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Impact of human operational factors on drinking water quality in small systems: an exploratory analysis

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ABSTRACT

Small distribution systems face numerous challenges in drinking water production because of financial insufficiency. In these systems, where treatment installation is often based on a simple step of disinfection, every element of water production and monitoring is under the responsibility of local operators. As a result, drinking water quality in small systems becomes more sensible to operators' interventions, which should be considered in the comprehension of the variability of water quality. The objective of this study is to define the impact of human operational factors on drinking water quality. Observations and individual interviews were conducted with operators of 21 small systems in two Canadian provinces. Drinking water quality was sampled at the same time in the systems under study. A first analysis allowed to categorize systems according to their human operational factors and to identify factors contributing the most to drinking water quality. Results suggest that the most important human operational factor is experience, which has a positive correlation with other factors, as motivation and autonomy. In order to determine the relative influence of human operational factors, raw water quality and the applied treatment were also considered. Multi-level analysis has revealed that global human operational factors do not explain global drinking water quality, as raw water quality and treatment are the main explanatory parameters. However, when drinking water quality was assessed daily, only the variability of human operational factors could explain the variability of drinking water quality.

1. Introduction

Small drinking water systems have financial and technological issues that routinely make water delivery a challenge. Indeed, small systems cannot afford complex water treatment installations and, in many cases, have limited capacities to remove contaminants from source water (MDDEFP, 2004; Dore et al., 2013). In Canada, several small systems use one treatment alone: a disinfection step usually ensured by chlorine (Conestoga-Rovers and Associates, 2010; Canadian Municipal Water Consortium, 2014). Consequently, small systems become more vulnerable to water quality failures than larger systems. Moreover, as recent studies have reported, the temporal variability of source water quality may significantly affect the final quality of distributed water (Coulibaly and Rodriguez, 2003; Al Khatib et al., 2005; Ouyang et al., 2006). This presents an additional difficulty for drinking water operators, especially in small municipalities. Because of the lack of multibarrier and automatized water treatment installations, small system operators have to be extremely cautious regarding the stability of water quality produced all along the distribution system. As a result and compared to large systems, it is possible that the final drinking water quality in small systems may be affected much more by the operator's ability to properly control water quality changes and intervene in timely fashion. Thus, this human element in operation and control is potentially an important variable in small systems to promote drinking water compliance with regulations and guidelines.

In the field of drinking water, some studies have investigated the impact of humans on drinking water quality. However, this influence has mostly been defined in terms of the impact of human activities (agricultural, recreational, etc.) on the source environment. The *human* appellation is most commonly used to designate anthropogenic pressure or contamination (Rizzi et al., 2014; Charlier et al., 2015). Some authors have used that definition in order to distinguish this type of human factor from the actions of a

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person directly involved in drinking water management. Studies focusing on these individual human elements use several appellations, such as *human reliability* or *human error* (Sträter, 2001, 2004), and *human elements* or *human factors* (Charlton and O'Brien, 2002; Blackman et al., 2008; Berges et al., 2011). In order to make a clear delineation between this type of impact and the anthropogenic impacts, we chose to use the appellation *human operational factors* to designate the impact of drinking water operators.

Human operational factors (HOFs) such as motivation, experience and performance have already been investigated in several other fields (aviation and the oil and gas industries) owing to the possible fatal consequences of human error (U.S. Nuclear Regulatory Commission Office of Nuclear Regulatory Research, 2002; Chang and Wang, 2010). However, there is very little information on how HOFs could affect the final quality of drinking water. The quality of produced and distributed drinking water depends on raw water quality, treatment and control (monitoring, maintenance, etc.). Treatment and control include both technical and human operational aspects. According to studies carried out on the causes and conditions preceding waterborne diseases, it has been pointed out that in many cases water quality failures could indeed be associated with human errors (Hrudey and Hrudey, 2004; Maal-Bared et al., 2008). For these reasons, the importance of HOFs is obvious, and should be considered when evaluating drinking water production. The lack of information on HOFs in this area is probably due to the difficulty of evaluating and quantifying the parameters associated to human behavior in this type of industry. Nevertheless, HOFs cannot be ignored, since they constitute a critical component of drinking water production. In fact, everyday water treatment and management operations depend on the judgment and the decisions of operators; such decisions are based on their experience, knowledge and perceptions. Final drinking water quality is thus constantly dependent of HOFs.

This paper explores HOFs in drinking water management, first by establishing appropriate indicators representing HOFs and second by investigating HOF impacts on drinking water quality. The study involves water monitoring programs and operator surveys conducted in 21 small systems in Canada. The impact of HOFs on both long-term and short-term water quality variability is considered in this investigation.

2. Methods

In order to study the impact of HOFs on drinking water quality, HOFs and raw and drinking water quality were assessed using surveys and sampling campaigns in 21 small systems in Canada: eleven in the province of Newfoundland and Labrador (NL), and ten in the province of Quebec (QC) (Fig. 1). The systems under study were selected according to their size (500–5000 inhabitants), the simplicity of their treatment system (chlorination only or filtration and chlorination) and the feasibility of collaboration of local operators. Additionally, sampling campaigns and surveys were organized in six systems among the original 21 in order to study the short-term temporal variability of HOFs. Section 2.1 presents the procedures for the assessment of drinking water quality and Section 2.2 presents the methodology for the assessment of HOFs. Fig. 2 illustrates the overall methodology.

2.1. Water quality data

2.1.1. Sampling campaigns

In order to generate water quality data, a one-year sampling campaign (C1) was organized in the selected systems. The first campaign consisted of a monthly sample collection in each system from September 2010 to October 2011. In each system, sampling points were located at the raw water intake and at three locations in the distribution system: at the beginning, in the middle and at the extremity. Distribution systems in the case-studies were all linear. Measured parameters were total organic carbon (TOC), ultraviolet absorbance at 254 nm (UV_{254}) pH, temperature (T), heterotrophic plate counts (HPC), trihalomethanes (THMs), haloacetic acids (HAAs), turbidity, and free chlorine (free Cl). A second sampling campaign was organized (C2) in July and August 2012. It included daily samplings in six small systems (selected among the original 21 participants according to their HOF assessed during the first survey). This program included the measurement of the same parameters as C1 in raw water and three points of the distribution system.

2.1.2. Water quality index

In order to express water quality in one single expression, the set of water quality parameters were integrated into one formulation using an index (Silvert, 2000; Boyacioglu, 2007; Sowlat et al., 2011). The Canadian Council of Ministers of Environment (CCME) has developed a water quality index to express the global quality of natural waters (CCME, 1999). This index was adapted and applied in this study to assemble raw water quality indicators on a monthly (C1) and daily (C2) basis. A raw water quality index (RWQI) was calculated for each system, including results of the five measured parameters (TOC, UV_{254}, pH, T, and turbidity). This process resulted in thirteen monthly index values for each system. An annual average was then calculated for the expression of global raw water quality. The overall formula is presented by equation (1), as follows,

$$\mathrm{CCMEWQI} = 100 - \left(\frac{\sqrt{F_1^2 + F_2^2 + F_3^2}}{1.732} \right) \tag{1}$$

where the scope (F1) represents the number of parameters that do not meet the objectives. The frequency (F2) corresponds to the percentage of measures (tests) that do not meet guidelines in the period of interest. The amplitude (F3) is the amount by which failed test values do not meet their objectives. The factor 1.732 is applied for normalization purposes to obtain a maximum value of 100. According to the value of the index, water quality is classified in five categories: Excellent (95–100), good (80–95), fair (65–80), marginal (45–65) and poor (0–45).

The index calculation was also adapted to express global drinking water quality according to Scheili et al. (2015). The overall formula remained the same (Equation (1)) and was applied to drinking water parameters. A drinking water quality index (DWQI) was calculated monthly (C1) and daily (C2) for each system, including results of the eight parameters at three points of the distribution system (TOC, pH, UV_{254}, T, HPC, THMs, HAAs, free Cl). An annual average was then calculated for the expression of global drinking water quality. Seasonal values were obtained by applying the index to the data of three consecutive months (Fall: September, October, November; Winter: December, January, February; Spring: March, April, May; Summer: June, July, August). Each calculation included measurements of the eight parameters for each system for three months.

2.2. Human operational factor data

During the assessment of water quality in the systems under study, HOFs were also documented for monthly and daily dimensions. While the first survey (S1) served to establish an overall portrait of HOFs, daily observations in a second survey (S2) served to study their short-term temporal variability.