The predictive value of total coliforms in drinking water using life table analysis

Corinne A. Krentz, Kay Teschke, Hui Shen and Judith Isaac-Renton

ABSTRACT

Total coliform monitoring in distribution systems is no longer a required parameter in many countries but is still mandated in Canada and the USA. The value of reporting total coliform results in drinking water is a topic of debate. Total coliform and *Escherichia coli* results from small drinking water systems tested over a 3-year period in British Columbia were analyzed using life table analysis. Small drinking water systems that have a non-*E. coli* total coliform positive result have a slightly higher probability that a subsequent sample will contain *E. coli* compared to small drinking water systems with no prior total coliforms detected in the distribution system (relative risk = 2.04). One month after a non-*E. coli* total coliform positive test, the probability of the system having an *E. coli*-positive test was nearly four times that of systems with no prior total coliforms. This is of minor practical significance due in part to the low rate of *E. coli*-positive drinking water samples, reflected in the low absolute risk increase at 1 month after a non-*E. coli* total coliform test (1.6%).

Key words | drinking water quality, indicator bacteria, risk, water system

Corinne A. Krentz (corresponding author)
Kay Teschke
Hui Shen
Judith Isaac-Renton
The University of British Columbia,
Rm. G227 – 2211 Wesbrook Mall,
Vancouver,
BC, V6T 2B5,
Canada
E-mail: *Corinne.Krentz@bccdc.ca*

Corinne A. Krentz
Judith Isaac-Renton
The British Columbia Centre for Disease Control,
655 W 12th Ave,
Vancouver,
BC, V5Z 4R4,
Canada

INTRODUCTION

Ensuring that drinking water meets Canadian health-based standards (Health Canada 2012) and is safe for human consumption is dependent upon application of a multi-barrier approach. From source to tap, this involves adequate protection and management of watersheds, the removal of harmful compounds and organisms using appropriate water treatment practices, and delivery via a well-maintained distribution system. Drinking water quality is monitored for indicator bacteria within the distribution system because it gives the best representation of the safety of the drinking water being consumed.

Routine monitoring for all possible waterborne pathogens is not feasible for drinking water systems. Therefore, surrogate parameters, namely total coliforms and *Escherichia coli*, are used to measure microbiological drinking water quality. Total coliforms and *E. coli* can be detected simultaneously in a drinking water sample using a variety of chromogenic and fluorogenic tests (Edberg *et al.* 1991; Wang & Fiessel 2008). Total coliform bacteria inhabit the gastrointestinal tracts of animals and are present at up to 13 million viable cells per gram of animal waste (Geldreich *et al.* 1962). As such, their presence can be associated with fecal contamination. However, several species of bacteria belonging to the total coliform group are of non-fecal origin (Leclerc *et al.* 2001). *E. coli* is a member of the total coliform group that is almost exclusively of gut or fecal origin. Therefore it is generally recognized as a stronger indicator of fecal contamination than total coliforms (Edberg *et al.* 2000).

One consequence of the fact that total coliforms are not exclusively present in the gut and feces is that a positive total coliform test result may falsely suggest that fecal contamination is present. Total coliform bacteria and *E. coli* can also be absent when waterborne pathogens are present (Keswick *et al.* 1984; Rose *et al.* 1991). Non-bacterial pathogens including viruses and protozoa can be more resistant to disinfection treatments (Hoff & Akin 1986) than bacterial indicators and persist for longer periods. Thus, pathogens may go undetected in water that is presumed safe for human consumption.

doi: 10.2166/aqua.2013.058

The reliability of total coliforms as an indicator of water safety has been questioned since the 1970s (Barrell *et al.* 2000; Leclerc *et al.* 2001; Reynolds 2003). In response to the mounting evidence that highlights the limitations of total coliforms as a water safety indicator, governing bodies in some jurisdictions, including Australia and the European Union, have opted to use *E. coli* and Enterococci as water safety indicators and no longer require distribution system monitoring for the total coliform group of bacteria (Stevens *et al.* 2003; Standridge 2008; Figueras & Borrego 2010). Total coliforms are used more often with the intent only of the test being a process indicator to evaluate performance of treatment operations. In Canada and the USA, total coliform testing is required for all drinking water systems, although the presence of *E. coli* remains the actionable standard measure for indicating presence of fecal contamination in drinking water. Measurement of *E. coli* in water is part of an evidence-based approach to make important decisions concerning public safety related to drinking water consumption. Currently, presence of total coliforms in drinking water is taken as evidence that a system is vulnerable to contamination, but there is no immediate health risk as few of the members of the total coliform group are harmful to humans (Health Canada 2011). This is reflected in the current Canadian guidelines where the maximum allowable concentration of total coliform bacteria in finished water immediately after treatment or drawn from an untreated well is none detectable per 100 mL, but water within the distribution system may contain up to 10 colony forming units (CFU) per 100 mL (British Columbia Regulation 200/2003).

There is a need for more sensitive measures indicative of elevated risk of illness from drinking water consumption. While fecal coliforms and *E. coli* are superior water safety indicators, they are less numerous than total coliforms and thus a less sensitive indicator of change in microbial water quality (Fricker & Eldred 2009). In a preliminary examination of the microbiological water testing dataset used in this study, it appeared that some drinking water systems had detected non-*E. coli* total coliform bacteria days or weeks prior to an *E. coli*-positive test result.

The objective of this study was to investigate the value of non-*E. coli* total coliform bacteria as predictive indicators and determine how often non-*E. coli* total coliform events were followed by more health relevant changes in water quality. The hypothesis tested was that the probability of obtaining an *E. coli* positive drinking water test result from a system, given that prior samples have tested positive for non-*E. coli* total coliform bacteria, is greater than the probability of obtaining an *E. coli* positive drinking water test result from a system given that prior samples have not tested positive for total coliforms.

METHODS

Drinking water system metadata

A database of all drinking water systems in British Columbia (BC) that were registered with regional health authorities was developed in Microsoft Excel using publicly available data (http://www.healthspace.com/clients.html). It contained the facility name, size and regional health authority.

Drinking water sample test data

Total coliform and *E. coli* water sample test result data were obtained from the Laboratory Information System archive at the British Columbia Public Health Microbiology Reference Laboratory in Vancouver, BC. The test data were from samples received between January 2007 and December 2009. Each sample record contained the collection date, client name, facility name, total coliform result (CFU per 100 mL) and *E. coli* result (CFU per 100 mL). The sample dataset was trimmed using inclusion and exclusion criteria.

Inclusion criteria included the following: samples were collected from a drinking water system that was a registered drinking water system with fewer than 15 connections, and the client name on the sample requisition was one of the regional health authorities in BC (i.e., Vancouver Coastal Health Authority, Vancouver Island Health Authority, Interior Health Authority, Northern Health Authority, Fraser Health Authority).

The following exclusion criteria were applied. Data from systems that had fewer than two samples tested from 2007 to 2009 were excluded. All microbiological test results from samples of beach water, ice, sewage, swimming pool water, hot tub water and raw or pre-treatment water were excluded.

Sample data from water systems with 15 or more connections were omitted as these systems contain many sample sites representing distinct areas of the distribution system pipe network; thus, results at one location in the system may not reflect water quality at another location in the system. In comparison, all sample sites from a given small drinking water system were assumed to be interchangeable, which is supported by the findings of Sekar *et al.* (2012).

Quantitative total coliform and *E. coli* test results were transformed into binary variables. A zero was assigned if no total coliform bacteria were detected, and a '1' was assigned if there were at least 1 CFU per 100 mL present. Sample data were grouped according to drinking water facility name ($n = 1{,}519$) and arranged in chronological order. Only one sample per month was used for the analysis. If a system submitted more than one sample per month, a single sample was randomly selected for that month to be used in the analysis.

Life table analysis

A life table was calculated using the actuarial approach. All drinking water systems that had at least one non-*E. coli* total coliform (TC) positive sample were placed in the 'Prior TC' group. Any system whose first recorded sample was positive for *E. coli* was not included in the analysis ($n = 25$), as no subject can fail at the initial time point (Jiang & Fine 2007). The starting point for the Prior TC group was defined as the date that the result of the first total coliform positive sample from a drinking water system was obtained. All other systems were placed in the 'No Prior TC' group. This included systems that did not have any total coliform positive samples, and those that had an *E. coli* positive sample that was not preceded by a non-*E. coli* total coliform result. The starting point for each system in the No Prior TC group was the earliest sample collection date in the dataset. The interval period was defined as the length of time, in months, between sample data points.

The end point was defined as the date that the first *E. coli* positive sample result from the drinking water system was obtained. All observed end points fell into one of the interval periods. If data collection ended before the endpoint was reached, systems were considered 'lost-to-follow-up' in the interval after the final sample was submitted.

The data were analyzed using the assumption that any missing data for an interval were negative for *E. coli*. That is, the system remained 'event-free' until it either stopped submitting samples or had an *E. coli*-positive sample. The data were also analyzed without the event-free assumption. In this case, if no sample was submitted during an interval period, the system was counted as 'lost-to-follow-up' and any subsequent data for that system were discarded.

Life table function

The time elapsed between the starting point and each sample submitted for testing was calculated using built-in time formulas in Microsoft Excel.

The analysis was repeated using several interval widths. These were defined as 1, 2, 3, 4 and 6 months. For each interval the number of systems 'at risk' of an *E. coli*-positive result, the number of systems that reached the endpoint and the number of systems 'lost-to-follow-up' (also known as right-censored) was recorded (Breslow 1975). These values were used to calculate the probability of reaching the endpoint, or hazard, for each interval.

The probability of reaching the end of the interval without an *E. coli*-positive sample result for each interval and the cumulative probability were calculated. The cumulative probability was used to construct life table curves for the Prior TC and the No Prior TC group. Standard error for each interval was calculated using the method proposed by Peto *et al.* (1977), shown in Equation (1), where P_i is the cumulative probability of not observing an *E. coli*-positive result and R_i is the number of systems at risk at the beginning of interval i.

$$\mathrm{SE}(P_i) = P_i[(1 - P_i)/R_i]^{1/2} \quad (1)$$

Comparison of groups

The Mantel-Cox log-rank test was used to compare the life table functions of the Prior TC and the No Prior TC groups (Mantel 1966). This involved comparing the number of observed events to the number of expected events under the assumption that the null hypothesis was

true (i.e., that there was no difference between the two groups).

The total expected frequency of observing an *E. coli*-positive sample was determined for the Prior TC and the No Prior TC group, and similarly the total observed frequency for each group was determined. The Mantel-Cox chi-squared test was used to determine whether the expected rate differed from the observed rate. The overall relative risk (RR) was calculated using Equation (2), where O is the number of observed *E. coli* events and E is the number of expected *E. coli* events.

$$RR = (O_{\text{Prior TC}}/E_{\text{Prior TC}})/(O_{\text{No Prior TC}}/E_{\text{No Prior TC}}) \quad (2)$$

The Mantel-Cox chi-squared value was compared to the critical value for the chi-squared test with 1 degree of freedom to evaluate the significance of the result. A RR of 1 meant that there was no difference between the groups, whereas a RR greater than 1 indicated that the outcome was more likely to occur in the Prior TC group compared to the No Prior TC group.

Descriptive statistics

RR increase and absolute risk increase were calculated as described in Barratt *et al.* (2004). For the Prior TC group, the positive predictive value was calculated to determine the probability of an *E. coli*-positive result after 1 and 36 months. For the No Prior TC group, the negative predictive value was calculated to determine the probability of no *E. coli* being detected after 1 and 36 months. Positive and negative likelihood ratios were also calculated at 1 and 36 months as an additional measure to evaluate whether total coliform presence was predictive of *E. coli* in the short and long term (McGee 2002; Deeks & Altman 2004). A positive likelihood ratio is the ratio of the probability that the system had a prior non-*E. coli* total coliform event and detected *E. coli* in a subsequent sample to the probability that the system had a prior non-*E. coli* total coliform event but did not detect *E. coli* in future samples. Similarly, a negative likelihood ratio is the ratio of the probability of *E. coli* detection in samples that were not preceded by a non-total coliform positive result to the probability of no prior total coliform positive results and no *E. coli* in subsequent samples.

RESULTS

Of the 1,544 drinking water systems included in this analysis, 815 had one or more tests that were positive for non-*E. coli* total coliform bacteria and were placed in the Prior TC group, 704 had no total coliform positive tests or had an *E. coli*-positive result that was not preceded by a non-*E. coli* total coliform positive test and were placed in the No Prior TC group and 25 drinking water systems were removed from the dataset because the first sample in the dataset was *E. coli*-positive. A total of 139 and 78 outcomes were observed in the Prior TC group and No Prior TC group, respectively, by the end of the data collection period. The proportion of positive tests that occurred in 3 months or less was 0.35 for the Prior TC group and 0.23 for the No Prior TC group. There was little difference between the two groups in terms of the average time to reach the outcome. The mean time to reach the outcome for systems in the Prior TC group was 10 and 12 months for the No Prior TC group.

Five interval periods were analyzed, 1, 2, 3, 4 and 6 months, to evaluate the effect that data assumptions had on the measures of risk. The number of data points used in the analysis decreased and more information was lost as interval width increased. Overall, interval width (i.e., the number of months selected for the interval period) had a minor effect on RR estimates, when the data were analyzed under the assumption that a missing monthly sample was equivalent to a sample testing negative for *E. coli* (Figure 1). The probability of remaining *E. coli*-free was significantly lower for systems in the Prior TC group, compared to the No Prior TC group.

The Mantel-Cox log-rank test was used to test the null hypothesis that there was no difference between the life table functions of systems with prior total coliforms and systems with no previous record of total coliforms in the distribution system. This difference was statistically significant ($p < 0.01$) for all interval widths when data were analyzed using the event-free assumption. However, the difference between groups was not significant when the

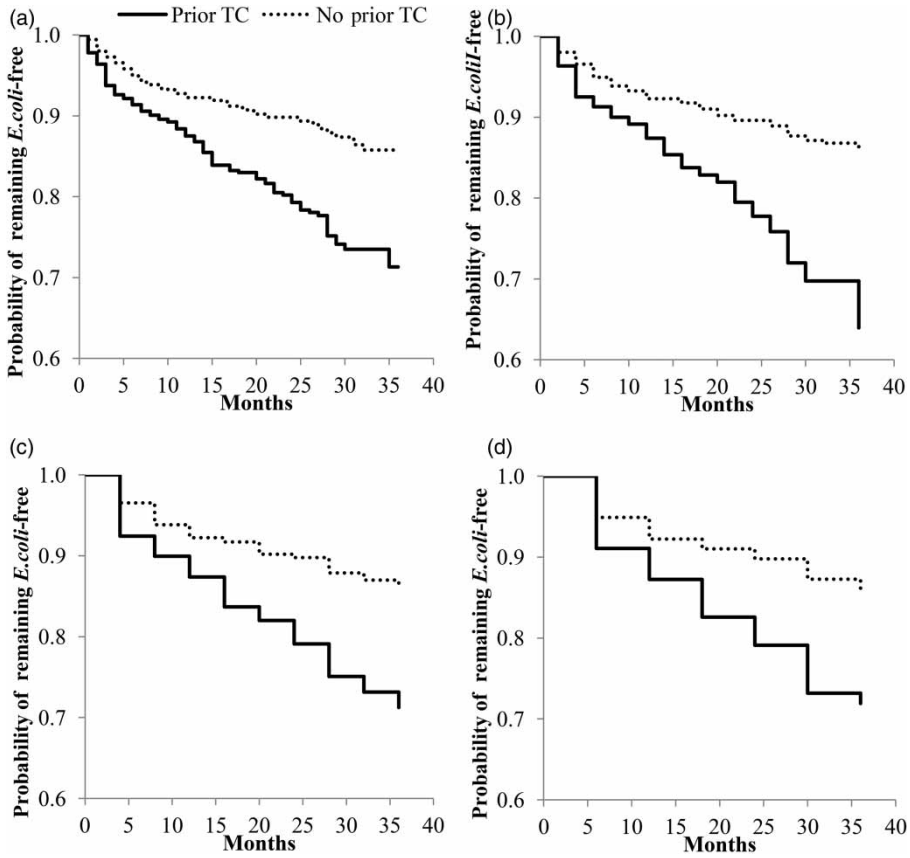

Figure 1 | Life table functions of drinking water systems with prior total coliform events and no prior total coliform events using the event-free assumption. Interval widths of 1 (a), 2 (b), 4 (c) and 6 (d) months are shown.

event-free assumption was not used and interval widths were less than 3 months (Figure 2).

The difference between the probability of observing an *E. coli* in the No Prior TC group and the Prior TC group was usually the most substantial in the first interval relative to the other intervals. The hazard ratios for the first interval in some scenarios were greater than 2 (Table 1). This meant that 1–4 months after a non-*E. coli* total coliform positive result, these drinking water systems were twice as likely to have *E. coli* detected in a subsequent drinking water sample. Up to 1 month after non-*E. coli* total coliform bacteria were detected in a water sample, the water system was almost four times more likely to have *E. coli* in a water sample compared to a system that did not have previously detected non-*E. coli* total coliform bacteria.

Life table data used to calculate descriptive statistics are shown in Table 2. It is noteworthy that nearly two-thirds (i.e., 139 out of 217) of the systems that detected *E. coli* had prior non-*E. coli* total coliform events and this is not a trivial number. The low event rates are reflected in the low absolute risk increase at 1 and 36 months. These values are 6.0% at 36 months and 1.6% at 1 month, which illustrates that there is little difference in the absolute rates at which *E. coli*-positive samples were observed between the two groups. The large RR increase at 1 month indicates that there is a large difference in the event rates between the two groups in relative terms. However, this can be misleading. Even though the event rate for the Prior TC is higher than that of the No Prior TC group, the event rates for both groups are low. The odds ratio at 1 month shows that a system with a prior non-*E. coli* total coliform result has four times the odds (i.e., the ratio of the probability of having an *E. coli*-positive sample and the probability of not having an *E. coli* in water) of a system with no prior total coliforms of having an *E. coli*-positive sample. Given that the odds are extremely low in the first place (1:175

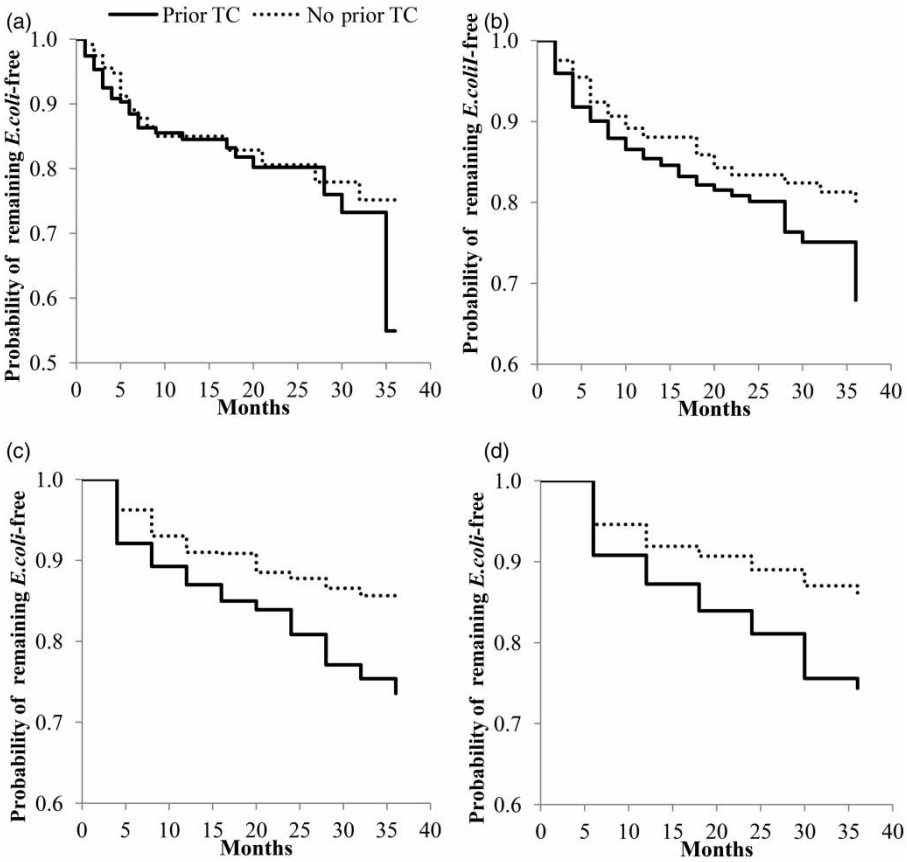

Figure 2 | Life table functions of drinking water systems with prior total coliform events and no prior total coliform events without the event-free assumption. Interval widths of 1 (a), 2 (b), 4 (c) and 6 (d) months are shown.

Table 1 | Relative risk of *E. coli* presence in drinking water

Interval width	Mantel-Cox chi-squared	Relative risk	Hazard ratio in interval 1
With event-free assumption			
One month	26.5[b]	2.04	3.88
Two months	29.7[b]	2.12	1.84
Three months	24.2[b]	1.98	2.33
Four months	23.4[b]	1.96	2.19
Six months	21.4[b]	1.90	1.75
Without event-free assumption			
One month	2.80	1.49	3.17
Two months	3.81	1.41	1.63
Three months	9.78[a]	1.66	2.19
Four months	11.0[b]	1.69	2.10
Six months	12.4[b]	1.70	1.71

[a]$p < 0.01$.
[b]$p < 0.001$.

Table 2 | Life table for prior TC and no prior TC groups at 1 and 36 months[a]

	1 month		36 months	
	Prior TC	No prior TC	Prior TC	No prior TC
Events	18	4	139	78
Systems lost	0	0	665	537
Non-events	797	700	11	89
Total systems	815	704	815	704
Event rate	0.0221	0.00568	0.171	0.111

[a]Assumption: systems that did not submit a sample during the interval period were event-free.

for the No Prior TC group), four times those odds is still a small number (1:44) but is substantial considering that British Columbia has thousands of small water systems.

The positive and negative predictive values for non-*E. coli* total coliform positive results are summarized in

Table 3 | Descriptive statistics of prior TC and no prior TC groups at 1 and 36 months[a]

	1 month	36 months
Absolute risk increase	0.0164	0.0598
Odds ratio	3.95	1.56
Positive predictive value of TC test	0.0311	0.171
Negative predictive value of TC test	0.986	0.889
Positive likelihood ratio	1.22	1.23
Negative likelihood ratio	0.553	0.748

Table 3. The positive predictive values were low due in part to the low outcome frequency and the large number of systems. The slightly higher positive predictive value at 36 months compared to 1 month after a non-*E. coli* positive result suggests that the total coliforms are better predictors of future contamination in the long term. However, even the long-term predictive value appears too low to be of practical significance.

The positive likelihood ratios are greater than one, which indicates an association between having a positive non-*E. coli* total coliform result and having an *E. coli*-positive result in the future. The negative likelihood ratios are less than one, which indicates that having no prior total coliform positive results is associated with not having an *E. coli*-positive result in the future. The strength of these associations is weak to moderate as both the positive and negative likelihood ratios are close to one.

DISCUSSION

First the role of total coliforms as indicators of fecal contamination will be presented, followed by a discussion of the potential of non-*E. coli* total coliforms to act as an early indicator of a vulnerability in one or more of the barriers in place to reduce microbial hazards. The likelihood that these system failures indicated by non-*E. coli* total coliforms will precede human health-relevant changes in microbial water quality has not been investigated previously.

The public health relevance of total coliform bacteria in water has been scrutinized for decades. Criticisms of total coliforms as public health indicators point to a lack of evidence that demonstrates a strong association between total coliforms and outbreak occurrence (MacKenzie *et al.* 1994; Craun *et al.* 1997), endemic gastrointestinal illnesses (Payment *et al.* 1993), or presence of protozoan or viral pathogens (Keswick *et al.* 1984; Rose *et al.* 1991). While some studies have found a weak relationship between total coliform presence and presence of pathogens (Wilkes *et al.* 2009), the relationship appears to be site-dependent.

Since system failures that lead to microbiological contamination of treated drinking water are infrequent, most total coliform positive results will be false positives (Hrudey & Leiss 2003). False positive results are those that indicate that fecal contamination is present when it is not. They can be due to presence of interferents that have enzyme activity, water sample contamination during collection or presence of total coliforms in water that are of non-fecal origin. Natural reservoirs, including soils and plants (Grimont *et al.* 1981; Brady *et al.* 2008), have been documented for many species belonging to the total coliform group. Some types of total coliform bacteria are recognized plant pathogens (Chung *et al.* 1993; Leclerc *et al.* 2001).

By comparison, *E. coli* would presumably falsely indicate fecal contamination less frequently than non-*E. coli* total coliforms because *E. coli* is almost exclusively of fecal origin. Thus, non-*E. coli* total coliforms in drinking water are less likely to indicate a true danger to human health than *E. coli*. Further support that non-*E. coli* total coliforms are less likely than *E. coli* to indicate a true hazard is the finding of Strauss *et al.* (2001) that the odds ratio for acquiring acute gastrointestinal illness from consumption of water that tested positive for *E. coli* was 1.52, while that for total coliforms was 0.39.

It is clear that the value of non-*E. coli* total coliform bacteria in estimating the immediate risk to human health is limited. High levels of fecal contamination in water should be indicated by presence of *E. coli* along with other species from the total coliform group since *E. coli* is present at concentrations that range from 10 to 10,000 CFU per gram of feces (Leclerc *et al.* 2001). However, non-*E. coli* total coliforms may have predictive value as non-*E. coli* total coliforms in water indicate an increase in microbial loading rate, which is the result of a failure of system barriers to effectively reduce microbiological hazards. While total coliform positive samples may not be attributable to the same cause, multiple total coliform events over time indicate a weakness in system barriers that requires investigation. If

such weaknesses in system barriers are not addressed, the system may be vulnerable to future contamination events, which could have human health consequences.

It appears that the frequency at which small increases in microbial loading rates, indicated by non-*E. coli* total coliforms, is followed by detection of *E. coli* in drinking water is low. The fact that 1 month after a non-*E. coli* total coliform positive test, only 3% of systems had further evidence of fecal contamination supports the argument that most non-*E. coli* total coliform positive results do not predict human-health-significant contamination events in the short term. Other groups have also shown that positive predictive values for rare hazards tend to be low (Hrudey & Leiss 2003).

Drinking water samples infrequently tested positive for *E. coli* so the event rate was low for both groups of small water systems analyzed. The difference in absolute risk between the group of systems with prior non-*E. coli* total coliforms and the group with no prior total coliforms indicates that systems with prior total coliforms are only slightly more likely to have *E. coli* in a future water sample because *E. coli*-positive events are extremely rare for both groups at 1 month. Consequently, the absolute risk increase for systems that had previously detected non-*E. coli* total coliforms was only 1.6% at 1 month, and only slightly higher in the long term with an absolute risk increase of 6.0% up to 3 years after the initial non-*E. coli* total coliform event.

Although the absolute risk increase was low, the RR value showed that drinking water systems that had non-*E. coli* total coliforms in the distribution system were about twice as likely to have an *E. coli*-positive test in the months following the initial total coliform event compared to systems with no prior total coliforms (RR = 2.04). The hazard ratio suggested that systems in the Prior TC group were nearly four times more likely to detect *E. coli* 1 month after a non-*E. coli* total coliform event compared to systems in the No Prior TC group. The likelihood ratios suggest that an association between detection of non-*E. coli* total coliforms and detection of *E. coli* in a subsequent water sample exists, but both the positive and negative ratios fall short of those considered significant for practice. Thus, it is a challenge to interpret non-*E. coli* total coliform positive test results when there is no evidence of an operational failure in the water system.

In order to interpret the meaning of microbiological testing results it is necessary to understand the multitude of factors that govern microbial loading rates and survival in different environments. Microbial water quality of surface water may be affected by factors that can vary widely temporally and spatially such as weather patterns (i.e., heavy rainfall, long periods of drought), seasonal variations in temperature and watershed land uses (i.e., agricultural, urban, industrial). The complex interactions that occur between each of these factors and their impacts on water quality accounts for some of the challenges faced in developing predictive approaches to evaluating human health-relevant changes in water quality. This may be an area for future research. Some predictive water quality models have been proposed (Ailamaki *et al.* 2003; Wu *et al.* 2009), but are not widely used in practice.

Limitations of this study include that there were few systems for which monthly sampling data were available for the entire 3-year period. Many systems submitted samples on an irregular basis or for a limited period of time. This resulted in a high number of systems classified as 'lost' and a large discrepancy in sample size from the beginning to the end of the study period. The data points in the final intervals of the life table analysis were based on a small number of systems, which means that a single *E. coli* event had a greater impact on the cumulative probability of having an *E. coli*-positive sample in the final intervals. Information regarding type of water treatment was not available so it was not possible to control for total coliform events that may have occurred due to treatment malfunctions or *E. coli* events that may have been prevented due to installation of new treatment systems. It was assumed that all water samples were submitted for routine purposes, but collection may have been related to a specific event (i.e., turbidity spike, water-main break) in which case a sample bias towards total coliform and *E. coli*-positive samples may exist. Water system metadata that may be used to indicate a change in microbiological water quality including turbidity measurements, chlorine residual and documented water-main breaks were not available. Analysis of the relationship between total coliform events in small water systems and these variables may be an area of future study.

These results show that drinking water systems with one or more non-*E. coli* total coliform positive test results had a

greater chance of obtaining an *E. coli*-positive result in subsequent months relative to systems with no prior total coliforms detected in the distribution system. The absolute risk increase, however, is too low to justify executing immediate hazard-reduction measures based on detection of non-*E. coli* total coliforms alone, but evidence of non-*E. coli* total coliforms warrants an appropriate precautionary response. When using microbiological data to make risk management decisions, application of the appropriate degree of precaution is critical and should consider the likelihood of obtaining false-positive and false-negative errors (Hrudey & Leiss 2003). For rare events, the probability of obtaining a false negative is low but the false positive rate is high. On one hand, erring on the side of caution that total coliforms may be an early indicator of poor water quality and hence a possible threat to human health may be reasonable. It is clear, however, that issuing a boil-water notification immediately based on total coliform results alone may not be defensible before the possibility of a false positive error has been ruled out.

A stepwise response to non-*E. coli* total coliform positive drinking water test results would be appropriate to verify that the result was not due to sampling error, determine the likelihood of fecal contamination through further testing and characterize the inputs to the system. The majority of samples containing non-*E. coli* total coliforms are not indicative of fecal contamination but may represent a failure in the multi-barrier system to reduce microbial hazards, so the first follow-up response should be to rule out the possibility of sample contamination during collection by re-sampling the site. This is the first course of action recommended by Health Canada after a total coliform positive result is obtained (Health Canada 2011). Other responses may include increased diligence in system operations and further testing for presence of other fecal bacteria including *Clostridium perfringens* or fecal streptococci to gather further evidence as to whether the system is impacted by fecal contamination.

CONCLUSIONS

Using life table analysis, this research demonstrated that presence of non-*E. coli* total coliform bacteria indicates a slightly higher likelihood that a small drinking water system will test positive for *E. coli* in the following months compared to a small system that had no prior total coliforms detected (RR = 2.04). But given the rarity of viable *E. coli* detection in drinking water, the absolute risk increase is low. Although the presence of non-*E. coli* total coliform bacteria does not in itself indicate a health risk, they have value in the context of drinking water distribution system monitoring on the basis that they indicate a need to perform further investigations to confirm or dismiss the potential that the system is impacted by fecal pollution.

ACKNOWLEDGEMENTS

This work was funded in part by the Natural Science and Engineering Research Council and the Canadian Institute for Health Research. We would like to thank the British Columbia Provincial Public Health Microbiology Reference Laboratory data administrators for their assistance in providing the data used for this analysis.

REFERENCES

Ailamaki, A., Faloutos, C., Fischbeck, P. S., Small, M. J. & VanBreisen, J. 2003 An environmental sensor network to determine drinking water quality and security. *Assoc. Comput. Mach. Sig.* **32**, 47–52.

Barratt, A., Wyer, P. C., Hatala, R., McGinn, T., Dans, A. L., Keitz, S., Moyer, V. & Guyatt, G. 2004 Tips for learners of evidence-based medicine: 1. Relative risk reduction, absolute risk reduction and number needed to treat. *Can. Med. Assoc. J.* **171**, 353–358.

Barrell, R. A., Hunter, P. R. & Nichols, G. 2000 Microbiological standards for water and their relationship to health risk. *Comm. Dis. Public Health* **3**, 8–13.

Brady, C., Cleenwerck, I., Venter, S., Vancanneyt, M., Swings, J. & Coutinho, T. 2008 Phylogeny and identification of *Pantoea* species associated with plants, humans and the natural environment based on multilocussequence analysis (MLSA). *Syst. Appl. Microbiol.* **31**, 447–460.

Breslow, N. E. 1975 Analysis of survival data under the proportional hazards model. *Int. Stat. Rev.* **43**, 45–57.

British Columbia Regulation 200/2003 *Drinking Water Protection Regulation*. Queen's Printer, Victoria, British Columbia, Canada. http://www.bclaws.ca/EPLibraries/bclaws_new/document/ID/freeside/10_200_2003 (Accessed 27 January 2013).

Chung, Y. R., Brenner, D. J., Steigerwalt, A. G., Kim, B. S., Kim, H. T. & Cho, K. Y. 1993 *Enterobacter pyrinus sp.* nov., an organism associated with brown leaf spot disease of pear trees. *Int. J. Syst. Bacteriol.* **43**, 157–161.

Craun, G. F., Berger, P. S. & Calderon, R. L. 1997 Coliform bacteria and waterborne disease outbreaks. *J. Am. Water Works Assoc.* **89**, 96–104.

Deeks, J. J. & Altman, D. G. 2004 Diagnostic tests 4: likelihood ratios. *Brit. Med. J.* **329**, 168–169.

Edberg, S. C., Allen, M. J. & Smith, D. B. 1991 Defined substrate technology method for rapid and specific simultaneous enumeration of total coliforms and *Escherichia coli* from water: collaborative study. *J. Assoc. Off. Analytical Chem.* **74**, 526–529.

Edberg, S. C., Rice, E. W., Karlin, R. J. & Allen, M. J. 2000 *Escherichia coli*: the best biological drinking water indicator for public health protection. *Symp. Ser. Soc. Appl. Microbiol.* **29**, 106S–116S.

Figueras, M. J. & Borrego, J. J. 2010 New perspectives in monitoring drinking water microbial quality. *Int. J. Environ. Res. Public Health* **7**, 4179–4202.

Fricker, C. R. & Eldred, B. J. 2009 Identification of coliform genera recovered from water using different technologies. *Lett. Appl. Microbiol.* **49**, 685–688.

Geldreich, E. E., Bordner, R. H., Huff, C. B., Clark, H. F. & Kabler, P. W. 1962 Type distribution of coliform bacteria in the feces of warm-blooded animals. *J. Water Pollut. Con. Fed.* **34**, 295–301.

Grimont, P. A. D., Grimont, F. & Starr, M. P. 1981 *Serratia* species isolated from plants. *Curr. Microbiol.* **5**, 317–322.

Health Canada 2011 *Total Coliforms in Drinking Water*. Prepared by the Federal-Provincial-Territorial Committee on Drinking Water. http://www.hc-sc.gc.ca/ewh-semt/pubs/water-eau/coliforms-coliformes/index-eng.php (Accessed 27 January 2013).

Health Canada 2012 *Guidelines for Canadian Drinking Water Quality*. Prepared by the Federal-Provincial-Territorial Committee on Drinking Water. http://www.hc-sc.gc.ca/ewh-semt/alt_formats/pdf/pubs/water-eau/2012-sum_guide-res_recom/2012-sum_guide-res_recom-eng.pdf (Accessed 1 February 2013).

Hoff, J. C. & Akin, E. W. 1986 Microbial resistance to disinfectants: mechanisms and significance. *Environ. Health Persp.* **69**, 7–13.

Hrudey, S. E. & Leiss, W. 2003 Risk management and precaution: insights on the cautious use of evidence. *Environ. Health Persp.* **111**, 1577–1581.

Jiang, H. & Fine, J. P. 2007 Survival analysis. In: *Methods in Molecular Biology, Vol. 404: Topics in Biostatics* (W. T. Ambrosius, ed.). Humana Press Inc., Totowa, NJ, USA, pp. 303–318.

Keswick, B. H., Gerba, C. P., DuPont, H. L. & Rose, J. B. 1984 Detection of enteric viruses in treated drinking water. *Appl. Environ. Microbiol.* **47**, 1290–1294.

Leclerc, H., Mossel, D. A. A., Edberg, S. C. & Struijk, C. B. 2001 Advances in bacteriology of the coliform group: their suitability as markers of microbial water safety. *Annu. Rev. Microbiol.* **55**, 201–231.

MacKenzie, W. R., Hoxie, N. J., Proctor, M. E., Gradus, M. S., Blair, K. A., Peterson, D. E., Kazmierczak, J. J., Addiss, D. G., Fox, K. R., Rose, J. B. & Davis, J. P. 1994 A massive outbreak in Milwaukee of *Cryptosporidium* infection transmitted through the public water supply. *New Engl. J. Med.* **331**, 161–167.

Mantel, N. 1966 Evaluation of survival data and two new rank order statistics arising in its consideration. *Cancer Chemoth. Rep. Part 1.*, **50**, 163–170.

McGee, S. 2002 Simplifying likelihood ratios. *J. Gen. Intern. Med.* **17**, 647–650.

Payment, P., Franco, E. & Siemiatycki, J. 1993 Absence of relationship between health effects due to tap water consumption and drinking water quality parameters. *Water Sci. Technol.* **27**, 137–143.

Peto, R., Pike, M. C., Armitage, P., Breslow, N. E., Cox, D. R., Howard, S. V., Mantel, N., McPherson, K., Peto, J. & Smith, P. G. 1977 Design and analysis of randomized clinical trials requiring prolonged observation of each patient. *Brit. J. Cancer* **35**, 1–39.

Reynolds, K. A. 2003 Coliform bacteria: a failed indicator of water quality? *Water Cond. Purif. Mag.*, **45** (9) [online] http://www.wcponline.com/column.cfm?T=T&ID=2349.

Rose, J. B., Gerba, C. P. & Jakubowski, W. 1991 Survey of potable water supplies for *Cryptosporidium* and *Giardia*. *Environ. Sci. Technol.* **25**, 1393–1400.

Sekar, R., Deines, P., Machell, J., Osborn, A. M., Biggs, C. A. & Boxall, J. B. 2012 Bacterial water quality and network hydraulic characteristics: a field study of a small, looped water distribution system using culture-independent molecular methods. *J. Appl. Microbiol.* **112**, 1220–1234.

Standridge, J. 2008 *E. coli* as a public health indicator of drinking water quality. *J. Am Water Works Assoc.* **100**, 65–75.

Stevens, M., Ashbolt, N. & Cunliffe, D. 2003 Review of coliforms as microbial indicators of drinking water quality. Australian Government National Health and Medical Research Council. http://www.nhmrc.gov.au/_files_nhmrc/publications/attachments/eh32.pdf (Accessed 27 January 2013).

Strauss, B., King, W., Ley, A. & Hoey, J. R. 2001 A prospective study of rural drinking water quality and acute gastrointestinal illness. *BMC Public Health* **1**, 7–12.

Wang, D. L. & Fiessel, W. 2008 Evaluation of media for simultaneous enumeration of total coliform and *E. coli* in drinking water supplies by membrane filtration techniques. *J. Environ. Sci.* **20**, 273–277.

Wilkes, G., Edge, T., Gannon, V., Jokinen, C., Lyautey, E., Medeiros, D., Neumann, N., Ruecker, N., Topp, E. & Lapen, D. R. 2009 Seasonal relationships among indicator bacteria, pathogenic bacteria, *Cryptosporidium* oocysts, *Giardia* cysts, and hydrological indices for surface waters within an agricultural landscape. *Water Res.* **43**, 2209–2223.

Wu, J., Lu, J. & Wang, J. 2009 Application of chaos and fractal models to water quality time series prediction. *Environ. Model. Softw.* **24**, 632–636.

First received 14 June 2012; accepted in revised form 13 January 2013