

Acceptable microbial risk: Cost–benefit analysis of a boil water order for *Cryptosporidium*

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Water treatment plants typically issue a boil water order (BWO) to a potentially affected populace when *Cryptosporidium* is detected in the finished water. Although BWOs involve costs that may not be justified for very low risks of infection, there is no predetermined risk level or environmental concentration that triggers such an order. In this study, a cost–benefit analysis was used to identify a threshold level of risk for issuing a BWO. A decision tree was constructed, and the threshold level of risk at

which the expected benefits of a BWO exceed expected costs was identified. An exponential dose–response model was used to determine the dose of *Cryptosporidium* oocysts that corresponds to the threshold risk level. Results suggest that a daily risk of nine illnesses out of 10,000 people exposed would justify a BWO. Given typical 3-log removal of oocysts during treatment, this risk level would correspond to a finished water concentration of 0.046 oocysts/L and a raw water concentration of 46 oocysts/L.

Keywords: Actionable risk level, decision analysis, dose–response modeling, Monte Carlo simulation, risk management, sampling requirements

Cryptosporidium is an intracellular coccidian protozoan that causes cryptosporidiosis, a disease characterized by voluminous watery diarrhea accompanied by stomach cramps, nausea, vomiting, and slight fever (CDC, 2010; Fayer & Xiao, 2008). The organism lives in the intestine of infected humans or animals, and one bowel movement can release millions of oocysts, the environmental and infectious stage of the parasite. This disease can result in infections of long duration and even death among immunocompromised individuals. Putative sources of human cryptosporidiosis are soil, food, water, or surfaces that have been contaminated with infected human or animal feces. The disease is extremely contagious and can lead to secondary infection.

The vector stage of the disease, the oocyst, is highly resistant to chemical disinfection, and coagulation–flocculation–sedimentation–filtration has been shown to be the most effective means of removal during potable water treatment (Rose et al, 2002; Fayer et al, 2000; Haas & Aturaliye, 1999). Disinfection with ultraviolet light can also be highly effective (Slifko et al, 2002; Clancy et al, 2000). In addition, boiling has been shown to be an effective disinfection method for *Cryptosporidium*, and boil water orders (BWOs) or advisories are typically issued when there are concerns that the organism is present in finished water (USEPA, 2006a).

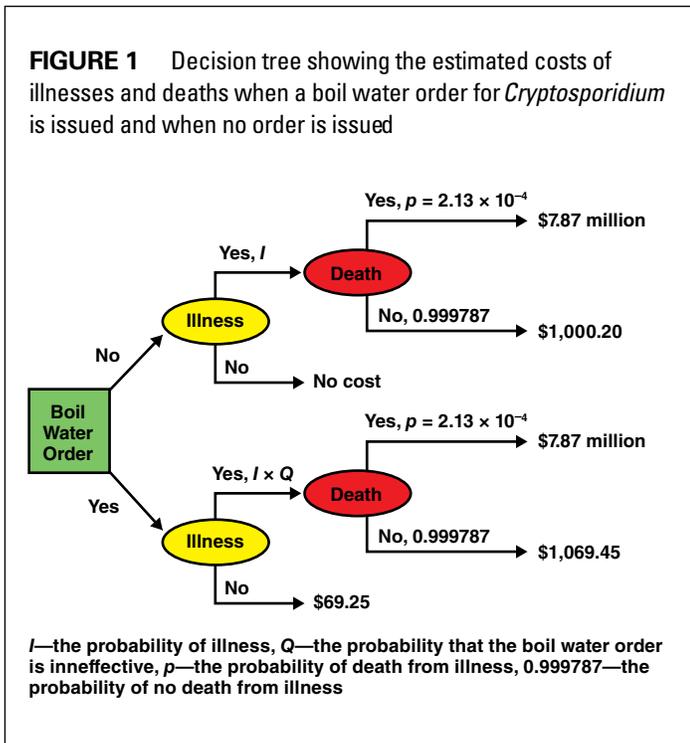
As a result of the 1996 Amendments to the Safe Drinking Water Act, cost–benefit analysis is now used in setting drinking water standards. Previous analyses have considered the benefits and costs of standards for arsenic (Gurian et al,

2001), uranium (Gurian et al, 2004), and the microorganisms regulated by the Long Term Enhanced Surface Water Treatment Rule (USEPA, 2005). This study used cost–benefit analysis to determine the environmental concentration of *Cryptosporidium parvum* that should be considered hazardous enough to a statistical individual to warrant a BWO or advisory, given a conventional filtration plant with no advanced treatment systems. BWOs involve costs as well as potential health risks and may not be justified for very low risks of infection; however, no predetermined risk level or environmental concentration has been agreed on for triggering such an order. The level of risk could be sufficiently low that detection of a corresponding concentration of *Cryptosporidium* oocysts in finished water might be difficult. Therefore, this study also considered raw water *Cryptosporidium* concentrations that, when adjusted for removal during treatment, would correspond to this level of risk.

DECISION MODEL

In this study, the authors first developed a decision model and then identified the lowest risk at which action would be justified on the basis of expected benefits (Mitchell-Blackwood, 2011). The decision tree in Figure 1 depicts the decision to issue a BWO given the presence of infectious oocysts in the water. One first decides whether to issue the BWO, represented by the rectangle at the left of Figure 1. If the BWO is not issued, there is a probability, I , of illness. If the BWO is issued, the probability of illness

FIGURE 1 Decision tree showing the estimated costs of illnesses and deaths when a boil water order for *Cryptosporidium* is issued and when no order is issued



becomes $I \times Q$, in which Q is the probability that the BWO is ineffective. In the event of illness, the probability of death, p , was estimated as 2.13×10^{-4} on the basis of the mean value of the US Environmental Protection Agency's (USEPA's) computation for a filtered (1.65×10^{-4}) and an unfiltered water supply (2.61×10^{-4}). This estimate is a weighted average of the estimated deaths of immunocompromised and nonimmunocompromised individuals, given the respective proportions of these groups in the population (USEPA, 2005).

An exponential dose–response model was used to evaluate the dose associated with a given level of risk (Haas, 1983; Haas et al, 1999; USEPA, 2005):

$$\text{Daily Risk} = 1 - e^{(-d \times k)} \quad (1)$$

in which daily risk = the predicted proportion of individuals infected, e = exponent, d = average daily dose, and k = the parameter characterizing host–pathogen interaction.

The literature review indicated that the most conservative estimate for the k value was 0.0572 with a 5th percentile value of 0.0246 (Enger, 2012). A 95th percentile value of 1.0 was used because this represented the theoretical upper bound of infectivity—i.e., ingestion of a single particle is certain to cause infection (Haas et al, 1999). The probability of illness given infection (morbidity) was determined to be 0.39–0.5 (USEPA, 2006c, 2002;), with the upper limit used in this study's model in order to be conservative. Other dose–response models have shown variations in k values for different *Cryptosporidium* data sets associated with different isolates (Mitchell-Blackwood, 2010; Teunis et al, 2002; Messner et al, 2001; Okhuysen et al, 1999). The k value used in this study was similar to the values

computed for the Texas A&M University isolate by Messner et al (2001), who found a k value of 0.0571, and Teunis et al (2002), who reported a k value of 0.0573.

COST ESTIMATES

The costs associated with different outcomes are shown at the right of Figure 1. It was assumed that 30 days was the time needed for environmental conditions to return to normal or for water authorities to take remedial action, and thus all costs were calculated accordingly (Casman, 2000; Kocagil et al, 1998). The average BWO cost used was \$69.25 (in 2011 dollars). This figure was based on the costs of boiling water (including electricity and time), hauling (including travel time), and purchasing safe water (Kocagil et al, 1998). Potential residual boiling costs associated with fires and injuries caused by burns were not included in the estimate by Kocagil et al and were not considered in this study. The value reported by Kocagil et al was in 1996 dollars and was adjusted for inflation using the annual average consumer price index values of 156.9 and 224.939 for 1996 and 2011, respectively (BLS, 2012).

The average loss resulting from illness was based on USEPA's "enhanced" cost of illness ($\$I$) of \$1,000.20 (in 2011 dollars), which took into account loss of personal, work, and family time as well as medical expenses (USEPA, 2005). This study used USEPA's value of statistical life ($\$V$) associated with death (USEPA, 2005) adjusted to a value of \$7.87 million in 2011 dollars.

THRESHOLD VALUE

The switchover threshold is the risk level at which the expected values of the two branches of the decision tree are equal to each other:

$$EV[B] = EV[\text{no } B] \quad (2)$$

in which $EV[B]$ is the expected value of the BWO branch and $EV[\text{no } B]$ is the expected value of the branch indicating that no BWO was issued. The expected value of the BWO branch of the decision tree is

$$EV[B] = I \times Q \times [p \times \$V + (1 - p) \times (\$I + \$B)] + [(1 - I \times Q) \times \$B] \quad (3)$$

in which I is the probability of illness, p is the probability of death from illness, $\$V$ is the value of statistical life, $\$I$ is the cost of illness, and $\$B$ is the cost of a BWO (values given in the literature review previously described); Q , the chance that boiling fails to remove the risk, is considered to be 0.01 (Clasen et al, 2008), and a sensitivity analysis was conducted on this value. Although unlikely, boiling may fail to eliminate the risk of infection as a result of microbes surviving boiling (possibly protected from heat in suspended particles), improper implementation (too little time), boiled water being transferred to a nondisinfected container, or other factors. The expected value of the no BWO branch of the tree is given by

$$EV[\text{no } B] = I \times [p \times \$V + (1 - p) \times \$I] \quad (4)$$

Thus at the threshold of risk

$$I \times Q \times [p \times \$V + (1 - p) \times (\$I + \$)] + [(1 - I \times Q) \times \$B] = I \times [p \times \$V + (1 - p) \times \$I] \quad (5)$$

The switchover threshold probability was solved as $I = \text{Probable}[\text{illness}] = 0.0261$; this represents the total risk of illness over 30 days because the costs and benefits of the BWO are based on this time range.

The daily risk of illness during the 30-day period of exposure was calculated as follows:

$$\begin{aligned} \text{Monthly Risk} &= 1 - [1 - \text{Daily Risk}]^{30} \\ \text{Daily Risk} &= 1 - [1 - 0.0261]^{1/30} = 8.82 \times 10^{-4} \end{aligned} \quad (6)$$

The dose–response model in this study was based on the probability of infection, calculated as follows:

$$\text{Probable}[\text{illness}] = \text{Probable}[\text{illness}|\text{infection}] \times \text{Probable}[\text{infection}] \quad (7)$$

in which $\text{Probable}[\text{illness}|\text{infection}]$ = the probability of illness given the condition of infection.

A $\text{Probable}[\text{illness}|\text{infection}]$ or infectivity rate of 0.39 (Haas et al, 1999) implies

$$\begin{aligned} \text{Probable}[\text{infection}] &= \text{Probable}[\text{illness}] \div \text{Probable}[\text{illness}|\text{infection}] \\ &= 8.82 \times 10^{-4} \div 0.39 = 2.36 \times 10^{-3} \end{aligned}$$

The exponential risk model (Eq 1) was then used to calculate the dose corresponding to this level of risk

$$\begin{aligned} 2.36 \times 10^{-3} &= 1 - e^{(-d \times 0.0572)} \\ d &= 0.0396 \text{ oocysts/d} \end{aligned}$$

Assuming independent daily risks, the annual risk of illness implied by the daily risk level derived from the model was calculated according to Haas (1996)

$$\begin{aligned} \text{Annual Risk} &= 1 - [1 - \text{Daily Risk}]^{365} \\ \text{Annual Risk} &= 1 - [1 - 8.82 \times 10^{-4}]^{365} = 0.276 \end{aligned} \quad (8)$$

FINISHED AND RAW WATER CONCENTRATIONS AND SAMPLING

The environmental concentration corresponding to the threshold of actionable risk is based on a 3-log removal of *Cryptosporidium* by a conventional treatment plant (USEPA, 2006c) and a mean per capita rate of water ingestion of 0.869 L/day for all ages (USEPA, 2011). This concentration was calculated according to the following equation:

$$F = d \div c = 0.0396 \text{ oocysts/d} \div 0.869 \text{ L/d} = 0.0456 \text{ oocysts/L} \quad (9)$$

in which F = the finished water concentration, computed as an average oocyst concentration over 30 days for a working 3-log removal treatment system, given the dose corresponding to the actionable risk, and c = the mean per capita rate of water ingestion,

or the contact rate. Because less than 1 oocyst/L is sufficient to justify a BWO, one may ask whether even a negative sample establishes that a finished water source contains concentrations below this level. Optimistically one might assume complete sensitivity of the assay and Poisson variability in the occurrence of oocysts. In this case, a negative sample allows one to reject the hypothesis that the finished water exceeds the concentration threshold when

$$\text{Probable}[X = 0] = e^{- (F \times \text{sample volume})} \leq \alpha \quad (10)$$

in which $\text{Probable}[X = 0]$ is the probability of an expected value X being equal to zero, and α is the acceptable false-negative error rate (the rate at which one fails to detect finished drinking water concentrations above the threshold). For $\alpha = 0.01$ and $F = 0.0456$, the sample volume = 101.0 L. Because recoveries of 20–50% are more realistic, sample volumes in the range of 200–500 L might be better indicators that risks are below the boil water threshold, particularly if the sample volume consists of multiple samples taken over time. Conversely, a single oocyst detected in a sample of hundreds of litres could well be interpreted as necessitating a BWO.

Raw water concentrations (R) are also of interest.

$$R = F \div 3\text{-log removal} = 0.0456/0.001 \approx 46 \text{ oocysts/L} \quad (11)$$

A raw water concentration (R) would therefore have to be 46 oocysts/L or greater to warrant a BWO or advisory on the basis of expected benefits and costs for a facility achieving 3-log removal. A facility meeting a 5.5-log removal standard, such as that required by the Long Term 2 Enhanced Surface Water Treatment Rule, could tolerate a raw water concentration of 14,400 oocysts/L.

SENSITIVITY–UNCERTAINTY ANALYSIS

Monte Carlo uncertainty analysis was used to conduct a sensitivity analysis on several parameters used in the model. The parameters included the risk of death (p), the probability that boiling would not be successful (Q), the probability that the pathogen causes an infection, the mean per capita rate of water ingestion (c), and the oocyst removal rate achieved by water treatment (L). Table 1 summarizes the input distributions used.

A lognormal distribution was assumed for all these parameters except Q , which was considered to be log–uniformly distributed. This decision was made in order to provide a wide range of boiling removal rates without the unrealistically high values that would be produced by a high variance distribution lacking a fixed upper bound. Thus the values chosen to model the distribution of Q used 0.001 as the lower bound and 0.1 as the upper bound. This range also encompasses the wide variance in compliance rates associated with consumers’ risk-aversion behavior in response to a BWO (O’Donnell et al, 2000).

USEPA’s lower and upper estimates for p — 1.65×10^{-4} and 2.61×10^{-4} (USEPA, 2005)—were used as the 5th and 95th percentiles, respectively.

As indicated previously, the most conservative k value of 0.0246 was used in this model with the reported 5th–95th percentile values of 0.0245 and 1.0.

TABLE 1 Range of values for model input distributions

	Probability of Death From Illness [*] <i>p</i>	Probability That Boiling Is Ineffective [†] <i>Q</i>	Contact Rate [‡] <i>c</i>	Log Removal of Oocysts During Water Treatment [§] <i>L</i>	Dose Response ^{**} <i>k</i> ^{††}
Distribution type	Lognormal	Uniform	Lognormal	Lognormal	Lognormal
5th percentile	1.65×10^{-4}	1.0×10^{-3}	8.69×10^{-1}	3.2×10^{-4}	2.46×10^{-2}
Mean	2.13×10^{-4}			1.0×10^{-3}	5.72×10^{-2}
95th percentile	2.61×10^{-4}	1.0×10^{-1}		1.0×10^{-2}	$1.00 \times 10^{-0\dagger\dagger}$
Standard deviation			1.12×10^{-0}		

* USEPA, 2005
 † Clasen et al, 2008
 ‡ USEPA, 2011
 § USEPA, 2006c
 ** Enger, 2012
 ††Based on the *Cryptosporidium parvum* Texas A&M University isolate
 ‡‡Theoretical upper bound on infectivity (i.e., ingestion of a single particle is certain to cause infection)

The values chosen to model the distribution of *L* were 3.2×10^{-4} (3.5-log removal) as the 5th percentile; 10^{-3} (3-log removal) as the mean; and 10^{-2} (2-log removal) as the 95th percentile (USEPA, 2006c). The values used to model the distribution of *c* were based on USEPA's recommendation for all ages, with a mean of 0.869 L/day and a standard deviation of 1.12 (USEPA, 2011).

Proprietary software¹ was used to fit the input distributions with the goal of minimizing the squared difference between the observed cumulative distribution functions and the model's cumulative distribution functions. This process resulted in values for the mean and standard deviation for each of the model's parameters. A Monte Carlo analysis of 1 million samples from the modeled distributions was then conducted. Spearman rank correlations (Table 2) were generated and used to assess the strength and direction of the relationships of *p*, *Q*, *k*, *c*, and *L* with *I* and *R*. Estimated action levels were also generated (Table 3). The sensitivity analysis was repeated with 1,000 iterations, using the solver nonlinear optimization routine in a commonly used spreadsheet software.² Similar results were obtained.

The sensitivity analysis indicated that the risk threshold had the highest sensitivity to uncertainty in *p* (rank correlation: -0.95) and *Q* (rank correlation: 0.25). There was no correlation between *k*, *c*, and *L* with *I*; this would be expected because these parameters relate risk to finished water and environmental concentrations and do not affect any of the probabilities and valuations that determine the risk threshold (i.e., the values given in Figure 1). Uncertainty in *L* was the greatest contributor to uncertainty in *R* (rank correlation: -0.76) followed by *k* (rank correlation: -0.54) and then *c* (rank correlation: -0.27). There was very little correlation between *p* and *R* and between *Q* and *R*. The highest sensitivity of *F* was associated with uncertainty in *k* (rank correlation: -0.87), *c* (rank correlation: -0.43), and *p* (rank correlation: -0.14).

This analysis indicates that to reduce the uncertainties in the risk level calculated in this study, one should focus on reducing uncertainties in *p*. To reduce uncertainty regarding finished water concentration, one would focus on *k*, the dose-response parameter; to reduce uncertainty in the raw water concentra-

tion, one would focus on improving the estimates of treatment plant removal.

DISCUSSION

This study included estimates of actionable risk thresholds for issuing a BWO for *Cryptosporidium*. Daily risk was estimated to be on the order of nine illnesses out of 10,000 people exposed, and annual risk was estimated at 28 illnesses out of 100 people exposed. These estimates are three orders of magnitude higher than the 1-in-10,000 annual risk often used as a benchmark for microbiological risk associated with routine water treatment. An annual risk target of 1 in 10,000 (Regli et al, 1991; USEPA, 1992) would imply a finished water concentration of 3.25×10^{-5} oocysts/L, which may be exceeded by surface water treatment plants (Almeida et al, 2010; Mason et al, 2010; Castro-Hermida et al, 2008). Establishing compliance with this target in finished water could pose a challenge if currently established detection techniques are used. However, USEPA suggested this benchmark with the intention of protecting consumers against waterborne disease outbreaks rather than preventing outbreaks (USEPA, 1989; USEPA, 2006c).

The range of actionable finished water concentrations determined in the current study, 0.02–0.14 oocysts/L (5th–95th percentile), is similar to the range of 0.1–0.3 oocysts/L suggested by

TABLE 2 Monte Carlo input-output rank correlations

	Monthly Risk (Risk Threshold)	Finished Water Concentration <i>F</i>	Raw Water Concentration <i>R</i>
Probability of death from illness— <i>p</i>	-0.95	-0.14	-0.09
Probability that boiling is ineffective— <i>Q</i>	0.25	0.04	0.03
Dose response— <i>k</i>	0.00	-0.87	-0.54
Contact rate— <i>c</i>	0.00	-0.43	-0.27
Water treatment log-removal rate— <i>L</i>	0.00	0.00	-0.76

TABLE 3 Estimated action level resulting from a Monte Carlo analysis

	Monthly Risk	Daily Risk	Annual Risk	Finished Water Concentration oocysts/L	Raw Water Concentration oocysts/L
Mean	0.027	0.00090	0.28	0.066	84
Standard deviation	0.0023	0.000079	0.00	0.042	97
5th percentile	0.023	0.00077	0.28	0.021	12
95th percentile	0.031	0.0010	0.28	0.14	250

a previous study (Haas & Rose, 1995). The report by Haas and Rose was based on monitoring studies of finished water *Cryptosporidium* concentrations and took into account measurements made during and after detected outbreaks. The three orders of magnitude difference in the 1-in-10,000 annual benchmark ($F = 3.25 \times 10^{-5}$ oocysts/L) compared with the much higher concentrations proposed by this study and the Haas and Rose study (1995) suggest that further analysis and discussion of this topic is warranted. The environmental concentration of 46 oocysts/L suggested by this study might only rarely be exceeded by surface water supplies (Castro-Hermida et al, 2009; USEPA, 2006b; Wilkes et al, 2009) in the United States. Although the possibility of exceeding this level exists, many water supplies that exceed this concentration may already be applying additional treatment, given that a concentration of 46 oocysts/L would require treatment beyond the 3-log removal required by the Long Term Enhanced Surface Water Treatment Rule.

This study had a number of limitations. First, it considered only a BWO or advisory, not other treatment methods. Household water boiling could be a burdensome practice, and other risk-mitigation options, such as the use of ultraviolet light disinfection (Le Goff et al, 2010), either in the home or at a centralized treatment plant, might prove more favorable from a cost-benefit perspective. Thus other options might be justified for lower levels of risk.

Utilities and regulators faced with different choices in the event of detecting *Cryptosporidium* oocysts should bear in mind the limitations not only of this specific study but also of benefit-cost analysis in general. Monetizing intangibles, such as the discomfort of illness and the risk of mortality, is always problematic. Though such analysis may be a useful input to help set priorities, it should not be the sole factor used in decision-making (Arrow et al, 1996). Factors such as compliance with existing notification requirements, public confidence in the water supply, and even potential litigation must be taken into consideration as well. Studies such as this may help inform responses to the detection of *Cryptosporidium* in raw and finished water supplies.

CONCLUSIONS

Results of this study indicated that a daily risk of roughly nine illnesses out of 10,000 people exposed to *Cryptosporidium* was

the point at which the expected monetized benefits of a BWO would exceed the expected costs. Key uncertainties in this analysis are the probability of mortality from illness and the probability of the public not adhering to or not properly implementing the BWO. The analysis is based on expected value decision-making and assumed preferences, including monetary values associated with the risk of illness and mortality that would not be uniformly applicable in all situations.

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PEER REVIEW

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FOOTNOTES

¹MATLAB® R2012b, MathWorks, Natick, Mass.

²Microsoft Excel 2010

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