Water Research 105 (2016) 602–614

Contents lists available at ScienceDirect

Water Research

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

The environmental impact of sewage and wastewater outfalls in Antarctica: An example from Davis station, East Antarctica

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A R T I C L E I N F O

Article history:
Received 17 May 2016
Received in revised form
1 September 2016
Accepted 17 September 2016
Available online 18 September 2016

Keywords:
Antibiotic resistance
Escherichia coli
Benthic communities
Coastal ecosystem
Pollution
Stable isotopes

A B S T R A C T

We present a comprehensive scientific assessment of the environmental impacts of an Antarctic wastewater ocean outfall, at Davis station in East Antarctica. We assessed the effectiveness of current wastewater treatment and disposal requirements under the Protocol on Environmental Protection to the Antarctic Treaty. Macerated wastewater has been discharged from an outfall at Davis since the failure of the secondary treatment plant in 2005. Water, sediment and wildlife were tested for presence of human enteric bacteria and antibiotic resistance mechanisms. Epibiotic and sediment macrofaunal communities were tested for differences between sites near the outfall and controls. Local fish were examined for evidence of histopathological abnormalities. Sediments, fish and gastropods were tested for uptake of sewage as measured by stable isotopes of N and C. *Escherichia coli* carrying antibiotic resistance determinants were found in water, sediments and wildlife (the filter feeding bivalve *Laternula eliptica*). Fish (*Trematomus bernacchii*) within close proximity to the outfall had significantly more severe and greater occurrences of histopathological abnormalities than at controls, consistent with exposure to sewage. There was significant enrichment of ^{15}N in *T. bernacchii* and the predatory gastropod *Neobuccinum eatoni* around the outfall, providing evidence of uptake of sewage. There were significant differences between epibiotic and sediment macrofaunal communities at control and outfall sites (<1.5 km), when sites were separated into groups of similar habitat types. Benthic community composition was also strongly related to habitat and environmental drivers such as sea ice. The combined evidence indicated that the discharge of wastewater from the Davis outfall is causing environmental impacts. These findings suggest that conditions in Antarctic coastal locations, such as Davis, are unlikely to be conducive to initial dilution and rapid dispersal of wastewater as required under the Protocol on Environmental Protection to the Antarctic Treaty. Current minimum requirements for wastewater treatment and disposal in Antarctica are insufficient to ameliorate these risks and are likely to lead to accumulation of contaminants and introduction of non-native microbes and associated genetic elements. This new understanding suggests that modernised approaches to the treatment and disposal of wastewater are required in Antarctica. The most effective solution is advanced levels of wastewater treatment, which are now possible, feasible and a high priority for installation. As a direct outcome of the study, a new advanced treatment system is being installed at Davis, effectively avoiding environmental risks.

1. Introduction

One of the ongoing challenges facing all 30 countries currently operating Antarctic stations (COMNAP, 2015) is the treatment and

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http://dx.doi.org/10.1016/j.watres.2016.09.026
0043-1354/

disposal of sewage and wastewater (hereafter referred to collectively as wastewater). Wastewater generated on Antarctic stations is a mix of human, domestic (e.g. from kitchens and bathrooms) and light industrial waste (from workshops, laboratories and medical facilities) (Stark et al., 2015) with properties in common with municipal wastewater, however it is more concentrated due to water supply limitations and the absence of stormwater runoff (Stark et al., 2015). Municipal wastewater treatment generally aims to reduce nutrients to prevent eutrophication of coastal waters. It is the more difficult to treat contaminants that pose environmental risks in Antarctica including metals (Stark et al., 2015), persistent organic pollutants (POPs) such as polybrominated diphenylethers (PBDEs) (Hale et al., 2008; Wild et al., 2015) and other emerging organic contaminants (Emnet et al., 2015). Antarctic wastewater contains high levels of human enteric pathogens and non-native microbes, which can survive in coastal Antarctic waters (Smith and Riddle, 2009) and could lead to the introduction of non-native microbes and genetic pollution e.g. Hernández et al. (2012). A variety of treatment practices and disposal methods are used in Antarctic stations but most are not capable of ameliorating these risks (Gröndahl et al., 2009; Stark et al., 2015). More than half of Antarctic stations have no treatment, and only two have tertiary treatment (Gröndahl et al., 2009).

Under the Protocol on Environmental Protection to the Antarctic Treaty (hereafter referred to as the Madrid Protocol) the disposal of wastewater into the sea is permitted with certain requirements, however, as key terms are not defined, there are inconsistencies in practice. The wastewater management provisions of the Madrid Protocol were developed over 25 years ago and since then there have been many developments in treatment capability and affordability. The key provisions in relation to disposal of sewage and domestic liquid wastes in Antarctica under the Madrid Protocol (Annex III) are: (i) that they may be discharged directly into the sea, taking into account the assimilative capacity of the receiving marine environment and provided that such discharge is located, wherever practicable, where conditions exist for initial dilution and rapid dispersal; and (ii) where the average summer population is > 30 it must be treated by maceration before discharge to the sea. The protocol envisages wastewater treatment by rotary biological contactor (RBC), or similar processes, but the minimum treatment required is only maceration, which does not effectively remove contaminants or microorganisms. There is no definition of what constitutes 'initial dilution' (by what factor?) and 'rapid dispersal' (at what rate, to what distances?), nor 'assimilative capacity' (assimilated where and by what?). Nations that are Party to the Madrid Protocol are required to give effect to its provisions, generally through domestic legislation. Under Australian domestic legislation the disposal of the by-product of treatment of Antarctic wastewater into the sea must be done "in a manner that does not adversely affect the local environment". In addition it requires that "all reasonable steps are taken to discharge the sewage or waste into the sea at a place where conditions exist for initial dilution and rapid dispersal of the sewage or waste".

No studies have previously addressed how well the discharge of treated wastewater into Antarctic coastal waters complies with the requirements of the Madrid protocol. Many studies have examined the distribution and dispersal (maximum distance detectable) of wastewater around stations using a range of tracers: microbes (Hughes, 2003; Hughes and Thompson, 2004); chemicals e.g. PBDEs (Hale et al., 2008) and hydrocarbons (Kennicutt et al., 1995); and sewage molecular markers (Martins et al., 2012). To address compliance issues in relation to Madrid Protocol, there is a need to understand how wastewater disperses from Antarctic outfalls and how it may cause environmental impacts The environmental impacts of sewage have only been assessed at a few stations, including McMurdo (Lenihan and Oliver, 1995; Conlan et al., 2004) and Casey (Stark, 2008; Stark et al., 2014). These studies focused on communities of benthic macrofauna, however, these may not be the most sensitive or appropriate indicator for Antarctica, but no other measures of environmental impacts have been used. Higher concentrations of metals and PBDEs have been found in biota around outfalls in comparison to control sites (Negri et al., 2006; Wild et al., 2015), however these have not been linked to corresponding effects on animal health. There is also emerging evidence that the release of human enteric bacteria via sewage outfalls has lead to the introduction of antibiotic resistance into native bacterial populations (Miller et al., 2009; Hernández et al., 2012), but further evidence of the extent of this is needed.

In the Antarctic summer of 2009/10 the Australian Antarctic Division conducted a comprehensive scientific assessment of the environmental impacts of a wastewater outfall, at Davis Station in East Antarctica. Since 2005 the secondary treatment plant at Davis (an RBC) had been non-operational, with only maceration of wastewater before discharge into the sea. This study was undertaken to better understand the risks associated with the current requirements for treatment and disposal under the Madrid Protocol, and to inform decisions regarding the most appropriate treatment facility to replace the old system. Previous work described the properties of the Davis wastewater effluent and established that it was toxic to local marine species at low concentrations (Stark et al., 2015). Under summer conditions of open water, wastewater was shown to disperse in a narrow band adjacent to the coast, with retention around the outfall of poorly diluted wastewater (Stark et al., 2016). Wildlife around the outfall were being exposed to levels of sewage-associated bacteria unsafe for primary or secondary human contact, and there was accumulation of metals, PBDEs, hydrocarbons, nutrients (Stark et al., 2016) and faecal sterols (Leeming et al., 2015) in marine sediments up to 2 km from the outfall. Dilution and dispersal conditions are likely to be further limited when sea ice is present (Hughes, 2003), which at Davis is 9–10 months. Davis is broadly representative of continental Antarctic coastal stations, in size, treatment methods, and coastal environmental conditions.

In this paper we determine the environmental impacts of exposure to contaminant and microbiological hazards associated with the Davis outfall. We investigated the presence of introduced non-native microbiota in sediments, water and wildlife; tested for the presence of genetic pollution in the form of antibiotic resistance in microbes in sediments, water and wildlife; investigated impacts on marine benthic communities; tested for impacts on the health of a local fish species, *Trematomus bernacchii* as determined by histopathological abnormalities; and tested for uptake of nitrogen and carbon from wastewater effluent into the food web as determined by enrichment of stable isotopes of ^{15}N and ^{13}C.

2. Methods

Davis station is located in the Vestfold Hills, an ice-free area of rocky peninsulas in East Antarctica at 68.5764° S, 77.9689° E (Fig. 1). The marine environment consists of shallow waters (2–40 m), rocky islands, fjords and embayments and is described further in O'Brien et al. (2015). The sea is frozen for most of the year and ice breaks out for periods of 1–3 months in summer, which varies with location. Sampling was conducted between January and March 2010. The Davis wastewater treatment system is described in Stark et al. (2015). The outfall is located adjacent to the Davis wharf at the high tide point, approximately 2 m above the water/beach level. The volume of wastewater discharged from the outfall, as calculated from water consumption data, is estimated to vary between 50,000 L/month in winter, to 300,000–400,000 L/month in