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QUANTIFYING HEALTH RISKS IN WASTEWATER IRRIGATION

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Contents

Summary

The guidelines developed by the World Health Organization for the safe use of wastewater in agriculture are based on a tolerable additional disease burden of 10^{-6} disability-adjusted life year loss per person per year, equivalent to rotavirus disease and infection risks of approximately 10^{-4} and 10^{-3} per person per year, respectively. The combination of standard quantitative microbial risk analysis techniques and 10,000-trial Monte Carlo risk simulations, using ranges of parameter values that reflect real life, are then used to determine the minimum required pathogen reductions for restricted and unrestricted irrigation which ensure that the risks are not exceeded. For unrestricted irrigation the required pathogen reduction is 6- 7 $\log_{10}$ units and for restricted irrigation 3- 4 $\log_{10}$ units. For both restricted and unrestricted irrigation wastewater treatment has to achieve a 3–4-$\log_{10}$ unit pathogen reduction, and in the case of unrestricted irrigation this has to be supplemented by a further 3–4-$\log_{10}$ unit pathogen reduction provided by post-treatment, but pre-ingestion, health protection control measures, such as pathogen die-off between the last irrigation and consumption (0.5- 2 $\log_{10}$ unit reduction per day, depending on ambient temperature) and produce washing in clean water (1 $\log_{10}$ unit reduction). Wastewaters used for both restricted and unrestricted irrigation also have to contain no more than 1 human intestinal nematode egg per liter; if children under the age of 15 are exposed then additional measures are required such as regular deworming at home or at school.

1. INTRODUCTION

In 1989 the World Health Organization (WHO) published guidelines for the microbiological quality of treated wastewaters used in agriculture for crop irrigation. The guidelines were: (a) for restricted irrigation (i.e., the irrigation of all crops except salad crops and vegetables that may be eaten uncooked), =1 human intestinal nematode egg l^{-1} (the nematodes are the human roundworm, *Ascaris* *lumbricoides*; the human whipworm, *Trichuris trichiura*; and the human hookworms, *Ancylostoma duodenale* and *Necator americanus*) (see *Helminth ova in wastewater and sludge intended for reuse in agriculture and aquaculture*); and (b) for unrestricted irrigation (i.e., including the irrigation of salad crops and vegetables eaten uncooked), the same nematode egg guideline and =1000 fecal coliforms (FC) per 100 ml. These guidelines caused considerable controversy since at the time of their introduction they had no rigorous epidemiological basis, and the FC guideline of =1000 per 100 ml was considered by some to be too lax, especially when compared with the Californian standard of =2.2 total coliforms per 100 ml.

New guidelines were published by WHO in 2006. These are based on a tolerable additional disease burden from working in wastewater-irrigated fields and consuming wastewater-irrigated crops of $=10^{-6}$ DALY (disability-adjusted life year) loss per person per year (pppy) (see *Burden of disease: current situation and trends*). They thus differ markedly from the 1989 guidelines which were based solely on required wastewater qualities, but they have the same basis as the 2004 WHO drinking-water quality guidelines (this is reasonable since people expect the food they eat to be as safe as the water they drink). Although this tolerable DALY loss of $=10^{-6}$ pppy is the fundamental basis of health protection in the guidelines for both drinking-water quality and wastewater use in agriculture, it has to be 'translated' into a tolerable risk of infection pppy as this is a metric that can be more easily used to derive wastewater qualities, as follows:

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

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

Tolerable disease and infection risks are determined for three 'index' pathogens: rotavirus (a viral pathogen), *Campylobacter* (a bacterial pathogen) and *Cryptosporidium* (a protozoan pathogen). Table 1 gives the DALY losses per case of rotavirus diarrhea, campylobacteriosis and cryptosporidiosis, the tolerable risks of these diseases pppy for a tolerable DALY loss of 10^{-6} pppy, the disease/infection ratios and the resulting tolerable risks of infection with these pathogens pppy. From this table the following suitable 'design' risks are determined: a rotavirus disease risk of 10^{-4} pppy and a rotavirus infection risk of 10^{-3} pppy. These risks are very safe since the design rotavirus disease risk of 10^{-4} pppy is 3- 4 orders of magnitude lower than the current global incidence of diarrheal disease of ~0.1–1 pppy.

Quantitative microbial risk analysis (QMRA) can then be used to determine appropriate wastewater qualities for various wastewater-use scenarios - for example restricted and unrestricted irrigation: with restricted irrigation the health of those working in wastewater-irrigated fields has to be protected, and with unrestricted irrigation it is the health of both those working in wastewater-irrigated fields and those consuming wastewater-irrigated crops eaten uncooked that has to be protected.

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

Pathogen	DALY loss per case of disease	Tolerable disease risk pppy equivalent to 10^{-6} DALY loss pppy	Disease/ infection ratio	Tolerable infection risk pppy
Rotavirus: (1) IC[a]	1.4×10^{-2}	7.1×10^{-5}	0.05	1.4×10^{-3}
(2) DC[a]	2.6×10^{-2}	3.8×10^{-5}	0.05	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] IC, industrialized countries; DC, developing countries.

2. QUANTITATIVE MICROBIAL RISK ANALYSIS

The 2006 Guidelines adopt a standard QMRA approach to risk analysis combined with 10,000-trial Monte Carlo simulations. The three basic equations are:

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

$$P_I(d) = 1 - \exp(-rd) \tag{1}$$

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

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

(c) Annual risk of infection:

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

where $P_I(d)$ is the risk of infection in an individual exposed to (here, following ingestion of) a single pathogen dose d, $P_{I(A)}(d)$ 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* $r = 0.0042$.

2.1. SPECIMEN QMRA CALCULATIONS

In order to illustrate the way in which these QMRA equations are used, the required pathogen (in this case, rotavirus) reduction in $\log_{10}$ units is determined for the consumption of lettuce, as an example of unrestricted irrigation. The following assumptions are made: there are 5000 rotaviruses per liter of untreated wastewater; 10 ml of treated wastewater remain on 100 g lettuce after irrigation; and 100 g of lettuce are consumed per person every second day throughout the year. The rotavirus dose per exposure (*d*) is the number of rotaviruses on 100 g lettuce at the time of consumption. The value of *d* is determined by QMRA as follows:

(1) Conversion of the tolerable rotavirus infection risk of 10^{-3} pppy ($P_{I(A)}(d)$ in Eq. 3 to the risk of infection per person per exposure event ($P_I(d)$ in Eq. 1 and 2) - i.e., per consumption of 100 g lettuce, which takes place every two days throughout the year, so *n* in Eq.3 is 365/2:

$$P_I(d) = 1 - \left(1 - 10^{-3}\right)^{\left[1/(365/2)\right]} = 5.5 \times 10^{-6}$$

(2) Calculation of the dose per exposure event from Eq. 2 (the β-Poisson dose-response equation, which is used for rotavirus):

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

i.e.:

$$d = \left\{\left[1 - P_I(d)\right]^{-1/\alpha} - 1\right\} \Big/ \left\{N_{50} \big/ \left(2^{1/\alpha} - 1\right)\right\}$$

The values of the 'infectivity constants' for rotavirus are $N_{50} = 6.17$ and $\alpha = 0.253$. Thus:

$$d = \left\{\left[1 - \left(5.5 \times 10^{-6}\right)\right]^{-1/0.253} - 1\right\} \Big/ \left\{6.17 \big/ \left(2^{1/0.253} - 1\right)\right\} = 5 \times 10^{-5} \text{ per exposure event}$$

(3) Required pathogen reduction: this dose of 5×10^{-5} rotavirus is contained in the 10 ml of treated wastewater remaining on the lettuce at the time of consumption, so the rotavirus concentration is 5×10^{-5} per 10 ml - i.e., 5×10^{-3} per liter. The number of rotaviruses in the raw wastewater is 5000 per liter and therefore the required pathogen reduction in log units is:

$$\log(5000) - \log\left(5 \times 10^{-3}\right) = 3.7 - (-2.3) = 6$$

2.2. MONTE CARLO RISK SIMULATIONS

The above calculations use 'fixed' values for each parameter (e.g., 10 ml of wastewater remaining on 100 g of lettuce after irrigation). However, there is usually some degree of 'uncertainty' about the precise values of the parameters used in these QMRA equations. This uncertainty is taken into account by assigning to each parameter a range of values (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 risk. The program repeats this process a large number of times (e.g., 10,000 times) and then determines the median 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.

2.3. RESTRICTED IRRIGATION

2.3.1. Exposure Scenario

The model scenario developed 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 is up to ~100 mg per person per day of exposure. Two 'sub-scenarios' are used: (a) highly mechanized agriculture and (b) labor-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 practises in developing countries in situations where tractors are not used and gloves (and often footwear) are not worn, and where hygiene is likely to be low.

2.3.2. Risk Simulations

Labor-intensive agriculture. The results of the Monte Carlo-QMRA risk simulations are given in Table 2 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 2 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 from 10^7-10^8 to 10^3-10^4 *E. coli* per 100 ml.

Highly mechanized agriculture. The simulated risks for various wastewater qualities and for 100 days exposure per year are given in Table 3, 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 not exceed the tolerable rotavirus infection risk of 10^{-3} pppy.

2.4. UNRESTRICTED IRRIGATION

2.4.1. Exposure Scenario

The exposure scenarios used for unrestricted irrigation are the consumption of wastewater-irrigated lettuce and wastewater-irrigated onions (a leaf and a root vegetable, respectively).

Table 2. Restricted irrigation - labor-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

Soil quality	Median infection risk pppy		
(*E. coli* per 100 g)	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}
10^4	4.4×10^{-3}	1.4×10^{-4}	3.0×10^{-6}
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}

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 a = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and a = 0.145 ± 25% for *Campylobacter*; r = 0.0042 ± 25% for *Cryptosporidium*; no pathogen die-off - taken as a worst case scenario; and the wastewater quality is taken to be the same as the soil quality - i.e., the soil is assumed, also as a worst case scenario, to be saturated with wastewater.

Table 3. 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

Soil quality	Median infection risk pppy		
(*E. coli* per 100 g)	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}
10^5	1.5×10^{-3}	4.5×10^{-5}	1.0×10^{-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}	$=1 \times 10^{-8}$

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 a = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and a = 0.145 ± 25% for *Campylobacter*; r = 0.0042 ± 25% for *Cryptosporidium*; no pathogen die-off - taken as a worst case scenario; and the wastewater quality is taken to be the same as the soil quality - i.e., the soil is assumed, also as a worst case scenario, to be saturated with wastewater .

2.4. UNRESTRICTED IRRIGATION

2.4.1. Exposure Scenario

The exposure scenarios used for unrestricted irrigation are the consumption of wastewater-irrigated lettuce and wastewater-irrigated onions (a leaf and a root vegetable, respectively).

2.4.2. Risk Simulations

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) (the footnote to the Table gives the range of values assigned to each parameter). From Table 5 it can be seen that the median rotavirus infection risk is below 10^{-3} pppy for a wastewater quality of 1-10 *E. coli* per 100 ml, so the tolerable rotavirus infection risk of 10^{-3} pppy is achieved by a 7-log unit pathogen reduction. Thus the 3- 4-log unit reduction by wastewater treatment which is required for restricted irrigation (see section 2.3.2) must be supplemented by a further 3-4-log unit reduction achieved by the post-treatment, but pre-ingestion, health-protection control measures detailed in section 3.

Table 4. Unrestricted irrigation: median infection risks from the consumption of wastewater-irrigated lettuce estimated by 10,000-trial Monte Carlo simulations

Wastewater quality	Median infection risk pppy		
(*E. coli* per 100 ml)	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7-10^8	1	1	0.86
10^6-10^7	1	0.99	0.19
10^5-10^6	1	0.67	1.9×10^{-2}
10^4-10^5	0.96	0.11	1.9×10^{-3}
10^3-10^4	0.29	1.1×10^{-2}	2.0×10^{-4}
100-1000	3.2×10^{-2}	1.1×10^{-3}	2.0×10^{-5}
10-100	3.3×10^{-3}	1.1×10^{-4}	2.0×10^{-6}
1-10	3.3×10^{-4}	1.1×10^{-5}	2.0×10^{-7}

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 and *Campylobacter*, and 0.01-0.1 *Cryptosporidium* oocyst, per 10^5 *E. coli*; no pathogen die-off; N_{50} = 6.7 ± 25% and a = 0.253 ± 25% for rotavirus; N_{50} = 896 ± 25% and a = 0.145 ± 25% for *Campylobacter*; and r = 0.0042 ± 25% for *Cryptosporidium*.

3. POST-TREATMENT HEALTH-PROTECTION CONTROL MEASURES

The principal post-treatment health-protection control measures and the log unit pathogen reductions they achieve are listed in Table 5. These log unit reductions are extremely reliable: in essence they always occur, so it is not sensible to ignore them - if they are ignored more money has to be spent on additional wastewater treatment to achieve the required total pathogen reduction. Hygiene education may be required in some societies to ensure that salad crops and vegetables eaten raw are always washed in clean water prior to consumption, but this is not (at least in hygiene education terms) an arduous task. On the other hand, root crops (such as onions, carrots) are almost always peeled before they are eaten.

Table 5. 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	2	Washing salad crops, vegetables and fruit with a weak disinfectant solution and rinsing with clean water.
Produce peeling	2	Fruits, root crops.

Thus the 2006 WHO Guidelines effectively require the same level of wastewater treatment for both restricted and unrestricted irrigation, bur for the latter additional pathogen reduction is required to be achieved by the health-protection control measures detailed in Table 5.

4. HELMINTH EGGS

The recommendation in the 2006 Guidelines is that wastewater used in agriculture should contain =1 human intestinal nematode egg per liter. This is the same as in the 1989 Guidelines, but with two important differences: (1) when children under the age of 15 are exposed (by working or playing in wastewater-irrigated fields) additional measures are needed, such as regular deworming (by their parents or at school); and (2) when high-growing crops are drip-irrigated, no recommendation is made as the chance of a helminth egg reaching the edible part of the crop is negligible.

5. WASTEWATER TREATMENT

In most situations in most developing countries waste stabilization ponds are the most appropriate option for wastewater treatment as they are a low-cost and low-maintenance, but high-performance, treatment system. In warm climates a series of ponds comprising an anaerobic pond, a secondary facultative pond and 1-2 maturation ponds can achieve a 3-4-log unit pathogen reduction and produce an effluent with =1 helminth egg per liter. Additionally the anaerobic ponds can be covered to collect the biogas generated within the ponds; the gas, which contains over 70% methane, can be profitably used for electricity generation - this is another form of wastewater use.

GLOSSARY

DALY: Disability-adjusted life year(s), used as a means of quantifying and comparing the health outcomes (or 'costs') of different diseases and disabilities.

E. coli: *Escherichia coli*, used here as an indicator of pathogen numbers.

FC: Fecal coliforms, used here as an indicator of pathogen numbers.

Helminth eggs: here, eggs of human intestinal nematodes (chiefly *Ascaris lumbricoides, Trichuris trichiura, Ancylostoma duodenale* and *Necator americanus*).

Monte Carlo simulations: the assignment of a range of values (rather than a 'fixed' single value) to parameters in equations (such as the QMRA equations) in order to minimize the uncertainty with which the parameter values are known; a computer program then selects at random a value for each parameter in the equations and determines the solution (here, the resulting health risk); it does this 10,000 times and then calculates the median solution (here, the median risk).

QMRA: Quantitative microbial risk analysis

Restricted irrigation: the irrigation of all crops except salad crops and vegetables that may be eaten uncooked.

Unrestricted irrigation: the irrigation of all crops, including salad crops and vegetables eaten uncooked.

WHO: World Health Organization

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