Understanding and Updating the 2006 WHO Guidelines for the Safe Use of Wastewater in Agriculture

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Duncan Mara and Andrew Sleigh
School of Civil Engineering, University of Leeds, United Kingdom

1. INTRODUCTION

The World Health Organization published the third edition of its Guidelines for the safe use of wastewater in agriculture in September 2006 (WHO, 2006). These Guidelines are essentially a code of good management practices to ensure that, when wastewater is used in agriculture (mainly for irrigating crops, including food crops that are or may be eaten uncooked), it is used safely and with minimal risks to health. They are therefore much more than a set of guideline values. However, in practice wastewater treatment and reuse engineers need to know how to use the recommendations in the Guidelines to design wastewater reuse systems that do not adversely affect public health. This means that they have to understand in detail the basis of the Guidelines so that the wastewater reuse systems they design are safe.

There are two broad groups of diseases considered in the Guidelines:

- viral, bacterial and protozoan diseases, for which the health risks are determined by quantitative microbial risk analysis (QMRA − see section 2), and
- helminthic diseases, for which the Guidelines set a guideline value on the basis of epidemiological studies (see section 6).

The basis of human health protection in the Guidelines is that the additional disease burden due to viral, bacterial and protozoan diseases which results from working in wastewater-irrigated fields or consuming wastewater-irrigated crops should not exceed 10^{-6} disability-adjusted life year (DALY) loss per person per year (pppy). This level of health protection was used by WHO in its 2004 guidelines on drinking-water quality (WHO, 2004). Thus the health risks resulting from wastewater use in agriculture are the same as those from drinking fully treated drinking water, and this is basically what consumers want as they expect the food they eat to be as safe as the water they drink.

For the viral, bacterial and protozoan diseases this tolerable additional disease burden of 10^{-6} DALY loss pppy is 'translated' into tolerable disease and infection risks as follows:

$$\text{Tolerable disease risk pppy} = \frac{\text{Tolerable DALY loss pppy (i.e., } 10^{-6})}{\text{DALY loss per case of disease}}$$

$$\text{Tolerable infection risk pppy} = \frac{\text{Tolerable disease risk pppy}}{\text{Disease/infection ratio}}$$

Three 'index' pathogens were selected: rotavirus, viral pathogen; *Campylobacter*, a bacterial pathogen; and *Cryptosporidium*, a protozoan pathogen. Table 1 gives the DALY losses per case of rotavirus diarrhoea, campylobacteriosis and cryptosporidiosis and the corresponding disease/infection ratios.

From the data in Table 1 'design' values of 10^{-4} pppy were chosen for the tolerable risk of rotavirus disease and 10^{-3} pppy for the corresponding tolerable rotavirus infection risk. The former is extremely safe as it is three orders-of-magnitude lower than the actual incidence of diarrhoeal disease in the world (Table 2).

Table 1. DALY losses, disease risks, disease/infection ratios and tolerable infection risks for rotavirus, *Campylobacter* and *Cryptosporidium*

Pathogen	DALY loss per case of disease[a]	Tolerable disease risk pppy equivalent to 10^{-6} DALY loss pppy[b]	Disease/ infection ratio	Tolerable infection risk pppy[c]
Rotavirus: (1) IC[d]	1.4×10^{-2}	7.1×10^{-5}	0.05[e]	1.4×10^{-3}
(2) DC[d]	2.6×10^{-2} [d]	3.8×10^{-5}	0.05[e]	7.7×10^{-4}
Campylobacter	4.6×10^{-3}	2.2×10^{-4}	0.7	3.1×10^{-4}
Cryptosporidium	1.5×10^{-3}	6.7×10^{-4}	0.3	2.2×10^{-3}

[a] Values from Havelaar and Melse (2003).
[b] Tolerable disease risk = 10^{-6} DALY loss pppy ÷ DALY loss per case of disease.
[c] Tolerable infection risk = disease risk ÷ disease/infection ratio.
[d] IC, industrialized countries; DC, developing countries.
[e] For developing counties the DALY loss per rotavirus death was reduced by 95 percent as ~95 percent of these deaths occur in children under the age of 2 who are not exposed to wastewater-irrigated foods. The disease/infection ratio for rotavirus is low as immunity is mostly developed by the age of 3.

Table 2. Diarrhoeal disease (DD) incidence pppy in 2000 by region and age[a]

Region	DD incidence in all ages	DD incidence in 0−4 year olds	DD incidence in 5−80+ year olds
Industrialized countries	0.2	0.2–1.7	0.1–0.2
Developing countries	0.8–1.3	2.4–5.2	0.4–0.6
Global average	0.7	3.7	0.4

[a]Source: Mathers *et al*. (2002).

2. QUANTITATIVE MICROBIAL RISK ANALYSIS

The Guidelines adopted a standard QMRA approach (Haas *et al*., 1999) to risk analysis combined with 10,000-trial Monte Carlo simulations (Mara *et al*., 2007). The basic equations are:

(a) Exponential dose-response model (for *Cryptosporidium*):

$$P_I(d) = 1 - \exp(-rd) \quad (1)$$

(b) β-Poisson dose-response model (for rotavirus and *Campylobacter*):

$$P_I(d) = 1 - [1 + (d/N_{50})(2^{1/\alpha} - 1)]^{-\alpha} \quad (2)$$

(c) Annual risk of infection:

$$P_{I(A)}(d) = 1 - [1 - P_I(d)]^n \quad (3)$$

where $P_I(d)$ is the risk of infection in an individual exposed to (here, following ingestion of) a single pathogen dose d − i.e., the number of pathogens ingested on any one occasion; $P_{I(A)}(d)$ is the annual risk of infection in an individual from n exposures per year to the single pathogen dose d; N_{50} is the median infective dose; and α and r are pathogen 'infectivity constants' − for rotavirus $N_{50} = 6.17$ and $\alpha = 0.253$, for *Campylobacter* $N_{50} = 896$ and $\alpha = 0.145$, and for *Cryptosporidium* $r = 0.0042$ (Haas *et al*., 1999).

In practice equations 1−3 are used as follows:

1. $P_{I(A)}(d)$ in equation 3 is set equal to 10^{-3} pppy (the tolerable rotavirus infection risk).
2. The number of days of exposure (n in equation 3) is determined (or selected) − e.g., for lettuce consumption on alternate days $n = 365/2$.
3. $P_I(d)$ is then calculated from equation 3 (e.g., for $n = 365/2$, $P_I(d) = 5.5 \times 10^{-6}$ per person per exposure).
4. For this value of $P_I(d)$ d is calculated from either equation 1 or equation 2.
5. This number of d pathogens, which is the number of pathogens ingested with the lettuce (or other crop), is assumed to be in whatever volume of treated wastewater that remains on the lettuce (or other crop) after irrigation − for example, Shuval *et al*. (1997) found 11 ml to remain on 100 g lettuce.
6. This pathogen count (e.g., d per 11 ml) is expressed per litre and, knowing the pathogen count per litre of untreated wastewater, the required log reduction (actually the required $\log_{10}$ reduction) of the pathogen is determined.

This required log pathogen reduction is achieved by a combination of wastewater treatment and the post-treatment health-protection control measures detailed in Table 3.

Table 3. Post-treatment health-protection control measures and associated pathogen reductions

Control measure	Pathogen reduction (log units)	Notes
Drip irrigation	2−4	2-log unit reduction for low-growing crops, and 4-log unit reduction for high-growing crops.
Pathogen die-off	0.5−2 per day	Die-off after last irrigation before harvest (value depends on climate, crop type, etc.).
Produce washing	1	Washing salad crops, vegetables and fruit with clean water.
Produce disinfection	3[a]	Washing salad crops, vegetables and fruit with a weak disinfectant solution and rinsing with clean water.
Produce peeling	2	Fruits, root crops.

[a]Amoah *et al*. (2007).

Monte Carlo risk simulations

There is commonly some degree of uncertainty about the values of the parameters used to determine required log pathogen reductions − for example, it is unlikely that exactly 11 ml of wastewater are always left on 100 g of lettuce after irrigation. Therefore, in order to take this uncertainty into account, it is better to assign a range of values to each parameter (e.g., 10−15 ml of wastewater remaining on 100 g of lettuce after irrigation), although a fixed value can be assigned to any parameter if so wished. A computer program then selects at random a value for each parameter from the range of values specified for it and then determines the resulting annual infection risk. The program repeats this process a large number of times (commonly for a total of 10,000 times) and then determines the median annual infection risk. This large number of repetitions removes some of the uncertainty associated with the parameter values and makes the results generated by multi-trial Monte Carlo simulations much more robust, although of course only as good as the assumptions made.

3. RESTRICTED IRRIGATION

The exposure scenario developed in the Guidelines for restricted irrigation is the involuntary ingestion of soil particles by those working, or by young children playing, in wastewater-irrigated fields. This is a likely scenario as wastewater-saturated soil would contaminate the workers' or children's fingers and so some pathogens could be transmitted to their mouths and hence ingested. The quantity of soil involuntarily ingested in this way has been reported (but not specifically for this restricted-irrigation scenario) as up to ~100 mg per person per day of exposure (Haas *et al*. 1999; WHO 2001). Two sub-scenarios were investigated: (a) highly mechanized agriculture and (b) labour-intensive agriculture. The former represents exposure in industrialized countries where farm workers typically plough, sow and harvest using tractors and associated equipment and can be expected to wear gloves and be generally hygiene-conscious when working in wastewater-irrigated fields. The latter represents farming practices in developing countries in situations where tractors are not used and gloves (and often footwear) are not worn, and where hygiene is commonly not promoted.

Labour-intensive agriculture. The results of the Monte Carlo-QMRA risk simulations are given in Table 4 for various wastewater qualities (expressed as single log ranges of *E. coli* numbers per 100 ml) and for 300 days exposure per year (the footnote to the Table gives the range of values assigned to each parameter). From Table 4 it can be seen that the median rotavirus infection risk is ~10^{-3} pppy for a wastewater quality of 10^3−10^4 *E. coli* per 100 ml. Thus the tolerable rotavirus infection risk of 10^{-3} pppy is achieved by a 4-log unit reduction − i.e., from 10^7−10^8 to 10^3−10^4 *E. coli* per 100 ml. The table also shows that the *Campylobacter* and *Cryptosporidium* infection risks are all lower than those for rotavirus.

Highly mechanized agriculture. The simulated risks for various wastewater qualities and for 100 days exposure per year are given in Table 5, which shows that a 3-log unit reduction, from 10^7−10^8 to 10^4−10^5 *E. coli* per 100 ml, is required to achieve the tolerable rotavirus infection risk of 10^{-3} pppy.

Table 4. Restricted irrigation − labour-intensive agriculture with exposure for 300 days per year: median infection risks from ingestion of wastewater-contaminated soil estimated by 10,000-trial Monte Carlo simulations[a]

Soil quality	Median infection risk pppy		
(*E. coli* per 100 g)[b]	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7–10^8	0.99	0.50	1.4×10^{-2}
10^6–10^7	0.88	6.7×10^{-2}	1.4×10^{-3}
10^5–10^6	0.19	7.3×10^{-3}	1.4×10^{-4}
10^4–10^5	2.0×10^{-2}	7.0×10^{-4}	1.3×10^{-5}
10^3–10^4	1.8×10^{-3}	6.1×10^{-5}	1.4×10^{-6}
100−1000	1.9×10^{-4}	5.6×10^{-6}	1.4×10^{-7}

[a]Assumptions: 10−100 mg soil ingested per person per day for 300 days per year; 0.1−1 rotavirus and *Campylobacter*, and 0.01−0.1 *Cryptosporidium* oocyst, per 10^5 *E. coli*; N_{50} = 6.7 ± 25% and α = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and α = 0.145 ± 25% for *Campylobacter*; r = 0.0042 ± 25% for *Cryptosporidium*. No pathogen die-off (taken as a worst case scenario).
[b]The wastewater quality is taken to be the same as the soil quality − i.e., the soil is assumed, as a worst case scenario, to be saturated with the wastewater .

Table 5. Restricted irrigation − highly mechanized agriculture with exposure for 100 days per year: median infection risks from ingestion of wastewater-contaminated soil estimated by 10,000-trial Monte Carlo simulations[a]

Soil quality	Median infection risk pppy		
(*E. coli* per 100 g)[b]	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7–10^8	0.50	2.1×10^{-2}	4.7×10^{-4}
10^6–10^7	6.8×10^{-2}	1.9×10^{-3}	4.7×10^{-5}
10^5–10^6	6.7×10^{-3}	1.9×10^{-4}	4.6×10^{-6}
10^4–10^5	6.5×10^{-4}	2.3×10^{-5}	4.6×10^{-7}
10^3–10^4	6.8×10^{-5}	2.4×10^{-6}	5.0×10^{-8}
100−1000	6.3×10^{-6}	2.2×10^{-7}	$\leq 1 \times 10^{-8}$

[a]Assumptions: 1−10 mg soil ingested per person per day for 100 days per year; 0.1−1 rotavirus and *Campylobacter*, and 0.01−0.1 *Cryptosporidium* oocyst, per 10^5 *E. coli*; N_{50} = 6.7 ± 25% and α = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and α = 0.145 ± 25% for *Campylobacter*; r = 0.0042 ± 25% for *Cryptosporidium*. No pathogen die-off (taken as a worst case scenario).
[b]The wastewater quality is taken to be the same as the soil quality − i.e., the soil is assumed, as a worst case scenario, to be saturated with the wastewater .

4. UNRESTRICTED IRRIGATION

The exposure scenarios used in the Guidelines for unrestricted irrigation are the consumption of wastewater-irrigated lettuce (Shuval *et al*., 1997) and the consumption of wastewater-irrigated onions (a leaf and a root vegetable, respectively).

Risk simulations

For unrestricted irrigation a slightly different approach was adopted. The QMRA-Monte Carlo program determined the required log rotavirus reductions for various levels of tolerable

rotavirus annual infection risk. The results, given in Table 6, show that, for the tolerable rotavirus infection risk of 10^{-3} pppy, the required pathogen reductions are 6 log units for non-root crops and 7 log units for root crops. The table also shows that the consumption of root crops requires a 1-log unit pathogen reduction greater than the consumption of non-root crops, and that the required pathogen reductions change by an order of magnitude with each order-of-magnitude change in tolerable risk.

This 6−7-log unit reduction for unrestricted irrigation is best achieved by a 3−4-log unit reduction by wastewater treatment, as required for restricted irrigation, supplemented by a 2−4-log unit reduction from post-treatment health-protection control measures (Table 3). These post-treatment health-protection control measures are extremely reliable: in essence they always occur.

Table 6. Unrestricted irrigation: required pathogen reductions for various levels of tolerable risk of rotavirus infection from the consumption of wastewater-irrigated lettuce and onions estimated by 10,000-trial Monte Carlo simulations[a]

Tolerable level of rotavirus infection risk (pppy)	Corresponding required level of rotavirus reduction (log units)	
	Lettuce	Onions
10^{-2}	5	6
10^{-3}	6	7
10^{-4}	7	8

[a]Assumptions: 100 g lettuce and onions eaten per person per 2 days; 10−15 ml and 1−5 ml wastewater remaining after irrigation on 100 g lettuce and 100 g onions, respectively; 0.1−1 and rotavirus per 10^5 *E. coli*; N_{50} = 6.17 ± 25% and α = 0.253 ± 25%. No pathogen die-off.

5. EPIDEMIOLOGICAL VERIFICATION OF THE QMRA APPROACH

Mara *et al*. (2007) used the field data reported by Blumenthal *et al*. (2003) on diarrhoeal disease incidences amongst fieldworkers and consumers in Mezquital Valley, Mexico to obtain QMRA estimates of rotavirus infection risks in the five-month dry season. It was found that, provided the assumptions used in the QMRA-Monte Carlo risk simulations closely reflected field conditions, the agreement between the observed incidences of diarrhoeal disease and the estimated rotavirus infection risks was very close for both fieldworkers and consumers (Table 7).

6. HELMINTH EGGS

The recommendation in the Guidelines is that wastewater used in agriculture should contain ≤1 helminth egg per litre. The helminths referred to here are the human intestinal nematodes:

Table 7. Comparison between observed incidences of diarrhoeal disease and estimated rotavirus infection risks in Mezquital Valley, Mexico

Irrigation scenario	Wastewater quality (*E. coli* per 100 ml)	Observed diarrhoeal disease incidence per person per 5 months	Estimated median rotavirus infection risk per person per 5 months
Restricted irrigation	10^3–10^5	0.37	0.33[a]
Unrestricted irrigation	10^3–10^5	0.38	0.39[b]

[a]Assumptions: soil quality per 100 g taken as wastewater quality per 100 ml; 10−100 mg soil ingested per person per day for 65 days in five months; 0.1−1 rotavirus per 10^5 *E. coli*; ID_{50} = 6.7 ± 25% and α = 0.253 ± 25%. No pathogen die-off.
[b]Assumptions: 100 g of onions consumed per person per week for five months; 1−5 ml wastewater remaining on 100 g onions after irrigation; 0.1−1 rotavirus per 10^5 *E. coli*; 0−1 log unit rotavirus die-off between harvest and consumption; ID_{50} = 6.7 ± 25% and α = 0.253 ± 25%.
Source: Mara *et al*. (2007).

Ascaris lumbricoides (the human roundworm), *Trichuris trichiura* (the human whipworm), and *Ancylostoma duodenale* and *Necator americanus* (the human hookworms); details of the diseases they cause and their life cycles are given in Feachem *et al*. (1983).

This recommendation is the same as was made in the 1989 Guidelines (WHO, 1989), but with two important differences: (1) it is now based on epidemiological evidence which shows that ≤1 egg per litre protects adults but not children under 15 (Blumenthal *et al*., 2000), and (2) when children under the age of 15 are exposed additional control measures are needed, such as regular deworming (by their parents or at school).

7. SUMMARY OF RECOMMENDATIONS IN THE GUIDELINES

The 2006 WHO Guidelines make the following recommendations, either explicitly or implicitly:

1. To protect the health of those working in wastewater-irrigated fields against excessive risks of viral, bacterial and protozoan infections, there should be a 3−4-log unit pathogen reduction, which is to be achieved by wastewater treatment.
2. To protect the health of those consuming wastewater-irrigated food crops against excessive risks of viral, bacterial and protozoan infections, there should be a 6−7-log unit pathogen reduction, which is to be achieved by a wastewater treatment (a 3−4-log unit reduction as for restricted irrigation) supplemented by post-treatment health-protection control measures providing together a further 2−4-log unit pathogen reduction.
3. To protect the health of those working in wastewater-irrigated fields and those consuming wastewater-irrigated food crops against excessive risks of helminthic

infections, the treated wastewater should contain ≤1 human intestinal nematode egg per litre.

8. UPDATING THE GUIDELINES

Since the publication of the 2006 WHO Guidelines there have been several pertinent developments in risk analysis techniques and the interpretation of the resulting risks. These include:

1. Recognition that a tolerable additional disease burden of $\leq 10^{-6}$ disability-adjusted life year (DALY) loss per person per year (pppy) may be too stringent in many developing country settings and that a DALY loss of $\leq 10^{-5}$ or even $\leq 10^{-4}$ pppy may be sufficiently protective of human health (WHO, 2007),
2. A more robust method for estimating annual risks (Karavarsamis and Hamilton, 2009; Benke and Harrison, 2008),
3. The availability of dose-response data for *Norovirus* (Teunis *et al*., 2008), and
4. Application of QMRA to estimate *Ascaris* infection risks (Navarro *et al*., 2009).

Less stringent tolerable burden of disease

In *Levels of Protection*, one of the documents in the rolling revision of its drinking-water quality guidelines, WHO (2007) states that "in locations or situations where the overall burden of disease from microbial, chemical or radiological exposures by all exposure routes is very high, setting a 10^{-6} DALY [loss] per person per year annual risk from waterborne exposure will have little impact on the overall disease burden. Therefore, setting a less stringent level of acceptable risk, such as 10^{-5} or 10^{-4} DALY [loss] per person per year, from waterborne exposure may be more realistic, yet still consistent with the goal of providing high-quality, safer water and encouraging incremental improvement of water quality." Following the principles of the Stockholm Framework (Fewtrell and Bartram, 2001), this can be applied *mutatis mutandis* to wastewater use in agriculture.

Thus, for communities with high levels of diarrhoeal disease (see Table 2) it is probably unrealistic to set a tolerable addition burden of disease of $\leq 10^{-6}$ DALY loss pppy; a more realistic level could be $\leq 10^{-5}$ DALY loss pppy for consumers of wastewater-irrigated food crops eaten uncooked and $\leq 10^{-4}$ DALY loss pppy for those who work (or play) in wastewater-irrigated fields − a less stringent level is set for the latter as they are a readily identifiable group of people who can be easily given treatment when necessary (e.g., oral rehydration salts and antihelminthic drugs).

Fieldworkers would therefore be, at least partially, protected by wastewater treatment that achieved a pathogen reduction of two orders-of-magnitude lower than that for $\leq 10^{-6}$ DALY loss pppy − i.e., a reduction of only 1−2-log units. Similarly, consumers would be protected by a total pathogen reduction one order-of-magnitude lower than that for $\leq 10^{-6}$ DALY loss pppy − i.e., a reduction of only 1−2-log units by wastewater treatment supplemented by 4−5

log units achieved by post-treatment health-protection control measures (Table 3). This is discussed further below.

More robust method to estimate annual risks

Hamilton recommends the use of a more robust and theoretically superior method of estimating annual infection risks from QMRA-Monte Carlo simulations (Karavarsamis and Hamilton, 2009; Benke and Hamilton, 2008). This method is as follows:

1. Using equations 1, or 2, and 3 in an appropriate QMRA-Monte Carlo computer program, a single simulation of annual infection risk is determined by a Monte Carlo simulation in which the number of iterations is equal to the number of days of exposure per year (*n* in equation 3),
2. This is repeated 9,999 times, so that there are 10,000 simulations of annual infection risk, and
3. The median and 95-percentile values of these 10,000 simulations are then determined to provide robust estimates of the median and 95-percentile annual infection risks.

Thus the program determines 10,000 estimates of annual risk, each of which is based on what happens in any one year (*n* exposures to a pathogen dose *d*), rather than (as in the procedure used in the 2006 WHO Guidelines) an estimate of median annual risk determined from 10,000 estimates of annual risk based on what happens on any one day of exposure.

The Hamilton method and that used in the 2006 Guidelines yield similar median estimates of annual infection risk, but the former has 95-percentile risks much closer to the median than the latter (Table 8).

Table 8. Comparison of the WHO and Hamilton methods for determining annual rotavirus infection risks per person per year from the consumption of wastewater-irrigated lettuce estimated by 10,000 Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 ml)	Rotavirus infection risk per person per year			
	WHO		Hamilton	
	Median	95-percentile	Median	95-percentile
10^7–10^8	1	1	1	1
10^3–10^4	0.29	0.70	0.36	0.39
100–1000	3.4×10^{-2}	0.11	4.5×10^{-2}	4.9×10^{-2}
10–100	3.5×10^{-3}	1.3×10^{-2}	4.6×10^{-3}	5.1×10^{-3}
1–10	3.4×10^{-4}	1.2×10^{-3}	4.6×10^{-4}	5.1×10^{-4}

[a]Assumptions: 100 g lettuce eaten per person per 2 days; 10–15 ml wastewater remaining on 100 g lettuce after irrigation; 0.1–1 rotavirus per 10^5 *E. coli*; no pathogen die-off; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$.

Estimates of norovirus infection risks

The 'index' viral pathogen used in the 2006 Guidelines was rotavirus. However, a better index virus is norovirus (NV), which is a very common, if not the commonest, cause of gastroenteritis, and certainly the commonest viral cause of gastroenteritis, affecting all age

groups (Widdowson *et al*., 2005), − whereas rotavirus mainly affects children under the age of three − and for which dose-response data are now available (Teunis *et al*., 2008).

The tolerable NV disease and infection risks corresponding to a tolerable DALY loss of 10^{-5} pppy were determined using a DALY loss of 9×10^{-4} per case of NV disease (Kemmeren *et al*., 2006) and an NV disease/infection ratio of 0.8 (Moe, 2009), as follows:

$$\text{Tolerable NV disease risk} = \frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of NV disease}} = \frac{10^{-5}}{9 \times 10^{-4}} = 1.1 \times 10^{-2} \text{ pppy}$$

$$\text{Tolerable NV infection risk} = \frac{\text{Tolerable NV disease risk pppy}}{\text{NV disease/infection ratio}} = \frac{1.1 \times 10^{-2}}{0.8} = 1.4 \times 10^{-2} \text{ pppy}$$

The NV dose-response dataset of Teunis *et al*. (2008) was used in place of the β-Poisson equation in the QMRA-MC computer program developed to determine median NV infection risks pppy (Teunis and Havelaar, 2000); the program was based on the Benke and Hamilton method described above. A series of 10,000-trial QMRA-MC risk simulations was run and the resulting estimates of median risk obtained are given in Table 9, together with the assumptions on which they are based (which are the same as those used in the 2006 Guidelines but without pathogen die-off). This shows that a reduction of 5 log units results in an NV infection risk of 2.9×10^{-2} pppy, which is only marginally higher than the tolerable NV infection risk of 1.4×10^{-2} pppy determined above.

Table 9. Median norovirus infection risks per person per year from the consumption of 100 g of wastewater-irrigated lettuce every two days estimated by 10,000 Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 ml)	Median norovirus infection risk pppy
10^7–10^8	1
10^6–10^7	1
10^5–10^6	1
10^4–10^5	0.94
10^3–10^4	0.25
100–1000	2.9×10^{-2}
10–100	2.9×10^{-3}
1–10	2.9×10^{-4}

[a]Assumptions: 10–15 ml wastewater remaining on 100 g lettuce after irrigation; 0.1–1 norovirus per 10^5 *E. coli*; no die-off between last irrigation and consumption.

Estimates of *Ascaris* infection risks

The 2006 WHO Guidelines for the safe use of wastewater in agriculture (WHO, 2006) make the same recommendation for helminth eggs as was made in the 1989 Guidelines (WHO, 1989): ≤1 human intestinal nematode egg per litre of treated wastewater − the human

intestinal nematodes of importance here are *Ascaris lumbricoides* (the human roundworm), *Trichuris trichiura* (the human whipworm), and *Ancylostoma duodenale* and *Necator americanus* (the human hookworms). However, epidemiological studies in Mexico have shown that, while this guideline value protects adults, it does not protect children under the age of 15 (Blumenthal *et al*., 1996). Blumenthal *et al*. (2000) therefore recommended lowering the guideline value to ≤0.1 egg per litre wherever children under 15 are exposed and the soil conditions are favourable to egg survival, but this recommendation was not accepted by the international group of experts who participated in the development and review of the Guidelines at a meeting held in Geneva in June 2005, on the grounds that it was too difficult to measure an egg concentration as low as 0.1 per litre. However, if the wastewater is treated in waste stabilization ponds (WSP), which are generally the best wastewater treatment process in developing countries (Mara, 2004), the effluent egg concentration can be simply determined from the egg concentration in the untreated wastewater (which is relatively easy to measure) by using the design equation for egg removal in WSP given by Ayres *et al*. (1992).

Since the 2006 WHO Guidelines do not protect the health of children under 15 against intestinal nematode disease (unless, additionally, they are dewormed at home or at school), QMRA can be used to determine how best regularly children under 15 can be protected against *Ascaris* infection, now that *Ascaris* dose-response data are available (Navarro *et al*., 2009).

For a tolerable DALY loss of 10^{-5} pppy, a DALY loss per case of ascariasis of 8.25×10^{-3} (Chan, 1997) and, as worst-case scenario, an *Ascaris* disease/infection ratio of 1 (i.e., all those infected with *Ascaris* develop ascariasis), the tolerable *Ascaris* infection risk is given by:

$$\frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of ascariasis}} = \frac{10^{-5}}{8.25 \times 10^{-3}} = 1.2 \times 10^{-3} \text{ pppy}$$

Median *Ascaris* infection risks pppy from the consumption by children under 15 of raw carrots irrigated with wastewaters containing specified numbers of *Ascaris* eggs were determined by a QMRA-Monte Carlo computer program based on the Benke and Hamilton method described above. The resulting estimates of median *Ascaris* infection risk obtained, and the assumptions on which they are based, are given in Table 10. This shows that 1 egg per litre results in an *Ascaris* infection risk of $\sim 6 \times 10^{-3}$ pppy and 0.1 egg per litre in one of $\sim 6 \times 10^{-4}$ pppy; these risks are higher and lower, respectively, than the tolerable *Ascaris* infection risk of $\sim 10^{-3}$ pppy determined above. This could be taken to confirm the finding of Blumenthal *et al*. (1996) that ≤1 egg per litre is not protective of children under 15, and thus reinforce the recommendation of Blumenthal *et al*. (2000) that, when children under 15 are exposed, the guideline value should be ≤0.1 egg per litre. However, post-treatment health-protection control measures (Table 3) achieve significant pathogen reductions, so that

wastewater treatment does not have to achieve the total pathogen reduction required to protect consumer health. This is discussed further below.

Table 10. Median *Ascaris* infection risks for children under 15 from the consumption of raw wastewater-irrigated carrots estimated by 10,000 Monte Carlo simulations[a]

Number of *Ascaris* eggs per litre of wastewater	Median *Ascaris* infection risk pppy	Notes
100–1000	0.86	Raw wastewaters in hyperendemic areas.
10–100	0.24	Raw wastewaters in endemic areas.
1–10	2.9×10^{-2}	Treated wastewaters.
1	5.5×10^{-3}	Wastewater quality required to comply with the 1989 and 2006 WHO Guidelines.
0.1–1	3.0×10^{-3}	Highly treated wastewaters.
0.1	5.5×10^{-4}	Wastewater quality recommended by Blumenthal *et al*. (2000).
0.01–0.1	3.0×10^{-4}	Treated wastewaters in non-endemic areas.

[a]Assumptions: 30–50 g raw carrots consumed per child per week (Navarro *et al*., 2009); 3–5 ml wastewater remaining on 100 g carrots after irrigation (Mara *et al*., 2007); N_{50} = 859 ± 25% and α = 0.104 ± 25%; no *Ascaris* die-off between final irrigation and consumption.

Application to urban agriculture in developing countries

Seidu *et al*. (2008) reported that people in urban Ghana commonly consume ~10−12 g of lettuce in 'fast food' on each of four days per week − this is substantially less than the 100 g of lettuce consumed on alternate days used by Shuval *et al*. (1997) and Mara *et al*. (2007) and in the 2006 Guidelines. The norovirus infection risks for this level of lettuce consumption were simulated by a QMRA-Monte Carlo computer program based on the Benke and Hamilton method described above. The resulting risks, together with the assumptions on which they are based, are given in Table 11, which shows that a reduction of 4 log units

Table 11. Median norovirus infection risks per person per year from the consumption of 10−12 g of wastewater-irrigated lettuce on four occasions per week estimated by 10,000 Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 ml)	**Median norovirus infection risk pppy**
10^7−10^8	1
10^6−10^7	1
10^5−10^6	0.97
10^4−10^5	0.30
10^3−10^4	3.6×10^{-2}
100−1000	3.6×10^{-3}
10−100	3.6×10^{-4}

[a]Assumptions: 10−15 ml wastewater remaining on 100 g lettuce after irrigation; 0.1−1 norovirus per 10^5 *E. coli*; no die-off between last irrigation and consumption.

results in a norovirus infection risk of 3.6×10^{-2} pppy, which is only marginally higher than the tolerable norovirus infection risk determined in section 2.4.4 for a tolerable DALY loss of 10^{-5} pppy. This required 4-log unit reduction could be achieved by, for example, a 1-log unit reduction by wastewater treatment and a 3-log unit reduction by produce disinfection (or, if disinfection is not routinely or reliably practised, a 2-log unit reduction through die-off and a 1-log unit reduction by produce washing in clean water).

Implications for wastewater treatment

In the above example wastewater treatment is required to produce only a single log unit pathogen reduction. This can be readily achieved by very simple treatment processes, such as an anaerobic pond, a three-tank or three-pond system, and overnight settling. The three-tank or three-pond system is operated as a sequential batch-fed process: on any one day one tank or pond is filled with wastewater, the contents of another are settling, and the contents of the third are used for irrigation; this is a very reliable, almost foolproof system. In small-scale urban agriculture, as opposed to large-farm agriculture, a single tank is generally sufficient (and more affordable): on any day in the morning the tank contents are used for crop watering, and the tank is then refilled and its contents allowed to settle until the following morning.

For helminth eggs, if it is assumed that in areas where ascariasis is endemic untreated wastewater contains 100 *Ascaris* eggs per litre, a 3-log unit egg reduction is required to achieve 0.1 egg per litre. For root vegetables eaten raw and assuming that a 2-log unit reduction occurs through produce peeling prior to consumption (WHO, 2006), wastewater treatment is required to effect a reduction of 1 log unit from 100 to 10 eggs per litre. This reduction can also be achieved by any of the three methods described above. In hyperendemic areas (1000 eggs per litre of untreated wastewater) a further log unit reduction is required; this could be achieved by rinsing the peeled produce in a weak detergent solution and rinsing with clean water.

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Note:

The QMRA-Monte Carlo computer programs referred to above are available at: http://www.personal.leeds.ac.uk/~cen6ddm/QMRA.html.