Quantitative microbial risk assessment of drinking water treated with advanced water treatment process

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ABSTRACT

Campylobacter jejuni is one of the major causes of waterborne disease in Japan. A quantitative microbial risk assessment (QMRA) was conducted to evaluate the health risk caused by this pathogen in drinking water treated with a supposed advanced treatment process including ozonation and granular activated carbon adsorption. Coagulation-sedimentation, rapid sand filtration, ozonation, and chlorine disinfection are considered as the main microbial barriers of the process. The overall removal efficacy by four treatment steps was estimated to be the median and mean values of 11.1 $\log_{10}$ and 10.4 $\log_{10}$, respectively. The mean value of the yearly risk of infection was estimated to be 1.09×10^{-7} infection/person/yr. The sensitivity analysis shows that the complete removal of suspended solids and particulates in the source water is extremely important to stably produce safe drinking water. The uncertainty analysis demonstrated that the factor with large impact on yearly risk of infection was the hydraulic condition of ozone contactor. It can be pointed out that an accurate estimation for the dispersion number for full-scale ozone contactor is needed. Furthermore, data collection to determine the *C. jejuni/Escherichia coli* (C/E) ratio in the source water is highly required to improve the accuracy of the quantitative microbial risk assessment (QMRA).

Key words | advanced water treatment process, *C. jejuni*, QMRA, removal and inactivation efficacy, sensitivity analysis, uncertainty analysis

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INTRODUCTION

In order to guarantee the microbial safety of drinking water in Japan, by law, drinking water is currently maintained with a sufficient concentration of residual chlorine. However, chlorination raises problems, e.g. chlorination by-products and odor, in addition to benefits. While it might be desirable to decrease the concentration of residual chlorine in the water supply, such a countermeasure would increase health risks and lead to a deterioration in drinking water quality. Therefore, advanced management techniques for microbial risk are required. Quantitative microbial risk assessment (QMRA) has been applied to quantify the microbial safety of drinking water since the 1980s (Haas *et al.* 1999; Medema *et al.* 2006). Exposure (or dose) is calculated from a pathogenic microbe concentration in drinking water coupled with the consumption of unboiled drinking water. Risk of infection is calculated from the chance of ingesting pathogens and the chance of developing an infection from this exposure (dose-response relationship). The yearly risk of infection is quantitatively estimated by a Monte Carlo simulation.

Campylobacter is considered to be one of the major causes of waterborne disease (Risebro *et al.* 2006). Of the cases of waterborne infectious diseases transmitted through drinking water that were recently reported in Japan, *Campylobacter* is the second most important pathogenic bacteria after diarrheagenic *Escherichia coli* (*E. coli*) (Kaneko 2006; Yamada & Akiba 2007). With respect to *Campylobacter*, one of the main disease-causing species is *Campylobacter jejuni* (*C. jejuni*). It has been pointed out that close attention should be paid to *C. jejuni* as a potential cause of infection via drinking water, since surface water is the major source of drinking water in Japan.

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The aim of this study is to apply the QMRA method to the quantitative estimation of the level and variation of microbial risk in drinking water treated with a supposed advanced treatment process including ozonation and granular activated carbon (GAC) adsorption. First, the data needed to conduct the QMRA were collected and the yearly infection risk of *C. jejuni* was estimated in a case study. Second, sensitivity and uncertainty analyses were performed on the obtained results. As a result, the most important variable to affect the yearly risk of infection was identified, and components or variables that can contribute to the improvement of the predictive accuracy of the estimates were highlighted.

METHODS

Case description

A model water treatment process with ozonation and GAC adsorption (Figure 1) was supposed in this study. The water source for this treatment process is the Yodo River. GAC filtration is not aimed at reducing pathogens, although some micro-organisms and particles would be removed by GAC filtration (Medema *et al.* 2006). Coagulation-sedimentation, rapid sand filtration (RSF), ozonation, and chlorine disinfection are considered as the main microbial barriers of the supposed treatment process. Therefore, the removal and inactivation efficacies were estimated for these four steps. Since it would be desirable to decrease the concentration of residual chlorine in the water supply in the future, in this study, the inactivation efficacy of chlorine disinfection was estimated for a case where the minimized residual chlorine level was set to approximately 0.1 mg/L.

Pathogen and its indicator

A large dataset of pathogen concentrations monitored before and after water treatment would be ideal for assessing treatment efficacy. However, it is not easy to measure the concentrations of pathogens in source water, treatment plant water or drinking water, and often there are not a large number of monitored concentrations. For pathogenic bacteria such as *C. jejuni*, indicator bacteria (e.g. *E. coli* and enterococci) have been proposed as process indicators to assess the elimination capacity of water treatment processes (Hijnen & Medema 2010). For RSF, Hijnen *et al.* (1998) showed that *E. coli* is removed slightly better than environmental *Campylobacter* bacteria. It has been found that *E. coli* and *C. jejuni* can be similarly inactivated by ozonation and chlorine disinfection (Vidar 1996; Smeets *et al.* 2005). Since the sizes of *E. coli* and *C. jejuni* are almost the same, it is reasonable to assume the same removal efficacy of coagulation-sedimentation for these bacteria. The fact that *E. coli* is more frequently measured, as prescribed by law, also makes the indicator data valuable for assessing treatment efficacy. For these reasons, *E. coli* was used as a surrogate for *C. jejuni* in this study. *E. coli* concentrations were translated into *C. jejuni* concentrations using the ratio of *C. jejuni* to *E. coli* (C/E ratio) measured in surface water.

Data collection and preparation

The QMRA procedure is as shown in Figure 2. Among the data and parameters required, the *E. coli* concentration in the source water and the ratio of *C. jejuni* to *E. coli* in the Katsura River were obtained by field surveys. The removal and inactivation efficacy in coagulation-sedimentation was determined by the survey at an actual treatment plant. The inactivation efficacies during ozonation and chlorination were estimated by pilot-scale experiments. Literature values were used for other data and parameters.

Measurements of *C. jejuni* and *E. coli* in river water

The presence of *C. jejuni* in the actual source water (the Yodo River) is not clear to date. In order to estimate the C/E ratio, a survey was conducted in the Katsura River (note: at the point of the Miyamae Bridge, where the river water was mixed with a large volume of effluent from a

Figure 1 | Model water treatment process.

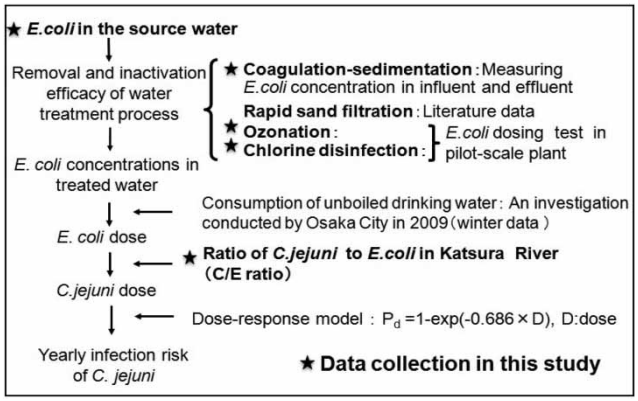

Figure 2 | QMRA procedure.

wastewater treatment plant) where a higher frequency of *C. jejuni* would likely be detected. *E. coli* and *C. jejuni* concentrations were measured in the same water taken from the Katsura River. The *E. coli* concentration was determined by the most probable number (MPN) method using O-Nitrophenyl-β-D-Galactoside and 4-Methylumbelliferyl-β-D-Glucuronide cultures with Isopropyl-β-D-Thiogalactopyranoside. *C. jejuni* were isolated from 10, 1, and 0.1 L of river water using a 0.2 μm pore size membrane filter. *C. jejuni* on the membrane filter were cultured in Bolton broth at 37 °C for 24 hours, and then the temperature was changed to 42 °C for a further 24 hours of culture. After the enrichment culture, 10% of the cultured sample was pelleted by centrifugation. DNA was extracted and identified using a polymerase chain reaction (PCR) method that detects a *C. jejuni*-specific DNA sequence. Then, the *C. jejuni* concentration was determined by means of the MPN method based on the PCR results.

Removal and inactivation efficacy of the water treatment process

(1) Coagulation-sedimentation. Over a period from November 2009 to December 2012, the concentrations of *E. coli* in the source water and in water treated by coagulation-sedimentation of the actual treatment plant were measured at the same time 27 times. The removal efficacy of coagulation-sedimentation was calculated from the concentration of *E. coli* in the influent and effluent. Generally, there are three pairing methods (Smeets *et al.* 2008), e.g. rank method, date method and random method, to determine the removal and inactivation efficacy of the water treatment process. It is necessary to select an appropriate pairing method before performing QMRA. Therefore, the rank, date, and random methods were compared in this study.

(2) Rapid sand filtration. The removal efficacy of RSF could be supposed to be lower than those of other treatment processes based on literature information. For example, 12 experimental studies have shown that mean elimination capacity (MEC) of bacteria such as *E. coli*, coliforms and fecal streptococci is just 0.6 $\log_{10}$, with a range of 0.1 $\log_{10}$ to 1.5 $\log_{10}$ (Medema *et al.* 2006). Therefore, in this study, the removal efficacy of RSF was tentatively set according to a literature value. The 12 experimental studies above include the results obtained by experiments conducted in laboratories with cultured bacteria with or without a preceding coagulation. With a preceding coagulation/sedimentation process, the removal efficacy by RSF normally increases. Based on Hijnen & Medema (2010), a maximum of 2.9 $\log_{10}$, MEC of 1.6 $\log_{10}$ and minimum of 0.5 $\log_{10}$ were adopted in this study. A triangular distribution with these parameters was constructed as a probability density function that describes the removal efficacy of RSF.

(3) Ozonation. In order to estimate the inactivation efficacy of ozonation under a full-scale hydraulic condition, a series of pilot-scale experiments and numerical simulation with an axial dispersion reactor model (ADR model developed by Kim *et al.* (2002)) were performed. First, *E. coli* dosing tests and tracer tests with KBr using a pilot-scale ozone bubble-diffuser contactor were conducted. The contactor was a column with an internal diameter of 0.165 m and a height of 6.3 m. Then, the *E. coli* inactivation rate constants were determined with the ADR model and the results of *E. coli* dosing tests. Finally, using these obtained *E. coli* inactivation rate constants and operation conditions including the hydraulic condition of the actual treatment facility, the inactivation efficacies of ozonation with an ozone injection dose of 0.25 mg/L for each cell under a full-scale hydraulic condition were estimated by the ADR model.

(4) Chlorine disinfection. Water treated by chlorine disinfection is the drinking water supplied to the city.

E. coli concentrations in drinking water are generally below the limit of detection. In order to estimate the inactivation efficacy, a pilot-scale plant installed at the treatment plant was dosed with *E. coli*, and *E. coli* was measured in the effluent. The total length, width and depth of the chlorine contact tank were 0.8 m, 0.55 m and 1 m, respectively. The effective volume of the chlorine contact tank was over 0.265 m^3, corresponding to a hydraulic residence time of approximately 7.5 min. Water treated with ozonation and activated carbon passed into the chlorine contact tank with a target minimized residual chlorine level in the range of 0.05 and 0.15 mg/L of free chlorine, and the chlorine injection was regulated accordingly. Cultured *E. coli* at a high concentration was continuously injected into the chlorine contact tank. After achieving a steady state (10 minutes after starting the *E. coli* injection), the effluent water was collected several times. The concentration of free residual chlorine was measured and the concentration of viable *E. coli* was determined with XM-G agar medium. *E. coli* dosing tests were performed in the winter (January 2011) four times.

Consumption of unboiled drinking water

Water consumption data were provided through an investigation conducted by the Osaka City Waterworks Bureau in 2009 (Komatsu *et al.* 2013). To account for the variability in water consumption with the population, an exponential distribution with a mean value of 327 mL/day was applied for performing the QMRA.

Dose-response model

A dose-response relationship of *C. jejuni* presented by Tenuis *et al.* (2005) is a Beta-Poisson model where $\alpha = 0.024$ and $\beta = 0.011$. When the Beta-Poisson model was applied, however, it was noted that the Beta-Poisson model can exceed the maximum risk curve at low doses (Medema *et al.* 2006). In this study, an exponential model ($P_d = 1 - \exp(-0.686 \times D)$, D: dose) proposed by Itoh (2010) was used.

Risk calculation

The parametric distributions of *E. coli* concentrations in source water, the removal and inactivation efficacy of water treatment, and the C/E ratios were expressed by probability density functions (PDFs). The overall removal efficacy by four treatment steps was calculated using a Monte Carlo simulation performed by drawing random values from each PDF given to the four steps. *E. coli* concentrations in treated water were calculated from the *E. coli* concentration in source water and the reduction efficacy of the treatment processes. Daily exposure was calculated by multiplying the estimated *E. coli* concentration in treated water with the consumption of unboiled drinking water per day. The *E. coli* dose was translated into the *C. jejuni* dose using the C/E ratio in the river water. The daily risk of infection (P_d) with *C. jejuni* was calculated from the *C. jejuni* dose using the dose-response model. The individual health risk was expressed by the average yearly risk of infection (P_y). Under the assumptions of a binomial process, the yearly risk of one or more infections was calculated by $P_y = 1 - (1 - P_d)^{365}$.

A Monte Carlo simulation was performed by drawing random values from each PDF of *E. coli* concentrations in the source water, the four treatment steps, the water consumption, and the C/E ratios to calculate the yearly infection risk (P_y). Correlations between the variables were not assumed in the simulation. Stable results were achieved with acceptable calculations 100,000 times. Crystal Ball 7® (Oracle Corporation) was used for selecting parametric PDFs fitted to variables and performing the Monte Carlo simulation.

Sensitivity analysis

Because the model contained a series of steps, sensitivity analysis was performed to identify which components or variables within the model were most important to the outcome. The sensitivity of the overall removal efficacy by four treatment steps, *E. coli* concentrations in treated water, *E. coli* dose, and the yearly risk of infection were analyzed. For a sensitivity analysis, Spearman's rank correlation coefficients are computed between the assumed variables and predicted variables. Contribution to variance is calculated

by squaring the rank correlation coefficients and normalizing them to 100%. Contribution to variance shows sensitivities as values that range from 0 to 100% and indicate relative importance by showing the percentage of the variance of the predicted variable contributed by each model variable.

Uncertainty analysis

It is natural that the estimated values of target variables and the yearly risk of infection have large uncertainty. The influence of any hypothesis or assumption that can greatly affect the outcome was tested by uncertainty analysis. Uncertainty analysis was performed on the impact of the concentration interpolation method for undetected data in water treated by coagulation-sedimentation, the impact of statistical methods to define water consumption data and the impact of the hydraulic condition of the ozone contactor.

RESULTS AND DISCUSSION

Data collection

Measurements of *C. jejuni* and *E. coli* in river water

E. coli and *C. jejuni* concentrations were measured in the Katsura River at the point of the Miyamae Bridge a total of 31 times from November 2010 to December 2012. As *C. jejuni* was detected 22 times in the water, a total of 22 C/E ratios were obtained. In this study, the data were presented as a complementary cumulative 'histogram' to fit a complementary cumulative distribution function (CCDF) on a double log scale. This form of presenting data is generally applied in other fields of risk assessment. Figure 3 shows the CCDF of the measured *E. coli* and *C. jejuni* concentrations in the Katsura River (without undetected data).

Removal and inactivation efficacy of the water treatment process

(1) Coagulation-sedimentation. Concentrations of *E. coli* in the source water and in water treated by coagulation-sedimentation were measured at the same time for 27 times. *E. coli* was detected only 13 times in water treated by coagulation-sedimentation. Therefore, a statistical method (Zhou & Itoh 2010) based on the theory of the MPN method and the Poisson distribution was used to extrapolate these undetectable data. Since it is assumed that the concentration interpolation method has uncertainty, the impact of the concentration interpolation method on the yearly risk of infection was analyzed. Figure 4 shows the concentrations of *E. coli* in the source water and water treated by coagulation-sedimentation (including extrapolated data) as CCDF.

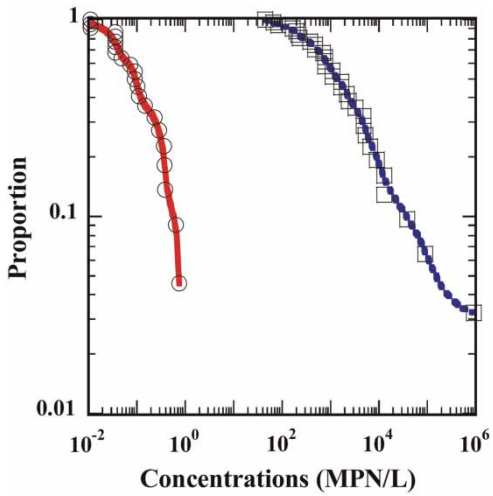

Figure 3 | The *E. coli* concentrations (□) and *C. jejuni* concentrations (○) in the Katsura River.

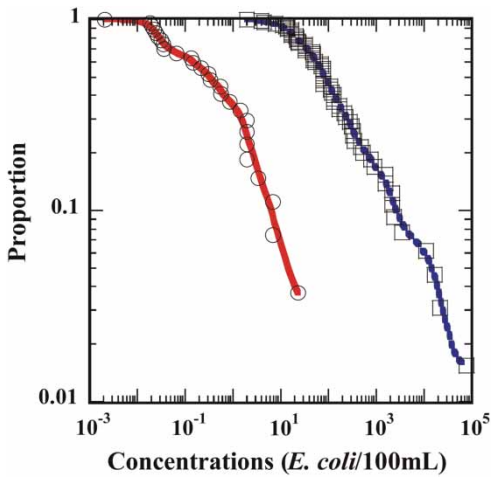

Figure 4 | The concentrations of *E. coli* in the source water (□) and water treated by coagulation-sedimentation (○).

The *E. coli* concentrations in the water treated by coagulation-sedimentation that were predicted by the date, rank and random methods were compared to the monitored *E. coli* concentrations. It was found that the rank method provided an appropriate estimate of the removal efficacy for Monte Carlo simulation since the monitored concentrations were consistent with the predicted concentrations. Consequently, the rank method was used in the following analyses.

(2) Ozonation. Based on the results of the tracer tests, the dispersion number of the pilot-scale ozone-bubble diffuser contactor was estimated to be 0.037 by using a model developed by Mariñas *et al.* (1993). The *E. coli* inactivation rate constants that agree with the results of the *E. coli* dosing tests were determined by a trial-and-error approach with the ADR model: a total of five *E. coli* inactivation rate constants, 0.47, 0.52, 0.55, 0.57, and 0.73 $L\,mg^{-1}\,s^{-1}$, were obtained. With an ozone injection dose of 0.25 mg/L for each cell under a full-scale hydraulic condition, the inactivation efficacies of ozonation for each cell are summarized in Table 1. Since the tracer test could not be performed in the actual treatment facility, the dispersion number used for the full-scale ozone-bubble diffuser contactor was an estimate based on the value determined in the pilot-scale ozone-bubble diffuser contactor and the value reported in a reference (Tang *et al.* 2005) where the ozone contactor had a similar shape and size to the one in the treatment plant. Taking 0.037 of the dispersion number for the pilot-scale ozone-bubble diffuser contactor as the smallest, and the literature value of 1.45 as the largest, we used 0.23 (the geometric average of the two values) as the dispersion number for the full-scale ozone-bubble diffuser contactor. Since it is assumed that the dispersion number used for the full-scale ozone-bubble diffuser contactor has large uncertainty, the impact of the dispersion number on the yearly risk of infection was analyzed.

(3) Chlorine disinfection. With free residual chlorine ranging from 0.05 to 0.15 mg/L, the inactivation efficacies of chlorine disinfection are summarized in Table 2.

Table 1 | Inactivation efficacy of ozonation in the full-scale contactor

Inactivation rate constants ($L\,mg^{-1}\,s^{-1}$)	Log reduction
0.47	1.61
0.52	1.73
0.55	1.79
0.57	1.85
0.73	2.17

Note: with an ozone injection dose of 0.25 mg/L.

Table 2 | Inactivation efficacy of chlorine disinfection in the pilot-scale plant

CT (mg min/L)	Log reduction
1.25	5.82
1.08	5.83
0.79	4.36
0.69	4.30

Note: with free residual chlorine concentration ranging from 0.05 to 0.15 mg/L.

Injected free residual chlorine and a supposed ozone injection dose are minimized levels in order to detect survived *E. coli* after the treatments. Therefore, log reductions by actual ozonation and chlorination are expected to be much larger than those shown in Tables 1 and 2.

Risk calculation

Overall removal efficacy

PDFs were selected to describe the distribution of *E. coli* concentrations in the source water; the removal and inactivation efficacy by coagulation-sedimentation, RSF, ozonation, and chlorine disinfection; the water consumption; and the C/E ratio. The selected PDFs and estimated parameters are shown in Table 3. It shows that the four treatment steps have removal/inactivation efficacies in the following order: chlorine disinfection (MEC = 4.62 $\log_{10}$) > coagulation-sedimentation ($\mu = 2.64$ $\log_{10}$) > ozonation (MEC = 1.79 $\log_{10}$) > RSF (MEC = 1.6 $\log_{10}$). Although the chlorination and ozone doses were minimized in this study, the removal efficacy by RSF was the lowest as supposed in the Methods section. A Monte Carlo frequency distribution of the overall log reduction is shown in Figure 5. The median was 11.1 $\log_{10}$ and the mean was 10.4 $\log_{10}$. It is noteworthy that the overall log reduction was estimated to

Table 3 | Probability density functions (PDFs) fitted to the target variables

		PDF type	Estimated parameters
E. coli in the source water (*E. coli*/100 mL)		Lognormal	$\mu = 1{,}450$; $\sigma = 19{,}400$
Treatment efficacy (log reduction) of *E. coli*	Coagulation-sedimentation	Normal	$\mu = 2.64$; $\sigma = 0.49$
	RSF	Triangular	Min. = 0.5; MEC (Mean Elimination Capacity) = 1.6; Max. = 2.9
	Ozonation	Triangular	Min. = 1.61; MEC = 1.79; Max. = 2.17
	Chlorine disinfection	Triangular	Min. = 4.30; MEC = 4.62; Max. = 5.83
C/E ratio		Lognormal	$\mu = 4.46 \times 10^{-3}$; $\sigma = 0.351$
Water consumption		Exponential	$\lambda = 3.06 \times 10^{-3}$

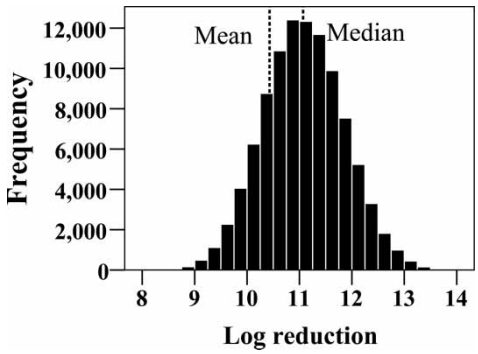

Figure 5 | Monte Carlo frequency distribution of over-all log reduction.

be 11.1 $\log_{10}$ (median) instead of setting overall removal to be 100%, although almost all of the *E. coli* concentrations measured after chlorination were 0.

Yearly risk of infection

The statistics estimated in the QMRA are summarized in Table 4. The mean yearly risk of infection was estimated to be 1.09×10^{-7} infection/person/yr, and the median was 3.22×10^{-11} infection/person/yr. As described in the Methods section, it is obvious that the calculated infectious risk is not the actual risk of drinking water produced at the treatment plant. It can be demonstrated, however, that the mean, median, and 97.5 percentile are far below 10^{-4} infection/person/yr that is acceptable yearly risk of infection proposed by the World Health Organization and the United States Environmental Protection Agency (EPA) (US EPA 1989). This result demonstrates that the water treatment process supposed in this study produces safe drinking water in terms of eliminating *C. jejuni*. In other words, based on the data in Table 3, an overall removal and inactivation efficacy with a mean value of 7.72 $\log_{10}$ is sufficient to achieve the mean yearly risk of infection of 10^{-4} infection/person/yr.

Sensitivity analysis

The sensitivity of the overall removal efficacy by four treatment steps, *E. coli* concentrations in treated water, *E. coli* dose, and the yearly risk of infection were analyzed. Figure 6 shows the result of the sensitivity analysis for the yearly risk of infection. It exhibits that the C/E ratio in the river water has the largest impact on the yearly risk of infection.

Among the four treatment steps, RSF treatment has the greatest impact, which means that the rank correlation coefficient between the removal efficacy by RSF and the yearly risk of infection was the largest. This is because the *E. coli* removal efficacy by RSF varies greatly from 0.5 to 2.9 $\log_{10}$. As described in *Overall removal efficacy*, chlorine disinfection contributes most to the decrease of the yearly risk of infection, while RSF contributes least. The meaning of the greatest impact by RSF shown in Figure 6 is that the stable performance of RSF removal is the most important to stably produce safe drinking water by the water treatment process supposed in this study. Since the contribution to the variance of coagulation-sedimentation is similar to that of RSF, it can be suggested that the complete removal of suspended solids and particulates in the source water is extremely important. The removal efficacy by RSF, however, was set to be a literature value. It would be desired to estimate the removal efficacy by RSF actually employed.

Table 4 | Statistics estimated in the QMRA

	Lower 95% CI boundary	Median	Mean	Upper 95% CI boundary
Overall log reduction	9.59	11.1	10.4	12.6
E. coli in the treated water (*E. coli*/100 mL)	5.46×10^{-12}	9.59×10^{-10}	5.09×10^{-8}	2.47×10^{-7}
E. coli dose (*E. coli*/day)	4.98×10^{-12}	1.82×10^{-9}	1.58×10^{-7}	7.10×10^{-7}
C. jejuni dose (*C. jejuni*/day)	9.32×10^{-17}	1.29×10^{-13}	4.35×10^{-10}	4.11×10^{-10}
Daily risk of infection (infection/person/day)	1.11×10^{-16}	8.82×10^{-14}	2.99×10^{-10}	2.82×10^{-10}
Yearly risk of infection (infection/person/yr)	4.05×10^{-14}	3.22×10^{-11}	1.09×10^{-7}	1.03×10^{-7}

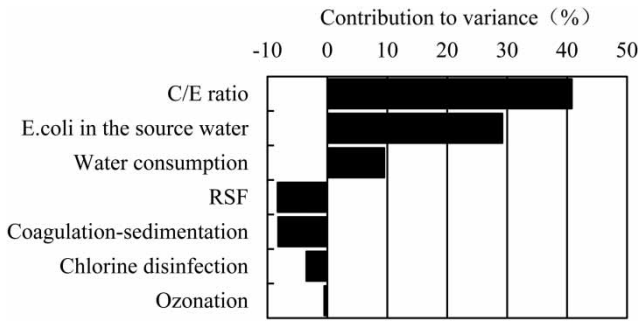

Figure 6 | Sensitivity analysis of yearly risk of infection.

Uncertainty analysis

After selecting the target variables that might greatly affect the estimates of the yearly risk of infection, an uncertainty analysis was conducted. The results of the analysis are shown in Table 5. It was clear that the dispersion number of the full-scale ozone contactor has the greatest impact on the yearly risk of infection. In order to estimate the inactivation efficacy of ozonation under full-scale hydraulic conditions, the dispersion number used was an estimate based on the value determined in the pilot-scale contactor and the value reported in a reference. The result shown in Table 5 demonstrates that the dispersion number depending on the hydraulic characteristics inside the ozone contactor greatly affects the inactivation efficacy of ozonation as well as the yearly risk of infection. An accurate estimation of the dispersion number for the full-scale ozone contactor is needed. On the other hand, the *E. coli* inactivation rate constants of ozonation obtained in this study (pilot-scale experiments, 0.47, 0.52, 0.55, 0.57, 0.73 L mg^{-1} s^{-1}) were extremely small values when compared to the rate constants reported in the literature (Hunt & Mariñas 1997). The small inactivation rate constants may lead to an under-estimation of the inactivation efficacy of ozonation and a large yearly risk of infection.

An uncertainty analysis for the C/E ratio could not be performed due to limited information. The C/E ratios used were values obtained in river water (the Katsura River) that was mixed with a large volume of effluent from a wastewater treatment plant, and are not the values of the actual source water (the Yodo River) for the water treatment

Table 5 | Uncertainty analysis of yearly risk of infection

		Yearly risk of infection (infection/person/yr) Lower 95% CI boundary	Mean	Upper 95% CI boundary
Base case		4.05×10^{-14}	1.09×10^{-7}	1.03×10^{-7}
Without using undetected data in water treated by coagulation-sedimentation		0	1.13×10^{-7}	9.85×10^{-8}
Water consumption statistics	Poisson distribution	8.10×10^{-14}	1.14×10^{-7}	1.3×10^{-7}
	Discrete value	0	1.03×10^{-7}	9.89×10^{-8}
Dispersion number	$d=0.037$	0	2.18×10^{-8}	1.93×10^{-8}
	$d=1.45$	2.43×10^{-13}	1.01×10^{-6}	9.77×10^{-7}

plant. Taking into consideration the difference in the viability of *C. jejuni* and *E. coli* when found in surface water, and the variability of *C. jejuni* and *E. coli* concentrations with respect to season and location, data collection of C/E ratio in the actual source water throughout the year is highly required to improve the accuracy of the QMRA. In addition, it is preferable to directly monitor the *C. jejuni* concentration, when possible.

CONCLUSIONS

A QMRA was conducted to estimate the infectious risk of *C. jejuni* for a supposed water treatment process with an advanced treatment. The mean yearly risk of infection was estimated to be 1.09×10^{-7} infection/person/yr – far below the acceptable yearly risk of infection of 10^{-4} infection/person/yr. The calculated infectious risk is not the actual risk of drinking water produced at a specific treatment plant, however, it was demonstrated that the water treatment process supposed in this study produces safe drinking water in terms of eliminating *C. jejuni*.

Among the four treatment steps, chlorine disinfection contributes most to the decrease of the yearly risk of infection, while RSF contributes least. On the other hand, from the sensitivity analysis, RSF was identified as the most important process affecting the variance of the yearly risk of infection. Stable performance in removing *E. coli* by RSF is the most important factor in the reliable production of safe drinking water. It was also suggested that the complete removal of suspended solids and particulates in the source water by coagulation-sedimentation and RSF is extremely important.

The uncertainty analysis demonstrated that the factor with the largest impact on the yearly risk of infection was the hydraulic condition of the ozone contactor. It should be noted that an estimation of the dispersion number for the full-scale ozone contactor is needed to improve the accuracy of QMRA. Data collection to determine the C/E ratio in the source water is highly required to improve the accuracy of the QMRA. In addition, it is preferable to directly monitor the *C. jejuni* concentration, when possible.

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