Comparing probabilistic microbial risk assessments for drinking water against daily rather than annualised infection probability targets

R. S. Signor and N. J. Ashbolt

ABSTRACT

Some national drinking water guidelines provide guidance on how to define 'safe' drinking water. Regarding microbial water quality, a common position is that the chance of an individual becoming infected by some reference waterborne pathogen (e.g. *Cryptsporidium*) present in the drinking water should $<10^{-4}$ in any year. However the instantaneous levels of risk to a water consumer vary over the course of a year, and waterborne disease outbreaks have been associated with shorter-duration periods of heightened risk. Performing probabilistic microbial risk assessments is becoming commonplace to capture the impacts of temporal variability on overall infection risk levels. A case is presented here for adoption of a shorter-duration reference period (i.e. daily) infection probability target over which to assess, report and benchmark such risks. A daily infection probability benchmark may provide added incentive and guidance for exercising control over short-term adverse risk fluctuation events and their causes. Management planning could involve outlining measures so that the daily target is met under a variety of pre-identified event scenarios. Other benefits of a daily target could include providing a platform for managers to design and assess management initiatives, as well as simplifying the technical components of the risk assessment process.

Key words | drinking water, quantitative microbial risk assessment, risk benchmark, risk management

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HEALTH TARGETS AND STOCHASTIC RISK

Influential drinking water regulations (e.g. European Commission (EC) 1998; The Netherlands (Staatsblad 2001); United States Environmental Protection Agency (USEPA) 2002) and guidelines (e.g. Health Canada 1996; (Australian) National Health & Medical Research Council (NH&MRC) 2004; World Health Organization (WHO) 2004) have either advocated or were developed around the principle of setting and aiming to meet health-based targets with regard to microbial contaminant levels in treated drinking water. Such targets are intended to be reflective of contaminant levels that would pose an 'acceptably low' risk of waterborne infection to consumers. An often adopted benchmark, notably used by the USEPA within its original versions of the *Surface Water Treatment Rule* (USEPA 2002), is that the probability of an individual becoming infected by any type of reference waterborne pathogen following independent drinking water exposures over one year should not exceed 1×10^{-4}. That measure was used to derive standards in the United States for raw water treatments initially against *Giardia lamblia* (Macler & Regli 1993) and more recently, for *Cryptosporidium parvum* (USEPA 2002). The Netherlands has passed legislation requiring water suppliers to collect system-specific pathogen occurrence data to statistically demonstrate compliance with the 10^{-4} target for a selection of reference viruses and protozoa (Staatsblad 2001). Nonetheless, the issue of what

doi: 10.2166/wh.2009.101

represents an appropriate target is debatable and situation-dependent (Haas 1996*a*; Hunter & Fewtrell 2001).

Concurrently with the above developments, quantitative microbial risk assessment (QMRA) techniques (Haas *et al.* 1999) have emerged and have been promoted as one way of assessing water supplies to estimate whether health targets are being met (WHO 2004). Increasingly, QMRAs are performed probabilistically, which involves characterizing the infection probability as a variable, rather than as a point-estimate. Probabilistic analyses are most advantageous when assessing situations where there is considerable observed variability and/or uncertainty about the extent of the risks posed (USEPA 1998). Such characteristics are commonly attributed to communicable disease risks from water-based exposure pathways for various reasons (most commonly scarce availability of applicable data), and hence there are many recently documented examples of probabilistic QMRAs (e.g. Teunis *et al.* 1997; Westrell *et al.* 2003; Pouillot *et al.* 2004; Schijven *et al.* 2006).

Citing the recent trend in the use of probabilistic QMRA, this paper is a discussion on the implications of continuing to express infection targets for drinking water in terms of annualised infection probabilities. A theoretical and practical experience-based case is made calling for more widespread adoption of a shorter-duration reference period (i.e. daily) target against which to assess and report microbial risks. This is especially pertinent for drinking water, assuming people in developed nations are typically exposed to tap water every day in some form. This manuscript concludes with a brief discussion of what may be a suitable daily risk target.

RELEVANT QMRA PROPERTIES

Though they can vary in practice, and avoiding technicalities as far as possible, the methods described below constitute the general framework that a QMRA practitioner would apply to assess a water supply system (Teunis *et al.* 1997; Haas *et al.* 1999; Benford 2001; Haas & Eisenberg 2001; Medema *et al.* 2003). This is also the current guideline course of action for Dutch utilities to follow when assessing their systems as required by domestic law (de Roda Husman *et al.* 2005).

The daily probability of infection p (i.e. the quantified measure of 'risk') to consumers is estimated by inputting knowledge about the pathogen dose d consumed during exposure to some quantity of drinking water. The theoretical dose is inferred from knowledge about the measured viable pathogen concentration in the raw drinking source water c, the recovery fraction of the pathogen enumeration method r, the ratio of pathogens present in the raw water that pass unharmed through treatment processes ε, and the volume V of water consumed during one day:

$$d = c \times \frac{1}{r} \times \varepsilon \times V \tag{1}$$

The p from one exposure event is ascertained by inputting d into a pathogen-specific dose-response function, of which the most commonly applied is the exponential function: $p = 1 - e^{-d\theta}$, where $e = 2.718\ldots$ and θ is the average probability of a person becoming infected after ingesting one organism. At very low doses, as is typically encountered from urban treated water supplies, the exponential dose-response curve is approximately linear. Hence the following generally approximates p from a single exposure incident, particularly for very low doses (Haas *et al.* 1999):

$$p \approx d \times \theta \tag{2}$$

When calculating the 'typical' dose one may encounter, say on average over a long period of exposures, it may be possible to identify specific conditions for each parameter on the right hand side of Equations (1) and (2) for which that parameter will undertake a significant and unique value, to the exclusion of other condition types (e.g. value of ε during 'nominal' treatment efficiency vs. 'failure' periods, variation in value of V during different seasons or between population groups, θ values for immuno-competent vs. immuno-compromised persons, etc.). Hence, any parameter X in Equations (1) and (2) can be characterised as:

$$X = \sum_{j=1}^{m} l_j X_j \tag{3}$$

where X_j and l_j are the parameter values under, and likelihood of occurrence of, the jth of m identified conditions (noting that $\Sigma l_j = 1$, $j = 1, 2, \ldots, m$).

Assuming that pathogen doses consumed on separate days are independent of each other (i.e. no interaction of pathogens ingested on separate days within the host), and that a person could reasonably be expected to consume some volume V of water daily (i.e. number of doses $n = 365$ per annum), the annualised infection risk p_{ann} is calculated as:

$$p_{ann} = 1 - \prod_{i=1}^{365} (1 - p)_i \quad (4)$$

In a stochastic setting, two important principles are that following water exposure: (i) there is no possibility of 'zero risk' to the consumer, where $0 < p < 1$, though sometimes the risk is so low as to be considered negligible; and (ii) the magnitude of p at any time is not constant but fluctuates over a time period, such as the course of one year. To account for this variability, any or all of the parameters c, r, ε, V, θ in Equations (1) and (2) may be considered random, and represented by probability density functions (PDFs) that account for the range and likelihood of possible values each parameter may undertake at any time. A stochastic representation of the value of p is then determined using Monte Carlo sampling methods (Vose 1996), whereby a large number (ideally many thousands) of p estimates are generated by repeatedly drawing random point values from the parameter PDFs and inputting them into the relevant equations. Note that care should be taken when conducting the sampling to reflect that each daily risk estimate was determined on the basis that no parameter can be simultaneously under more than one relevant condition at any time. From the sampling outputs the long-term variability in the magnitude of expected daily risk p can be determined (e.g. Teunis *et al.* 1997; Pouillot *et al.* 2004; Signor 2007).

For estimating annualised risk, simply inputting each of the Monte Carlo derived p estimates into Equation (4) neglects to account for daily risk variability over the course of a year, and would lead to an exaggerated range of p_{ann}. A simplified approach advocated by Teunis *et al.* (1997) involves randomly sampling (with replacement) 365 individual values of p from the larger number of previously derived Monte Carlo outputs, and inputting them into Equation (4) as specific values of $p_1, p_2, \ldots, p_{365}$. Repeating this over, say, 1,000 times would provide for that many p_{ann} estimates from which its variable value can be determined. Finally the value p_{ann} can then be compared against a target value (e.g. 1×10^{-4}) to assess system performance.

CASE FOR SHORTER-TERM TARGETS

To aid in the management of chemical risks from media to which humans are exposed daily (e.g. for indoor air pollutants and quality), many authorities (e.g. NH&MRC 1996) have adopted two-tiered pollutant exposure criteria, so that targets are set for both acute *and* long-term exposures to contaminants. That is in recognition that some hazardous substances may cause acute health effects in a human, and also because consistent long-term exposure to smaller quantities of the same substance can result in harmful build-ups of toxins in the body. However for microbial hazards, particularly with regard to drinking water consumers, there is far more concern associated with acute rather than chronic disease impacts (Haas *et al.* 1999). Hence for microbial risks from drinking water, management could ideally involve aiming to ensure that humans are exposed to negligible pathogen levels on each and every occasion that they consume the water. Further, the case outlined below for adopting daily health targets is built around providing: (i) incentives to control water quality and risk fluctuations; (ii) opportunities for risk management; and (iii) simplification of the probabilistic risk assessment process as described in turn below.

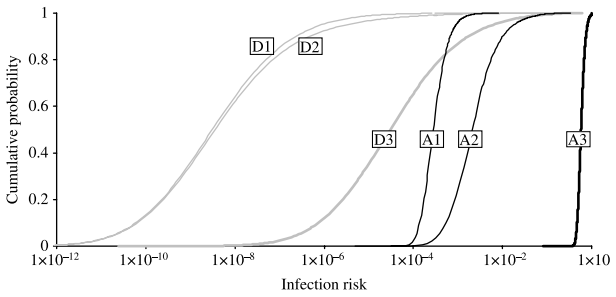
Incentive to exercise control over risk fluctuations

Adoption of an annualised risk target recognises that some risk fluctuation is acceptable over the course of the year provided the longer-term target is met. Stochastic methods for assessing risks have been heavily used recently in acknowledgment that risks inevitably *will* fluctuate, and they offer a way to examine the extent of and uncertainty about that anticipated variability. From above, as the daily risk estimate p is essentially the product of a series of random variables, and if it is assumed that all parameters are independent, then upon any QMRA application, p's annual long-term variability will generally be described by a lognormal PDF, as dictated by the central limit theorem (Vose 1996). The lognormal PDF is typically highly skewed

and has the property that its overall mean value is highly sensitive to the rarely occurring but relatively 'extreme' higher risk periods. Further, modelling dependence among some parameters may mean that the outputted risks from a QMRA model will have a very high skew that would be underestimated even by the lognormal PDF (Englehardt 2002; Englehardt *et al.* 2007).

It is evident from earlier probabilistic QMRAs that daily risks from drinking water will generally have inter-decile ranges that stretch over several orders of magnitude. The formidable influence of short-duration risk fluctuations on the typical (say mean) risks observed over a longer-term period has already been documented by Teunis *et al.* (2004): '…as [health] risk usually varies between occasions (exposure events), we need to concentrate not only on nominal risk levels (mean or median risk) but also on reducing the [short-term] variation in risk levels'. Shorter periods of extreme adverse risk fluctuation, whatever the nature of the driving cause, are also more likely to lead to community disease outbreaks (e.g. Hrudey & Hrudey 2004). Additionally, a higher prevalence of communicable disease in a community from one pathway (i.e. drinking water exposure) has the 'knock-on' effect of increased direct person-to-person transmission rates (Eisenberg *et al.* 2002) and enhanced disease risks from other indirect pathways, such as wastewater reuse applications.

The influence of short-term adverse risk fluctuations is evident in Figure 1. The variable infection probability curves and tabulated statistics displayed were derived from an actual stochastic QMRA of an Australian water supply system undertaken using the framework of methods described earlier (Signor 2007). A series of different event type scenarios were assessed for their impact on overall risk estimates. One was sub-optimal coagulation brought about by mechanical failure at the treatment plant, which in turn adversely affected the efficacy of the physical treatment step in each of six parallel treatment cells at the plant. Assuming water consumed from the system was treated under either 'nominal' or 'failing' coagulation treatment conditions, two daily risk curves were derivable pertaining to each condition. The overall daily risk curve was derived by mixing those two PDFs in proportion to the likelihoods of either condition predominating at any time (as per Equation (3)). From plant incident records the total proportion of time



		Cryptosporidium infection probability (risk) statistics		
Curve name	*lcoag. fail*	Mean	Median	95th percentile
Daily infection risk curves (i.e.)				
D1	0.00036	2×10^{-6}	3×10^{-9}	8×10^{-7}
D2	0.036	8×10^{-5}	3×10^{-9}	3×10^{-6}
D3	1	2×10^{-2}	3×10^{-5}	6×10^{-3}
Annualised infection risk curves				
A1	0.00036	3×10^{-4}	2×10^{-4}	1×10^{-3}
A2	0.036	5×10^{-3}	7×10^{-4}	3×10^{-3}
A3	1	6×10^{-1}	6×10^{-1}	9×10^{-1}

Figure 1 | Daily and annualised variability of *Cryptosporidium* infection probability (risk) from a QMRA of an Australian water supply system (Signor 2007); $l_{\text{coag. fail}}$ = likelihood of drinking water being treated during a coagulation failure event.

the coagulator was assumed to be 'failing' over a year was $l_{\text{coag. fail}} = 0.036\%$. Under 'nominal' conditions each physical treatment cell was assumed to remove on average $>99.99\%$ of *Cryptosporidium* oocysts, while during coagulant 'failure' a near total loss of removal efficiency was assumed so that anywhere between 3 and 100% of oocysts would pass through the barriers (dependent on other conditions at the time).

In Figure 1, three variable daily and annual *Cryptosporidium* infection risk curves (D1-3 and A1-3, respectively, derived from 1,000,000 Monte Carlo sampling iterations) are shown for $l_{\text{coag. fail}}$ values of 0.00036 (the actual estimate for the plant), 0.036 and 1. The daily risk curves for the two lower likelihoods of 'failure' are visually similar. However a failure event that predominated for just 3.6% of the time over one year (curve A2, $l_{\text{coag. fail}} = 0.036$) increased the overall mean daily and annualised risks by more than a factor of ten, as opposed to when 'failure' was virtually negligible (curve A1). Note that those figures relate to risks posed to and averaged out over a large population over

many exposures. If an individual were to consume water treated under 'failure' conditions just once in one year (mean infection probability from that single exposure episode = 2.6%, curve D3), the mean annualised risk to him or her would be more than 1,000-times greater than to a person who had only ingested water treated during 'nominal' conditions.

Aiming to meet an annualised health target will encourage water utilities to limit the extent of adverse risk fluctuations. Essentially whatever maximum risk per annum is adopted also translates to the theoretical absolute maximum number of 'tolerable' infections over a shorter period, such as a week or a day, provided daily risks are otherwise very low. From that perspective massive outbreaks such as the Milwaukee or Walkerton incidents, where some 25% and 50% of serviced populations may have been rendered ill over the course of a few weeks, would comprise a massive violation of a regulated $p_{ann} < 1 \times 10^{-4}$ target. However that annualised target alone offers only limited incentive to be concerned about the manner of such fluctuations. For instance, consider the situation where for 51 weeks of a year a water system serving 1 million people supplied water that posed such little risk it may be considered that $p \approx 0$ on all those days; yet every 52nd week the source water was knowingly contaminated (e.g. from temporally occurring combined sewer overflows into the system's catchment) to such an extent that as a consequence approximately 100 to 1,000 ($p \approx 1 \times 10^{-4}$ on each of those days) consumers become infected, with on average 50% probably becoming ill from exposure to the one type of pathogen (Haas *et al.* 1999). In such a scenario, risks from the pathogen are $1 \times 10^{-4} \leq p_{ann} \leq 1 \times 10^{-3}$ which may come under the banner of meeting the annualised target adopted by the regulator. Indeed any higher number of infections in the population over that time would have been in breach of the target. Yet despite the concentrated period of higher risk, which may have resulted in a minor outbreak condition, there would be no (annualised) health target-driven incentive to address the issue.

Applying control over the extent of risk fluctuations, then, appears a critical philosophy, not only to keep annualised risks under the target level, but also to protect against shorter-term periods of higher risk that may be synonymous with outbreak conditions. Aiming to meet an annualised target provides incentive to meet the first criterion, but only limited incentive to meet the second. Taking the view that health target adoption should provide a means to address both issues, one way to address it would be to adopt even lower annualised targets (say to $< 1 \times 10^{-5}$ or less). The problem then is with the potential costs of complying with such stringent targets, even to water supply systems considered to be performing well, which was largely behind Haas's (1996*a*) call for more lenient widespread targets than the 1×10^{-4} value. Another simple option advocated here would be to adopt and assess QMRAs against a shorter timeframed (i.e. daily) risk target, chosen so as to ensure the shorter-term risks do not fluctuate to 'extreme' levels. The daily target could be chosen so that adherence with it would automatically result in meeting any annualised target it was based on.

Opportunity for risk management

From a risk management perspective the only parameters from Equations (1–4) one may reasonably attempt to exercise control over in order to mitigate risks and meet targets are c and ε. High-impact/short-duration adverse event conditions in the water supply system, leading to adverse risk fluctuations, even those that have minor impacts on risks assessed over an annual period and averaged out over a large population, can still lead to a significantly increased mean risk on the day(s) within which it occurred (Westrell *et al.* 2003; Signor 2007).

Aiming to meet a daily target can offer more immediately apparent guidance to a risk manager aiming to address those 'shorter-duration, higher-risk' events. To illustrate the point, consider that at the water treatment plant (WTP) studied by Signor (2007), high turbidity measurements in the filtrate are considered the primary indicator of coagulant 'failure'. Often though, turbidity 'spikes' are observed as a result of measurement error and quickly stabilise after several minutes. As such it is not necessary or practical to react immediately to every observed 'spike'. To compensate, utility protocol stipulates reacting to the problem (by plant shutdown and investigation) when abnormally high turbidity measurements were observed consistently for (an arbitrarily chosen) 20 minutes.

Now consider again Figure 1. Curve D1 displays the variability in daily risks averaged out over a year where within that year $l_{\text{coag. fail.}} = 0.00036$. That likelihood was derived based on incident records at the WTP that indicated a certain number of approximately 20 minute coagulation loss events had occurred over several years. Say the WTP operates every day for exactly 10 hours per day, then 'failure' predominates for about 1.3 hours per year. However, the condition does not last for one consecutive period per annum, but rather as a series of separate 20 minute periods. Then the daily risk on a day that failure occurs can be considered as a conditional probability of infection: p (inf |coagulation 'failure' event). A 20-minute 'failure' event in a 10-hour operational period means that 3.3% of water was treated under failure conditions on that day, which coincidentally happens to be about the same as the likelihood of the 'failure' in the D2 curve in Figure 1. Hence, the curve D2, referred to initially as the daily risk variability over a year when $l_{\text{coag. fail.}} = 0.036$, may alternatively be interpreted as the risk on any day on which a 20 minute coagulation failure event was known to have occurred. On a day that the coagulation failure event occurred, the risk is >10 times greater than on a day where it does not. With a daily risk target in mind, the water manager then can use that information to derive a more appropriate reaction time to an observed turbidity rise, or verify the adequacy of the 20 minute reaction, so that, should the turbidity increase be due to coagulation failure, the daily target was not compromised. Note also the ramifications of failing to react at all to the coagulation failure for a whole day: the risk on that day to the population would be as per curve D3, resulting in a mean infection risk of >1 in 100 for that day and, subsequently, also for the year.

The concept of 'conditional' infection probabilities is an important one here. In essence where specific conditions associated with increased risks on a day can be identified, their likelihoods and impacts assessed (as per Equation (3)), and where there is some alarm that would indicate the change from one condition to another, then it is possible to generate risk management/response strategies specific to each (or combinations of) condition(s) aimed at meeting the daily target. For instance, Signor (2007) demonstrated that significantly different daily infection probabilities may be associated with different climatic seasons, primarily due to seasonal differences in source water quality (i.e. summer, autumn, winter, spring were considered specific events with unique water quality characteristics, and p (inf|Winter) $>p$ (inf|Summer)). If a daily risk target of $p < 1 \times 10^{-6}$ were adopted (as discussed below as one alternative), the QMRA indicated that it would be breached by the mean daily risk value in winter/spring, but not summer/autumn. Hence, were it more economical to do so, additional measures (perhaps added treatment) may need to be applied only to the winter/spring period.

Such a philosophy is already employed, for example, where coagulation practices at a water treatment plant differ during months where the raw water is cooler as opposed to when it is warmer, to optimise flocculation. Similarly, with reference to the earlier example of the 'known' catchment contamination period, additional management options may be targeted at it (e.g. modified catchment management strategy, additional treatment during the known contamination period, etc.) to bring the risk to below the (daily) target value. Additionally, it may be apparent that ensuring the value of p (inf|coagulation 'failure', winter) is below the daily health target may require a different, more severe strategy than for p (inf|coagulation 'failure', summer). Thus adopting daily risk targets creates an opportunity to develop frameworks that could result in economically optimised, conditions-based risk management strategies (e.g. critical reaction times to an alarm, specified level of redundancy in treatment efficiency, etc.).

Simplifying the risk assessment process

While in a deterministic setting the inference of p_{ann} from p is a simple one-step process (Equation (4)), as described earlier within a stochastic setting it involves a high degree of additional random numerical sampling, data output organisation and computations of a more complex nature than even the more straightforward Monte Carlo methodologies utilised to simply output variable p. As calculating the daily risk p is a necessary step on the way to assessing the annualised risk p_{ann} anyway, then the assessment process would be simplified by using p as the risk characterisation end-point.

DISCUSSION

What is an appropriate daily target?

The selection of an appropriate drinking water health target is a debatable issue and should reflect the situational aspects of any case, and also the local regulator's policy with regard to water quality management (Hunter & Fewtrell 2001).

This discussion has: (i) considered targets being expressed in terms of a probability of infection over some time period; (ii) noted that a 1 in 10,000 annual probability of infection target has had widespread adoption for urban water supply systems; and (iii) argued that targets expressed in terms of daily infection probabilities may provide more incentive and guidance for water managers to control short-term, high-risk fluctuations in water quality. On the premise that the 1 in 10,000 annual infection probability target is a reasonable one, the equivalent daily target would be a probability of infection of 2.7×10^{-7} from each daily exposure to the water (from solving Equation (4)). To make the target more easily communicable this is virtually equivalent to 1×10^{-6} (i.e. 'one in a million') on any day. Adhering to that daily target would see the annual 1 in 10,000 target being achieved anyway, as well as providing an incentive to control the extent of risk fluctuations. Another daily target could be inferred similarly from any other preferred annualised target: for instance Haas (1996*a*) has argued that a 1 in 1,000 annual target would be sufficient, which relates to about a 1 in 100,000 daily target equivalent.

For the purpose of illustration, the discussion so far has focused on the use of targets expressed as 'infection probability' end-points only. However, most recently some guidelines (e.g. NH&MRC 2004; WHO 2004) have recommended using disability adjusted life years (DALYs) as the measure for setting targets and assessing systems. DALYs are a measure of the disease burden (number of years spent with illness or disability plus life-years lost due to the infection) over the course of some time period. DALYs are promoted because, unlike infection probabilities, they also take into account the different levels of disease consequences and burden from the different reference pathogens modelled: for example, viruses, *Cryptosporidium* and *Campylobacter* exposures can each have different disease outcomes (Benford 2001). For drinking water, both the Australian (NH&MRC 2004) and WHO (2004) guidelines recommend a value of 1×10^{-6} DALYs per person per year from waterborne pathogens in domestic supplies as the target 'tolerable' disease burden. However, it is important to note that in the microbial risk context, deriving a DALY estimate from pathogen exposures is reliant on first estimating infection probabilities from certain pathogens anyway (Prüss & Havelaar 2001). To incorporate the emergence of the DALY as a risk measure with the case outlined in this paper for daily timeframed health targets, it is suggested that a DALY target could be adopted, and that this could be used to determine equivalent pathogen-specific daily infection probability targets for various pathogen types in treated water. Then the health target would be reflective of two recent waterborne disease management paradigms: (i) the use of DALYs to assess disease burden and inform risk management needs; and (ii) the recognition that management should focus on mitigating adverse risk fluctuation occurrence and effects.

Variability in risk and probabilistic QMRA outputs

An upshot of the 'no possibility of zero risk' principle is that there can also then be no absolute conviction that a daily health target will always be met. Hence, acknowledging that on occasion the target value will be exceeded, when comparing a variable risk output with a deterministic target, compliance will need to be based on some chosen statistic of the stochastic QMRA output. The only precedent to date is from Schijven *et al.* (2006), who has used probabilistic QMRA models to recommend ground aquifer soil zone sizes such that there would be 95% likelihood that the treated groundwater source would pose an annual infection risk to consumers of less than 10^{-4}. That criterion was based on the common supposition that a 95% likelihood of target compliance at any time seemed reasonably conservative. However, basing daily target compliance purely on showing that some risk percentile meets the target places no restrictions on the extent of how much the risk can fluctuate beyond that percentile (which, when using the 95th percentile would correspond to more than two weeks in every year) and negates the main case presented here for

adopting daily targets in the first place: to provide incentive to control short-term, high-risk water quality fluctuations. Using the mean value would be somewhat more appropriate as it includes extreme percentile values when calculated (Haas 1996*b*). However, sole reliance on the mean also implies that short periods of extreme risk levels may be tolerable if they were 'balanced' by symmetrical periods of extreme low risk. As such, adherence should be based on both the mean and some chosen high (say >90th) percentile of variable daily infection probability being below any chosen target.

When assessing drinking water risks or when using the daily health target as a design parameter for determining treatment methods for a new water supply system, it may be beneficial for managers to outline and verify how the daily infection probability target would be achieved under a variety of identified relevant hazardous event scenarios (such as short-term failures of treatment, fluctuating source water concentrations following rainfall in a catchment, etc.). These could be examined by having the events incorporated into, and management options examined by using, probabilistic QMRA models.

CONCLUSION

The extent of the longer-term health risks posed to drinking water consumers in developed regions will typically be heavily (nearly totally) governed by short-duration periods of higher risk. Risk fluctuations are brought about especially by variability in levels of contamination in source waters and in treatment efficiency, each of which may have any number of potential causes (Hrudey & Hrudey 2004). Quantitative risk estimation techniques continue to develop to allow practitioners to better measure the possible extent of those fluctuations. These factors should be considered when adopting health targets: that is, the adopted target should provide guidance and incentive to combat impacts of adverse or hazardous risk fluctuations. Where the selected health target/assessment methods are tailored towards expressing risks in terms of a probability of infection over some time period, it is recommended that a daily rather than annualised target be adopted. Based on widespread current practice of aiming to adhere to a 1×10^{-4} annual infection probability target, it is suggested that a design/operational target of 1×10^{-6} daily infection probability would meet the aims of the original target, as well as promote the undertaking of measures to control the extent of short-term adverse risk fluctuations. In a stochastic QMRA setting, system 'compliance' could be based on both the mean and 95th percentile of the variable daily risks being estimated to be below that target. Risk management could involve outlining measures so that the daily target may be met under a variety of pre-identified, relevant, condition-based hazardous event scenarios, which can be explored within a probabilistic QMRA setting (e.g. Equations (1–4)).

Water quality health targets aim to encourage risk managers to: (i) assess the potential waterborne disease risk associated with using the water supply; and (ii) adopt measures to meet targets and protect consumers from waterborne disease. The primary benefit of adopting a daily target is that it would promote the importance of risk fluctuation control within drinking water supplies that large numbers of people may rely on every day. Other benefits would include providing a platform for managers to design and assess management initiatives to deal with short-term hazardous events as well as simplifying the technical components of the risk assessment process.

ACKNOWLEDGEMENTS

The primary author was supported through an Australian Research Council doctoral scholarship and the University of New South Wales' Centre for Water & Waste Technology. The work presented here has been subjected to a United States Environmental Protection Agency review and approved for publication.

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First received 8 September 2008; accepted in revised form 23 January 2009. Available online July 2009