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Quantitative microbial risk assessment for drinking water intake threat prioritization: a comparison of vulnerability and threat assessment according to source water protection regulations of two Canadian provinces

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1. Vulnerability and threat assessment

1.1. Vulnerability assessment

1.1.1. Ontario approach

In Ontario, municipalities must carry out vulnerability assessments for their drinking water intakes every 5 years. It is a mandatory process through which the vulnerable areas (of a Drinking water intake) to contamination are determined and assigned a vulnerable score from 1-10; the higher the score is, the more vulnerable the area will be [1]. The vulnerability assessment typically compromised of 3 sections: 1) intake classification, 2) delineation of Intake Protection Zone (IPZ) and 3) vulnerability scoring. In Ontario, the vulnerability approach is a score-based system in which the area surrounding the intake is assigned a score rather than the intake [1]. Based on the type of intake and its location within a waterbody, the IPZ of the intake would be established according to the fixed distance, travel time and potential contribution to the intake. Definition of each IPZ is provided in Table S1. IPZ1 recognized as the areas immediately adjacent to the intake within which minimum dilution of contaminant would be assumed. IPZ2 delineation is based on a 2-hour water flow travel time to the intake, during which treatment plant operator has sufficient time to shut down the intake in the event of spill accident. Having delineated the three types of IPZs, the vulnerability of each area (V) is calculated according to susceptibility of the area to contamination (expressed as area vulnerability factor (B)) as well as the location-based characteristics of the intake in the water body (expressed as source vulnerability factor (C)). Key factors in defining the vulnerability score are provided in Table S2. The vulnerability score obtained in this step is applied to evaluate the risk of a threat within an IPZ. The Ontario vulnerability assessment focuses mainly on the physical and hydrodynamic conditions of the intakes regardless of the contamination type.

1.1.2. Quebec approach

Quebec's intake vulnerability assessment approach entirely relies on the intake itself while the method of determining the level of vulnerability of surface water intake is unique and based on 6 criteria including 1) physical vulnerability of the site, 2) vulnerability to microorganisms, 3) vulnerability to fertilizers, 4) vulnerability to turbidity, 5) vulnerability to inorganic substances, 6) vulnerability to organic substances [2, 3]. Unlike Ontario's assessment, the type of contamination in the Quebec framework is explicitly identified.

Although, delineating IPZs in Quebec's approach has some similarities with Ontario's, there are different terminologies and definitions with regard to the intake type and extent of each IPZ (See Table S1). In equivalence to IPZ1, IPZ2 and IPZ3 introduced in Ontario approach, there are areas of inner, intermediate and outer featured in Quebec IPZ classification. There is no area delineated by the travel time according to the Quebec approach but rather a distance upstream (and partially downstream) of the intake. The concentration-based comparison of each contamination type measured at the intakes of drinking water sources forms the basis of this approach to assign different vulnerability classes. The vulnerability of surface water intakes to microorganisms (described in Table S3) is generally expressed in terms of being high, medium or low based on the median values or 95th percentile of *E. coli* concentrations at the intake (Method 1). The reason behind the selection of the fixed values, i.e. 15, 150 and 1500 CFU/100mL (in Method 1) is due to the fact that the Quebec drinking water requirement is based on the fecal indicator bacteria concentration, i.e. *E. coli* in raw waters for microbial contaminant removal. In other words, the amount of treatment required to remove the microbial contaminant is determined based on the mean value of *E. coli* concentrations at intakes [4]. The vulnerability of an intake to microorganisms can be interpreted as an indication of log-removal requirement. Therefore, the vulnerability assessment of an intake would enhance the understanding the treatment process required for safe drinking water recommended by the guidelines. There is also another method (Method 2) which is independent of microbiological status level measured at the intake and more relies on the location of the outfalls. Method 2 qualitatively accounts for the potential contribution of those outfalls to the microbiological water quality level at the nearby intake by characterizing the intake as highly vulnerable considering the presence of a CSO outfall within inner or intermediate areas of the intake in an urban environment.

1.2.Threat assessment

The threat assessment is a shared directive by the regulations of both provinces. The concept typically relies on recognizing drinking water issues within the IPZs that contributes to quality and quantity of water. Then the current or potential activities/conditions that are or would be worsening the problem are considered as threats to drinking water quality and quantity. Ultimately, the level of threats to drinking water intake would be determined. The method of threat classification differs from Ontario to Quebec, a summary of which is provided in the following sections.

1.2.1. Ontario approach

In Ontario, there is a list of 22 pre-described activities that are considered as drinking water threats among which storage, application and discharge of chemicals or pathogenic materials have been addressed Ontario regulation 287/07 [1]. Depending on the type of threat (microbiological), the level of threat is defined as high, moderate or low (Tables of Drinking Water Threats [5], as a part of [6]) based on the current/potential location of the threats within the IPZ of an intake along with associated vulnerability score (Table S4). Depending on the vulnerability scoring of areas around the intake where the threat is/would be located, the level of threat is determined. Ontario's threat assessment is directly dependent on the vulnerability assessment of IPZs and the position of a threat within those areas.

1.2.2. Quebec approach

The Quebec threat assessment approach is based on a more qualitative technique where the level of threat depends on the magnitude of impacts of an activity/a condition (i.e. severity) and its frequency/probability of occurrence [2, 3]. Prior to threat assessment (or potential risk evaluation) an inventory is required of anthropogenic activities and potential events within the inner and intermediate areas of the intake. With inventory, the approach qualitatively takes into account the characteristics of a threat including the type and the amounts of contaminant to be released to the environment. Four classes of severity of a threat are allocated as minor, serious, severe and catastrophic (Table S5). The frequency/probability of an activity/event is also considered (Table S5). The combination of severity of consequences and the frequency/probability of an activity/event would result in 6 classifications of the risk of a threat; very low, low, moderate, high and very high. Unlike Ontario's threat assessment, Quebec's approach considers the nature of the threat in terms of magnitude of negative effects as well frequency of the phenomena while it is somewhat independent of vulnerability assessment.

2. CSO load model

The CSO loading model used in this study considered the dynamic behavior of CSO discharges with regards to both overflow and contaminant concentration (*E. coli*) [6]. The following is a brief explanation of the results that were used for CSO model in this study. The proposed CSO loading model was based on normalizing the scale-related parameters of an event, i.e. overflow, concentration and duration period. By dividing the parameter of normalized duration (i.e. t/T_{total})

into 10 portions, it was found that the normalized overflow showed linear increasing trend until the occurrence of the peak flow sometime within the second decile, followed by decreasing logarithmic trend. Therefore, CSO overflow hydrograph of any event can be produced by knowing the total discharge volume and duration of the event to be modeled. To include the variability of *E. coli*, probability distribution of *E, coli* in course of CSO events including the first, 2^{nd} and the remaining portions were obtained. Identifying the peak *E. coli* concentration, the time series of *E. coli* concentration can be produced by random selection of values from the related probability distribution function of normalized *E. coli* concentration. Therefore, the two loading terms, i.e. CSO hydrograph and *E. coli* pollutograph could be generated to be used as the inputs of the river model for CSO simulations.

3. Selection of *Cryptosporidium* and *Giardia* for QMRA in Drinking Water Safety

Pathogens are a major concern to produce safe drinking water, as they pose risks to public health when present in untreated or insufficiently treated surface water [7]. Among them, *Cryptosporidium* and *Giardia* are two of the most common protozoan parasites associated with waterborne disease outbreaks worldwide [8]. These pathogens were responsible for at least 60% and 35% of global waterborne outbreaks from 2004 to 2010, and 63% and 37% of protozoan-related outbreaks from 2011 to 2016 [9].

Heavy rainfall and inadequate treatment of surface water sources have been identified as key factors contributing to waterborne disease outbreaks caused by *Cryptosporidium* [10-14], *Giardia* [10, 15], norovirus [16], and *Shigella sonnei* [17]. However, *Cryptosporidium* and *Giardia* remain a primary concern for drinking water safety due to their persistence in the environment and their ability to bypass conventional disinfection processes, particularly chlorination [18]. As a result, regulatory agencies such as the U.S. Environmental Protection Agency [19] and Quebec regulation [4] mandate their removal based on raw water concentrations.

These protozoan pathogens enter surface waters through fecal contamination from infected humans and animals, including combined sewer overflows (CSOs), making them particularly relevant for risk assessments in urban water systems. *Cryptosporidium* and *Giardia* are widely recognized as reference protozoan pathogens for QMRA in surface drinking water sources due to their high prevalence and resistance to treatment [18].

Given these considerations, *Cryptosporidium* and *Giardia* were selected for this study as representative protozoan pathogens for QMRA. Their inclusion ensures alignment with regulatory requirements, addresses key microbial risks associated with CSOs, and provides a robust basis for evaluating drinking water treatment needs.

Table S1. River flow statistics based on daily records

Month	Valid N (number of records)	River flow (m^3/s)				
		Most Probable	Mean	Minimum	Maximum	Standard Deviation.
Jan	1737	-	1229	498	2200	311
Feb	1559	-	1212	547	2810	269
Mar	1719	800	1271	538	3360	400
Apr	1680	1416	2061	648	4740	784
May	1736	1478	2028	359	5060	914
Jun	1680	996	1292	383	3330	539
Jul	1767	585	886	348	2600	380
Aug	1767	431	677	242	1890	267
Sep	1710	620	616	165	2150	232
Oct	1767	540	840	259	2560	411
Nov	1710	-	1145	367	2760	483
Dec	1767	-	1261	494	3480	435

Table S2. Vulnerability scoring of the areas around the intake (Ontario's approach) (adapted from Government of Ontario [1])

Vulnerability score (V=B×C)					
	Parameters of the factor	**Description**	**IPZ1**	**IPZ2**	**IPZ3**
Area vulnerability factor (B)	Percentage of land area	Based on weight-average, to be calculated for each Intake Protection Zone (IPZ)	B=1	7 <B< 9	1 <B< 9
	Land use				
	Imperviousness				
	Percentage of land area drained by stormwater				
Source Vulnerability factor (C)	Depth of intake	Constant for all IPZ, dependent on the type of intake	Type A[a]	0.5-0.7	
	Distance from river bank		Type B[b]	0.7-0.9	
	Presence of drinking water issue		Type C[c]	0.9 or 1	
			Type D[d]	0.8-1	

[a]Type A: Located in a Great Lake
[b]Located in a connecting channel
[c]Located in a river, direction and velocity of the flow not impacted by a water structure impoundment
[d]Other cases not covered as type A, B and C

Table S3. Classes of vulnerability of an intake to microorganism (Quebec's approach) (adapted from Government of Quebec [2])

	Quebec Vulnerability of the intake				
Vulnerability indicator	**Description**		**High**	**Medium**	**Low**
Vulnerability to microorganisms	A consecutive enumeration of *E. coli* over a period of five years	Method 1	Median greater than 150 cfu/100 mL or value of 95th percentile exceeds 1500 cfu/100 mL	Neither low nor high	Median less than 15 cfu/100 mL or value of 95th percentile less than 150 cfu/100 mL
	When method 1 not applied	Method 2	Banks of the inner protection areas located entirely in an urban environment or at least one item of an overflow network likely to discharge wastewater in an inner or intermediate area	Neither low nor high	i: sampling site is located in a lake,ii: no combined sewage discharge upstream

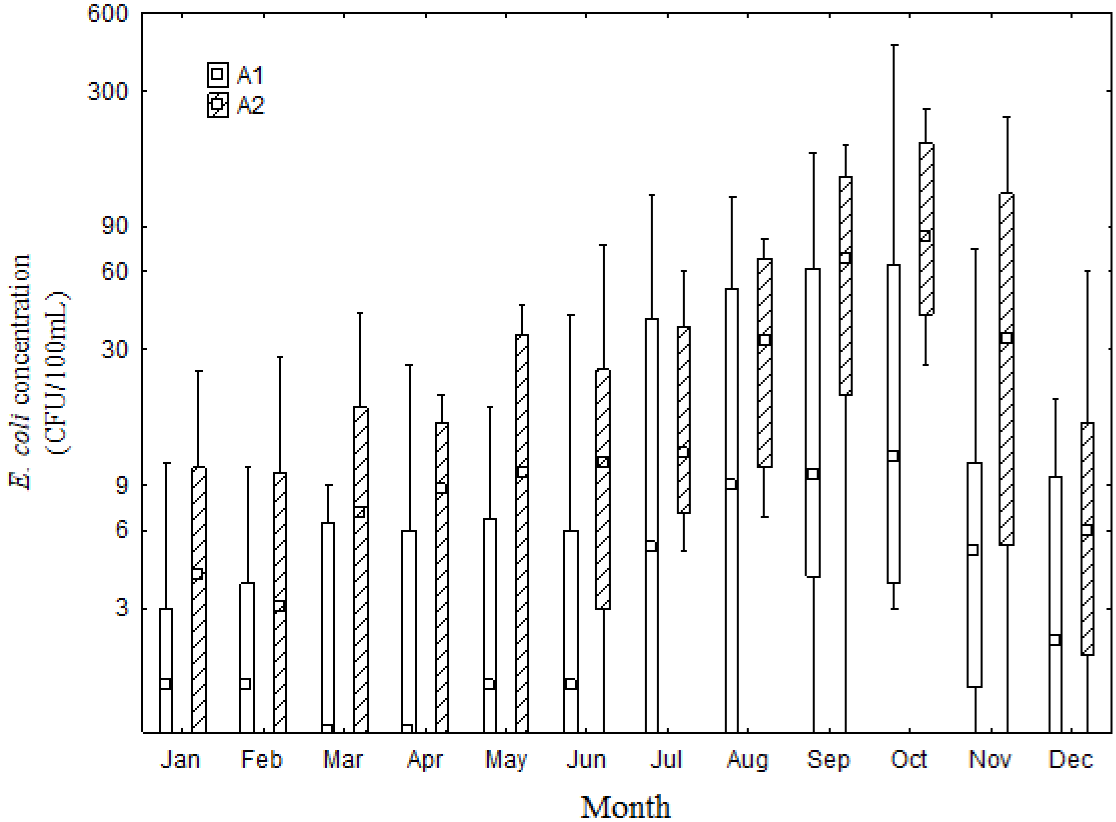
Table S4. Ontario's threat assessment of combined sewer overflow (CSO) outfalls (adapted from Tables of Drinking Water Threats, Government of Ontario [5])

Reference Number	Description	Significant threat if located within the area with vulnerability score of	Moderate threat if located within the area with vulnerability score of	Low threat if located within the area with vulnerability score of
1947	The system is a combined sewer that may discharge sanitary sewage containing human waste to surface water	8-10	6-7.2	4.2-5.6
	The discharge may result in the presence of one or more pathogens in surface water			

Table S5. Quebec's threat classification (adapted from Ministère de l'Environnement et de la Lutte contre les changements climatiques (MELCC) [3])

	Level of threat				
	Level of severity [a]	**Minor**	**Serious**	**Sever**	**Catastrophic**
Frequency of occurrence [b]	Very frequent	Moderate	High	Very high	Very high
	Frequent	Low	Moderate	High	Very high
	Occasional	Very low	Low	Moderate	Very high
	Rare	Very low	Very low	Low	High
Probability of occurrence [c]	Almost certain	Low	Moderate	High	Very High
	Possible	Very low	Low	Moderate	High
	Unlikely	Very low	Very Low	Low	Moderate

[a] Level of Severity	Minor: Aesthetic water quality problem, acceptable by the consumers
	Serious: Aesthetic water quality problem, inacceptable by the consumers
	Sever: Health issue as a result of long-term exposure (chemical contamination representing risk of chronic toxicity)
	Catastrophic: Health issue as a result of short-term exposure (microbiological or chemical contamination representing risk of acute toxicity)
[b] Frequency classification	Very frequent (≥ one time/week): Discharge of contaminant at least one time per week
	Frequent (≥ one time/year): Discharge of contaminant at least one time per year or month etc but not in the category of "very frequent"
	Occasional (> one time/5 years): Discharge of contaminant more than one time in course of 5 years, but not in the category of "frequent"
	Rare (≤ one time/5 years): Discharge of contaminant almost one time in course of 5 years, or even less
[c] Probability classification	Almost certain: It is almost certain to happen at least once in the next 5 years
	Possible: It is possible to happen in the next 5 years
	Unlikely: It is imaginable to happen, but very unlikely to happen in the next five years


600
300
90
60
30
9
6
3
A1
A2
E. coli concentration (CFU/100mL)
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

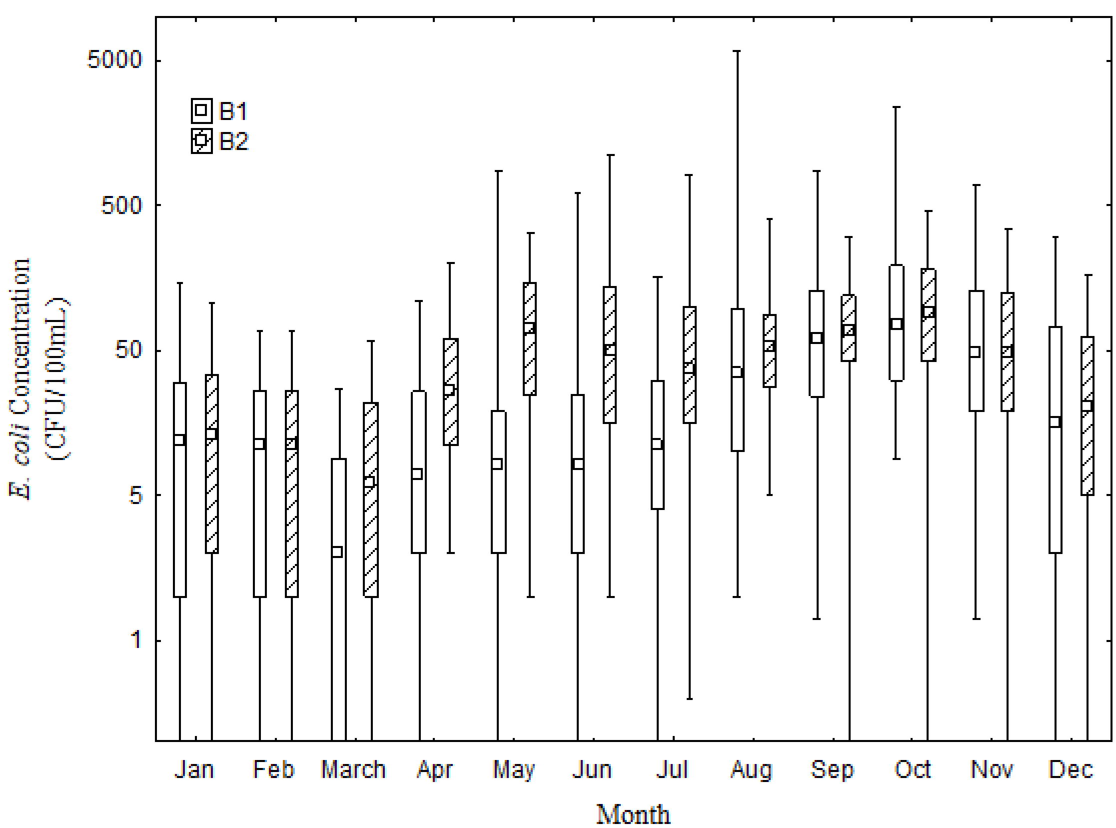
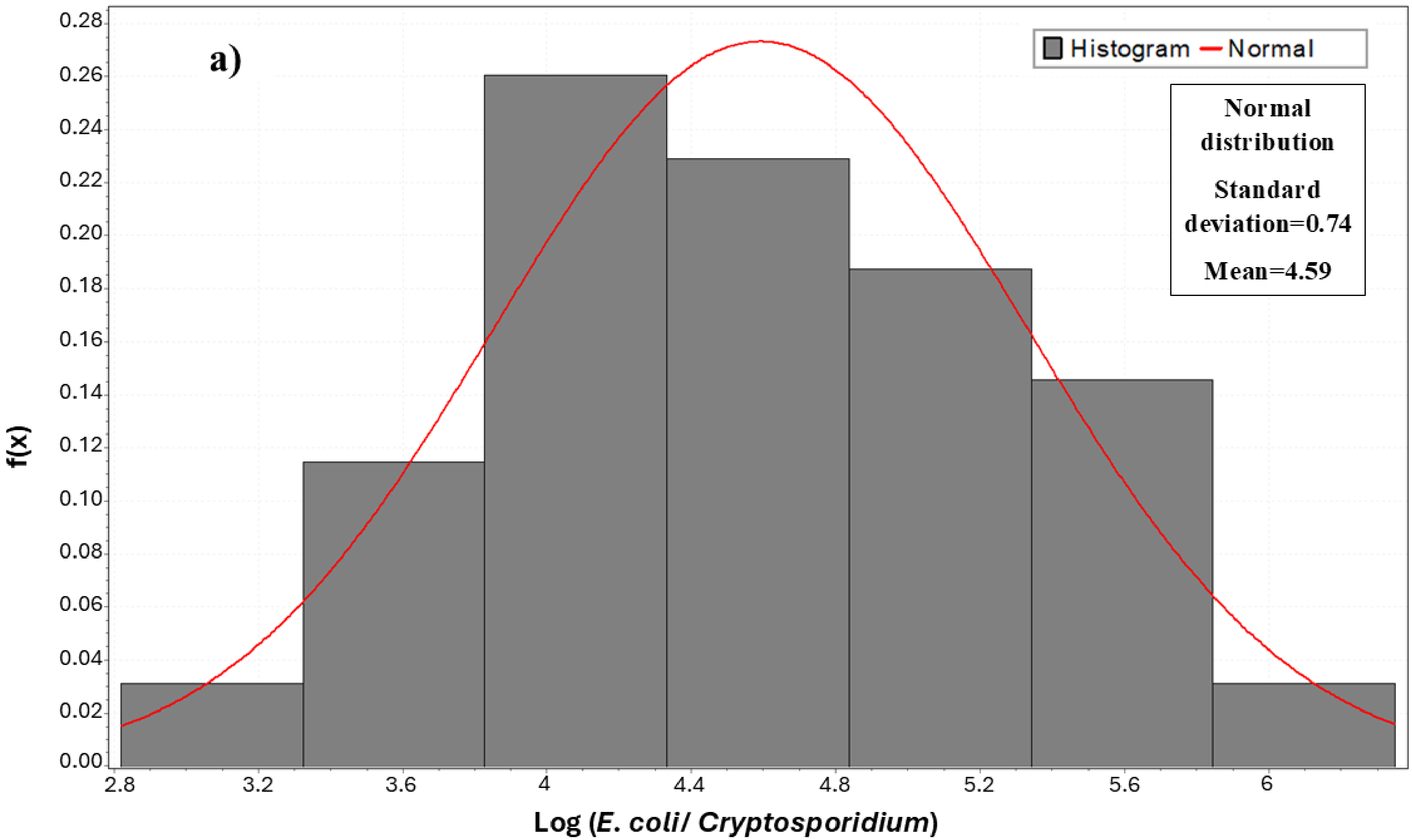

5000
500
50
5
1
B1
B2
E. coli Concentration (CFU/100mL)
Jan
Feb
March
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
Month

Fig. S1. Monthly *E. coli* concentrations. Box plots represent 10^{th} and 90^{th} percentile (box), median values (square in the box) and whiskers show minimum and maximum. *E. coli* measurements at A1 and A2 (City A's drinking water intakes) were conducted weekly from 2013 to 2016, while fecal coliform data were available from 2010 to 2013. At B1 and B2 (City B's intakes), *E. coli* concentrations were monitored daily from 1999 to 2013.


a)
Histogram
Normal
Normal distribution
Standard deviation=0.74
Mean=4.59
f(x)
0.28
0.26
0.24
0.22
0.20
0.18
0.16
0.14
0.12
0.10
0.08
0.06
0.04
0.02
0.00
2.8
3.2
3.6
4
4.4
4.8
5.2
5.6
6
Log (E. coli/ Cryptosporidium)

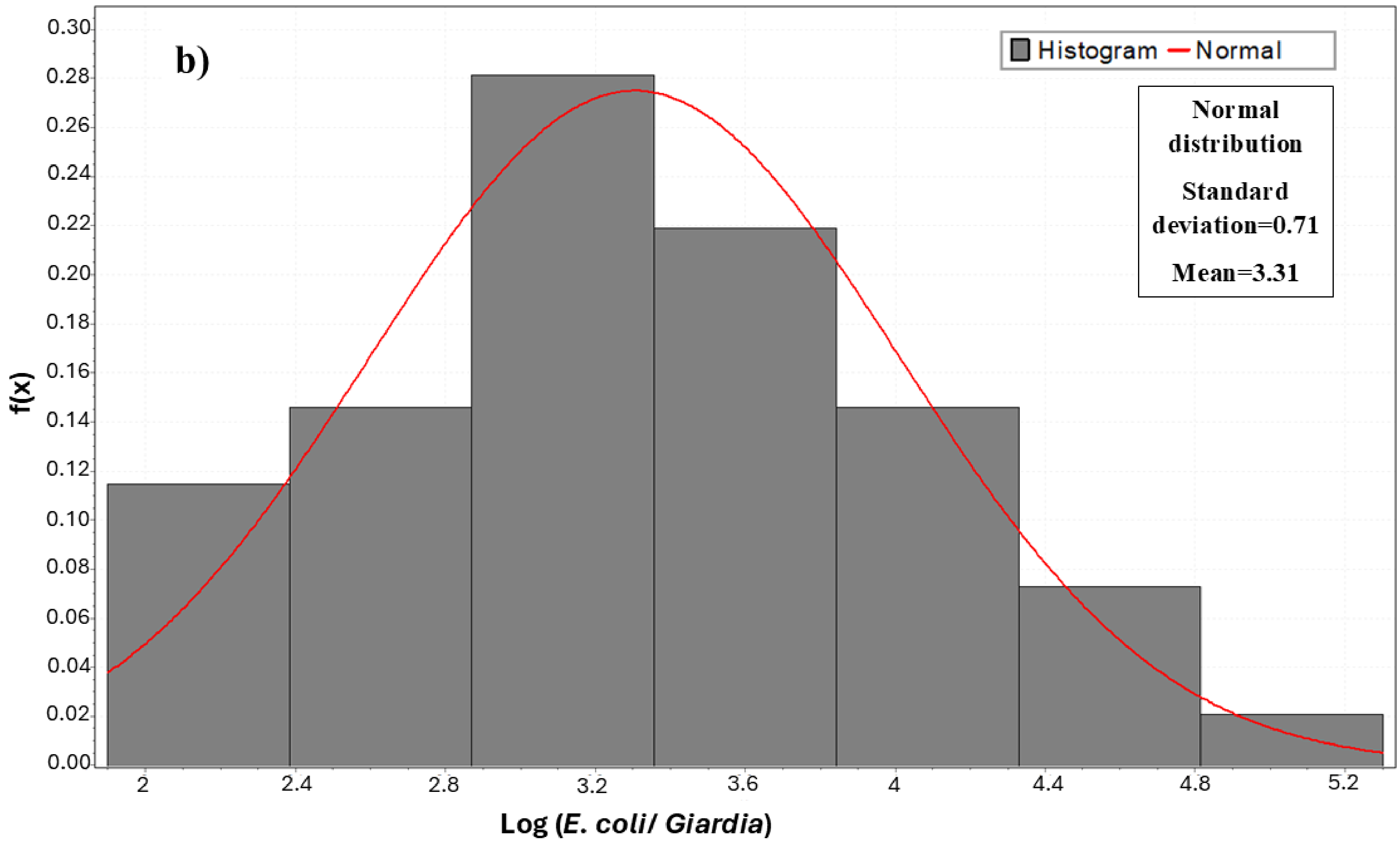


Fig. S2. Probability distribution function of the ratio (in log values): a) *E. coli* to *Cryptosporidium*, b) *E. coli* to *Giardia* adapted from [6] and [20].

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