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Small Scale Direct Potable Reuse (DPR) Project for a Remote Area

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Abstract: An Advanced Water Treatment Plant (AWTP) for potable water recycling in Davis Station Antarctica was trialed using secondary effluent at Selfs Point in Hobart, Tasmania, for nine months. The trials demonstrated the reliability of performance of a seven barrier treatment process consisting of ozonation, ceramic microfiltration (MF), biologically activated carbon, reverse osmosis, ultra-violet disinfection, calcite contactor and chlorination. The seven treatment barriers were required to meet the high log removal values (LRV) required for pathogens in small systems during disease outbreak, and on-line verification of process performance was required for operation with infrequent operator attention. On-line verification of pathogen LRVs, a low turbidity filtrate of approximately 0.1 NTU (Nephelometric Turbidity Unit), no long-term fouling and no requirement for clean-in-place (CIP) was achieved with the ceramic MF. A pressure decay test was also reliably implemented on the reverse osmosis system to achieve a 2 LRV for protozoa, and this barrier required only 2–3 CIP treatments each year. The ozonation process achieved 2 LRV for bacteria and virus with no requirement for an ozone residual, provided the ozone dose was >11.7 mg/L. Extensive screening using multi-residue gas chromatography–mass spectrometry (GC–MS) and liquid chromatography–mass spectrometry (LC–MS) database methods that can screen for more than 1200 chemicals found that few chemicals pass through the barriers to the final product and rejected (discharge) water streams. The AWTP plant required 1.93 kWh/m^3 when operated in the mode required for Davis Station and was predicted to require 1.27 kWh/m^3 if scaled up to 10 ML/day. The AWTP will be shipped to Davis Station for further trials before possible implementation for water recycling. The process may have application in other small remote communities.

Keywords: potable water recycling; ceramic microfiltration; reverse osmosis; ozonation; disinfection by-products

1. Introduction

Davis Station, Antarctica, is operated by the Australian Antarctic Division (AAD) for the purposes of undertaking environmental research. The AAD is committed to minimizing the impact of their presence on this pristine environment and a desire to minimize the effect of their wastewater discharge on the Antarctic receiving waters offered the opportunity to consider a direct potable reuse (DPR) scheme at Davis Station.

An environmental impact assessment of wastewater discharges to the receiving environment conducted by the AAD identified the need for tertiary treatment of sewage. Given the high quality of tertiary treated wastewater, only incremental additional treatment would be required for potable recycling that would enable greater water availability at Davis Station and reduced energy consumption for producing drinking water compared to the current treatment of a cold, hypersaline source water. Therefore, a demonstration trial of a potable recycling plant was undertaken for the AAD to ascertain its suitability for implementation at Davis Station, Antarctica.

Davis Station has a population of approximately 120 people during the summer and 10–20 people over winter. An annual supply ship provides the necessities for the station to function. The personnel responsible for the operation and maintenance of water and wastewater services are also changed annually. Operating a potable water recycling plant in Antarctica is challenging, as the treatment process must consistently treat water to the quality required for drinking. In addition, for Davis Station, the quality of any discharge stream must also be high, supplies can only be received annually so inventories of chemicals and maintenance items must be kept low, and the plant operators change every year and are responsible for site services apart from the water and wastewater systems. Remote monitoring of the water recycling process is possible through a secure internet service to Davis Station, and this will allow access to expert water treatment skills for resolution of process issues. Site operators will have expertise in mechanical operations. Therefore, the potable recycling process must be reliable and its performance verifiable on-line.

A quantitative microbial risk assessment (QMRA) was undertaken for Davis Station [1], to determine the minimum Log Reduction Values (LRV) required for the small station population. Minimum LRVs of 12.3 for bacteria, 12.1 for virus and 10.4 for protozoa were identified as necessary to achieve a disability adjusted life year (DALY) of $<10^{-6}$, the disease burden specified by the Australian water recycling guidelines [2]. This analysis was based on a disease outbreak scenario at Davis station.

A membrane bioreactor was installed at Davis Station to attain secondary treatment in 2016, and an Advanced Water Treatment Plant (AWTP) will treat the secondary effluent to potable water standards and produce high quality discharge water. The AWTP will be housed in a 19 °C temperature controlled room at Davis Station.

In this study, the AWTP to be taken to Davis Station was tested at Selfs Point Wastewater Treatment Plant (SPWWTP), Hobart, Tasmania, for a period of nine months. The AWTP performance was assessed based on the key design requirements and ability for critical control point (CCP) verification of process performance. The assessment provides a reference for a small scale potable reuse plant design, i.e., barrier selection, requirements and critical control point (CCP) selection. The LRV assigned for each unit operation is given in Zhang et al. [3] and the total claimed was 12.5 for virus, 12.5 for bacteria and 10 for protozoa (an additional 2 LRV was also claimed for the membrane bioreactor (MBR) for protozoa). Furthermore, some new technologies, such as the combination of ozonation, ceramic microfiltration (MF) and biologically activated carbon (BAC), and pressure decay tests (PDT) for online RO integrity verification, were used in this plant. This study demonstrated the effectiveness of these technologies, and in particular the membrane processes.

2. Materials and Methods

2.1. Feed Water Characterization

The SPWWTP is a biological nutrient removal plant that receives a mixture of municipal and industrial wastewater, as well as stormwater infiltration during rain events. The feed to the AWTP was sourced from the discharge channel of the SPWWP prior to ultraviolet disinfection (UV) and chlorine disinfection, and was screened (2 mm) prior to entry. At Davis Station, the feed will be from a MBR, so the SPWWTP effluent is expected to be higher in suspended solids than the feed at Davis Station. Feed water pH, temperature, turbidity and ammonia concentration were measured by in-line sensors.

2.2. Design and Experimental Challenges of the Pilot Plant

2.2.1. Major Operational Parameters and Verification Method for Each Barrier

The performance of the AWTP is considered here. The plant consisted of a seven barrier process designed to meet the stringent LRV requirements for the small scale water recycling plant.

The seven barriers selected for the AWTP were:

1. Ozonation, employing a strong oxidation effect of ozone on pathogen inactivation, bio-degradability improvement of organic matter, degradation of chemicals of concern (CoC), a lower chemical consumption associated with cleaning of the downstream ceramic micro-filtration (MF) and improved backwash efficiency [4,5].
2. Ceramic microfiltration membranes (MF), providing a size exclusion barrier to pathogens and suspended solids and direct ozone compatibility to lower chemical consumption for membrane cleaning. Ceramic MF has much better robustness and long-term integrity than polymeric membranes, excluding the need for pinning of broken fibres.
3. Biologically activated carbon (BAC) filter, biologically removes DOC to lower the organic fouling potential of the reverse osmosis (RO) feed so as to extend the RO element replacement period and reduce chemical consumption for clean-in-place (CIP) and also removes additional trace organic compounds from the RO brine that will be discharged to the Antarctic Ocean. However, the BAC will also increase the concentration of particulates in the BAC effluent and increases the frequency of cartridge filter replacement upstream of the RO array.
4. Reverse osmosis (RO) uses size exclusion to remove metals, pathogens and chemicals of concern (CoCs). No anti-scalant was used and only acids and alkalis used for RO membrane cleaning.
5. Ultraviolet radiation (UV), employs ultraviolet C (UVC) radiation to deactivate pathogens, especially protozoa.
6. Calcite contactor dissolves calcium carbonate into the RO permeate to increase water stability thereby reducing product water corrosivity, and
7. Chlorination via hypochlorite to provide an additional pathogen inactivation and chlorine residual to suppress pathogen regrowth in the distribution system.

A schematic diagram of the pilot plant is shown in Figure 1. Ozone production was via a Wedeco OCS-GSO 10 system with a nominal ozone production rate of 30 g/h. The unit was set at 19–20 mg per litre wastewater (≈24 g/h). The ozone system included a 480 L contact tank with an internal tank, a circulating Venturi dosing system operating at a circulation flowrate of 2 m^3/min, a pressure swing absorption oxygen generator and an ozone generator. The ozone system started approximately 10 to 15 min earlier than the feed pump to build up the ozone concentration in the ozone contact tank. The ozone mass transfer efficiency to the feed water was estimated by measuring the difference between the gas flow rate from the ozone destroyer between operation in dry mode (ozone generator not operating) and operational mode. The residual ozone concentration was measured by an in-line ozone sensor positioned in the discharge line from the ozone system.

The MF barrier comprised two 0.1 µm Metawater® (Chiyoda-ku, Tokyo, Japan) ceramic membranes operated alternatively (duty/standby) in dead end mode. The area of each membrane was 25 m^2. The operating flux was approximately 50 $Lm^{-2} \cdot h^{-1}$. A pressure decay test (PDT) was used to ensure membrane integrity after each online period and the filtrate turbidity was used to trigger the integrity test during operation. To minimise labour requirements, clean-in-place (CIP) of the ceramic MF membranes with manual chemical addition to the CIP tank was not practiced. However, 100 mg/L NaClO solution was used for chemically enhanced backwash (CEB) instead of 50 mg/L as recommended by the manufacturer. The backwash pressure was also reduced to 1.6 bar from the manufacturer recommendation of 4 bar, which minimised hydraulic shock and vibration within the treatment system during backwash. The MF backwash was returned to an upstream trickling filter at SPWWTP and will also be returned to start of the wastewater treatment process at Davis Station.

The BAC barrier used Acticarb® (El Segundo, CA, USA) BAC GA1000N activated carbon with an Empty Bed Contact Time (EBCT) of 20 min. Monitoring of the BAC filtrate was performed by an in-line turbidity meter located in the BAC filtrate line. Turbidity was used to detect high turbidity filtrate flowing from the BAC into the RO mixing tank. The BAC backwash was activated when the head-loss increased to 25 mbar (on-line sensor) or the filtrate turbidity reached 1.5 NTU. Reticulated Hobart tap water (flowrate 3.3 L/s) was used to backwash the BAC. BAC backwash was returned to SPWWTP and at Davis station the BAC backwash will be returned to the start of the wastewater treatment plant. As the BAC was operated intermittently because of the batch operation of the treatment plant, air was intermittently fed to the BAC filter.

Five FILMTEC BW30-4040 RO elements were used in the RO array, and the designed transmembrane pressure and permeate flow were 9.4 bar and 14 L/min, respectively. The RO system incorporated a recycle stream to increase the overall recovery to 70%, with a single pass recovery of approximately 50%. The membrane integrity was monitored by both conductivity and PDTs. The PDT was conducted based on the method described by Zhang et al. [6]. The RO PDT was used to achieve the required LRV for protozoa and a protozoa LRV of 2 across the RO membranes was claimed. For this system, the initial pressure used for the PDT was 85 kPa (transmembrane pressure of 45 kPa and a static head pressure of 40 kPa) and a pressure decay rate below 3.7 kPa/min indicated a protozoa LRV of 2 could be claimed for the RO system. The RO permeate would fill a head tank first before supply to the product pipeline. The RO permeate in the head tank was used to flush the concentrate side of the RO elements when the plant switched to standby mode to dilute the concentrate and reduce fouling and osmotic pressure. To reduce the chemical inventory and storage capacity, only 90 L of 600 mg/L NaOH and 90 L of 550 mg/L HCl solutions were used for the RO CIP and no anti-scalant was used. The RO integrity was challenged using rhodamine WT dye by adding the dye into the mixing tank and measuring the dye concentration in the feed and combined permeate. A membrane autopsy was performed once the RO membranes fouled. The RO housing was cut open, samples of fouled membrane dried at 40 °C and the sample weight determined before the samples were ultrasonically cleaned in water and again dried at 40 °C before weighing. The dried sample weights before and after cleaning were used to determine the dry foulant load. A sample of the foulants was also removed from the membrane, dried at 80 °C overnight in a pre-weighed crucible, before the crucible was placed in a preheated (565 °C) muffle furnace for 2 h. The crucible and dried foulant were cooled and weighed before being re-loaded into the Muffle furnace (565 °C) overnight. The crucible and residual foulant were then cooled and weighed. Organic matter was designated as the difference between weights and inorganic matter was designated as the residue left after heating.

Two UV units (Wedeco Spectron 6) were used in series to achieve a minimum UV-C dose of >189 mJ/cm^2, as required for 4 LRV of virus. Each UV lamp was able to achieve an UV-C output of 25 W maximum, and the two units were operated to ensure water quality was maintained if one failed during service. The 10% residence time for CT value calculation, T10 (10% of the feed passes through the contactor) for the ozone contact tank and UV units were measured using the step dose method (USEPA, 1991) with rhodamine WT dye.

The calcite contactor (Puretec®, Box Hill, Victoria, Australia) had an EBCT value of 5 min to achieve a Ca^{2+} concentration no less than 20 mg/L. The need to replenish the calcite contactor with calcite was monitored using filtrate pH.

The designed free chlorine dose was 0.9 mg/L with a residual no less than 0.7 mg/L after 30 min of contact time. Both doses were monitored by online chlorine meters. All CCP related instrumentation, except for the pressure transmitters and flowrate meters, were verified weekly.

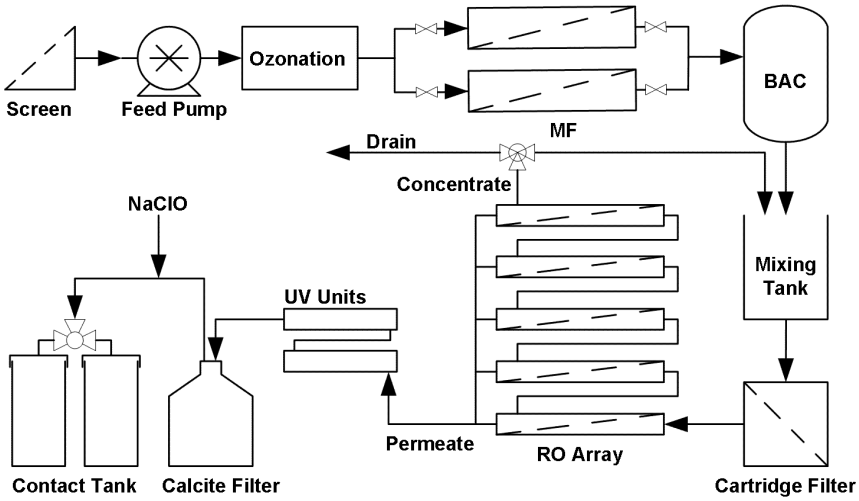

Figure 1. Schematic of the pilot plant.

2.2.2. Plant Tests and Monitoring

The AWTP was designed to achieve a water recovery of 70% at a constant feed rate of 20 L/min (1200 L/h) and could be remotely operated. The AWTP was designed to operate intermittently for a maximum of 21 h/day and had the capacity to reduce to 4 h operation every two days. It was designed to start and stop automatically and to enter standby mode when the feed tank to the treatment plant fell below a low level set point and to re-start once the tank exceeded a high level set point. The feed water quality was monitored to ensure it met the assumed feed water quality of the design, and target and alarm levels set for feedwater quality are shown in Table 1.

The plant was commissioned for 2 months to establish remote operation, verify the detection of critical control point values, and confirm automatic start/stop operation. It also established criteria for the calibration of sensors, and the frequency required to re-fill chemical tanks. Assessment was also made of the level and types of interventions (level of technical expertise) required to re-start operations after critical faults. The plant typically operated for five days per week, while intermittent operation was controlled by levels in a 'virtual' tank so actual production and standby times were similar to what might be expected at Davis Station (i.e., 6–7 h operation and 4 h standby). A formal hand-over process was not conducted at the end of the commissioning period, and an ongoing process of fault improvement continued.

Two samples were taken for each barrier weekly for analysing dissolved organic carbon (DOC) (measured by a Shimadzu (Chiyoda-ku, Tokyo, Japan), TOC_V with TNM-1 unit), total nitrogen (TN measured by Shimadzu (Chiyoda-ku, Tokyo, Japan), TOC_V with TNM-1 unit), total phosphate (TP, Shimadzu (Chiyoda-ku, Tokyo, Japan), ICP2000), calcium (Shimadzu (Chiyoda-ku, Tokyo, Japan), ICP2000) and other metals (Shimadzu (Chiyoda-ku, Tokyo, Japan), ICP2000) for comparison with the Australian Drinking Water Guideline (ADWG). *E. coli* and total coliforms were tested weekly by plate counting for samples of plant feed, ozone effluent, ceramic MF filtrate, BAC filtrate, RO permeate and product water. *Somatic coliphage* as a surrogate for virus in the plant feed, ozonation effluent, ceramic MF filtrate, BAC filtrate and product water were analysed five times during the operation period.

Biodegradable dissolved organic carbon (BDOC) of feed, ozonation effluent, ceramic MF filtrate and BAC filtrate were analysed three times during the trial by the Joret method, and were performed by Research Laboratory Services Pty Ltd. (Eltham, Victoria, Australia). The chemical consumption and plant operation time were calculated based on the data recorded by the supervisory control and data acquisition (SCADA) system. The required critical values for each barrier are listed in Table 1.

Following operation for 6 months, SCADA faults were corrected and adjustments made to the plant based on operational performance during the first operational period. Trend analysis of operational performance was formally captured on the SCADA for each barrier in the AWTP and fault analysis was recorded in the operator log. The plant did not operate during days 160–170 (Easter holiday period) or around day 180 when serious maintenance issues at SPWWTP resulted in feed water quality exceeding the set limits. Periods of high flow because of rainfall also resulted in high feed turbidity and the plant was shut down.

Table 1. Required critical control values for each barrier.

Feed Wastewater Quality	**Key Control Measure(s):**	**Ammonia (mg/L)**	**Temperature (°C)**	**Turbidity * (NTU)**	**pH**
	Target Criteria:	<1 mg/L	19 °C	<0.5 (<3)	6.5–7.5
	Alert Limit:	>1 mg/L	<16 or >28	>0.5 (>4)	pH <6.5 or >7.5
	Critical Limit:	>2 mg/L	<15 or >30	>0.5 (>5)	<6 or >8
Ozonation	**Key Control Measure(s):**	**Ozone residual (mg/L)**			
	Target Criteria:	0.25 mg/L			
	Alert Limit:	<0.1 mg/L			
	Critical Limit:	< 0.05 mg/L			
Ceramic MF	**Key Control Measure(s):**	**LRV (Based on PDT for Particle size ≥3 μm)**		**Turbidity (NTU)**	
	Target Criteria:	4.5 log		<0.3 NTU	
	Alert Limit:	<4.2 log		>0.4 NTU for >10 min	
	Critical Limit:	<4 log		> 0.5 NTU	
RO system	**Key Control Measure(s):**	**LRV (Based on PDT for Particle size ≥3 μm)**		**LRV (Based on conductivity)**	
	Target Criteria:	>2.5 log		1.5 log	
	Alert Limit:	<2.1 log		<1.2 log for >10 mins	
	Critical Limit:	<2		<1 log	
UV System	**Key Control Measure(s):**	**Dosing (mJ/cm^2)**			
	Target Criteria:	300			
	Alert Limit:	<300 mJ/cm^2 for >10 min			
	Critical Limit:	<186 mJ/cm^2			
Calcite System	**Key Control Measure(s):**	**pH**			
	Target Criteria:	7.5–8.5			
	Alert Limit:	pH <7.0 and >8.7 for >10 min			
	Critical Limit:	pH <6.5 and >9.0			
Chlorination System	**Key Control Measure(s):**	**Chlorine residual (mg/L)**			
	Target Criteria:	0.7 mg/L			
	Alert Limit:	chlorine residual <0.5 mg/L			
	Critical Limit:	chlorine residual <0.38 mg/L			

Notes: * Turbidity values are for the Davis Station MBR effluent; Values in brackets are for Selfs Point wastewater effluent.

2.2.3. Plant Challenge for Disinfection By-Products

A risk identified for AWTP was the formation of brominated and iodated disinfection by-products as ozone was used on the feedwater. While the current plant was to be operated at Davis Station, it was envisaged the same AWTP design could also be used at other locations for potable water recycling. Therefore, the AWTP was challenged with increased concentrations of bromide (Br^-) and iodide (I^-) to ensure efficient removal of disinfection by-products (DBPs) could be achieved. The AWTP feed water was spiked with bromide and iodide to produce three different feedwater concentrations: low (200 μg/L Br^-, 9 μg/L I^-), medium (490 μg/L Br^-, 37 μg/L I^-) and high (693 μg/L Br^-, 63 μg/L I^-). The high feedwater concentrations were chosen to be similar to the concentrations found in high bromide and iodide natural waters. Spiking with bromide and iodide occurred prior to any oxidative process and chlorination was the final disinfection process. Samples were taken throughout the plant (Plant Feed, Post Ozone, Post MF, Post BAC, RO Feed, RO Concentrate, RO Permeate and Product

Water) and analysed for a variety of DPBs (bromate (BrO_3^-), iodate (IO_3^-), Adsorbable Organic Halides (AOCl, AOBr and AOI), trihalomethanes (THMs) and haloacetic acids (HAAs)). Duplicate measurements were carried out for all samples.

Samples (24) were collected in amber bottles. Residual ozone in the Post ozone and Post MF samples was quenched with sodium sulphite during collection, while Product Water samples were quenched for chlorine.

Ion chromatography (IC) (Dionex (Sunnyvale, CA, USA) ICS3000 ion chromatograph) was used to analyse for halides (Br^- and I^-) and oxyhalides (BrO_3^- and IO_3^-). The IC was fitted with an anion exchange column (Dionex IonPac® (Sunnyvale, CA, USA) AS9-HC 4 × 250 mm), used sodium carbonate as the eluent and utilised conductivity and UV for detection. Filtered samples (500 µL) were injected into the IC and the anions were measured simultaneously. Br^- and I^- were detected using conductivity. BrO_3^- and IO_3^- were detected using an online post-column reaction (using acidified potassium iodide, catalysed by heptamolybdate) with UV/Vis detection.

The method of Kristiana, et al. [7] was used to analyse for specific adsorbable organic halides (AOCl, AOBr and AOI). Acidified (pH 2) 50 mL of samples were passed through two activated carbon columns in series, the activated carbon columns combusted (Mitsubishi AQF-100), the hydrogen halide gases collected in MilliQ water and subsequently analysed in an IC system using an anion exchange column (Dionex IonPac® (Sunnyvale, CA, USA) AS19-HC 4 × 250 mm) and conductivity detector.

Head-space solid phase micro-extraction (SPME), followed by gas chromatography separation and mass spectrometry detection (GC–MS) was used to analyse for 10 trihalomethanes (THMs) according to a published method [8]. The THMs analysed were Iodoform (CHI_3), Bromodiiodomethane ($CHBrI_2$), Dichloroiodomethane ($CHCl_2I$), Bromochloroiodomethane (CHBrClI), Dibromoiodomethane ($CHBr_2I$), Chlorodiiodomethane ($CHClI_2$), Bromoform ($CHBr_3$), Bromodichloromethane ($CHBrCl_2$), Chlorodibromomethane ($CHBr_2Cl$), and Chloroform ($CHCl_3$).

Liquid–liquid extraction (LLE) with methyl-tert-butyl-ether (MtBE), subsequent derivatisation with acidic methanol, followed by quantification using GC-was used to analyse the haloacetic acid concentrations. The nine haloacetic acids (HAAs) measured were Bromodichloroacetic acid (BDCAA), Tribromoacetic acid (TBAA), Dibromoacetic acid (DBAA), Chlorodibromoacetic acid (CDBAA), Bromochloroacetic acid (BCAA), Bromoacetic acid (MBAA), Trichloroacetic acid (TCAA), Dichloroacetic acid (DCAA) and Chloroacetic acid (MCAA).

Specific ultraviolet absorbance at 254 nm ($SUVA_{254}$), defined as the ultra-violet absorbance at 254 nm (UV_{254}) divided by dissolved organic carbon (DOC) concentration, was measured for all DBP Plant Feed and Post Ozone samples. $SUVA_{254}$ was used as a measure of the aromatic content of the organic matter (i.e., strong reactive sites). A Shimadzu TOC-Vws Total Organic Carbon (TOC) analyser was used to measure DOC concentrations and UV_{254} was measured using a Cary 60 UV-Vis Spectrophotometer (Agilent Technologies, Santa Clara, CA, USA).

2.2.4. Screening for Trace Organic Chemicals (TrOCs)

An Automated Identification and Quantification System database method (AIQS-DB) was linked to gas chromatographic–mass spectrometric (GC–MS) and liquid chromatographic-time of flight mass spectrometric (LC-TOF-MS) methods to allow the determination of more than 1250 trace organic chemicals (TrOCs) in extracted water samples. These methods differ from many current operations, where a few chemicals (surrogates) are often chosen to be representative of many, because of the difficulty and cost of assessment of the very large range of chemicals that could be present in secondary effluent.

Samples of the feed, reject and product water were collected in 1 L amber glass bottles on a monthly basis and kept on ice until prepared for analysis (within 48 h). After addition of appropriate buffers and/or internal standards or other reagents, the samples were extracted by solid phase extraction (SPE): Empore SDB-XC disks for GC–MS; Waters Sep Pak PS-2 and AC-2 SPE cartridges (for LC-TOF-MS). SPE extracts were refrigerated until they were further analysed. Full methodological details can be found in [9,10].

The AIQS-DB method uses internal standard calibration curves, obtained under set operating conditions, to identify and quantify chemical substances using retention times and mass spectra. The GC–MS or LC-TOF-MS instrument conditions are required to be adjusted to the designated conditions used to compile the database in order to obtain accurate results. The results obtained from performance check standards were evaluated against three criteria (spectrum validity, inertness of column and inlet liner, and stability of response) and the difference between the predicted and actual retention times will be less than 3 s. The method detection limits (MDL) for target substances are estimated from the concentration ratio and the instrument detection limit (IDL) of model compounds and are in the range 0.01 to 0.1 µg/L for GC–MS, and 2.5–5 ng/L for LC-TOF-MS. The AIQS-DB GC–MS method can detect 940 semi-volatile substances including a variety of polychlorinated biphenyl compounds (PCBs); halogenated and non-halogenated hydrocarbons; pharmaceutical and personal care products (PPCPs); polycyclic aromatic hydrocarbons (PAHs); and agricultural compounds. The AIQS-DB LC-TOF-MS method can analyse 265 polar and non-volatile compounds, including 180 agricultural compounds and 70 pharmaceuticals.

3. Results

3.1. Feed Water Quality

Ammonia and TN data for the feedwater during the AWTP trials are given in Figure 2. The data shows that the ammonia concentration was below the target feedwater criteria for 14 days and increased above the critical limit of 5 mg/L after the SPWWTP doubled the required inflow rate of the settlers (maintenance on one settler). The feedwater ammonia levels returned to <1 mg/L after 50 days. However, another two ammonia feed concentration peaks were also found around 150 days and 210 days. The DOC (7.3–9.4 mg/L), temperature (>15 °C) and pH (6.5–7.5) did not vary significantly. Turbidity, as shown in Figure 2, was usually between 1 and 3 NTU in the feedwater, but during wet weather events this increased to 3–5 NTU. The ammonia, DOC and TN data were obtained from grab samples of the feedwater, while the turbidity, temperature and pH were collected from on-line instruments. During the high ammonia and TN period, the turbidity values averaged 2.5 NTU. Peaks in turbidity were recorded at 5 NTU and on occasion at 10–15 NTU. These turbidity results suggest that larger particles were present in the feed. The turbidity values were measured in the effluent channel. The feed was then screened (2 mm) before it entered the plant. Hence, some of the turbidity may have been removed before entering the AWTP.

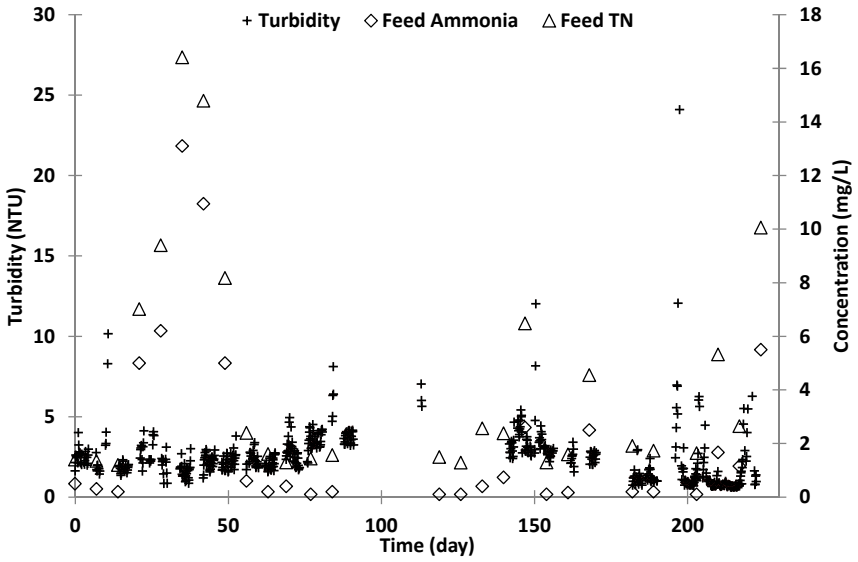

Figure 2. Feedwater ammonia, DOC and TN concentration.

In total, for about 90 days of the 230 test days, the ammonia concentrations and Turbidity were not in the CCP required range, and all the other CCPs met the required values for the feedwater.

The measured metal concentration of the feed water is shown in Table 2. It is shown that all metals of interest for ADWG in the feed water were lower than the guideline value.

Table 2. Metal concentration in the feed water.

Metal	ADWG Value (mg/L)	Concentration (mg/L)
Aluminium	0.1	<0.03
Antimony	0.003	Not detectable
Arsenic	0.01	<0.009
Barium	2	<0.008
Beryllium	0.006	Not detectable
Boron	4	<0.06
Cadmium	0.002	Under detection limit
Chromium	0.05	<0.03
Copper	2	<0.006
Iron	0.3	<0.25
Lead	0.01	Under detection limit
Manganese	0.1	<0.05
Mercury	0.001	Not detectable
Nickel	0.02	<0.005
Selenium	0.01	<0.009
Silver	0.1	<0.009

3.2. Ozonation Barrier

The ozone residual at the outlet of the ozone contact tank is shown in Figure 3, with about 50% of the measured ozone residual value less than the critical value (0.01 mg/L) and 37% greater than the targeted value (0.1 mg/L). It was found that the depletion of the ozone was directly related to the turbidity rather than the ammonia concentration [11].

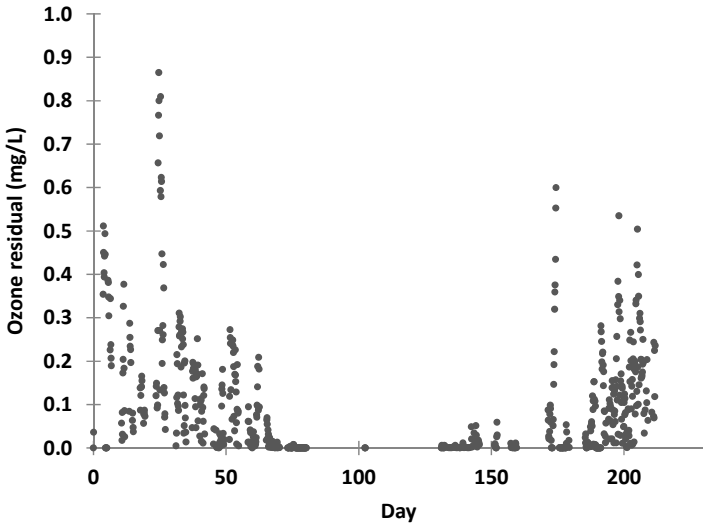

Figure 3. Ozone residual at the ozone contact tank outlet.

The Davis Station MBR should produce a reliable, low turbidity feedwater that will enable an ozone residual to be maintained, and subsequently allow the use of CT values set by the US EPA Long-Term 2 Enhanced surface water treatment rule to define the LRV value.

Figure 4 shows the variation of ozone residual along with the varying pressure of the ozone contact tank. The pressure in the ozone contactor varied as a result of downstream fouling of the ceramic MF membrane resulting in a higher upstream pressure and increasing the dissolved ozone

concentration in the water. This suggests that controlling the pressure of the ozone system by either placing a control valve on ceramic MF outlet or by including a pressure control valve on the ozone outlet and using a separate ceramic MF feed pump would provide greater control of ozone residuals for high turbidity waters. However, the short trial timespan prevented the installation of such control and inclusion of a MBR upstream of the ozone unit at Davis Station will eliminate high turbidity feed to the ozone system and hence the need for such control.

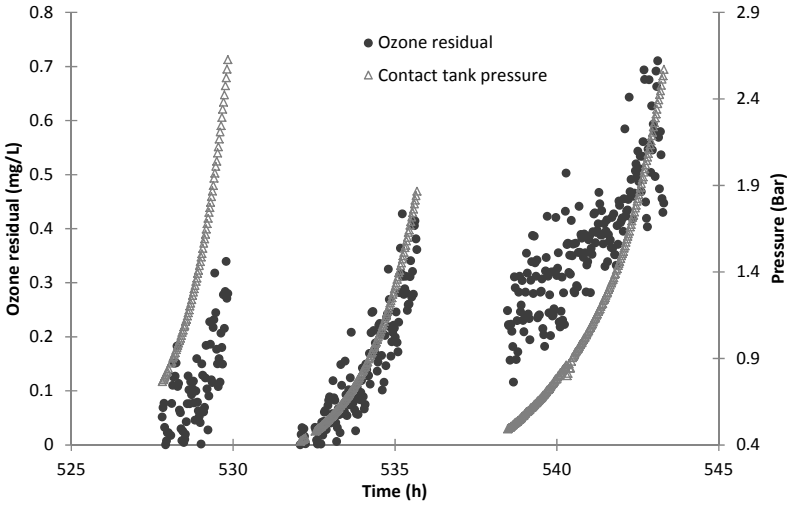

Figure 4. Relationship between the contact tank pressure and ozone residual.

The ratio of produced and transferred ozone to the wastewater is listed in Table 3. The ozone transferred to the feed water was in the range of 60% to 80%, and did not show a clear relationship to the pressure in the contact tank. However, maintaining the dosed ozone >11.7 mg/L was sufficient to ensure >2 LRV for bacteria and virus [11].

Table 3. Ozone transferred into the contact tank.

Day	Pressure in Contact Tank (bar)	Temperature (°C)	Transferred Ozone (mg/L)	Produced Ozone (mg/L)	Percentage (%)
65	0.3	20.5	13.5	20.7	65.0
126	0.4	21.4	14.8	20.6	71.9
140	0.4	22.7	11.7	19.3	60.5
155	0.7	22.7	14.9	20.3	73.3
212	0.4	19.7	16.9	20.8	81.4
224	0.4	18.0	12.9	20.9	61.8

3.3. Ceramic MF

The PDT rates of the two ceramic membranes were all below the 1.4 kPa/min limit for the entire test period, apart from when there were leaking valves [11]. The PDT data always met the required CCP limit, confirming the reliability of the ceramic MF membranes for attaining this CCP.

The filtrate turbidity from the ceramic MF measured by the online turbidity meter and the handheld meter are shown in Figure 5. The turbidity readings of the handheld meter all met the target value. However, the reading of the online turbidity meter was occasionally unable to meet the target value, and would trigger an alarm if used as a critical control point. The sample point was moved to the BAC weir from the 123th day to avoid possible influence from air bubbles in the filtrate. The initial on-line turbidity readings remained high, but after 10 min filtration, the turbidity readings were less than 0.2 NTU and mostly less than 0.1 NTU demonstrating the high quality filtration performance of the ceramic MF membranes.

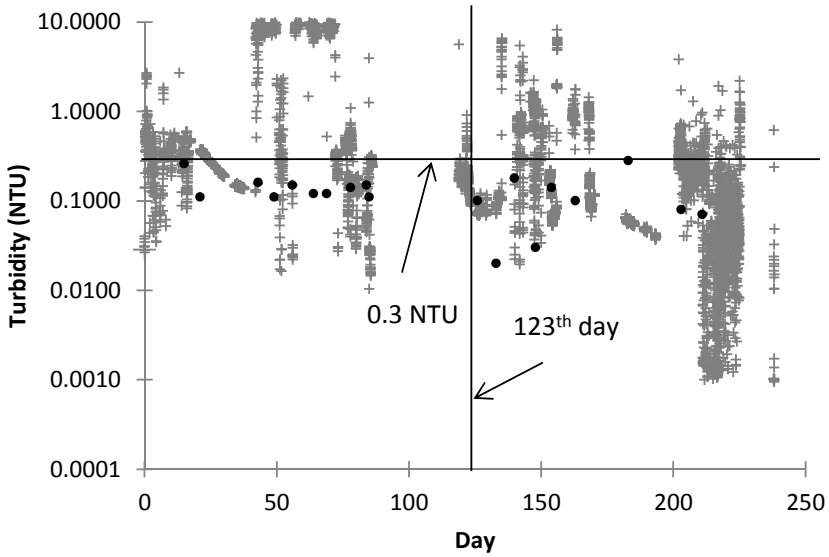

Figure 5. Turbidity of the ceramic MF filtrate (● handheld turbidity readings, + on-line turbidity readings).

No long-term fouling of the ceramic MF was observed over the entire operational period, as shown by the pressure recovery data in Figure 6. The feed pressure to the ceramic MF units increased as they fouled during filtration, but the feed pressure returned to the initial value upon backwashing and with occasional chemically enhanced backwashing. This confirms that the approach of applying a 100 mg/L NaOCl CEB was sufficient to prevent the requirement for a CIP.

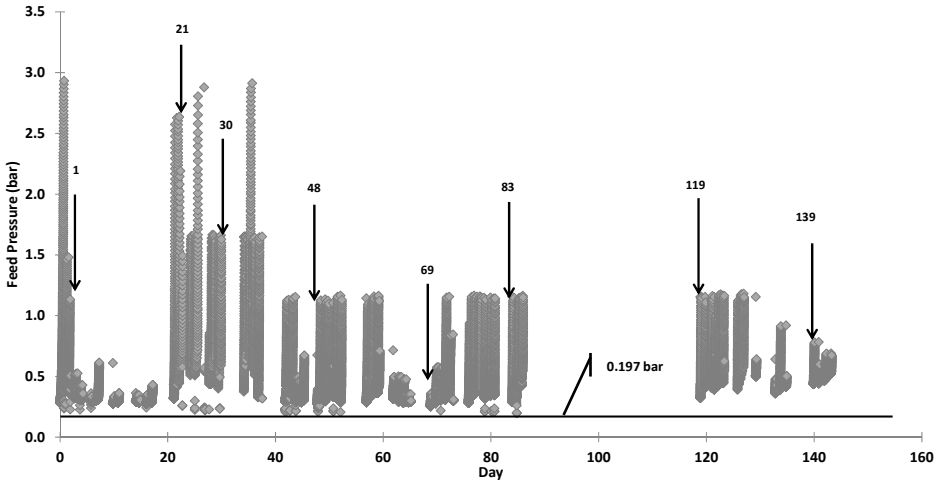

Figure 6. Feed pressure to MF number 1 over the life of the demonstration trials. The continuous line shows the initial feed pressure at the start of the trials.

3.4. Biological Activated Carbon (BAC)

An indication of bacterial concentrations on the activated carbon from three depths within the BAC were used to confirm that there was biological activity within the BAC. Activated carbon samples were taken from the top, middle and bottom of the BAC and the indicative bacterial concentrations measured by Research Laboratory Services Pty Ltd. Bacterial concentrations were determined by washing the bacteria from the surface of the activated carbon using a standard washing procedure, and growing the bacteria on agar plates. The measured microbial concentrations were 312,500 cfu/100 mL at the top; 153,333 cfu/100 mL in the middle and 103,667 cfu/100 mL at the bottom of the BAC.

These bacterial concentrations were high and reduced from the top to the bottom, consistent with declining food (biodegradable organic matter) availability as water flows through the BAC.

The head loss of the BAC filter is shown in Figure 7. Based on the data, it is seen that during the trial, the BAC filter triggered the backwash alarm twice. However, after day 123 of the test, a new protocol was used whereby a backwash was triggered on treated water volume (300 m^3). The BAC filter did not show significant head loss from this point forward.

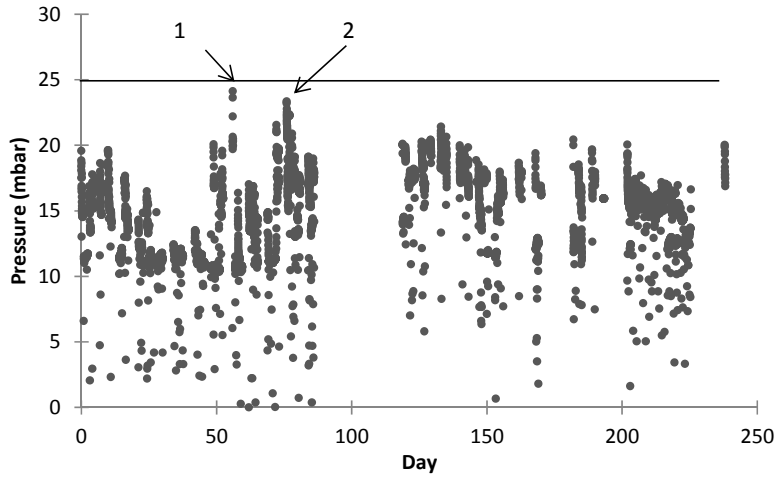

Figure 7. Head loss of the BAC filter (1 and 2 indicate times when the backwash was triggered because of high pressure drop across the BAC).

Both adsorption of organic matter and biological activity can remove organic carbon from solution as it travels through the BAC. In Figure 8, the DOC reduction over time is shown. DOC was consistently reduced by 30%–50% in the effluent in comparison with the influent.

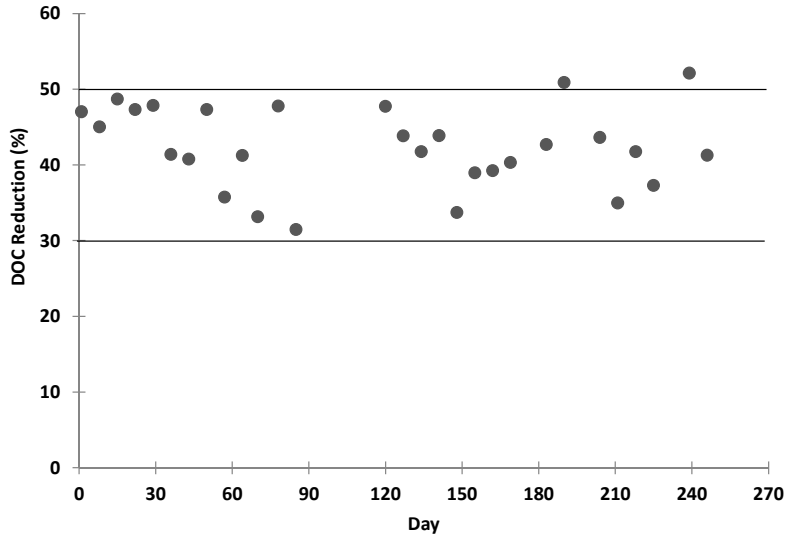

Figure 8. DOC removal across the BAC with time.

Performance monitoring of the BAC utilised on-line turbidity measurements of the BAC effluent. Turbidity values should be low and increases in turbidity may be indicative of changes in biological activity. A high turbidity (>0.2 NTU) would trigger a plant shutdown. A typical turbidity trend recorded by the online turbidity meter is shown in Figure 9. High turbidity was recorded when the plant transited from standby mode to operation mode but stabilised over the first 20 min after

commencing operation. This time is similar to the EBCT. However, a small spike, over 0.2 NTU, was also observed corresponding to backwash of the ceramic MF. It was caused by vibrational disturbance due to the sudden pressure released in the ceramic MF backwash process. Therefore, these turbidity spikes were ignored in the SCADA system to avoid regular plant shutdown.

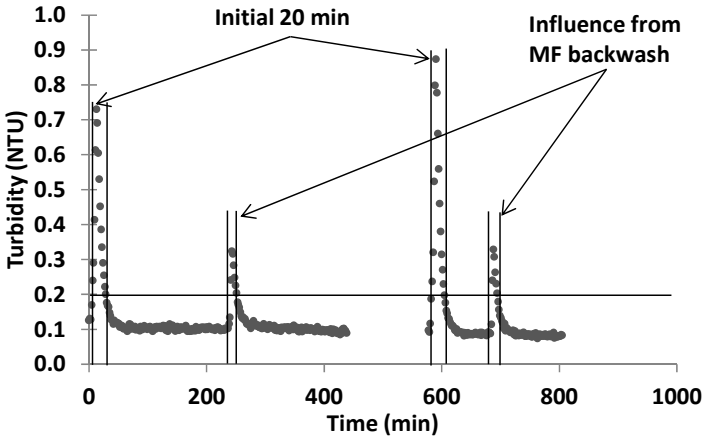

Figure 9. Typical turbidity values in the BAC filtrate.

Decreases in pH and alkalinity across the BAC can indicate that nitrification is occurring within the filter. Alkalinity and pH changes across the BAC were measured for two months and the results are shown in Table 4. The results indicate reductions in alkalinity and pH, confirming that nitrification was taking place. This is probably related to the intermittent operation of the BAC and insufficient aeration during standby operation.

Table 4. pH and alkalinity changes across the BAC.

Day	pH		Δ pH	Alkalinity (mg/L $CaCO_3$)		Δ Alkalinity (mg/L $CaCO_3$)
				Influent	Effluent	
120	7.65	7.56	0.09	/	/	/
127	/	/	/	165	157	8
134	7.74	7.62	0.12	172	163	9
141	/	/	/	163	155	8
148	7.57	7.18	0.39	166	140	26
163	7.57	7.41	0.16	138	128	10
168	7.04	6.87	0.17	152	126	26
183	7.06	7.04	0.02	135	128	7

Notes: / no data available.

3.5. RO Barrier

The RO system consisted of five-element array preceded by a 0.1 μm cartridge filter. The CCPs of RO were conductivity and PDTs, which were all in the required value range during the testing period. The RO was also challenged with Rhodamine WT, and the results are shown in Figure 10. The RO membrane barrier was able to achieve greater than 2.1 LRV for Rhodamine WT, which indicates that the membrane was able to achieve 2 LRV for virus, although only 1 LRV was claimed based on on-line conductivity measurements.

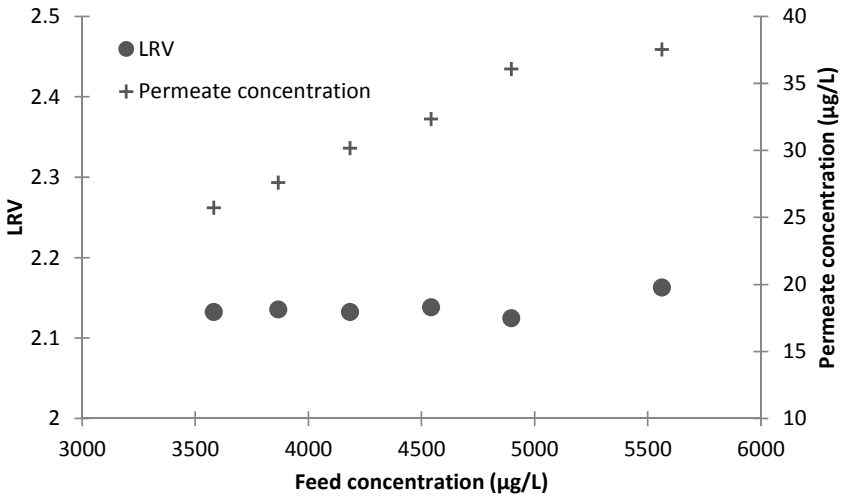

Figure 10. Rhodamine WT concentration in RO permeate and the measured Rhodamine WT LRV across the RO process.

The pressure of the cartridge filter immediately upstream of the RO was also monitored, since the blockage of the filter would lower the suction head, causing the RO high pressure pump to shut down if the pressure was less than −80 kPa. Figure 11 shows three recorded pressure drops of the cartridge filter. Based on the fitting equations in Figure 11, the cartridge filter was able to be used for 7.5 days.

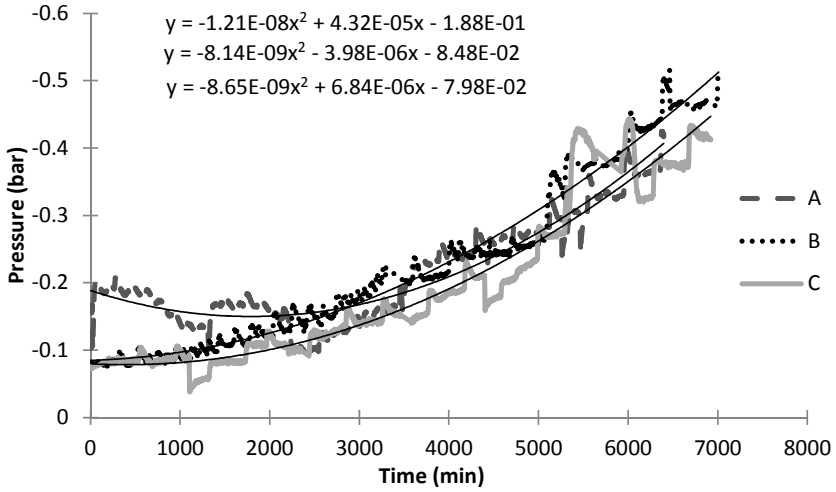

Figure 11. Pressure drop across the cartridge filter.

A fouled cartridge filter underwent an autopsy and was shown to be extensively fouled by black particles with little Mn present. It was concluded that the main foulant was carbon particles, as these particles were also observed at the bottom of the mixing tank. These fine carbon particles were assumed to be broken activated carbon. The frequent replacement of cartridge filters may be problematic for some locations, but was deemed acceptable by the AAD as the process of cartridge filter replacement could be easily achieved by their operator. However, for other locations, such frequent replacement may not be acceptable, and placement of the BAC prior to the ceramic MF may be appropriate.

Fouling of the RO membrane also occurred and a CIP was required after a period of 4–5 months, indicating a need for 2–3 CIPs each year [11]. A fouled RO membrane was also subjected to autopsy. The average foulant load was 4 g/m^2 and the ratio of inorganic matter to the organic matter was 9:100. This is consistent with the foulant layer being predominantly biofouling.

During the autopsy, it was apparent that the fouling layer could be simply removed by wiping the membrane surface. Ozone oxidation is known to oxidise membrane foulants such as protein rich, aromatic, and hydrophobic organic compounds, and the oxidation of these compounds may result in easier membrane cleaning [12].

A PDT was used to verify the integrity of the RO membranes with respect to protozoa, and the results are shown in [11]. The RO PDT confirmed >2 LRV removal across the RO membrane system for the test period. No statistically relevant decrease in RO performance was detected as a result of the PDT test.

3.6. Ultraviolet (UV) Disinfection

The T10 of the two UV units connected in series was 2.2 min, as shown in Figure 12. The online measured UVC intensities of both UV units were greater than 90 w/m^2. Therefore, the dosing for each unit is about 600 mJ/cm^2, which is much greater than the critical value of 186 mJ/cm^2.

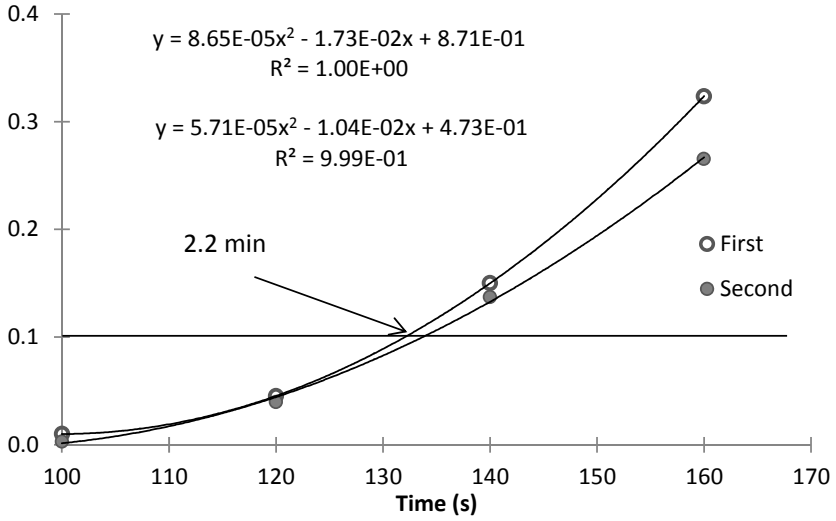

Figure 12. The residency time of the two UV units.

The UV units were problem free for all the testing period and the decayed lamp intensity at the end of the test was greater than 94% of the starting intensity.

3.7. Calcite Contactor

The average calcium concentration in the post-contactor water was 80 mg/L, and the contactor required additional calcite every 3–4 months. However, the calcium concentration changed with time and consequently the stability of the water also varied as it related to the calcium concentration, temperature, pH and alkalinity. The water stability was determined by calculating the calcium carbonate precipitation potential (CCPP) and the Langelier Saturation Index (LSI) from grab samples taken weekly and the on-line pH data in the post calcite contactor line.

Figure 13 shows the measured pH, alkalinity and total dissolved solids (TDS) against time. This data, along with the temperature, was used to calculate the CCPP and LSI values. The CCPP values were all below 0, and three points were significantly lower than 20 mg/L (−88, −64, −52 mg/L). The three outliers were believed to have arisen from pH measurement errors, as pH was hard to measure occasionally. Ignoring these three outliers resulted in an average CCPP of −8.55 mg/L $CaCO_3$ that corresponds to mildly aggressive water, with most CCPP data being between −2 to −12 mg/L $CaCO_3$. Calculated LSI values also indicated mildly aggressive water with values between −0.5 and −1.3. The amount of water processed by the calcite contactor between re-filling events was estimated to be 600,000 L of water.

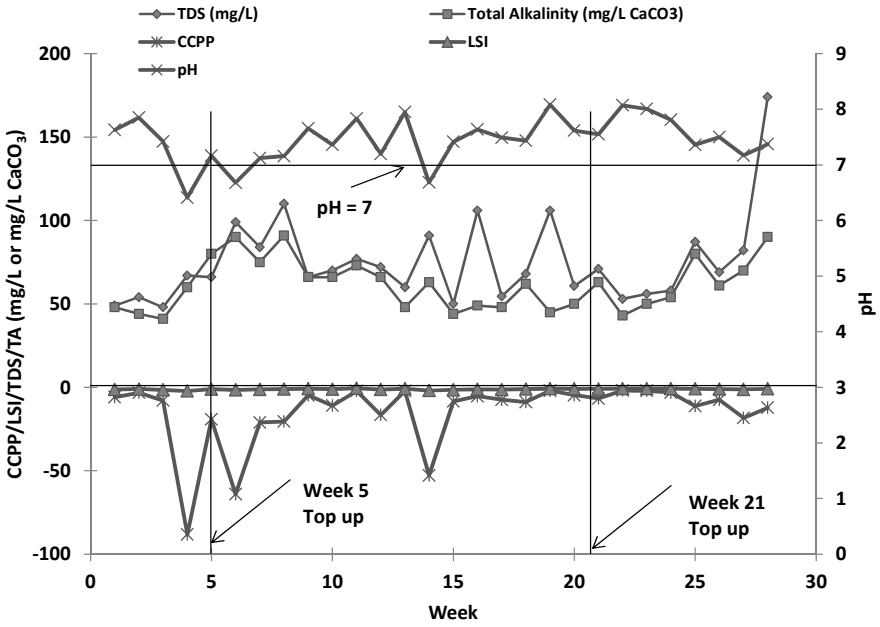

Figure 13. CCPP, LSI, pH, TDS and alkalinity of the product water.

3.8. Chlorination

Chlorination of the final product water was achieved by dosing sodium hypochlorite (12.5%). Chlorine CT data for the product water is shown in Figure 14, and demonstrates that the required CCP CT values were consistently achieved. Therefore, despite dosing concentrated hypochlorite into this small system, compliance was reliably obtained.

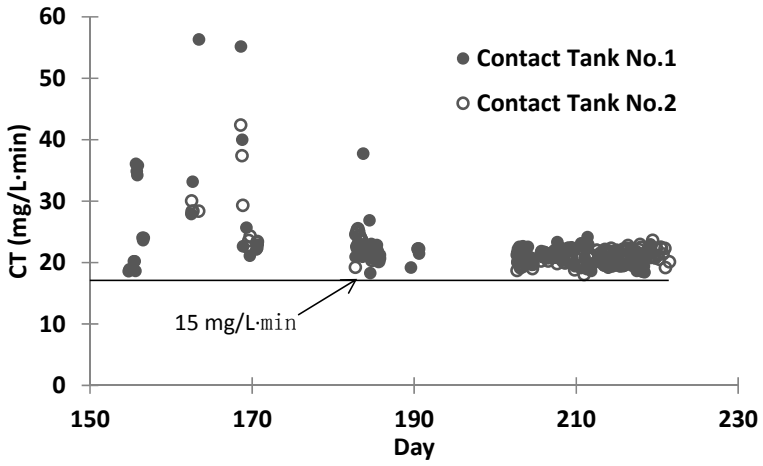

Figure 14. CT values for the product water.

3.9. Overall Assessment of the Treatment Plant

3.9.1. TN and Dissolved Organic Matter

The TN and DOC post each barrier are presented in Figure 15. BAC and RO are the major barriers for TN and DOC. There were about 44% and 94% DOC rejection and 9% and 95% TN rejection on average through the BAC barrier and RO barrier respectively. The ammonia in the BAC effluent was only detectable if the ammonia concentration in BAC influent was greater than 2.0 mg/L, which means ammonia was nitrified in the BAC [13].

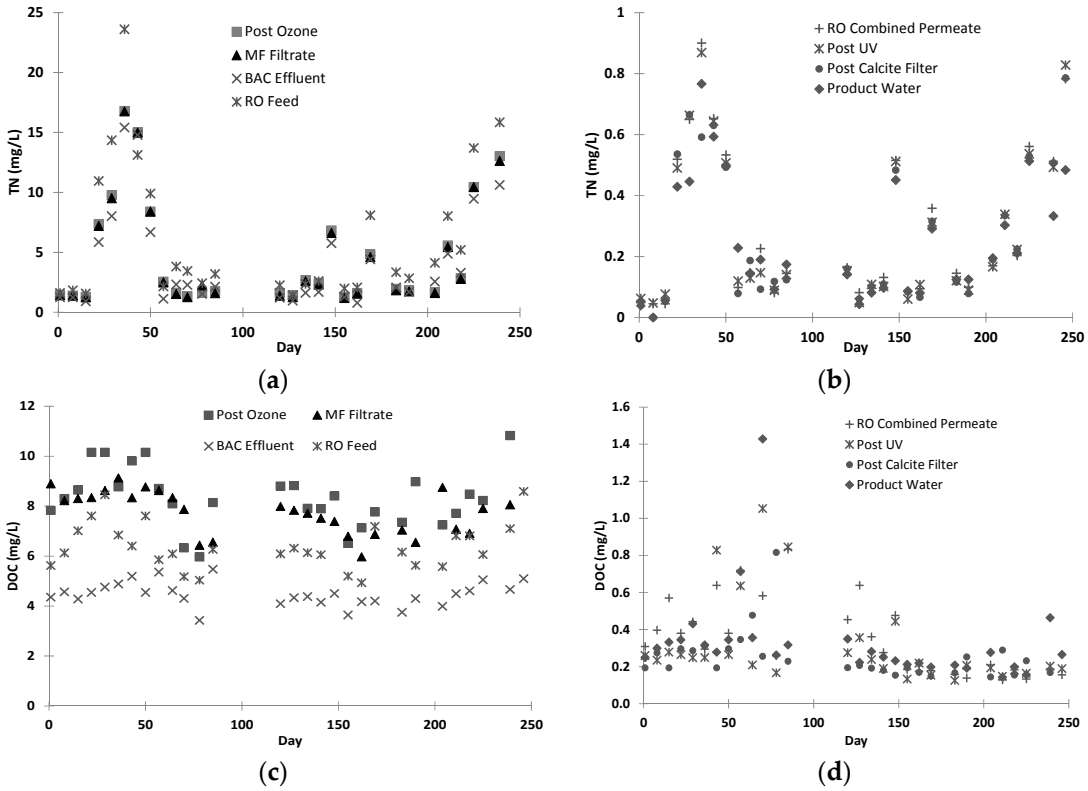

Figure 15. TN and TOC across each barrier: (**a**) TN in the streams prior to RO; (**b**) TN in the streams post RO; (**c**) DOC in the streams prior to RO; (**d**) DOC in the streams post RO.

3.9.2. Pathogens

Naturally occurred *E. coli* and *Somatic coliphage* were used as the surrogates for bacteria and virus LRV determination across the ozone system. Figure 16 shows that the minimum LRVs of the surrogates were greater than 2, and was not directly related to the detected ozone residual as shown in Figure 16. Therefore, it demonstrated that the ozone system was able to achieve 2 LRV for bacteria and virus under the test conditions, regardless of the ozone residuals. Furthermore, there was no detected *E. coli* and *Somatic coliphage* downstream of the Ceramic MF barrier.

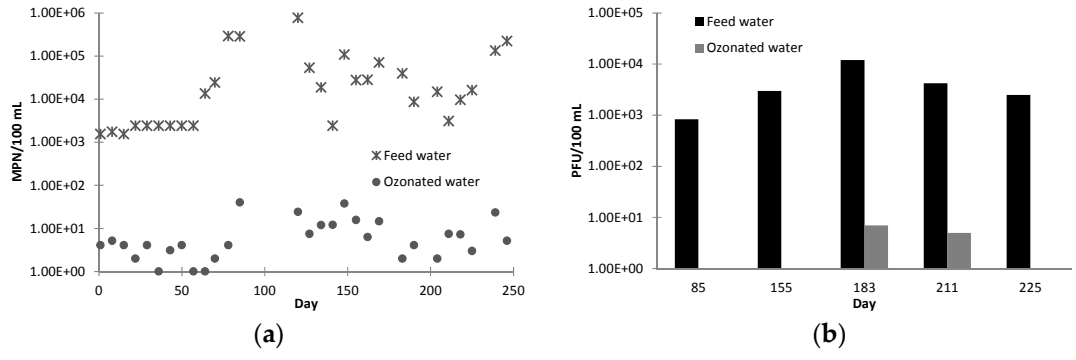

Figure 16. Ozone inactivation of bacteria and virus surrogates: (**a**) *E. coli*; (**b**) *Somatic coliphage*.

The required LRV of 10.1 for protozoa were achievable based on the integrity validation (PDT) of the ceramic MF and RO membranes and UVC dosing. An extra 0.5 LRV might be gained at Davis Station, since the feed turbidity will be significantly reduced as a result of treatment with the upstream MBR plant.

3.9.3. BDOC Removal

The BDOC across each barrier is shown in Figure 17, and the BDOC increased up to 88% post ozonation, reduced about 10% post the ceramic membrane, and reduced further by up to 70% post BAC. However, the BDOC concentration post BAC was still greater than 1 mg/L, which is sufficient to cause bio-fouling of the RO membrane. Therefore, an increase of the BAC EBCT is suggested.

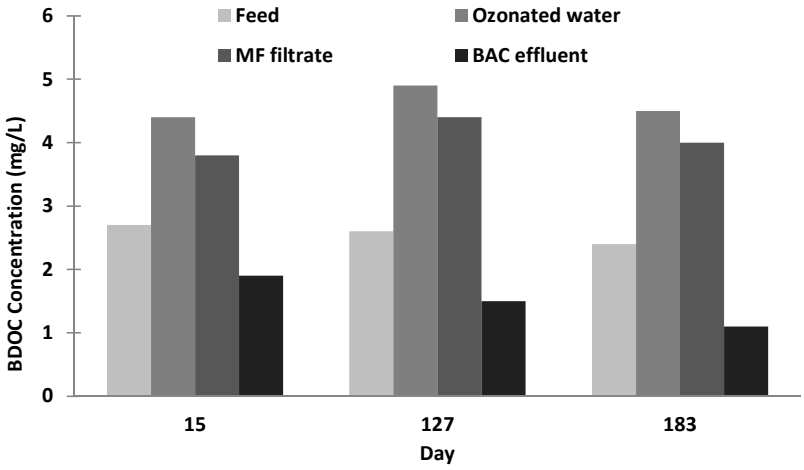

Figure 17. BDOC across process barriers prior to RO.

3.9.4. Trace Organic Compounds (TrOCs)

Analysis for TrOCs in the feed water identified 80 chemicals, with 40% detected more than once. The detected compounds included disinfection by-products (1), antibiotics (7), non-steroidal pharmaceuticals (1), other pharmaceuticals (18), pesticides (7), antioxidants (2), fatty acid methyl esters (5), fragrances (3), fire retardants (3), sterols/stanols (11), and other miscellaneous organic chemicals (20). Antibiotics and PPCPs, including chemicals such as carbamazepine, sulfamethoxazole and triclosan comprised the majority of compounds detected. Natural compounds, such as coprostanol and stigmasterol, were also detected.

Only sixteen TrOCs were observed in the RO brine concentrate and all but two were at sub-µg/L levels. This indicates that most TrOCs were removed by the treatment process. For the 16 chemicals that were detected in the RO concentrate, the range of compounds included fragrances (3), fire retardants (1), pharmaceuticals (5), fatty acid methyl esters (2), antioxidants (1), and other miscellaneous organic chemicals (4). All TrOC concentrations were below the ADWG values and none of the TrOCs identified were listed in the Australian and New Zealand Environment and Conservation Council (ANZECC) and the Agricultural and Resource Management Council of Australia and New Zealand (ARMCANZ) guidelines [14] for marine discharge.

Twenty different TrOCs were detected in the product water, and this included fire retardants (2), pharmaceuticals (2), fragrances (5), antioxidants (1), sterols/stanols (2), fatty acid methyl esters (2), and other miscellaneous organic chemicals (6). Less than half of these compounds were detected more than once and all at very low concentrations (sub-µg/L and close to their limits of reporting). Only 2-pheonoxy ethanol was identified in more than half of the product water samples. All TrOCs were below the ADWG values.

3.9.5. Bromide and Iodide Spiking

The concentrations of halide and oxyhalide ions are shown in Figure 18, in which 0 was given to the limit of detection (LOD) value. As expected, the iodide was oxidised completely post ozonation (Figure 18d), in comparison to the 14%–18% conversion of bromide to bromate [15]. The BAC and RO (Figure 18a–c) were the main barriers for bromide, bromate and iodate. Although BAC is not

usually considered able to remove bromate and bromide [16], more than 15% removal was observed for bromate and bromide. BAC filtration removed approximately 46% of the bromide for the medium and high bromide/iodide concentrations. This is considered to result from ozonation of the feed in the presence of high organic carbon concentrations. The reaction of ozone with bromide to form bromine is rapid ($HOBr + BrO^-$) ($k = 160\ M^{-1} \cdot s^{-1}$), but the subsequent reaction for bromate formation is relatively slow. Hence, the bromine preferentially reacts with organic carbon to form AOBr that is adsorbed onto the activated carbon. While high bromide concentrations were detected, it is proposed that it was actually in the form of bromine. Quenching of the samples during collection reduced bromine to bromide. Since the BAC had been soaked in the plant water for more than 10 months (earlier than the plant trial) before sampling and should have reached adsorption equilibrium, the reduction of bromide and bromate could also be partly due to biological activity. RO removed about 98.5% of total bromide and bromate, and about 99% of the iodate.

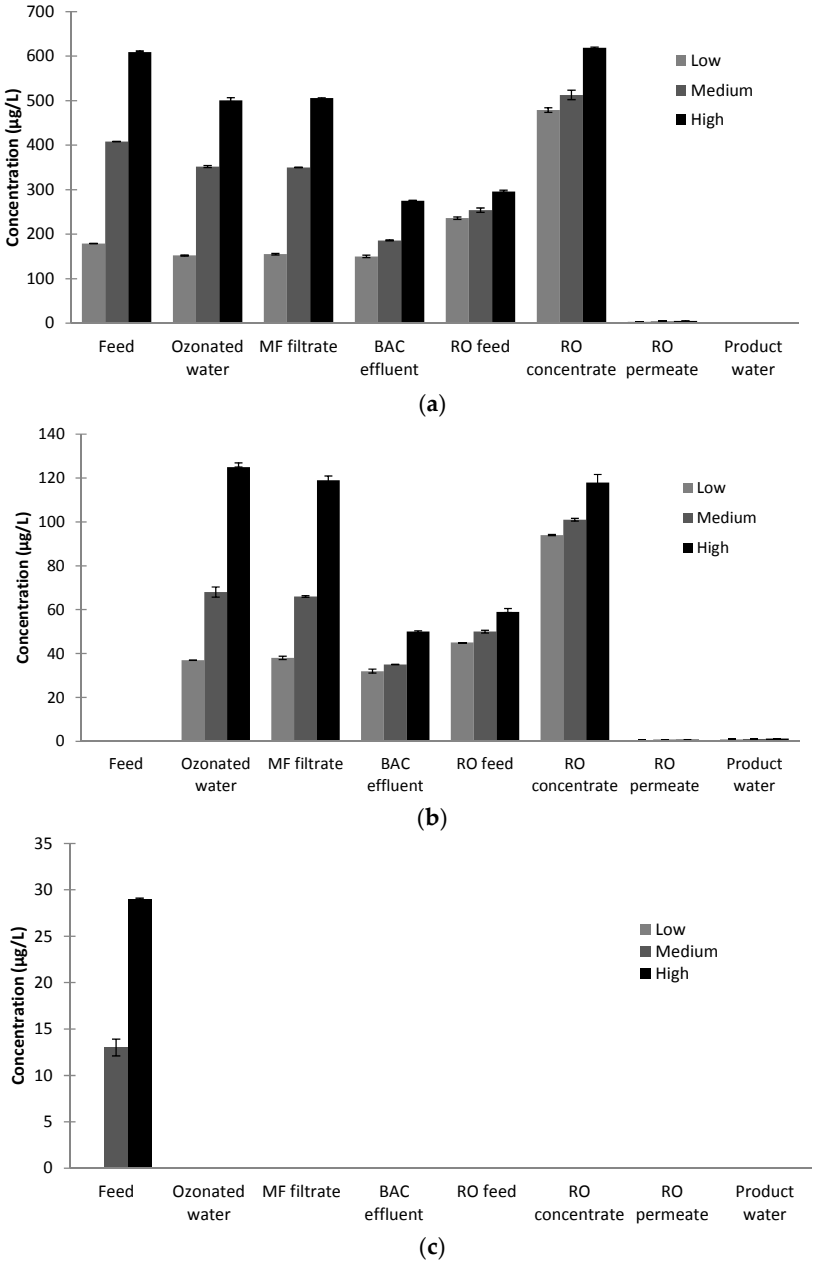

Figure 18. *Cont.*

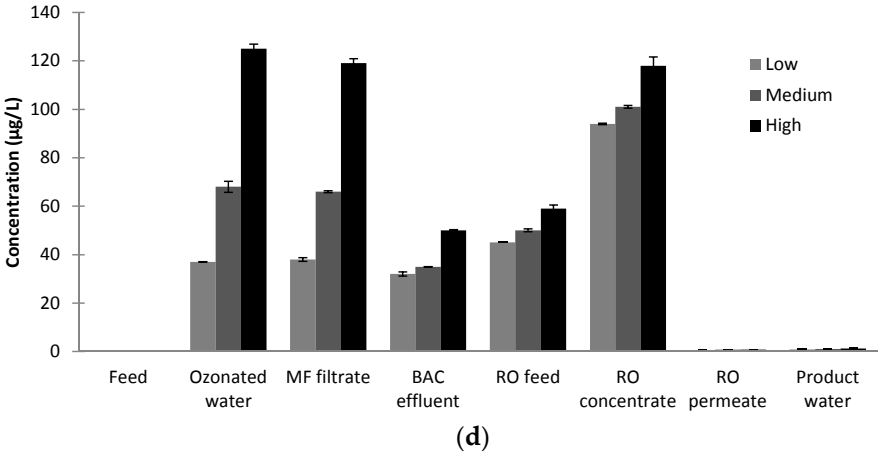

Figure 18. (**a**) Bromide concentration in each process stream; (**b**) Bromate concentration in each process stream; (**c**) Iodide concentration in each process stream; (**d**) Iodate concentration in each process stream for low, medium and high dosing of bromide and iodide.

Concentration data for specific adsorbable organic halides (AOX) and HAAs after each unit process and for the high, medium and low bromide and iodide spiked feeds can be found in Zhang et al. [17], along with similar data for the concentrations of different THM species. These results show:

- Bromate, dichloroacetic acids (DCAA) and total trihalomethanes (TTHMs) were all below the Australian Drinking Water Guideline values for all samples.
- THMs such as chloroform, chlorodibromomethane, bromodichloromethane and bromoform, bromate and dichloroacetic acid were only detected at very low concentrations in the product water following UV and chlorination. Of the possible iodinated THMs, only dibromoiodomethane was detected in low concentrations (nanograms per litre) in the product water, and this was only for the medium and high bromide/ iodide feed concentration feeds. The low $SUVA_{254}$ values for the plant feed (2.5 $L \cdot mg^{-1} \cdot m^{-1}$) refer to low aromatic-C content DOC and hence had low reactivity, leading to low concentrations of DBPs.
- Chloroform ($CHCl_3$) concentrations increased after BAC treatment, and it was considered that this was due to release of previously adsorbed chloroform from saturated BAC filters.
- Iodinated THMs were detected at only very low concentrations because the rapid kinetics of iodate (IO_3^-) formation favoured its production over the slower formation of AOI.

3.9.6. Plant Discharge Water Quality

The RO concentrate is to be discharged to pristine marine receiving waters when the AWTP is located at Davis Station. The AAD did not provide any water quality targets for RO concentrate discharge so direct comparison of the rO concentrate water quality to target values is not possible. Therefore, contaminant concentrations in the RO concentrate were compared to the ANZECC and ARMCANZ guideline [14] values. Many metals present in the RO concentrate (B, Ba, Fe, and Mn) have no guidance value for marine waters. However, Zn has a value of 15 µg/L for the protection of 95% of species and 7 µg/L for the protection of 99% of species. Zn concentrations in the RO concentrate were between 155 and 348 µg/L (30 samples), values that are 10–70 times higher than the guideline values. Phosphorus (P) also had high discharge concentrations (1.2–10.5 mg/L) compared to the concentrations for pristine marine waters (0.01–0.02 mg/L P). Ammonia concentrations in the RO concentrated were estimated from the post-BAC and RO permeate concentrations, and knowing the water recovery was set at 70%. A maximum ammonia concentration of 0.43 mg/L was estimated, which is below the guideline value of 0.91 mg/L for 99% protection of species in marine waters.

The ANZECC and ARMCANZ guidelines only list 13 TrOCs with a guideline value for discharge to marine waters. Of these 13, only nine were analysed and none of these were detected in the RO concentrate. Additionally, the microbiological quality also improved for the RO concentrate compared to the feedwater, as there were only three *E. coli* values above the limit of detection (<1 MPN/100 mL). Hence, it is claimed that the RO concentrate had improved quality for discharge compared to the feedwater.

3.9.7. Plant Energy Use

In the design of the AWTP, low use of energy was a key target but not at the expense of low membrane fouling rates, efficient and reliable removal of pathogens and chemicals of concern, and process flexibility to process variable flow conditions. The energy consumption was assessed using actual AWTP data, as well as data taken from larger, continuous throughput plants that use similar treatment barriers.

An energy meter was installed on the AWTP and was used to measure the total energy consumption of the plant. The energy consumption for the different operating modes (production, standby, etc.) could be measured by reading the energy meter during these relevant operating modes. The energy consumption of each process barrier was also measured.

The AWTP feed flowrate was 1.2 m^3/h (20 L/min) and with 70% recovery the treated product water flowrate was 0.84 m^3/h (nominal capacity of 20 m^3/day). Energy use during continuous production was calculated by measuring the average instantaneous power during a batch run. The average instantaneous AWTP power consumption during continuous production was 1.5 kW and the minimum energy requirement for water production was 1.8 kWh/m^3. An approximate power draw for each process barrier and its energy contribution to the production of purified water is shown in Table 5.

Table 5. Instantaneous power draw and the energy contribution to the purified water production for each AWTP process barrier.

Section	Power (kW)	Energy Demand (kWh/m^3)
Ancillary including lights, computer, and instruments	0.28	0.33
Feed pump	0.11	0.13
Oxygen pressure swing adsorption (PSA) and ozone circulation pump	0.32	0.38
Ozone generator	0.17	0.20
Total for ozone barrier	0.60	0.71
MF	0	0.00
BAC	0	0.00
RO (pumps)	0.35	0.42
UV	0.19	0.23
Cl_2 (pumps)	0.10	0.12
Total	**1.52**	**1.81**

The minimum energy consumption value did not include energy used for the air compressor and a hot water system. This ancillary equipment operates intermittently and their power draw is 1.72 and 3.5 kW respectively. Therefore, the maximum power draw for the AWTP was 7.02 kW. Energy consumption for three days of AWTP production was 75.3 kWh for production of 38.95 m^3 of purified water. During this period, the plant operating mode was 6.7 h production followed by 4 h standby (15 h/day), and the energy use was 1.93 kWh/m^3.

For comparison, the energy use from several larger plants was accessed and Table 6 shows this data.

It is possible that the AWTP flowsheet could find application at other locations where continuous, larger scale operation is appropriate. Estimation of energy consumption for a larger continuously

operated plant was, therefore, made by comparison of the energy use of the AWTP to larger operating plants with similar process units.

Table 6. Energy comparison to the AWTP at larger scale.

Section	Energy Use (kWh/m^3)	Comments
Ozone/BAC/UF	0.58	Based on 8 ML/day pressurized membrane plant
Ozone/BAC/UF	0.56	Based on 18 ML/day pressurized membrane plant
UF/ozone/BAC	0.15	Based on 126 ML/day submerged membrane plant
RO	0.56	Based on 1 ML/day plant at 3000 µS/cm
RO	1.3	Small scale brackish water plant at 5000 mg/L (approx. 10,000 µS/cm)
UV	0.004	100 ML/day for plant
Cl_2	0.1	Estimate of pumping energy only
Ancillary	0.1	Estimate only

A larger scale pressurized UF/O_3/BAC plant is more energy efficient than the same process units in the AWTP (comparison of Table 5 to Table 6). The energy consumption for the larger plants is for the total plant energy demand and includes feed pumping and ancillary energy. While a substantially lower energy use was found for the submerged membrane plant, an equitable energy use comparison appears to be of order 0.57 kWh/m^3 for larger scale continuous plants to 0.90 kWh/m^3 for the smaller, intermittent AWTP once ancillary energy use is included.

RO energy use varies with the feed water salinity. The AWTP feed had a conductivity of 600 µS/cm, but recycling of water in the RO system meant that this increased to 1000 µS/cm. Energy use for the AWTP RO system was 0.48 kWh/m^3 plus ancillaries. At larger scale, the energy use was similar being 0.56 kW·h/m^3 for a 5000 µS/cm feed and increased to 1.3 kWh/m^3 for a 10,000 µS/cm feed. The improved energy use at larger scale is because they operate in single pass rather than recycle mode, saving 10%–20% in energy use.

Energy consumption of UV and Cl_2 dosing at larger scale was calculated from equipment specifications. While there were energy improvements at larger scale, these barriers use very little energy relative to the ozone and RO barriers.

Overall energy consumption for a larger AWTP (>1 ML/day) operating in continuous processing mode is, therefore, estimated to be 1.27 kWh/m^3 (0.57 kWh for the O_3/MF/BAC, 0.50 for the RO and 0.2 for UV, Cl_2 and ancillaries).

3.9.8. Operational Robustness

The operational robustness of the AWTP was investigated against a set of pre-formed criteria that are listed in Table 7.

Table 7. Robustness criteria for the AWTP.

Criteria	Comment
Remote access and operation	Operational control and monitoring of the AWTP should be possible from a remote location.
Automatic plant start/stop	Automatic starting and stopping of the AWTP should occur, as the AWTP is required to operate in batch mode to satisfy the variable wastewater flows from the MBR.
Low skilled local operation	Local operation should only require personnel with good mechanical knowledge of the AWTP and sills to calibrate instruments. High level water treatment skills are to be sourced remotely.
Product water and RO concentrate with low risk of non compliance	The product water should comply with the ADWG and the AGWR with only an extremely low risk of non-conformity. The RO concentrate should also have an extremely low risk of being harmful to the marine environment.
Low energy and chemical use	Chemical and energy requirements should be lower compared to other sources of potable quality water.
Extended plant lifetime	The plant should operate for 20+ years, and be able to withstand transport and saline, chemical and marine environments.

The assessment was that the AWTP met the remote operation, auto start/stop (224 sequences), low risk of non-conformant water and low chemical and energy use criteria.

The criteria of 'low skilled local operation' was slightly subjective and required a detailed fault analysis across three months of operation. Since the plant was being operated as a research facility, the main assessment was whether a fault could have been fixed remotely using skilled help (even though this may not have occurred) or by unskilled personnel on-site. In the assessment period, the AWTP faulted on 19 occasions and required intervention to restart. Of these, four were unable to be fixed remotely or by unskilled personnel on site and as such, did not meet the robustness criteria. Six faults were designated able to be fixed remotely, with one designated as requiring local intervention by advanced technical personnel and eight identified as only requiring normal operational personnel for remedy. Of the faults not able to be fixed remotely or needing skilled on-site assistance, four were all associated with the gradual failure of a cooling water pump and the fifth was associated with a leak in the ceramic MF PDT circuit. The SCADA logic was changed to make isolation of such issues easier in the future.

It was concluded that a further period of operation would be required to fully assess if the AWTP could meet the "unskilled local operation" criterion. The final criterion of a long plant lifetime also failed the robustness test on three components that showed signs of corrosion during the trial. These were replaced with alternative materials and are not expected to cause issues in the future.

4. Conclusions

The demonstration plant was operated for nine months and was able to reliably produce product water suitable for drinking and a brine of low environmental impact. Membrane processes were integral to achievement of this outcome, with the ceramic MF producing low turbidity filtrate of approximately 0.1 NTU, on-line verification of membrane pathogen integrity via PDT and required no CIP over the 9 months of the trial.

Similarly, the RO membrane was able to reliably meet its conductivity CCP for virus and bacteria, and an on-line PDT provided a 2 LRV CCP for protozoa. Rejection of disinfection by-products to less than the ADWG values was achieved by the RO system. It was hoped that the RO system could operate for 6–12 months without the need for cleaning, but CIPs were required every 4–5 months (2–3 CIPs/year). High rates of fouling were observed for the cartridge filter, and replacement of filters at <2 weeks intervals was required. The AAD considered this acceptable as cartridge filter replacement is easily achieved, but it may be problematic at other locations.

Even with no residual ozone concentration, the reduction in native *E. coli* and *Somatic coliphage* across the ozone system demonstrated that LRV 2 could be achieved when the ozone dose was >11.7 mg/L. Therefore, LRV of 2 across the ozone system was claimed for an ozone dose >11.7 mg/L.

The AWTP had an energy use of 1.8 kWh/m^3 when operated continuously and 1.93 kWh/m^3 when operated in the intermittent mode required at Davis Station, while a larger scale plant was predicted to consume only 1.27 kWh/m^3.

The AWTP is planned to be shipped to Davis Station, Antarctica, in the summer of 2017/18, and will be operated for a further 12 months to assess its reliability in the Antarctic prior to deciding whether or not to implement the water recycling system. The process could also find application in other small, remote communities.

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Jean-Philippe Croué analysed samples for disinfection by-products and interpreted this data; Writing of the manuscript was led by Jianhua Zhang, Stephen R. Gray, Peter J. Scales and Graeme Allinson, and all authors contributed to modifying and reviewing of the manuscript.

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References

1. Barker, S.; Packer, M.; Scales, P.; Gray, S.; Snape, I.; Hamilton, A. Pathogen reduction requirements for direct potable reuse in Antarctica: Evaluating human health risks in small communities. *Sci. Total Environ.* **2013**, *461*, 723–733. [CrossRef] [PubMed]
2. Australian Guidelines for Water Recycling: Managing Health and Environmental Risks (Phase 2) Augmentation of Drinking Water Supplies, E.P.a.H. Council, N.H.a.M.R. Council, N.R.M.M. Council, Eds.; 2008. Available online: https://www.environment.gov.au/system/files/resources/9e4c2a10-fcee-48ab-a655-c4c045a615d0/files/water-recycling-guidelines-augmentation-drinking-22.pdf (accessed on 7 February 2017).
3. Gray, S.; Zhang, J.; Knight, A.; Scales, P.; Northcott, K. Demonstration of Robust Water Recycling: Pathogen Log Reduction Value Table. Available online: http://www.australianwaterrecycling.com.au/research-publications.html (accessed on 7 February 2017).
4. Duke, M.; Dow, N.; Murphy, D.; Clement, J. Outcomes of the Australian ozone/ceramic membrane trial on secondary effluent: Performance results from a trial using ozone combined with ceramic membranes to treat secondary effluent at Eastern Treatment Plant in Melbourne. *Water J. Aust. Water Assoc.* **2013**, *40*, 45–51.
5. Dow, N.; Roehr, J.; Murphy, D.; Solomon, L.; Mieog, J.; Blackbeard, J.; Gray, S.; Milne, N.; Zhu, B.; Gooding, A. Fouling mechanisms and reduced chemical potential of ceramic membranes combined with ozone. *Water Pract. Technol.* **2015**, *10*, 806–813. [CrossRef]
6. Zhang, J.; Cran, M.; Northcott, K.; Packer, M.; Duke, M.; Milne, N.; Scales, P.; Knight, A.; Gray, S.R. Assessment of pressure decay test for RO protozoa removal validation in remote operations. *Desalination* **2016**, *386*, 19–24. [CrossRef]
7. Kristiana, I.; Gallard, H.; Joll, C.; Croué, J.-P. The formation of halogen-specific TOX from chlorination and chloramination of natural organic matter isolates. *Water Res.* **2009**, *43*, 4177–4186. [CrossRef] [PubMed]
8. Allard, S.; Charrois, J.W.A.; Joll, C.A.; Heitz, A. Simultaneous analysis of 10 trihalomethanes at nanogram per liter levels in water using solid-phase microextraction and gas chromatography mass-spectrometry. *J. Chromatogr. A.* **2012**, *1238*, 15–21. [CrossRef] [PubMed]
9. Kadokami, K.; Tanada, K.; Taneda, K.; Nakagawa, K. Novel gas chromatography–mass spectrometry database for automatic identification and quantification of micropollutants. *J. Chromatogr. A* **2005**, *1089*, 219–226. [CrossRef] [PubMed]
10. Kong, L.; Kadokami, K.; Wang, S.; Duong, H.T.; Chau, H.T.C. Monitoring of 1300 organic micro-pollutants in surface waters from Tianjin, North China. *Chemosphere* **2015**, *122*, 125–130. [CrossRef] [PubMed]
11. Zhang, J.; Knight, A.; Duke, M.; Northcott, K.; Packer, M.; Scales, P.J.; Gray, S.R. A new integrated potable reuse process for a small remote community in Antarctica. *Process Saf. Environ. Prot.* **2016**, *104*, 196–208. [CrossRef]
12. Stanford, B.D.; Pisarenko, A.N.; Snyder, S.A.; Holbrook, R.D. *Pilot-Scale Oxidative Technologies for Reducing Fouling Potential in Water Reuse and Drinking Water Membranes*; WateReuse Research Foundation (WRRF-08-08): Arlington, VA, USA, 2013.
13. Goreau, T.J.; Kaplan, W.A.; Wofsy, S.C.; McElroy, M.B.; Valois, F.W.; Watson, S.W. Production of NO(2)(-) and N(2)O by Nitrifying Bacteria at Reduced Concentrations of Oxygen. *Appl. Environ. Microbiol.* **1980**, *40*, 526–532. [PubMed]
14. Australian and New Zealand Guidelines for Fresh and Marine Water Quality, October 2000, Australian and New Zealand Environment and Conservation Council Agriculture and Resource Management Council of Australia and New Zealand and the Agriculture and Resource Management Council of Australia and New Zealand. Available online: https://www.environment.gov.au/system/files/resources/53cda9ea-7ec2-49d4-af29-d1dde09e96ef/files/nwqms-guidelines-4-vol1.pdf (accessed on 7 February 2017).

15. Allard, S.; Nottle, C.E.; Chan, A.; Joll, C.; von Gunten, U. Ozonation of iodide-containing waters: Selective oxidation of iodide to iodate with simultaneous minimization of bromate and I-THMs. *Water Res.* **2013**, *47*, 1953–1960. [CrossRef] [PubMed]
16. Asami, M.; Aizawa, T.; Morioka, T.; Nishijima, W.; Tabata, A.; Magara, Y. Bromate removal during transition from new granular activated carbon (GAC) to biological activated carbon (BAC). *Water Res.* **1999**, *33*, 2797–2804. [CrossRef]
17. Zhang, J.; Knight, A.; Scales, P.; Packer, M.; Northcott, K.; Croué, J.-P.; Allard, S.; Tan, J.; Gray, S. *Demonstration of Robust Water Recycling: Operating Performance and Water Quality Report*; Australian Water Recycling Centre of Excellence: Brisbane, Australia, 2015.