Water Research 122 (2017) 258–268

Contents lists available at ScienceDirect

Water Research

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

Reliability of pathogen control in direct potable reuse: Performance evaluation and QMRA of a full-scale 1 MGD advanced treatment train

Brian M. Pecson [a,*], Sarah C. Triolo [a], Simon Olivieri [b], Elise C. Chen [c], Aleksey N. Pisarenko [c], Chao-Chun Yang [d], Adam Olivieri [e], Charles N. Haas [f], R. Shane Trussell [c], R. Rhodes Trussell [d]

[a] Trussell Technologies, 1939 Harrison Street, Suite 600, Oakland, CA 94612, USA
[b] ARC Alternatives, Inc., 222 Sutter St, Suite 600, San Francisco, CA 94108, USA
[c] Trussell Technologies, 380 Stevens Avenue, Suite 308, Solana Beach, CA 92075, USA
[d] Trussell Technologies, 232 North Lake Avenue, Suite 300, Pasadena, CA 91101, USA
[e] EOA, 1410 Jackson Street, Oakland, CA 94612, USA
[f] Drexel University, 3141 Chestnut Street, 251 Curtis Hall, Philadelphia, PA 19104, USA

A R T I C L E I N F O

Article history:
Received 25 January 2017
Received in revised form
26 May 2017
Accepted 5 June 2017
Available online 6 June 2017

Keywords:
Direct potable reuse
Quantitative microbial risk assessment
Reliability
Redundancy
Treatment performance

A B S T R A C T

To safely progress toward direct potable reuse (DPR), it is essential to ensure that DPR systems can provide public health protection equivalent to or greater than that of conventional drinking water sources. This study collected data over a one-year period from a full-scale DPR demonstration facility, and used both performance distribution functions (PDFs) and quantitative microbial risk assessment (QMRA) to define and evaluate the reliability of the advanced water treatment facility (AWTF). The AWTF's ability to control enterovirus, *Giardia*, and *Cryptosporidium* was characterized using online monitoring of surrogates in a treatment train consisting of ozone, biological activated carbon, microfiltration, reverse osmosis, and ultraviolet light with an advanced oxidation process. This process train was selected to improve reliability by providing redundancy, defined as the provision of treatment beyond the minimum needed to meet regulatory requirements. The PDFs demonstrated treatment that consistently exceeded the 12/10/10-log thresholds for virus, *Giardia*, and *Cryptosporidium*, as currently required for potable reuse in California (via groundwater recharge and surface water augmentation). Because no critical process failures impacted pathogen removal performance during the yearlong testing, hypothetical failures were incorporated into the analysis to understand the benefit of treatment redundancy on performance. Each unit process was modeled with a single failure per year lasting four different failure durations: 15 min, 60 min, 8 h, and 24 h. QMRA was used to quantify the impact of failures on pathogen risk. The median annual risk of infection for *Cryptosporidium* was 4.9×10^{-11} in the absence of failures, and reached a maximum of 1.1×10^{-5} assuming one 24-h failure per process per year. With the inclusion of free chlorine disinfection as part of the treatment process, enterovirus had a median annual infection risk of 1.5×10^{-14} (no failures) and a maximum annual value of 2.1×10^{-5} (assuming one 24-h failure per year). Even with conservative failure assumptions, pathogen risk from this treatment train remains below the risk targets for both the U.S. (10^{-4} infections/person/year) and the WHO (approximately 10^{-3} infections/person/year, equivalent to 10^{-6} DALY/person/year), demonstrating the value of a failure prevention strategy based on treatment redundancy.

1. Introduction

The primary focus of all drinking water systems is to provide a safe water supply from the standpoint of public health. From this perspective, reliability, or the consistent protection of public health, is the most important goal (Pecson et al., 2015; Tchobanoglous et al., 2015). Modern constraints are forcing a re-evaluation of the strict separation of wastewater and drinking water, a fact particularly evident in the rapid growth of the planned reuse of

* Corresponding author.
E-mail address: brianp@trusselltech.com (B.M. Pecson).

http://dx.doi.org/10.1016/j.watres.2017.06.014
0043-1354/© 2017 Published by Elsevier Ltd.

wastewater for potable applications (Gerrity et al., 2013; NRC, 2012; Trussell et al., 2013). To ensure reliability, planned potable reuse projects supplement traditional design elements—e.g., treatment and monitoring—with an additional layer of protection in the form of an environmental buffer. Passage through a buffer, such as an aquifer or reservoir, further improves water quality through both dilution and additional treatment, while retention in the environment provides time for treatment excursions to be detected and corrected before water reaches the public (CDPH, 2014; NRC, 2012). Potable reuse has the potential to greatly expand existing supplies (NRC, 2012), but maximizing its potential assumes that future projects can be created that do not employ an environmental buffer. These so-called direct potable reuse (DPR) projects offer numerous potential benefits in terms of costs, water quality, and geographic distribution (Tchobanoglous et al., 2011). The critical hurdle to the implementation of these new projects, however, is the age-old concern: can we *reliably* produce safe water?

The goal of this study was to assess the public health reliability provided by a potential DPR treatment train in terms of pathogen control. The analysis was based on a year's worth of continuous online data collected from a full-scale, 1 million gallon per day (mgd, or 3785 m^3/d) potable reuse treatment train. The treatment train was built on the premise that reductions in certain potable reuse design elements—namely, the environmental buffer—could be compensated with enhancements in treatment and monitoring (Pecson et al., 2015). Accordingly, this study placed greater reliance on monitoring and the treatment of the nitrified, tertiary feedwater through ozone (O3), biological activated carbon (BAC), micro- or ultrafiltration (MF/UF), reverse osmosis (RO), and a UV-based advanced oxidation process (UV/AOP). One unit process that was not incorporated into the performance evaluation was chlorine disinfection.

The treatment train was designed to provide a high degree of reliability through redundancy and robustness. Redundancy refers to the provision of treatment beyond the minimum needed for public health protection (Pecson et al., 2015), a strategy that enhances reliability by reducing the likelihood that the treatment train will fail to meet the minimum requirements. In this context 'redundancy' does *not* refer to the provision of standby capacity, although this is also an important design feature of reliable systems. Robustness refers to the use of multiple treatment barriers, which provides benefits in two ways. By distributing the role of contaminant removal between several processes, a multiple barrier approach reduces the impact of any single process failure thereby reducing the chances of a complete, or catastrophic, system failure. Selecting barriers with different forms of contaminant control—physical, chemical, and biological—also improves the system's ability to mitigate the wide range of potential contaminants. The main focus of this study was the control of microbiological contaminants, as they pose the greatest acute threat to public health in water reuse (NRC, 2012; Trussell et al., 2013).

Starting in the 1980s, regulatory and health organizations began using risk-based water quality targets as the basis for regulations and guidance. Since the 1989 Surface Water Treatment Rule, federal and state drinking water regulations in the U.S. developed risk-based water quality targets for three pathogen groups: enteroviruses, *Cryptosporidium* oocysts, and *Giardia* cysts (EPA, 1989, 1998, 2006a; Regli et al., 1991). These same pathogens are also frequently used as potable reuse standards with the individual states (Texas Water Development Board, 2015; CDPH, 2014; Crook et al., 2013). A risk-based goal of 10^{-4} infections per person per year is frequently used as the basis for developing pathogen log removal targets in the U.S. (CDPH, 2014; EPA, 1989; Regli et al., 1991). There is general agreement that this same *de minimis* risk target should be used in potable reuse projects in the U.S. (CDPH, 2014; Crook et al., 2013; Tchobanoglous et al., 2015; Trussell et al., 2013). This value is in line with the 10^{-6} disability adjusted life years (DALYs) per person per year used by the WHO and other countries, as it represents an equivalent risk of acute gastrointestinal infection of approximately 10^{-3} infections per person per year, specifically for rotavirus and *Cryptosporidium* (Natural Resource Management Ministerial Council, 2008; World Health Organization, 1996; World Health Organization, 2006). Both goals were used in this study in assessing the adequacy of public health protection of the DPR treatment train.

Quantitative microbial risk assessment (QMRA) has been used to estimate pathogen risk in drinking water for over two decades (Gale, 2001; Haas and Eisenberg, 2001; Haas et al., 1999; Nadebaum et al., 2004; Regli et al., 1991; Westrell, 2004; Westrell et al., 2003). Fewer QMRA studies have been conducted on indirect potable reuse (Asano et al., 1992; Tanaka et al., 1998) and DPR (Amoueyan et al., 2017; Ander and Forss, 2011; Barker et al., 2013; Soller et al., 2016). One of the limitations of previous QMRA efforts was the lack of full-scale performance data. The use of site-specific treatment performance data is preferable to using general log removal credits since actual treatment efficacy can vary widely between plants (Smeets, 2010). The goals of this study were to (1) develop a robust data set on DPR treatment performance through continuous, year-long surrogate monitoring of a full-scale operating facility, and (2) use probability distribution functions (PDFs) from the data and QMRA to assess the ability of the treatment train to meet the risk-based targets, and produce a water that provides public health protection.

2. Materials and methods

2.1. Demonstration facility

The advanced water treatment facility (AWTF) treatment train consisted of ozone (O_3), biological activated carbon (BAC), micro- or ultrafiltration (MF/UF), reverse osmosis (RO), and a UV-based advanced oxidation process (UV/AOP). This train was tested from April 2015 to April 2016 at the Demonstration Pure Water Facility located at the North City Water Reclamation Plant (NCWRP) in San Diego, California. Design criteria for each unit process are provided in the Supplementary Information section. The feed water to the AWTF was nitrified, filtered tertiary effluent from the NCWRP. While pathogen removal performance of the NCWRP was not quantified in this study, the high degree of treatment provided upstream of the AWTF provides a number of benefits in terms of the consistency and quality of the feed water (Tchobanoglous et al., 2015). Demonstration of post-disinfection with free chlorine was not considered necessary.

2.2. Data collection

To increase system reliability, enhancements were made both in treatment and monitoring. Online monitors placed throughout the treatment train provided continuous information on process performance. Most processes were designed with monitoring redundancy to ensure that treatment performance was reliably demonstrated and to minimize the time when the system went "dark" or unmonitored. Pathogen removal performance was continuously quantified using on-line monitoring of surrogates (Table 1). While pathogen removal through BAC is likely to occur, it is not included in Table 1 due to (1) the lack of studies characterizing and confirming the degree of removal achieved, and (2) the absence of an accepted surrogate framework for the awarding of pathogen removal credit.

All data were collected at 10-s intervals and passed from the unit