Investigation of water consumption patterns among Irish adults for waterborne quantitative microbial risk assessment (QMRA)

Paul D. Hynds, Bruce D. Misstear and Laurence W. Gill

ABSTRACT

Microbial and chemical contamination of drinking water supplies can cause human health problems. Microbial pathogens are of primary concern and quantitative microbial risk assessment (QMRA) is employed to assess and manage the risks they pose. Estimates of drinking water consumption, or distributions, are required to assess levels of waterborne pathogen exposure. To establish distributions for the Irish population, water consumption data were collected from 549 rural survey respondents. A further 110 participants completed a five-day water consumption diary. Average daily consumption of tap-water among the primarily rural-dwelling questionnaire respondents was 940 ml day^{-1} (SD 670 ml day^{-1}) and 1,186 ml day^{-1} (SD 701 ml day^{-1}) among the principally urban-dwelling diary respondents. Both mean figures are significantly less than the 2,000 ml day^{-1} default figure currently used for QRMA; therefore its use may lead to overestimation of the waterborne health burden. As the observed daily consumption difference between rural and urban residents is statistically significant, use of separate consumption distributions for QMRA is advocated. Although males reported higher daily tap-water consumption rates than females, these differences were insignificant, so separate consumption distributions are not considered necessary. A log-normal distribution provides the most adequate fit for daily tap-water intake (ml day^{-1}) within both datasets.

Key words | consumption patterns, distribution functions, drinking water, risk assessment, waterborne pathogens

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INTRODUCTION

People are exposed to a variety of potentially harmful agents in the air they breathe, the liquids they drink, the food they eat, the surfaces they touch and the products they use. Differences exist within a population's exposure level to harmful agents, due to a number of factors, with exposure defined as '*contact over time and space between a person and one or more biological, chemical or physical agents*' (US NRC 1991). Therefore, exposure assessment is the measurement or estimation of actual human exposure to these agents (Ott & Roberts 1998). The two primary sources of exposure in any waterborne risk assessment are the contaminant concentration (microbial or chemical) and the water consumption rate (i.e. direct water intake excluding

both boiled water and water involved in food preparation) (Krewski *et al.* 2004). In order to determine the contaminant dose potentially reaching consumers it is therefore necessary to provide estimates of the volume of water ingested per day (Westrell *et al.* 2004).

A number of deterministic human health risk assessments, including Gerba *et al.* (1996), Chick *et al.* (2001), Webb *et al.* (2003) and Ashbolt (2004) assume a (default) daily water consumption rate of 2 l day^{-1}, with this rate based on assumptions published by the Safe Drinking Water Committee of the National Academy of Sciences (NAS 1977). However, a number of studies have found that the application of this rate may result in an overestimation

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of waterborne risks, as measured consumption rates tend to be lower (Robertson *et al.* 2000; Jones *et al.* 2006). For example, this consumption rate has been shown to agree with the 88th percentile of the per capita ingestion rate in the USA (USEPA 2000); equally, Asano & Cotruvo (2004) report that 80–85% of average daily water consumption in the USA was $<2,000$ ml day^{-1}. Similar studies have been carried out elsewhere previously, with results presented in Table 1.

As shown, there are significant differences in daily mean water consumption rates between studies and countries, with a minimum reported daily consumption rate of 153 ml day^{-1} by Teunis *et al.* (1997) from the Netherlands and a maximum reported consumption rate of 3,000 ml day^{-1} by Watanabe *et al.* (2004) among a small sample of Bangladeshi survey respondents. A review of previous water consumption studies by Mons *et al.* (2007) from a number of different countries found that the average consumer-reported consumption of cold (i.e. unboiled) tap water ranged from 200 to 1,550 ml day^{-1}. Roseberry & Burmaster (1992), Burmaster (1998) and Mons *et al.* (2007) have fitted probability density distributions to water

consumption data, with Westrell *et al.* (2004) noting that although point (deterministic) estimates may be used in exposure assessments associated with quantitative microbial risk assessment (QMRA), the application of statistical distributions is preferable, as it acknowledges both variability and uncertainty within the data. Moreover, Mons *et al.* (2007) advocate the use of country-specific water consumption distributions for all QMRA due to climatic and dietary variations. This approach allows for a more accurate estimate in the context of an entire population rather than a 'representative consumer'. To date, no similar daily water consumption study has been undertaken in Ireland, necessitating the use of existing water consumption estimates (deterministic) or distributions (stochastic) from other countries, which may not be suitable for application in an Irish context.

The aims of this paper are: (a) to provide a quantitative estimation of drinking water consumption in Ireland using two data recovery methods, (b) to investigate potential factors affecting daily consumption rates including gender, body mass, occupation and drinking water source and (c) to develop robust statistical distributions reflecting daily

Table 1 | Summary of drinking water consumption study findings

Country	Sample (*n*)	Study type	Mean daily consumption (ml day^{-1})	Reference
Australia	234	D	890	Robertson *et al.* (2000)
Australia	10	D	1,320	Froese *et al.* (2002)
Bangladesh	38	Q	3,000	Watanabe *et al.* (2004)
Canada	125	D	1,500	Levallois *et al.* (1998)
Canada	1,757	T	1,000	Jones *et al.* (2006)
Canada	2,332	T	1,390	Pintar *et al.* (2009)
Central Europe	1,392	Q	$1,200 \pm 500$	Lloyd Hough *et al.* (2010)
France	427	D	900	Gofti-Laroche *et al.* (2001)
Germany	195	Q	500	Dangendorf (2003)
Israel	5 m	D	$1,100 \pm 100$	Kristal-Boneh *et al.* (1995)
Netherlands	–	Q	153	Teunis *et al.* (1997)
Sweden	11,189	Q&D	860 ± 480	Westrell *et al.* (2006)
UK	416	Q	700	Hunter *et al.* (2004)
UK	3,564	D	200	Hopkin & Ellis (1980)
USA	26,081	Q	1,100	Roseberry & Burmaster (1992)
USA	73	Q	900 ± 600	Ryan *et al.* (2000)
USA	1,183	Q	1,900	Williams *et al.* (2001)

D: Direct measurement; Q: Questionnaire; T: Telephone survey.

water consumption among the Irish population for use in future waterborne QMRA. Furthermore, it is considered that the findings presented here may be applied to QMRA in other temperate maritime areas where similar data are not available.

METHODS

Study design and sampling

Two primary datasets were developed, using two data recovery methods. The first dataset ('rural one-day recall') was developed using a questionnaire as part of a larger overall investigation into the awareness of the potential human health effects of contamination of private groundwater sources in Ireland (Hynds *et al.* 2010). All questionnaires were carried out on a face-to-face interview basis; with respondents asked to self-report approximate mean daily cold water consumption, approximate consumption frequency, primary consumption source and the primary household consumption source. Rural households with unregulated private groundwater sources were randomly selected (during fieldwork investigations associated with a larger overall study), with the interviewer completing one questionnaire with one adult (>18 years) per household. The respondent was internally selected within the household based on availability for questioning. This dataset was collected between January 2008 and January 2010.

The second dataset ('five-day diary recall') was developed using a five-day respondent-administered water consumption diary, as this method produced a time homogenous dataset. Respondents were asked to actively measure and record their daily cold water consumption. This study was considered complimentary to the rural one-day recall study, as urban dwellers were specifically targeted for participation. Rural one-day recall study participants were asked to provide contact details for urban dwelling adults who might be prepared to participate in the five-day diary study. These potential participants were subsequently contacted through telephone or email ($n = 160$). Willing participants were additionally asked to record their gender, age, body mass, occupation and primary consumption source.

All participants were >18 years, with data collected over the three-month period April to June 2011.

As set out by Mons *et al.* (2007), the most accurate way of estimating daily consumption is by determining the amount of water consumed (in millilitres), as opposed to number of cups/glasses. Therefore, both data collection approaches required participants to report their daily average volume to the nearest 100 ml. Furthermore, it has been previously noted that short-term collection methods such as questionnaires and recall studies are more precise due to reduced recall bias (Levallois *et al.* 1998; Jones *et al.* 2006; Mons *et al.* 2007).

In all, 549 respondents completed the one-day recall survey, with a further 110 participants in the five-day recall study. Questionnaire respondents were provided with six daily water consumption ranges (<0.250 ml day^{-1}, 250–500 ml day^{-1}, 500–1,000 ml day^{-1}, 1,000–1,500 ml day^{-1}, 1,500–2,000 ml day^{-1}, >2,000 ml day^{-1}) and were asked to choose which range best described their approximate daily cold water consumption. Participants in the five-day diary study were asked to report their daily cold water volume to the nearest 100 ml. Individuals were not permitted to participate in both studies.

Statistical analysis

Continuous variables were tested for normality using normal quantile (Q-Q) plots and Anderson-Darling tests of normality. Standard R×C contingency chi-square tests of independence were used in comparing proportions within groups of the study populations, including proportional differences between daily consumption ranges, gender and treatment system usage. Independent samples *t*-tests were used to investigate significant mean differences between continuous and dichotomous variables. Spearman non-parametric rank-correlations were used to compare non-parametric continuous variables (i.e. age, body mass, etc.). One-way analysis of variance (ANOVA) was used to compare statistically significant mean differences between continuous and nominal (i.e. participant occupation, primary daily water source) variables, with post-hoc multiple comparisons tests (Tukey HSD) and multiple independent samples *t*-tests (LSD) applied to investigate significance.

All statistical analyses were performed in IBM SPSS Statistics 19, with the exception of Monte-Carlo simulation probability density function fitting, for which MS Excel 2007, with the add-on package @Risk (version 5.5, Palisade Corporation, New York, USA) were used. The significance level was set at 5% ($p < 0.05$) for all analyses.

RESULTS

Rural one-day recall

Overall, 610 potential respondents were asked to complete the questionnaire survey, with responses for the volume of cold water consumed per day obtained from 549 respondents; equating to a response rate of 90%. As shown (Table 2), 78% of respondents were male, while

Table 2 | Variable frequency table for rural one-day recall study

Variable	Frequency	%
Gender		
Male	430	78.3
Female	119	21.7
Source type		
Borehole	333	60.7
Hand-dug well	111	20.2
PrGWS[a]	44	8.6
PuGWS[b]	47	8.0
Other	14	2.6
Treatment system		
Yes	176	32.2
No	315	57.6
Don't know	56	10.2
Household source		
Household tap	524	95.6
Bottled	24	4.4
Gastroenteric symptoms		
Yes	75	13.7
No	472	86.3
Diagnosed gastroenteritis		
Yes	5	0.9
No	544	99.1

[a]Private group water scheme.
[b]Public group water scheme.

approximately 61% of respondents' primary drinking water source was a borehole (bored well >10 m depth), reflecting the population with whom the survey was primarily completed. In this paper, 'source type' is used to describe the source from which the household derived its primary drinking water supply (i.e. deep well, shallow well, public supply, etc.). Approximately 32% of respondents noted that a water treatment system of some kind was installed at their supply, with a chi-square test of independence finding a significant relationship between treatment system presence and supply type (χ^2 (10) = 133.1, $p < 0.001$), i.e. treatment system prevalence at boreholes, hand-dug wells, public group schemes and private group schemes were 35, 15, 75 and 64.5%, respectively.

Total daily water consumption ranged from <250 ml day^{-1} (10.2%) to >2,000 ml day^{-1} (9.1%), with a median value range of 500–1,000 ml day^{-1} (31.1%) and 25 and 75% percentiles of 250–500 ml day^{-1} and 1,000–1,500 ml day^{-1}, respectively (Figure 1). No significant difference was found between daily consumption range and source type, gender, the presence of water treatment, drinking source (i.e. household tap/bottled) or the occurrence of previous gastroenteric illness or symptoms (Table 3). As expected, a highly significant relationship was found to exist between consumption volume and consumption frequency ($p < 0.001$). In order to develop a discrete mean value, deterministic midpoint values were assigned to each consumption range, i.e. >250 ml day$^{-1} \approx 125$ ml day^{-1}; 250–500 ml day$^{-1} \approx 375$ ml day^{-1}, etc. Those respondents consuming
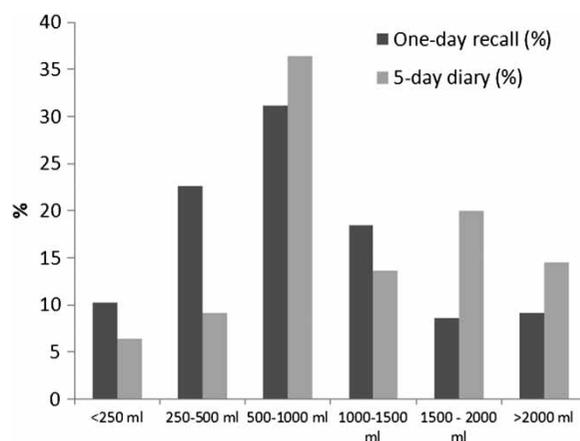
Figure 1 | Categorical daily cold tap-water consumption (one-day recall and five-day diary datasets).

Table 3 │ Results of chi-square tests of independence on categorized daily drinking water volume among rural one-day recall study respondents

| Variable	Sample number	χ^2	p
Gender	549	3.700	0.593
Drinking water source	549	12.353	0.983
Treatment system	547	14.589	0.148
Previous water quality analysis	546	4.596	0.467
Household source	548	5.715	0.335
Consumption frequency	549	438.185	<0.001
Previous illness (diagnosed)	540	3.513	0.621
Previous symptoms of waterborne illness	547	1.847	0.87

>2,000 ml day^{-1} were assigned a deterministic value of 2,500 ml day^{-1}. This yielded a mean daily cold water consumption rate of 969 ml day^{-1}, with a standard deviation of 814 ml day^{-1}. However, these figures include those respondents whose primary daily consumption source was bottled water (4.4%) of respondents. When bottled water consumers were removed, a mean daily consumption volume of 940 ml day^{-1} resulted, with a standard deviation of 670 ml day^{-1}. These daily figures agree with a number of previous studies (Gofti-Laroche *et al.* 2001; Westrell *et al.* 2004; Lloyd Hough *et al.* 2010). For example, Lloyd Hough *et al.* (2010) estimated a daily adult water consumption rate of $1,200 \pm 500$ ml day^{-1} in carrying out a lifetime exposure analysis of arsenic in residential drinking water sources in central Europe. Likewise, Gofti-Laroche *et al.* (2001) estimated a daily consumption rate (cold tap water) of 900 ml day^{-1} among 'average consumers' in French communities.

To determine the statistical distribution of the data, the exponential, gamma and log-normal distribution were applied to the datasets, as previously undertaken by Mons *et al.* (2007). Additionally, the normal distribution was also applied. Consumption intervals were imported into MS Excel 2007, with @Risk 5.5 risk analysis software used to fit the most suitable daily distribution. A parameter estimation fitting method was applied, with a lower fixed bound limit of 0 ml day^{-1} and an open upper limit (i.e. extending towards infinity). Fit ranking was achieved using both the Kolmogorov-Smirnof and Anderson-Darling

statistics. Only the potentially exposed subset was fitted, i.e. bottled water consumers were excluded. Due to a lack of convergence within the dataset, the gamma distribution could not be appropriately fit to the input data.

The resulting distribution fits are presented in Figure 2, which show adequate fits using the log-normal, exponential and normal distributions. Both Kolmogorov-Smirnof and Anderson-Darling statistics indicate that the log-normal distribution provided the best fit for total daily tap-water consumption. These findings concur with previous studies (Roseberry & Burmaster 1992; Burmaster 1998), which state that both daily total water intake and cold tap-water intake are well characterized by log-normal distributions among both children and adults and are therefore suitable for application in public health risk assessments.

Applying the log-normal distribution (Figure 2), total daily cold water consumption percentiles were calculated (Table 4). Notably, the log-normal model predicts that only 8.4% of the population currently consume >2,000 ml day^{-1} cold water, i.e. the commonly applied default value of 2,000 ml day^{-1} is close to the 90th percentile of the distribution. This would seem to confirm assertions made in previous studies (Havelaar *et al.* 2000; Robertson *et al.* 2000; Jones *et al.* 2006) that the use of this deterministic daily water consumption figure may result in overestimates of waterborne risks, as actual measured consumption rates tend to be significantly lower.
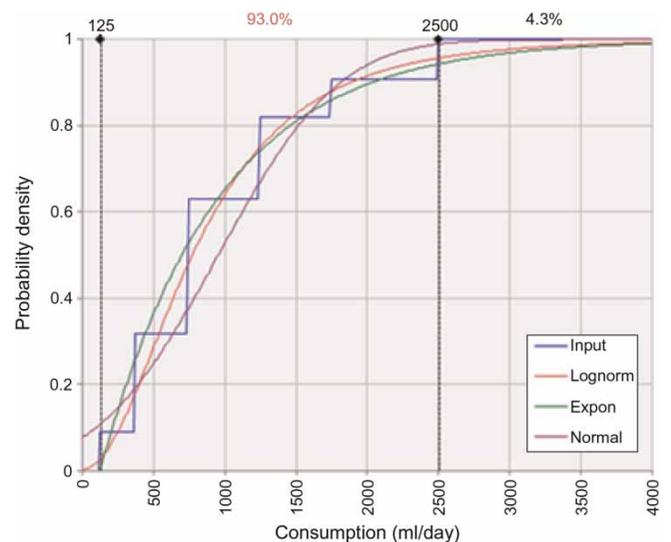
Figure 2 │ Discrete fit comparison for total daily tap-water consumption (one-day recall dataset).

Table 4 | Percentage of population and total daily cold water consumption (rural one-day recall)

Percentage of population (%)	Mean daily water consumption maxima (ml)
50	750
40	900
30	1,100
20	1,375
10	1,870
8.4	2,000
4.4	>2,500

Five-day diary recall

Responses for the volume of cold water consumed per day were received from 110 of five-day recall study participants, 59% of whom were male ($n = 65$). While 160 people were initially asked to complete the five-day recall study, 134 agreed, leading to a response rate of approximately 84%; however, completed surveys were submitted by 110 persons, equating to an 'effective response rate' of 68.7% and a 'survey dropout rate' of 17.9%. Frequency values and descriptive statistics associated with five-day diary study participants are presented in Tables 5 and 6, respectively. Male participants had a mean body weight of 80.1 kg, while female participants reported a mean body weight of 62 kg ($t = -8.811, p < 0.001$). Current occupation was also reported (Table 7).

During the five-day recall period, a mean daily consumption rate of 1,186 ml day^{-1} was recorded, with a standard deviation of 701 ml day^{-1}. Minimum and maximum daily water consumption rates of 0 and 4,500 ml day^{-1} were reported, with minimum and maximum five-day mean

Table 5 | Variable frequency table for five-day diary study

Variable	Frequency	%
Gender		
Male	65	59.1
Female	45	40.9
Consumption source		
Urban tap	64	58.2
Rural tap	17	15.5
Bottled	15	13.6
Water cooler	14	12.7

Table 6 | Descriptive statistics for variables associated with five-day diary study

Variable	Min.	Max.	Mean	SD
Age (years)	19	66	33.6	11.4
Weight (kg)	50	120	72.8	13.8
Hot beverages (cups/day)	0	17	3.3	2.4

Table 7 | Mean daily water consumption associated with occupation categories (five-day diary recall)

Occupation	Sample number	Mean daily consumption (ml day^{-1})	SD (ml day^{-1})
Education	41	1,344	729
Technical	37	1,207	688
Professional/ managerial	26	1,062	681
Retired	3	420	284
Unemployed	2	595	219

values of 0 and 3,260 ml day^{-1}, respectively. Upon exclusion of those participants whose primary daily consumption source was a water cooler or bottled water, based on the assumption that these sources are unlikely sources of pathogen exposure, a mean daily tap-water consumption rate of 1,149 ml day^{-1} resulted (SD 712 ml day^{-1}). The mean daily consumption rate among 'non-consumers' was 1,292 ml day^{-1} (SD 670 ml day^{-1}), with an independent samples t-test finding no significant difference between tap-water consumers and those drinking bottled water or from water coolers. Univariate analyses pertaining to the five-day diary recall study are outlined in Table 8.

An independent samples t-test found that, although male participants had a higher daily mean consumption (1,272 ml day^{-1}) than female participants (1,063 ml day^{-1}), this difference was not statistically significant. A weak inverse correlation was found between participant age and mean daily consumption volume (Table 8), suggesting decreasing water consumption with increasing age. This pattern was further reflected between stated occupation and mean daily consumption (Table 7), with retired participants ($\geq$65 years) recording the lowest daily average consumption volume. However, due to the small sample sizes associated with both unemployed and retired

Table 8 | Results of univariate analysis on daily drinking water volume among five-day diary study participants

| Variable	Sample number	Test statistic	p
Gender	110	1.615[a]	0.109
Age	110	−0.211[b]	0.027
Weight	109	0.026[b]	0.786
Household source (tap, bottled)	110	1.221[c]	0.263
Occupation	109	1.101[c]	0.387
Hot beverage consumption	110	−0.427[b]	<0.001

[a]Independent samples t-test.
[b]Spearman rank-order correlation.
[c]One-way ANOVA.

participants, this was not found to be significant. However, Spearman rank-order correlations suggest a significant (albeit weak) positive association between participant age and mean number of hot beverages consumed per day ($r = 0.483$, $p < 0.001$), while an increased level of hot beverage consumption was associated with decreased levels of cold water consumption.

One-way ANOVA found that there was significant difference between primary drinking water source and mean daily consumption volume, with participants associated with household tap-water from a private rural supply recording the lowest daily mean consumption volume (714 ml day^{-1}), and those drinking primarily bottled water consuming the highest mean volume (1,514 ml day^{-1}) ($F(3) = 4.477$, $p = 0.005$) (Table 9). An independent samples t-test found a significant mean difference between those urban and rural participants, with urban dwellers associated with a higher daily tap-water consumption rate than their rural counterparts ($t = -2.965$, $p = 0.003$). This pattern is also reflected in Figure 1, with higher levels of daily

Table 9 | Mean daily consumption associated with principal water source (five-day diary recall)

Source	Sample number	Mean daily consumption (ml day^{-1})	SD (ml day^{-1})
Urban tap	64	1,264	729
Rural tap	17	714	439
Bottled	15	1,514	791
Water cooler	14	1,055	419
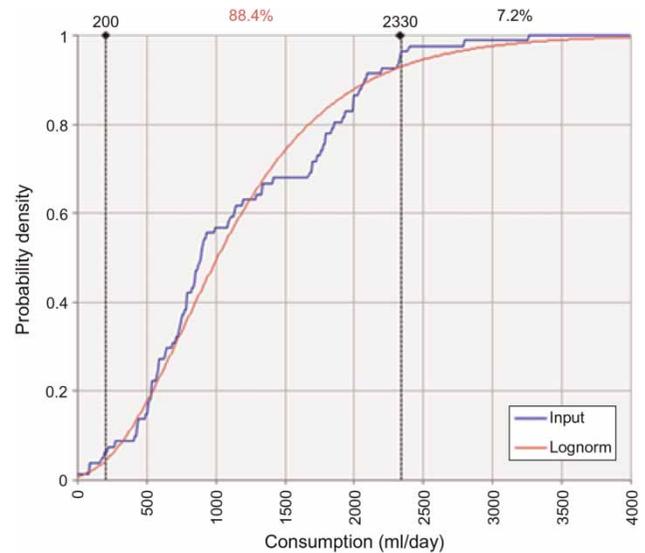
Figure 3 | Continuous fit comparison for total daily tap-water consumption (five-day diary dataset).

consumption apparent among the primarily urban five-day diary study participants.

The most suitable daily distribution was fit to the mean daily cold water consumption data, as previously discussed for the rural one-day recall dataset. Fit ranking was again undertaken using the Kolmogorov-Smirnof and Anderson-Darling statistics which indicated that the log-normal distribution provides the best fit for daily tap-water consumption (Figure 3). Similar results were again found when 'non-consumers' were included.

Using the log-normal distribution (Figure 3), total daily tap-water consumption percentiles were calculated, as presented in Table 10. In this case, the log-normal model predicts that 85.5% of the population currently consume <2,000 ml day^{-1} cold water per day.

DISCUSSION

This study found that drinking water consumption rates were variable among Irish adult consumers, with potential sources of variability including gender, bodyweight, occupation and primary drinking water source. Although neither dataset included daily boiled water intake (it has been assumed that boiling eliminates the majority of water-borne pathogens (Spinks et al. 2006)), the five-day diary

Table 10 | Percentage of population and total daily cold water consumption (five-day diary recall)

Percentage of population (%)	Average daily water consumption maxima (ml)
50	920
40	1,200
30	1,680
20	1,840
14.5	2,000
10	2,200
5	2,340

study included number of hot beverages consumed per day. Further work may focus on quantifying daily hot beverage volume, in order to assist in undertaking quantitative chemical risk assessments.

A mean daily tap-water consumption rate of 940 ml day^{-1} with a standard deviation of 670 ml day^{-1} resulted from the questionnaire survey ($n = 549$), which was almost entirely composed of rural respondents. Non-consumers were not included in this figure, with the proportion of bottled water consumers found in this study (4.3%) significantly lower than reported in previous studies. For example, Lee *et al.* (2002) reported a 17.8% rate of bottled water usage in the USA (with bottled water usage defined as greater than 50% of daily consumption volume). Likewise, Auslander & Langlois (1993) found that almost 20% of households in Ontario, Canada, were 'regular bottled water users'. Jones *et al.* (2006) reported that when a cut-off point of 50% was applied, approximately 33% of respondents in a Canadian community were classified as bottled water users. The relatively low level of bottled water consumption encountered during the one-day recall study was likely due to the primarily rural setting in which the majority of surveying was undertaken. Higher rates of bottled water consumption in urban areas may be due to a significantly increased density of commercial outlets (shops, cafes, etc.) offering these products.

Analysis of the five-day recall study resulted in a mean daily cold water consumption rate of 1,186 ml day^{-1}, with a standard deviation of 701 ml day^{-1} which is comparable with results obtained from the rural one-day recall study. Approximately 26% of participants stated their primary

daily consumption source as not being a household tap, i.e. 'non-consumers', which concurs with previous studies (Auslander & Langlois 1993; Lee *et al.* 2002; Jones *et al.* 2006) and reinforces the hypothesis that higher levels of 'non-household consumption' are associated with urban areas (given that 84.5% of respondents to the study were urban residents). Previous studies have reported similar findings (Abrahams *et al.* 2000; Ferrier 2001; Doria 2006).

The mean daily tap-water consumption rates among survey respondents (940 ml day^{-1}) and recall study participants (1,186 ml day^{-1}) concur with a number of previous studies (Kristal-Boneh *et al.* 1995; Ryan *et al.* 2000; Westrell *et al.* 2004; Lloyd Hough *et al.* 2010), both of which are significantly less than the 'default' daily water consumption rate of 2,000 ml day^{-1} recommended by the US EPA as the basis for exposure assessment within populations. Hence, the default figure would appear to be an overestimation for the Irish situation, the application of which may therefore result in inflated risk estimates. Based upon this study, it is considered appropriate to use a mean daily tap-water consumption figure of approximately 940 ml day^{-1} (SD 670 ml day^{-1}) within rural populations and 1,264 ml day^{-1} (SD 701 ml day^{-1}) within urban populations, respectively. This recommendation is supported by a statistically significant mean daily consumption difference between urban and rural consumers during this study ($t = -2.965$, $p = 0.003$).

It was considered that participant occupation may be used as a surrogate variable for occupational activity level, i.e. retired or unemployed participants expected to have lower levels of daily activity than those involved in professional or technical occupations. No statistically significant difference was found to exist between participant occupation and mean daily water consumption, therefore, no supportive evidence of differing 'occupational consumption rates' was found. It is important to note, however, that in this case low sample numbers were associated with both unemployed and retired participants; therefore, future work should focus on these subgroups.

Although both the exponential and normal statistical distribution functions were found to provide adequate fits for daily consumption data within both datasets, the log-normal distribution function provided the closest fit in both cases. It is therefore recommended that future

epidemiological studies relating to waterborne diseases in Ireland via drinking water consumption, employ the log-normal distribution. Application of the resulting log-normal distributions predict that only 8.4% of primarily rural residents currently consume more than the current default figure (2,000 ml day^{-1}) for cold water, while this figure was 14.5% among primarily urban residents.

Associations between a number of factors potentially affecting daily water consumption patterns were investigated, to identify the types of consumer that may be more or less susceptible to waterborne infection (or illness), due to increased or decreased daily consumption. The main factors investigated among survey respondents were gender, age, body mass, participant occupation, primary consumption source and the presence of a water treatment system.

Although both the survey questionnaire and five-day recall study found that male consumers had a higher mean total consumption rate, neither study found the mean difference to be statistically significant. Average daily consumption rates of 876 and 1,063 ml day^{-1} were attributed to female participants in the questionnaire survey and five-day recall study, respectively, while male respondents had mean consumption rates of 957 and 1,272 ml day^{-1}, approximately 10–15% greater than female consumers. However, in both cases, statistical analysis suggests that there is no necessity to separate male and female consumers at the exposure assessment stage when undertaking waterborne QMRA. Similar findings have been previously reported by Ershow & Cantor (1989), Foundation for Water Research UK (1996) and Levallois *et al.* (1998). It is important to note however, that this recommendation does not extend to hazard characterization (i.e. dose-response modelling), which was not included in this study.

No significant difference was found between daily consumption and source type among one-day recall survey respondents, due to the exclusion of urban dwellers from this dataset at the data recovery phase. However, there was significant difference between primary drinking water source and mean daily consumption volume among the five-day recall study participants. Consumers associated with household tap-water from a private rural supply (hand-dug well or borehole) recorded the lowest daily mean consumption volume (714 ml day^{-1}), and those drinking primarily bottled water consumed the highest mean

volume (1,514 ml day^{-1}). A previous study (Westrell *et al.* 2004) has noted a similar pattern, with consumers in receipt of municipal supplies consuming significantly more than those with private rural supplies. It is therefore recommended that separate daily consumption distributions be applied to urban and rural consumers when undertaking waterborne QRMA.

No statistical relationship existed between participant body weight and daily consumption volume, which may reflect the lack of significant difference with respect to daily water consumption and gender, thereby further demonstrating the lack of necessity for separating male and female exposure assessments when undertaking waterborne QMRA. It should be noted, however, that this does not eliminate the potential need for separate gender-specific QMRA, i.e. potential gender-specific differences at the dose-response stage of the overall health risk assessment, etc.

A weak association was found between participant age and mean daily consumption, indicating that mean consumption volume may decrease with increasing age, as might be expected. Furthermore, retired participants recorded the lowest daily mean consumption volume, further reflecting this assertion. Similar findings have been previously reported by Jones *et al.* (2006) in a Canadian community, with 'elderly residents' consuming approximately 10–20% less drinking water per day than residents between the ages of 20 and 64. Potential reasons for this may be decreased activity leading to decreased consumption or increased 'hot beverage' intake among the elderly demographic (as was also evidenced within this study). It is important to note that while decreased daily consumption among the elderly demographic suggests decreased exposure to waterborne diseases, they are considered a 'vulnerable sub-population' due to increased pathogen dose-response rates (Buzby 2002; Balbus & Malina 2009).

Other potential factors which may affect consumption rate, but were not investigated include personal preference, physical activity, medications, overall health status, seasonality/climate (i.e. temperature, humidity, etc.) and pregnancy (Ershow & Cantor 1989). For example, Gofti-Laroche *et al.* (2001) present clear seasonal differences pertaining to the French population, with mean daily consumption rates of 1,870 and 2,230 ml during winter and late spring, respectively. Similarly large seasonal consumption differences are

unlikely in Ireland due to the more temperate maritime climate, i.e. relatively stable yearly temperatures. It is considered that the main study limitations in this case were associated with study population representivity, i.e. disproportionate levels of male respondents (particularly with respect to the rural one-day recall dataset, e.g. 78% of respondents were male) and the lack of data pertaining to potentially vulnerable sub-populations (e.g. children and the elderly). Current Irish census data (CSO 2012) reports a mean age among the Irish adult population of 36.1 years, with 50.4% of the population being female. It is also reported that 62% of the Irish population now reside in categorically urban areas. Therefore, it is considered that the current study is representative with respect to participant age (e.g. mean age of five-day diary study participant was 33.6 years) and residence (e.g. at least 58.2% of five-day diary study participants reside in urban areas). However, it is considered that this study does not adequately represent the female population, which is a notable study limitation. Therefore, it is suggested that future studies should focus on improving the overall gender balance, in addition to focusing on younger and older population subsets.

CONCLUSIONS

The mean daily tap-water consumption rates within the primarily rural questionnaire population was 940 ml day^{-1} (SD 670 ml day^{-1}), while the primarily urban five-day diary participants had a mean daily rate of approximately 1,190 ml day^{-1} (SD 700 ml day^{-1}). Therefore, the application of the commonly used default water consumption figure of 2,000 ml day^{-1} may result in significant waterborne disease burden overestimates, not only in Ireland but in other temperate maritime areas. As the difference in daily tap-water consumption between rural and urban participants was found to be statistically significant, the use of separate exposure assessments for these populations is advocated both nationally and internationally, as similar findings have been reported in previous studies in countries such as Sweden and the UK. Based upon this study, it would appear that gender-specific exposure assessments are unnecessary when undertaking human health risk assessments of pathogenic exposure via daily water

consumption. The log-normal distribution was found to provide the most accurate fit within both modelled datasets, and is therefore recommended as the most suitable probabilistic daily consumption variable within waterborne human health risk assessments in Ireland. It is therefore concluded that the presented data and fitted distributions fitted can be used to represent the Irish adult population for pathogen-related quantitative risk analysis and assessment.

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