Water Research 81 (2015) 343–355

Contents lists available at ScienceDirect

Water Research

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

Review

Disinfection by-product formation during seawater desalination: A review

Daekyun Kim, Gary L. Amy, Tanju Karanfil*

Department of Environmental Engineering and Earth Sciences, Clemson University, Anderson, SC 29625, USA

ARTICLE INFO

Article history:
Received 28 February 2015
Received in revised form
17 May 2015
Accepted 19 May 2015
Available online 9 June 2015

Keywords:
Desalination
DBPs
Chlorine
Bromide
Iodide
Toxicity

ABSTRACT

Due to increased freshwater demand across the globe, seawater desalination has become the technology of choice in augmenting water supplies in many parts of the world. The use of chemical disinfection is necessary in desalination plants for pre-treatment to control both biofouling as well as the post-disinfection of desalinated water. Although chlorine is the most commonly used disinfectant in desalination plants, its reaction with organic matter produces various disinfection by-products (DBPs) (e.g., trihalomethanes [THMs], haloacetic acids [HAAs], and haloacetonitriles [HANs]), and some DBPs are regulated in many countries due to their potential risks to public health. To reduce the formation of chlorinated DBPs, alternative oxidants (disinfectants) such as chloramines, chlorine dioxide, and ozone can be considered, but they also produce other types of DBPs. In addition, due to high levels of bromide and iodide concentrations in seawater, highly cytotoxic and genotoxic DBP species (i.e., brominated and iodinated DBPs) may form in distribution systems, especially when desalinated water is blended with other source waters having higher levels of organic matter. This article reviews the knowledge accumulated in the last few decades on DBP formation during seawater desalination, and summarizes in detail, the occurrence of DBPs in various thermal and membrane plants involving different desalination processes. The review also identifies the current challenges and future research needs for controlling DBP formation in seawater desalination plants and to reduce the potential toxicity of desalinated water.

1. Introduction

Rapid population growth and frequent droughts have accelerated the demand for fresh water supply around the world. Fourteen of the world's largest cities (with populations in excess of 10 million) and two-fifths of cities with populations between 1 million and 10 million are located in coastal areas (Tibbetts, 2002). Since 96.5% of the earth's water is located in seas and oceans, seawater desalination is a useful technology for addressing water scarcity problems in coastal regions. For decades, desalination operations in many countries in the Middle East, the Mediterranean Basin, as well as Australia, and the United States (US) have provided drinking water to their populations (De Munari et al., 2009; Greenlee et al., 2009; Dawoud, 2005; Reuter, 2000). The largest number of desalination plants is found in the Arabian Gulf with a total seawater desalination capacity of approximately 11 million m^3/day (Lattemann and Höpner, 2008). Due to low costs of energy in the Middle East area, thermal desalination processes (MSF: multi-stage flash; MED: multi effect distillation) have been predominant, accounting for almost 90% of the production, whereas other parts of the world deploy more membrane-based desalination plants (e.g., the main process in Spain is reverse osmosis [RO], accounting for 95% of all plants) (Lattemann and Höpner, 2008). In addition, more large-scale desalination projects are being proposed in many countries, spurred by the development of novel desalination technologies combined with the increasing demands for freshwater in those regions.

Although seawater desalination plants receive feed water via different intakes and coastal locations, open seawater intakes are the most common option. To prevent bacterial growth and biofouling in the intake structures and to improve the performance of filters, chemical disinfectants are used as a pre-treatment before multi-media filtration. Free chlorine (i.e., HOCl/OCl^-) is the most commonly used disinfectant for pre-treatment as well as final disinfection. Chloramines, ozone, and chlorine dioxide are alternative disinfectants used frequently in water treatment to inactivate any residual pathogenic microorganisms (MWH, 2005). An

* Corresponding author.
E-mail address: tkaranf@clemson.edu (T. Karanfil).

http://dx.doi.org/10.1016/j.watres.2015.05.040
0043-1354/

Nomenclature

CTA	cellulose triacetate
DBP	disinfection by-product
DOC	dissolved organic carbon
DWTP	drinking water treatment plant
HAA	haloacetic acid
HAN	haloacetonitrile
HK	haloketone
HNM	halonitromethane
HOBr	hypobromous acid
HOCl	hypochlorous acid
HOI	hypoiodous acid
I-HAA	iodinated HAA
I-THM	iodinated THM
Log K_{OW}	octanol-water partition coefficient
MCL	maximum contaminant limit
MED	multi effect distillation
MSF	multi stage flash
NOM	natural organic matter
PA	polyamide
RO	reverse osmosis
$SUVA_{254}$	specific UV absorbance
THM	trihalomethane
TOC	total organic carbon
TOX	total organic halide
UV	ultraviolet

unintended consequence of the use of chemical disinfectants is the production of disinfection by-products (DBPs) that pose adverse public health effects and environmental risks. Most studies on the formation and control of DBPs have focused on drinking water treatment utilities using surface water sources, wastewater treatment systems, and power plants, while limited research has focused on DBPs in seawater desalination systems. Since desalinated waters are low in total organic carbon (TOC) levels, it is expected that the disinfection demand and DBP formation would be relatively low. However, high bromide and iodide levels in seawater at concentrations from 50,000 to 80,000 μg/L and from 21 to 60 μg/L, respectively (Le Roux et al., 2015; Shi et al., 2013; Abdel-Wahab et al., 2010; Duranceau, 2010; Agus et al., 2009; Martinelango et al., 2006; Magara et al., 1996; Kristiansen et al., 1996; Mayankutty et al., 1995), may enhance the formation of brominated and iodinated DBPs that are known to be much more cytotoxic and genotoxic than their chlorinated analogues (Richardson et al., 2008; Plewa and Wagner, 2009). Typical concentrations of bromide in freshwater are orders of magnitude lower than those in seawater. Bromide levels in the US natural waters ranged from non-detectable to 2200 μg/L with an average of 100 μg/L, according to a survey conducted by Amy et al. (1995) and 70 μg/L based on an American Water Works Association Committee Report (2000). Recently reported bromide values are also consistent with these values. Weinberg et al. (2002) and Uzun et al. (2015) reported bromide concentrations ranging 22–400 μg/L and 7–237 μg/L, respectively, in different surface waters used by water utilities in the US. In another survey of 23 source waters of drinking water treatment plants (DWTPs), iodide concentrations varied between <0.13 and 104 μg/L with a median of 10 μg/L, while bromide concentrations varied from 24 to 1120 μg/L with a median of 109 μg/L (Richardson et al., 2008). Although bromide and iodide concentrations are substantially reduced down to non-detectable levels along with other components such as chloride and minerals present in feed water after thermal desalination processes, considerable amounts of bromide (i.e., 250–600 μg/L) and iodide (<4–16 μg/L) can still remain in seawater RO permeate and increase the formation of DBP in distribution systems (Duranceau, 2010; Agus et al., 2009; Magara et al., 1996; Ali-Mohamed and Jamali, 1989).

Blending desalinated water with conventionally treated single or multiple fresh waters drawn from other sources is a preferred method to meet the demands of drinking water and to increase the concentration of some desired ions (i.e., water conditioning). Indeed, desalinated product waters are often blended with brackish ground waters prior to distribution in many Middle East countries with inherently limited fresh water resources (Al-Mudhaf and Abu-Shady, 2008; Al-Mudhaf et al., 2009, 2011; Tawabini et al., 2011; Fayad, 1993; Ali and Riley, 1989). According to an international survey, 64% of desalination plant operators surveyed indicated blending desalinated water with treated surface/ground water during post-treatment processes (Duranceau et al., 2011). When RO permeate rich in bromide (Agus et al., 2009; Magara et al., 1996) is mixed with treated surface water, more brominated DBP species will form in the distribution system since hydrophilic organic matter remaining after coagulation/flocculation/sedimentation incorporate bromide even at low dissolved organic carbon (DOC) levels such as 1–2 mg C/L (Kitis et al., 2002).

In the past decades, extensive research has been conducted to understand the stabilization of desalinated water by adjusting the pH and alkalinity, adding corrosion inhibitors, or through blending with pre-treated water for remineralization. However, little research has been undertaken to elucidate the formation and potential toxicity of DBPs in desalinated and blended waters. The purpose of this review is to document DBP formation in both thermal and membrane desalination systems and to suggest research requirements for the assessment of potential risks of DBPs which can form in distribution systems.

2. DBP formation during pre-treatment

2.1. DBPs of interest in disinfected water and DBP regulations

Disinfection of seawater and product water is essential in desalination plants to prevent biofouling and pathogen contamination, respectively. The types and concentrations of DBPs depend on several factors, but most specifically the type and amount of disinfectant used, the contact time, the organic and inorganic contents, the temperature, and the pH (Yu et al., 2015; Yang et al., 2013; Brookman et al., 2011; Agus and Sedlak, 2010; Abdel-Wahab et al., 2010; Kampioti and Stephanou, 2002; Mayankutty et al., 1995). To date, several classes of DBPs have been identified in drinking waters, specifically trihalomethanes (THMs), haloacetic acids (HAAs), haloacetonitriles (HANs), and halonitromethanes (HNMs), iodinated THMs (I-THMs), iodinated HAAs (I-HAAs), haloketones (HKs), *N*-nitrosamines, bromate, and chlorite. Table S1 summarizes the physicochemical properties of the most prevalent DBPs and some emerging DBPs that are now the subject of research because of their potential toxicity. Enhanced brominated and iodinated DBP species have been observed in bromide/iodide rich waters (Ged and Boyer, 2014; Richardson et al., 2003; Kampioti and Stephanou, 2002). Among more than 600 DBPs identified and reported in the literature (Richardson, 1998), THMs and HAAs are the most abundant and commonly detected DBPs in chlorinated waters. Because of the potential health risks, many countries have established maximum contaminant limits (MCLs) of total THMs for