Is the risk of illness through consuming vegetables irrigated with reclaimed wastewater different for different population groups?

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Abstract The use of reclaimed wastewater for irrigation of horticultural crops is commonplace in many parts of the world and is likely to increase. Concerns about risks to human health arising from such practice, especially with respect to infection with microbial pathogens, are common. Several factors need to be considered when attempting to quantify the risk posed to a population, such as the concentration of pathogens in the source water, water treatment efficiency, the volume of water coming into contact with the crop, and the die-off rate of pathogens in the environment. Another factor, which has received relatively less attention, is the amount of food consumed. Plainly, higher consumption rates place one at greater risk of becoming infected. The amount of vegetables consumed is known to vary among ethic groups. We use Quantitative Microbial Risk Assessment Modelling (QMRA) to see if certain ethnic groups are exposed to higher risks by virtue of their consumption behaviour. The results suggest that despite the disparities in consumption rates by different ethnic groups they generally all faced comparable levels of risks. We conclude by suggesting that QMRA should be used to assess the relative levels of risk faced by groups based on divisions other than ethnicity, such as those with compromised immune systems.
Keywords Enteric virus; ethnic group; horticulture; reclaimed water; risk analysis; wastewater reclamation

Introduction

In many parts of the world water is a scarce resource. Intense competition for freshwater resources amongst the agricultural, urban and industrial sectors has seen the commissioning of recycled water schemes, including many that use reclaimed wastewater to irrigate horticultural crops (Hamilton *et al.*, 2005a). Irrigation of horticultural crops with reclaimed wastewater (henceforth simply referred to as wastewater) has nonetheless been approached with trepidation, owing primarily to concerns about human health. With irrigation water being derived from human excrement, the possibility that enteric human diseases could potentially ultimately be transmitted to the consumers of crops is real and needs to be managed accordingly (Shuval, 1993; Shuval *et al.*, 1984).

QMRA (quantitative microbial risk assessment) is increasingly being recognised as a useful tool for objectively estimating risks to human health from consuming produce that has been irrigated with wastewater. For example, the brief for the revised World Health Organisation (WHO) guidelines for agricultural reuse (in progress) is to use QMRA (Blumenthal *et al.*, 1996; Carr *et al.*, 2004). Australia is also currently revising its national guidelines for recycled water use, and these will include QMRA. In short, QMRA is a formal probabilistic process for estimating risks associated with defined scenarios. It comprises four distinct steps: (i) hazard characterisation, (ii) exposure assessment, (iii) dose–response modelling,

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and (iv) risk characterisation (Lammerding and Paoli, 1997). Today, most QMRAs are stochastic (Hamilton *et al.*, 2005b). That is, where possible, model parameters are represented as probability distributions rather than simple point-estimates. This allows us to account for our lack of knowledge about the parameter estimate (uncertainty) and/or to include inherent natural variation (variability) in the risk assessment.

Several QMRA models for risks associated with the consumption of wastewater-irrigated vegetables have been constructed but most of these do not account for variation in consumption rates (Asano *et al.*, 1992; Shuval *et al.*, 1997; Tanaka *et al.*, 1998; Petterson *et al.*, 2001). The most comprehensive database on consumption behaviour is for the population of the USA (US EPA, 1997, 2003). This database presents empirical cumulative distribution functions (CDFs) for a wide range of food products. These are expressed in terms of grams of product consumed per kilogram of body mass, and thus per capita consumption rates can be determined if a distribution describing body mass is available for the population. Van Ginneken and Oron (2000) used such data to construct a QMRA for the consumption of fruit and vegetables (in general) irrigated with wastewater, whilst Hamilton *et al.* (2006) developed similar models for specific vegetables. In both cases, the population of the USA was considered as a whole. But consumption behaviour is known to vary between ethnic population groups (henceforth referred to as groups) and by other demographic factors also by age and geographic region (US EPA 1997, 2003), and presumably socio-economic status. Variation in the consumption behaviour is known to be important in QMRAs for irrigation with wastewater. Sensitivity analyses for the models of Hamilton *et al.* (2006) revealed that variation in the parameter describing consumption rate had the most significant effect of any parameter on the variation in the resultant probability of infection.

Here we address, for particular vegetables irrigated with non-disinfected, secondary-treated wastewater, the hypothesis that higher consumption rates place certain groups at higher risk than others. The specific risk being considered is enteric virus infection. Ethnicity was chosen as the category for consideration because for the vegetables of interest, broccoli, cabbage, cucumber, and lettuce, the disparities were much greater among groups based on ethnicity than among those based on geography. Also, such comparisons provide insights into important questions about the transferability of QMRAs between different countries and cultures.

Methods

Consumption data and group definitions

All data on consumption rates were obtained from the CSFII (Continuing Survey of Food Intakes by Individuals) Analysis of Food Intake Distributions publication of the US EPA (2003), which is an addendum to Exposure Factors Handbook (US EPA, 1997). This is the most recent database on consumption behaviour in the USA, and it is a collation and analysis of data from the 1994, 1995, and 1996 CFSII surveys, which were undertaken by the US Department of Agriculture. Collectively, about 16,000 individuals were surveyed across the three surveys, with each participant providing two consecutive days of data. A stratified sampling design covering all 50 states and Washington D.C. was employed. All age groups were surveyed, and the consumption distributions used here (Table 1) represent the total group, i.e. they are weighted accordingly for age-structure.

Four main ethnic categories were defined in the US EPA (2003) analysis: Asian and Pacific Islander; Black; Native American, Aleut, and Eskimo; and White. These were shortened to Asian; Black; Native American; and White in the body text. We have adopted these contracted versions, and have checked the usage notes in *The Australian Concise Oxford Dictionary* (1997) to ensure none are considered

Table 1 Comparison of consumption rates (g of product per kg of body mass per day) of various vegetables by different ethnic groups in the USA (from US EPA, 2003). Group names/categories are those used by the US EPA (2003)

Crop	Percentile (or mean)	Asian	Black	Native American	White	Total pop.
Broccoli	mean	0.192	0.120	0.119	0.097	0.102
	95	1.479	0.983	0.433	0.634	0.694
	99	4.091	2.167	6.761	2.149	2.154
Cabbage	mean	1.439	1.190	0.474	0.700	0.809
	95	3.890	3.635	1.424	2.067	2.381
	99	4.823	4.764	1.424	3.164	4.201
Cucumber	mean	0.232	0.045	0.074	0.085	0.085
	95	0.755	0.241	0.336	0.482	0.482
	99	7.262	1.055	1.102	1.385	1.385
Lettuce	mean	0.247	0.136	0.114	0.216	0.205
	95	1.461	0.728	0.669	1.092	1.054
	99	2.270	1.895	1.036	2.012	2.016

offensive. The shortened descriptions are used in the interest of brevity, and should not in any way be seen as excluding certain groups. Data for a fifth ethnic category, "don't know, no answer, some other race", are also presented by the US EPA (2003) but are not used here. Note that in contrast to the US EPA we chose to use the term ethnicity rather than race. This is because race typically refers to physiological subgroups in human populations, while ethnicity refers to different subcultures in human societies (Sobal, 2005). The latter is more relevant here as differences in consumption behaviour are presumably driven by cultural differences.

The model

A detailed description and justification of the model and the choice of datasets upon which it is based is provided in Hamilton *et al.* (2006), but its fundamental structure will be outlined briefly here. Firstly, the daily dose of enteric viruses, λ, taken by consuming product was calculated as

$$\lambda = M_{\mathrm{i}} M_{\mathrm{body}} c_{\mathrm{iw}} V_{\mathrm{prod}} e^{(-kt)} \tag{1}$$

where M_{i} = daily consumption in grams of produce per capita per kilogram of body mass (g (kg ca day)$^{-1}$), M_{body} = human body mass (kg), c_{iw} = concentration of enteric viruses in the irrigation water (number of plaque-forming units mL^{-1}), V_{prod} = volume of irrigation water caught by the product (mL), k = virus first-order kinetic decay constant (day^{-1}), and t = withholding period, i.e. time between last wastewater irrigation event and harvest/consumption (days). For the various scenarios run, M_{i} was described using an empirical cumulative probability density function (CDF), M_{body} and c_{iw} with log-normal probability density functions (PDFs), and k with a truncated-normal PDF. V_{prod} was described with a log-logistic PDF for broccoli, an empirical CDF for all cabbage cultivars, and a normal PDF for cucumber and lettuce. The cabbage cultivars Savoy King and Grand Slam were grouped as Hamilton *et al.* (2006) found that there was no significant difference in the volume of water caught by the two cultivars. Parameter values, and original references where appropriate, for all probability functions presented in Hamilton *et al.* (2006). The distribution for c_{iw} is derived from non-disinfected secondary effluent from the Monterey Regional Water Pollution Control Agency's activated sludge plant (Tanaka *et al.*, 1998) and the distribution for k is that determined by Petterson *et al.* (2002).

Having found λ, the daily probability of enteric virus infection, $P_{I(\lambda)}$, was calculated using the β-binomial infectivity model (Cassin *et al.*, 1998). The reasons for choosing this model are described below. The β-binomial infectivity model is given by:

$$P_{I(\lambda)} = 1 - \binom{\alpha + \beta - 1}{\alpha} \Big/ \binom{\alpha + \beta + \lambda - 1}{\alpha} \quad (2)$$

where α and β are fit parameters for the β-Poisson model. We used values of 0.167 and 0.191 for these parameters, respectively. These estimates were derived, using maximum likelihood estimation, by Teunis and Havelaar (2000), who fitted the exact β-Poisson to the empirical dose–response data of Ward *et al.*'s (1986) rotavirus infectivity trials. It is important to note that nearly all previous studies concerned with rotavirus dose–response modelling have used an approximate β-Poisson model (e.g. Rose and Gerba, 1991; Tanaka *et al.*, 1998; Gerba *et al.*, 1996; van Ginneken and Oron, 2000; Petterson *et al.*, 2001; US EPA, 2004). This approximate model, proposed by Furumoto and Mickey (1967), is convenient since the exact model involves the solution of the complex Kummer confluent hypergeometric function. However, the approximate model only holds when $\beta \gg 1$ and $\alpha \ll \beta$. This condition is not satisfied in any of the aforementioned applications of the model, with maximum likelihood estimates for α ranging from 0.23 to 0.27 and β from 0.25 to 0.42. The disparity between the exact and approximate models, when fitted to Ward *et al.*'s rotavirus data, is most notable at low doses, where the approximate model can produce illogically high risks of infection (Teunis and Havelaar, 2000). This could have important implications for horticultural re-use scenarios, where we would often expect to be dealing with very low doses. Finally, it is important to note that the β-binomial model used here is simply a modification of the β-Poisson. In fact, the parameters α and β were derived from fitting the β-Poisson to the dose–response data. The β-binomial assumes λ is known whereas the β-Poisson assumes it is Poisson distributed. The β-binomial is more appropriate for our Monte Carlo model because each iteration of the exposure model produces a known dose rather than a mean.

The annual risk of enteric virus infection, $P_{A(\lambda)}$, was calculated as

$$P_{A(\lambda)} = 1 - (1 - P_{I(\lambda)})^{365} \quad (3)$$

In the interest of conservativeness with respect to health protection we chose to report the upper 95% confidence limit ($UCL_{0.95}$) of the mean $P_{A(\lambda)}$ (Tanaka *et al.*, 1998). The random variables were sampled 10,000 times using Latin Hypercube Sampling (LHS), whereby samples are selected in a stratified manner without replacement (Iman *et al.*, 1980). LHS is particularly useful for dealing with very low probabilities, as was the case here, and it represents extreme values more appropriately than traditional Monte Carlo sampling (Vose, 2000). The simulations were run using @RISK version 4.5.2 Professional edition (Palisade Corporation, 2002).

Results

The Asian group tended to consume all vegetables at a higher rate than the other groups (Table 1). By virtue of being the numerically dominant ethnic group, the consumption rates of the White population group closely mirrored those of the population as a whole. Notably less cabbage and lettuce was consumed by the Native American group. Likewise, the Black group consumed relatively low amounts of cucumber.

Disparities between groups in the annual risk of infection were small for all scenarios considered (Table 2). While the model predicts that the Asian group faces a greater risk of infection than other groups, the difference between the Asian group and the total

Table 2 Estimated annual risk of infection, $P_{A(\lambda)}$, to different ethnic groups arising from consumption of vegetables irrigated with wastewater (values represent the $UCL_{0.95}$ of the mean). Savoy King, Grand Slam (GS), and Winter Head are cabbage cultivars. Withholding period is the time in days between the last wastewater irrigation event and consumption or post-harvest storage. Group names are those used by the US EPA (2003)

Crop	With-holding	Asian	Black	Native American	White	Total pop.
Broccoli	1	7.1×10^{-2}	5.2×10^{-2}	3.0×10^{-2}	2.9×10^{-2}	3.2×10^{-2}
	7	2.6×10^{-3}	1.5×10^{-3}	1.7×10^{-3}	1.2×10^{-3}	1.0×10^{-3}
	14	3.3×10^{-6}	1.2×10^{-6}	6.2×10^{-6}	3.4×10^{-6}	1.6×10^{-6}
Savoy/GS	1	9.3×10^{-2}	7.7×10^{-2}	2.5×10^{-2}	4.9×10^{-2}	5.0×10^{-2}
(Cabbage)	7	4.7×10^{-3}	2.7×10^{-3}	5.9×10^{-4}	1.6×10^{-3}	1.5×10^{-3}
	14	1.1×10^{-5}	4.6×10^{-6}	4.5×10^{-7}	1.9×10^{-6}	4.3×10^{-6}
Winter Head	1	1.2×10^{-1}	1.0×10^{-1}	3.4×10^{-2}	6.7×10^{-2}	7.1×10^{-2}
(Cabbage)	7	8.8×10^{-3}	5.3×10^{-3}	1.3×10^{-3}	3.1×10^{-3}	3.3×10^{-3}
	14	2.6×10^{-5}	1.0×10^{-5}	1.2×10^{-6}	8.3×10^{-6}	7.0×10^{-6}
Cucumber	1	3.2×10^{-2}	1.7×10^{-2}	2.0×10^{-2}	2.4×10^{-2}	2.3×10^{-2}
	7	4.9×10^{-4}	1.8×10^{-4}	2.0×10^{-4}	2.9×10^{-4}	3.0×10^{-4}
	14	3.8×10^{-7}	1.5×10^{-7}	1.5×10^{-7}	2.9×10^{-7}	2.5×10^{-7}
Lettuce	1	1.8×10^{-1}	1.3×10^{-1}	1.5×10^{-1}	1.9×10^{-1}	1.8×10^{-1}
	7	8.7×10^{-3}	5.8×10^{-3}	5.4×10^{-3}	9.2×10^{-3}	8.4×10^{-3}
	14	1.2×10^{-5}	8.3×10^{-6}	6.6×10^{-6}	1.4×10^{-5}	1.1×10^{-5}

population was never greater than one order-of-magnitude. In fact, for no groups was the estimated risk ever outside one order-of-magnitude of that for the entire population. There were, however, two scenarios where the probability of infection differed by more than an order-of-magnitude between groups: Asian and Native American for Savoy King/Grand Slam cabbage and Winter Head cabbage with a 14 day withholding period.

Discussion

In developing QMRAs for horticultural irrigation with wastewater, much attention has been paid to model parameters that are ultimately important in determining the likely concentration of pathogens on the product (e.g. concentration of pathogens in sewage, treatment system efficiency, volume of water caught by the plant, and rate of decay of pathogens in the environment). In contrast, little focus has been placed on another significant parameter, namely, the amount of product consumed. For example, Tanaka *et al.* (1998) assumed that through eating vegetables people would consume an equivalent volume of 10 mL of wastewater per day. Shuval *et al.* (1997) assumed that annually an *average* consumer would eat 100 g of lettuce *or* cucumber per day for 150 days. Petterson *et al.* (2001) simply reported risks per consumption event, defined as 100 g of lettuce. The QMRA presented here used CDFs to describe variation in consumption behaviour, and thus enabled a more complete estimation of the risks posed to a population on an annual basis. Despite marked disparities in consumption rates among different ethnic groups, the consequential levels of risks varied little among the groups. Most significantly, risk levels for the total population tended to be representative of all groups. This has important implications for the development of guidelines for wastewater irrigation of horticultural crops, suggesting that for such wastewater irrigation scenarios, it may be valid to address risk for the population as a whole.

It is worth noting, however, that the models presented in this paper did not account for differences in body mass distributions between groups; rather, a distribution describing the population as a whole (Hamilton *et al.* 2006) was used for all groups. This was done simply because body mass data were not available for the groups as defined here. This is an important knowledge gap that needs to be addressed. Nonetheless, when the model was run with the body-mass PDF shifted 5 kg to the left and to the right (i.e. lighter and heavier, respectively) the annual risk of infection to the total population changed for less than one order-of-magnitude for all scenarios.

The similarity of risk levels amongst ethnic groups also suggests that QMRAs for horticultural irrigation with wastewater *may* be transferable between countries and cultures (with respect to consumption behaviour). This assertion holds if we assume the variation between ethnic groups within the USA is greater than variation between countries/cultures. Is this a reasonable assumption? Are differences between the consumption rates of the American Asian population and populations in Asian countries likely to be less than the differences between the Asian group and other ethnic groups within the USA? Such questions need to be answered before the transferability of these QMRAs can be determined.

Consumption behaviour is just one factor to consider when assessing the transferability of results from wastewater irrigation QMRAs. Cultural differences in food preparation could also be significant. Plainly, in cultures where washing or high-temperature cooking are standard practice, risks will generally be lower. Here we have assumed the simple scenario where all food is eaten raw. This could, however, be seen as overly conservative and arguments can be progressed for accounting for reductions in pathogen load through typical food preparation methods, such as washing or peeling (e.g. Schwartzbrod, 1995; Shuval *et al.*, 1997). A one-log reduction through washing/rinsing has been suggested for the in-progress WHO Guidelines for Wastewater Reuse in Agriculture (Shuval, H.I., pers. comm. August 2005). But how typical is washing in different parts of the world, where water availability (and quality) is known to vary markedly? It can also be argued that ingestion of food should not be considered the sole route for infection: cross-contamination via surfaces (e.g. cutting boards) and from direct handling of contaminated produce could also pose a risk. Until all these household processes can be explicitly included into QMRAs it is probably most appropriate to assume that people could be exposed to all the pathogens on the produce, i.e. that safety of produce should be assessed at the point at which it enters the household.

Differences in the susceptibility of different populations to particular pathogens may also need to be considered when applying a QMRA to another country or culture. For example, populations of developing and under-developed countries tend to experience high exposure to enteric viruses, and consequently high levels of immunity to many viruses (e.g. hepatitis A and polio viruses) tends to develop early in life (Shuval, 1991). Conversely, exposure and subsequent immunity is likely to be much lower in developed countries. Unfortunately, dose–response studies are rare, and effectively all enteric virus QMRAs are based on Ward *et al.*'s (1986) clinical trial for rotaviruses. Owing to ethical concerns, it is unlikely that many, if any, dose–response trials on enteric viruses will be conducted. Therefore, the development of population-specific dose–response models could be difficult, although it may be possible to modify existing models based on observed patterns in population-level immunity. Regional variation in the concentration of pathogens in sewage is another important factor to consider when considering risks to different populations (Gerba and Rose, 2003).

While the focus of this paper is on comparative risks amongst groups, it is worth noting that the commonly propounded acceptable risk level of 10^{-4} or less (US EPA, 2004) was only satisfied when a 14-day withholding period was imposed. However, absolute levels of risk presented here, and in any QMRA, have to be considered in context, particularly with respect to the quality of the wastewater. For example, the non-disinfected secondary effluent represented in these models is likely to be of substantially higher quality than that used in many developing countries in Asia and Africa. In Africa, 18% of the population lives in large sewered cities and none of the sewered wastewater undergoes secondary treatment (Scott *et al.*, 2004). Likewise, in Asia 45% of people live in large sewered cities and only 35% of this water is treated to a secondary level (WHO and UNICEF, 2000). Conversely, in developed countries water quality is often likely to be markedly higher than that considered here, since tertiary treatment and disinfection are sometimes implemented (Hamilton *et al.*, 2005a).

Conclusion and future directions

It would not be unreasonable to state that common ethics dictate that all groups in a population should be afforded protection when it comes to horticultural irrigation with wastewater, or indeed, any risk to health. Here we conducted a preliminary QMRA that suggests that levels of risk are generally similar amongst different ethnic groups within the USA. In future QMRA, groups could also be examined on the basis of age or geographical region. Another important group that should be considered in future QMRAs comprises those who have compromised immune systems, such as people on immuno-suppressant drugs or with immune system disorders or diseases (e.g. Acquired Immuno-deficiency Syndrome, AIDS). The group comprising people with AIDS is substantial in many countries. For example, it accounts for 37.3%, 28.9%, 38.8%, and 24.6% of the adult populations of Botswana, Lesotho, Swaziland, and Zimbabwe, respectively (UNAIDS, 2004). However, there are currently several major impediments to the construction of such QMRAs, including, *inter alia*, the lack of empirical data to derive appropriate dose–response models. For example, the subjects in the rotavirus clinical trial of Ward *et al.* (1986) were healthy 18–45 year-old adult males. Plainly, parameter estimates derived from trials conducted on healthy sample populations are not appropriate for determining risks to people with compromised immune systems. However, determining parameter estimates for people with compromised immune systems is obviously problematic.

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