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Modeling of heterotrophic bacteria counts in a water distribution system

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ARTICLE INFO

Article history:
Received 20 June 2008
Received in revised form
14 November 2008
Accepted 22 November 2008
Published online 3 December 2008

Keywords:
Distribution systems
Water quality monitoring
Heterotrophic bacteria
Multi-level Poisson regression
Modeling

ABSTRACT

Heterotrophic plate count (HPC) constitutes a common indicator for monitoring of microbiological water quality in distribution systems (DS). This paper aims to identify factors explaining the spatiotemporal distribution of heterotrophic bacteria and model their occurrence in the distribution system. The case under study is the DS of Quebec City, Canada. The study is based on a robust database resulting from a sampling campaign carried out in about 50 DS locations, monitored bi-weekly over a three-year period. Models for explaining and predicting HPC levels were based on both one-level and multi-level Poisson regression techniques. The latter take into account the nested structure of data, the possible spatiotemporal correlation among HPC observations and the fact that sampling points, months and/or distribution sub-systems may represent clusters. Models show that the best predictors for spatiotemporal occurrence of HPC in the DS are: free residual chlorine that has an inverse relation with the HPC levels, water temperature and water ultraviolet absorbance, both having a positive impact on HPC levels. A sensitivity analysis based on the best performing model (two-level model) allowed for the identification of seasonal-based strategies to reduce HPC levels.

1. Introduction

For monitoring of microbiological water quality in distribution systems (DS), heterotrophic plate count (HPC) is used as a typical indicator (Grabow, 1996; Edberg and Allen, 2004; Pavlov et al., 2004). HPC is used as a sentinel in the surveillance of water quality and is generally non-pathogenic bacteria that can be found in DS, in particular when pipes are dirty or when levels of residual disinfectant are insufficient (Edberg et al., 1997; Rusin et al., 1997; Zhang and DiGiano, 2002; Berry et al., 2006). Growth of bacteria in DS depends on a number of physical, chemical and operational conditions (Zhang and DiGiano, 2002), as well as on seasonal fluctuations (Berry et al., 2006). According to literature the main factors contributing to this are free residual chlorine, the presence of easily assimilated organic carbon (AOC), water temperature, water pH, the nature of the pipes, presence of corrosion and shear in the biofilm–liquid interface (LeChevallier et al., 1990,

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0043-1354/$ – see front matter © 2008 Elsevier Ltd. All rights reserved.
doi:10.1016/j.watres.2008.11.030

1993; Ollos, 1998; Zhang and DiGiano, 2002; Liu et al., 2002; Ndiongue et al., 2005). Some authors also mention the distance from the water treatment plant (i.e., a surrogate for residence time), conductivity and water turbidity (Carter et al., 2000; Momba et al., 2004).

High HPC may indicate some failure in the treatment process, especially disinfection, and contamination events within the DS (Allen et al., 2004; Sartory, 2004). The spatial and temporal variability of HPC can indicate, in some cases, a non-specific contaminant intrusion in the DS. In other cases to detect intrusion, other parameters must be considered (such as total/faecal coliforms). In addition, HPC can then used as an early indicator of the deterioration of water quality (Sartory, 2004). In some DS, HPC may reach values greater than 10 000 cfu/ml (Allen et al., 2004). In conditions of high HPC in water, detection of coliforms in culture media with lactose may be inhibited (Geldreich et al., 1972; LeChevallier and McFeters, 1985; Allen et al., 2004; Reasoner, 2004). Largely for this reason, a threshold of 500 cfu/ml is frequently used as an operational criterion when monitoring HPC in North America (USEPA, 1989; Health Canada, 2004). In other countries (e.g., Japan and Germany), a count below 100 cfu/ml for HPC favors acceptable hygienic conditions in the distribution system (Pavlov et al., 2004; Hambsch et al., 2004).

Regular monitoring of HPC provides useful information for assessing microbiological drinking water quality. However, surveillance of HPC at high frequency in several locations of the DS, common for other parameters, is expensive and time-consuming. In addition, to insure control of water quality in the DS, proper understanding of operational and water quality parameters associated with HPC is required. Previous work in this area basically explored individual relationships between HPC and certain parameters (van der Kooij, 1992; Carter et al., 2000; Stine et al., 2005) using generally small databases and, in some cases, developed experimentally. It is important to investigate the simultaneous impact of operational and water quality parameters on HPC occurrence based on a large database collected in full DS and based on robust data analysis methodologies. The study is based on spatiotemporal information on HPC and other water quality and operational parameters generated during a long period in a large DS. The main objectives of this paper are to: i) identify factors empirically explaining the spatiotemporal distribution of HPC in DS and ii) develop and compare models that allow prediction of HPC occurrence.

2. Methodology

2.1. Case under study

The case under study is the main DS of Quebec City, Canada, serving nearly 240 000 people. Quebec City is located in a region that experiences major seasonal climate variations. For instance, summer is relatively short, relatively warm (water temperature may reach 25 °C) and often wet. On the other hand, winter is very long and very cold (water temperature slightly higher than the freezing point during five months approximately). The treatment plant (TP) of the DS under study draws raw water from the Saint-Charles River. This water undergoes a treatment process consisting of pre-chlorination followed by coagulation–flocculation–sedimentation, slow sand filtration, ozonation and finally post-chlorination (Rodriguez et al., 2007). Average yearly ozonation dose is about 1.75 mg/l O_3, whereas post-chlorination dose is about 1.8 mg/l in average. The average yearly value of total organic carbon (TOC) in the treated water (before distribution) is about 1.5 mg/l. The DS is divided into four (4) sub-systems (DSS) or networks (QC1–QC4), each having different hydraulic characteristics in terms of pipe material, pipe age and pressures, and serving specific sectors of Quebec City. The majority of pipe sections in the DS are made of cast iron, polyvinyl chloride and ductile iron. In all provinces of Canada, surveillance of HPC in drinking water is not mandatory, as it is for faecal and total coliforms (MDDEPQ, 2001). Thus, very little information is available on HPC spatiotemporal variability in DS.

2.2. Sampling and analytical methods

This study is based on an intensive sampling campaign carried out at several locations of the DS during 2003 (47 locations), 2004 (61 locations) and 2005 (56 locations). In most cases, locations were sampled every two weeks. This database is very rich spatially and temporally compared to those used in other studies. For instance, the database used by Zhang and DiGiano (2002) for the Raleigh DS serving over 250 000 people, contained a maximum of 140 samples. They were collected monthly on 10 sampling points during 14 months.

During each campaign, samples were collected to measure HPC, total and faecal coliforms, free residual chlorine, water temperature, ultraviolet absorbance at 254 nm (UV-254 nm), pH, turbidity, true and apparent color and conductivity. UV-254 nm was measured as an indicator of organic matter in water. All samples were collected in commercial and public buildings after flushing water for about 5 min. Water temperature and free residual chlorine were measured in the field. The other parameters were measured at the water quality laboratory. For sampling of microbiological parameters, bottles sterilized with sodium thiosulfate were used. Samples were transported to the laboratory in iceboxes to maintain their temperature at 4 °C.

Free residual chlorine was measured using the colorimetric method (DPD) with a Hach Pocket colorimeter II. pH was measured based on standard method 4500-H+B (APHA et al., 1998) with an Orion SA720 potentiometer. Turbidity was measured based on method 2130B using a Hach 2100N turbidimeter. Conductivity measurement was based on method 2510B using an Orion 1230 conductivimeter. An Ultrospec Biochrome 1000 spectrophotometer with a 5-cm quartz cell was used to measure UV-254 nm. The same spectrophotometer was used to measure color. Analysis of HPC was based on method 9215B using an R2A culture medium with incubation time of 48 h at 35.0 ± 0.5 °C. These incubation conditions are those recommended by the Standard Methods for the Examination of Water and Wastewater (APHA et al., 2005) and other organizations and associations in Europe and North America (Standing Committee of Analysts, 2002; Health Canada, 2006).