duration and a volume flow of 1200 L/h reaching 2.1 bar absolute (shorter backwash intervals <30s yield the same result, as shown in later experiments).

Figure 11.13.5. Water inlet during an algal bloom.

Figure 11.13.6 shows the process scheme of the pilot plant, Figure 11.13.7 shows a photo of the pilot plant and the resulting sludge/float layer during algal bloom operation.

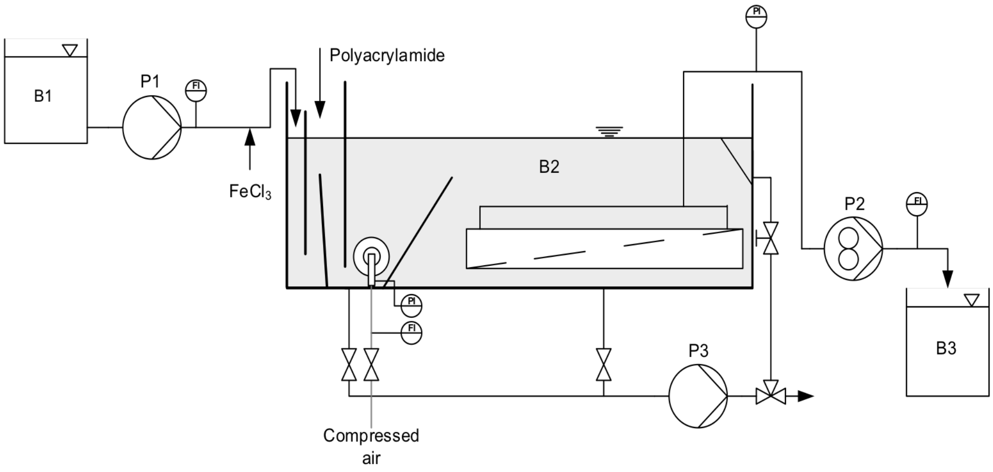


Figure 11.13.6. Process flow schematic of the pilot plant.

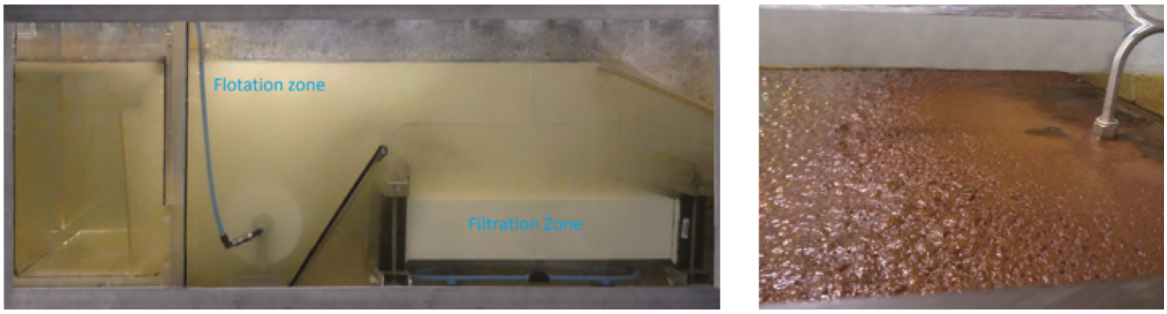


Figure 11.13.7. Side view of the akvoFloat pilot (left) and resulting float layer during operation (right).

11.13.2.1 Process Results

The process results are shown in Figure 11.13.8. Turbidity of the feed was constantly reduced by up to 95% with typical effluent turbidity < 0.1 NTU. TOC was reduced by 30-40%, with practically 100% of the microalgae removed within the test accuracy. No difference in plant performance was observed during algal bloom conditions – in permeate quality or plant performance (fouling, backwash effectiveness). The transmembrane pressure was always 0.1-0.2 bar. A combination of a CEB/CIP with sodium hypochlorite and a subsequent CIP with citric acid, 30 minutes each, allowed the complete recovery of the membrane performance at any given time.

11.13.3 Conclusions

The high efficiency of the akvoFloat process for surface water treatment during algal bloom conditions was demonstrated. A periodic backwash (2h) and a flux of up to 150 L/m^{2}h was shown to be sustainable, yielding low overall fouling, maintaining up-time and high quality permeate during an algal bloom. A combination of a CEB with sodium hypochlorite and a CIP with citric acid allows the full recovery of the membrane performance. akvola is currently collaborating with a large international EPC running trials for seawater pretreatment but the results are thus far confidential.

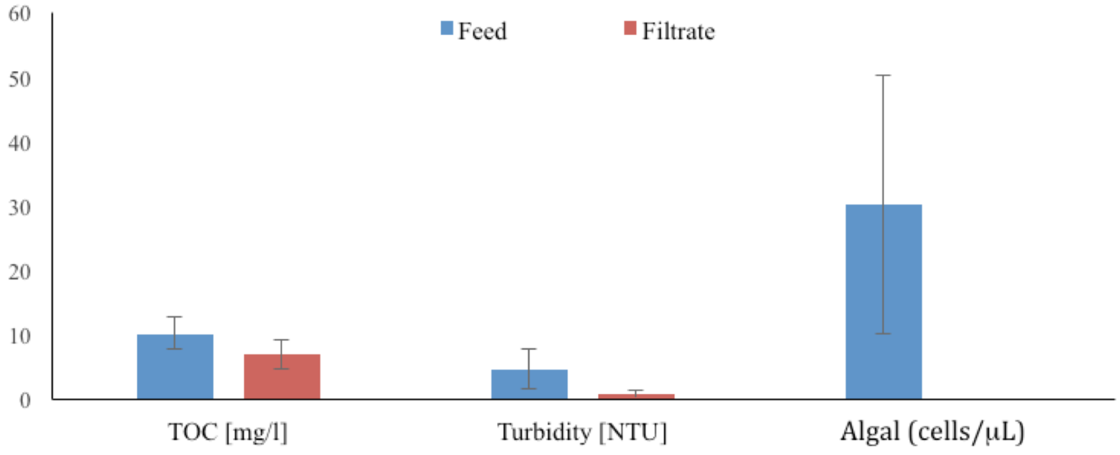


Figure 11.13.8. Water quality of feed and treated water.

11.13.4 References

Beery, M., Ludwig, J., and Hög, A. 2014. River Water Treatment using Ceramic Membranes in Berlin: Pilot Testing. In: *Proceedings of the American Membrane Technology Association Membrane Technology Conference*, Las Vegas, Nevada, USA.

Berline Senate, Department for Urban Development and the Environment (Senatsverwaltung für Stadtentwicklung und Umwelt Berlin), Abt. Integrativer Umweltschutz, Monitoring Wasserrahmenrichtlinie. 2014. "Ökologisches Monitoring und Bewertung von Oberflächengewässern VIII E 24", Berlin.

Hög, A., Ludwig, J., and Beery, M. 2015. The use of integrated flotation and ceramic membrane filtration for surface water treatment with high loads of suspended and dissolved organic matter. *Journal of Water Process Engineering* 6, 129-135.