Journal of Environmental Management 224 (2018) 122–129

Contents lists available at ScienceDirect

Journal of Environmental Management

journal homepage: www.elsevier.com/locate/jenvman

Research article

Wastewater recycling in Antarctica: Performance assessment of an advanced water treatment plant in removing trace organic chemicals

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ARTICLE INFO

Keywords:
GC-MS-AIQS screening
Recombinant receptor-reporter gene bioassay
Chemcatcher passive sampler
Direct potable reuse
Antarctica
Water quality

ABSTRACT

The Australian Antarctic Division (AAD) operates Australia's Davis Station in the Antarctic. In 2005, Davis Station's wastewater treatment plant failed and since then untreated, macerated effluent has been discharged to the ocean. The objectives of this study were to determine whether an advanced water treatment plant (AWTP) commissioned by the AAD and featuring a multi-barrier process involving ozonation, ceramic microfiltration, biologically activated carbon filtration, reverse osmosis, ultraviolet disinfection and chlorination was capable of producing potable water and a non-toxic brine concentrate that can be discharged with minimal environmental impact. The AWTP was tested using water from a municipal wastewater treatment plant in Tasmania, Australia. We used spot water and passive sampling combined with two multi-residue chromatographic-mass spectrometric methods and a range of recombinant receptor-reporter gene bioassays to screen trace organic chemicals (TrOCs), toxicity and receptor activity in the Feed water, in the environmental discharge (reject water), and product water from the AWTP for six months during 2014–15, and then again for three months in 2016. Across the two surveys we unambiguously detected 109 different TrOCs in the feed water, 39 chemicals in the reject water, and 34 chemicals in the product water. Sample toxicity and receptor activity in the feed water samples was almost totally removed in both testing periods, confirming that the vast majority of the receptor active TrOCs were removed by the treatment process. All the NDMA entering the AWTP in the feed and/or produced in the plant (typically < 50 ng/L), was retained into the reject water with no NDMA observed in the product water. In conclusion, the AWTP was working to design, and releases of TrOCs at the concentrations observed in this study would be unlikely cause adverse effects on populations of aquatic organisms in the receiving environment or users of the potable product water.

1. Introduction

The Australian Government's Australian Antarctic Division (AAD) is responsible for promoting Australia's interests in Antarctica. The AAD builds, supports and maintains Australia's Antarctic presence by providing three stations on continental Antarctica, including Davis Station. In 1991 a wastewater treatment plant (WWTP) was installed at Davis Station. Unfortunately due to biological, operational and maintenance limitations, the plant did not operate well and was returned to Australia in 2005/06. Until the installation of a new, secondary wastewater treatment plant using membrane bioreactor (MBR) technology in 2016, raw (macerated) wastewater was discharged to the ocean at Davis Station. Although disposal of the station's effluent by this method meets the minimum requirements specified by international agreements (Madrid protocol Annex III), an environmental impact assessment identified significant histological alteration in the gill and liver tissue of Antarctic rock-cod (*Trematomus bernacchii*) within 800 m of the Davis Station outfall (Corbett et al., 2014). Subsequently, the AAD decided to consider also installing an advanced water treatment plant (AWTP) based on a multi-barrier process involving ozonation, ceramic microfiltration, biologically activated carbon filtration, reverse osmosis, ultraviolet disinfection and chlorination to ensure discharges to the

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https://doi.org/10.1016/j.jenvman.2018.07.020
Received 30 January 2018; Received in revised form 1 July 2018; Accepted 6 July 2018
0301-4797/

environment meet world's best practice (Pyper, 2013). This plant was sent to Antarctica in the antipodean spring of 2017, and along with the MBR is housed in a temperature-controlled building (19 °C) to overcome operational and maintenance issues experienced with the previous wastewater treatment plant.

The AWTP enables augmentation of the water supply to Davis Station. Use of purified water in the drinking water supply without storage in an intermediate reservoir is called direct potable reuse (DPR). Although there are examples of DPR in Namibia and the USA, and indirect potable reuse (IPR) in Australia, Singapore, South Africa and the USA, there are currently no operational DPR schemes in Australia (Burgess et al., 2015), or at Australian Antarctic Territory stations. The water quality improvement technologies used in the AWTP mean it sits between what Burgess et al. (2015) described as the established concepts of 'clean' drinking water and 'dirty' wastewater streams, because it will use wastewater from the station as a source to generate potable water that can then augment potable water supplies. The Australian Guidelines for Water Recycling (AGWR; NRMMC et al., 2008) provide the framework for safe implementation of DPR systems in Australia, and hence at Davis Station. However, these guidelines are based on the water quality characteristics of large cities, not small communities (Barker et al., 2013). Moreover, municipal wastewater quality tends to be relatively stable, as a function of the dilution effect from a large population base. Davis Station, however, has around 150 expeditioners in the summer but only 15% of that number during the winter. Consequently, the process requirements of the AWTP are small (~20 kL/day) and although the inputs to the plant are source defined because of the known community size and chemical manifests, without the dilution achieved in large scale WWTPs, there is potential for spikes in both pathogenic and chemical contaminants.

Collection of grab (or spot) samples is most commonly used to characterise TrOCs concentrations in wastewaters, although integrative sampling with passive samplers (or passive sampling) is becoming a more commonly used alternative. The Interstate Technology and Regulatory Council (ITRC, 2006) defined a 'passive sampler' as "a device that is able to acquire a sample from discrete location without the active media transport induced by pumping or purge techniques." One commonly used device that relies on diffusion and sorption to accumulate analytes in the sampler is the in-situ Chemcatcher™ system (CC). The CC system uses a receiving phase with high affinity for organic chemicals, usually, but not always, separated from the aquatic environment by a diffusion limiting membrane (see Supplementary Material). In their review of the application of the CC system, Lissalde et al. (2016) noted that the CC system has principally been used as a tool in natural waters and little used to investigate TrOCs in wastewater treatment systems; those studies reported included screening of endocrine disrupting compounds in selected wastewater treatment plants in south east Queensland, Australia (Tan et al., 2007). Passive samplers had not been utilised on produced water samples in Australia at the inception of this study.

In 2005, Kadokami et al. reported an analytical method of that combines a mass-structure database with gas chromatography - mass spectrometry (GC-MS) to create a system (the Automated Identification and Quantification System: AIQS-DB) that can screen samples for 940 semi-volatile TrOCs, including numerous halogenated and non-halogenated hydrocarbons, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyl compounds (PCBs), natural compounds, a range of pharmaceutical and personal care products (PPCPs), and pesticides (Kadokami et al., 2005). Importantly, the analytical technique involves a single sample preparation and analytical step. More recently, Kadokami and his team developed a multi-residue method for liquid chromatography linked to time of flight mass spectroscopy (LC-TOF-MS) analysis that can screen samples for 265 non-volatile compounds, including 180 pesticides and 70 pharmaceuticals (antibiotics, antidepressants, beta blockers, analgesics, etc.; Kong et al., 2015). Prior to this study, the GC-MS multi-residue tool had only been used once to screen treatment plant effluents in Australia, namely in a study of more than 40 WWTP effluents (Allinson et al., 2012). More than 70 TrOCs were unambiguously identified in the effluents, including PAHs (e.g. acenaphthylene), food additives (e.g. dibenzylether), various tyre chemicals (e.g. 2(3H)-benzothiazolone), antioxidants, flame retardants (e.g. tris(2-chloroethyl)phosphate), PPCPs (e.g. caffeine, diethyltoluamide), and anticonvulsants (e.g. cabamazepine). Of the pesticides screened, carbamate insecticides (e.g. bendiocarb, propoxur), plant growth regulators (e.g. propham), and herbicides (e.g. atrazine, metolachlor, simazine) were amongst the TrOCs observed.

Clearly, even with the power of newer, database multi-residue methods, testing for all micro-contaminants/micro-pollutants is not practical or realistic. Bioassays are proven to be more sensitive than chemical analysis in evaluating the removal of organic micro-pollutants by reverse osmosis or other advanced treatment technologies by showing the observed mixed toxicity of chemicals that could fall below the quantification limit of chemical analysis (e.g. see Leusch and Snyder, 2015; Escher et al., 2014). There are a range of *in vitro* assays that have been developed to screen the receptor activity of TrOCs in water samples, including ligand-binding assays, recombinant receptor-reporter gene assays, assays based on the measurement of cell proliferation, and enzyme-linked immunosorbent assays (ELISA). The assay organism used in this study was yeast into which specific DNA sequences (response elements) have been added and linked to a reporter gene. Essentially, the assay works by quantifying the ability of a chemical to stimulate receptor-dependent transcriptional activity. Specifically, a ligand-dependent interaction of two proteins, a hormone receptor and a co-activator, and receptor activity is detected by β-galactosidase activity. In this assay, reporter gene expression is the result of a cascade of molecular events following receptor activation, and is considered to provide a more integral indication of the estrogenic activity of a compound than competitive ligand binding or cell proliferation assays. Essentially, the assay measures the activation of receptor, and allows for quantification of receptor activity, without having to know the precise chemical make up of the sample. This specific assay system was used to screen effluent samples from 45 waste water treatment plants (WWTPs) in Victoria, Australia by Allinson et al. (2010, 2011) who reported significant levels of estrogenic (ER), retinoid (RAR) and aryl hydrocarbon (AhR) receptor activity, but there had previously been no study of the Tasmanian WWTP to which the AWTP was connected.

One issue with operation of wastewater treatment and water production plants in remote areas is that of the logistical difficulties associated with transport of water samples to distant laboratories for analysis. Grab (or spot) samples are commonly used to characterise chemical residues in water samples. The advantage is that the matrix itself is analysed and concentrations can be easily related to toxicity values for assessing exceedances of regulatory threshold values (TVs) as well as for probabilistic risk assessment. The disadvantage of grab samples is that they may miss a residue peak if they are taken too infrequently. Such analytical programs become even more problematic for small and/or remote facilities where both the analytical cost per unit of water produced becomes prohibitive and the deployment of sampling expertise to site, or shipment of samples from the site to laboratory is also costly (relative to large facilities on a cost per unit of water production). Indeed, in the case of Antarctica, there are times of the year where deployment of expertise to site and shipment of samples from the site, is impossible. The broad aim of the TrOCs monitoring was to demonstrate that the water recycling process produces a saline effluent fit for disposal to the aquatic environment and a product water fit for recycling. Tools that allow sample batching and simple sampling and stabilization protocols are considered essential under such circumstances. In that context, a major aim of this study was to trial time integrative passive sampling as a means for cost-effective monitoring of chemical concentrations in the feed to the plant, the environmental discharge and the product waters. Other project objectives included