Chapter 1
The 2006 WHO Guidelines for Wastewater and Greywater Use in Agriculture: A Practical Interpretation

Duncan Mara(✉) and Annika Kramer

Abstract The World Health Organization (WHO) published the third edition of its guidelines for the safe use of wastewater, excreta and greywater in agriculture in September 2006. These new guidelines are intended to support the establishment of national standards and regulations. However, it is not straightforward for policymakers or practicing engineers to translate them into numerical values that are easy to implement. This chapter presents a practical interpretation of the main concepts of the new WHO guidelines and provides guidance on how to apply them in national settings.

Duncan Mara
School of Civil Engineering, University of Leeds, Leeds LS2 9JT, UK.
e-mail: d.d.mara@leeds.ac.uk

1. Introduction

The 1989 World Health Organization (WHO) guidelines for the safe use of wastewater in agriculture have long been the standard reference for regulating wastewater reuse. However, subsequent research and expert opinion has stressed the fact that the 1989 guidelines needed to be more easily adaptable to local conditions and should be co-implemented with such other health interventions as hygiene promotion, provision of adequate drinking water and sanitation, and other healthcare measures. The 1989 guidelines have therefore been revised based on new data from epidemiological studies, quantitative microbial risk assessments and other relevant information.

The revised WHO guidelines published in 2006 (WHO, 2006a, 2006b) 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. To reduce the health risks resulting from human exposure to pathogens in the wastewater, the new guidelines focus on health-based targets, instead of water quality standards, and offer various combinations of risk management options for meeting them.

This is a logical approach since the real question is not how many pathogens (or *E. coli*, fecal coliforms) are permissible in the treated wastewater (this was the approach adopted in the 1989 guidelines), but rather how many pathogens can be ingested, in the case of restricted irrigation (Section 1.2), with wastewater-contaminated soil or, in the case of unrestricted irrigation (Section 1.3), with wastewater-irrigated food, without the resulting infection and disease risks being unacceptably high.

The following sections elaborate on the methodology used in the 2006 WHO guidelines to determine the actual disease risk linked to wastewater irrigation. Moreover, they give numerical values of infection risk related to different wastewater qualities determined through risk simulations. The final section explains how the health-based targets can be adapted to existing public health, socio-economic and environmental circumstances when setting national standards.

1.2. Health-Based Targets in the 2006 WHO Guidelines

The sequence of the approach to human health protection in the 2006 guidelines is as follows:

1. establish the maximum additional disease burden resulting from the use of wastewater for crop irrigation;
2. determine the maximum number of pathogens that could be ingested without exceeding this tolerable disease burden;
3. determine, through realistic human exposure scenarios, the number of pathogens that could be ingested under different irrigation regimes for different crop types;
4. calculate the required reduction of pathogen numbers that needs to be achieved, depending on the initial wastewater quality and the crop type; and
5. select a combination of health-based control measures to achieve this required pathogen reduction.

This approach has been used to develop microbial reduction targets for viral, bacterial and protozoan pathogens. The steps are pursued through a combination of the analytical methods detailed later.

For helminth eggs, this approach cannot be used as data on the resulting health risks are not available. Instead, limit values were determined from epidemiological studies. The recommendation in the guidelines is that wastewater used in agriculture should contain ≤1 human intestinal nematode egg per liter. The helminths referred to here are the human intestinal nematodes: *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 is the same as was recommended in the 1989 guidelines (WHO, 1989), but with two important differences: (i) 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 (ii) the ≤1 egg per liter recommendation does not apply in the case of drip irrigation of high-growing crops (such as tomatoes); in this case, no recommendation is necessary.

1.2.1. Tolerable Additional Disease Burden and Disease and Infection Risks

The basis of human health protection in the 2006 guidelines is that the additional disease burden arising 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; see Box 1.1 for a brief description of DALYs). 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.

Three "index" pathogens were selected: rotavirus (the most common viral cause of diarrheal disease worldwide), *Campylobacter* (the most common bacterial cause of diarrheal disease worldwide) and *Cryptosporidium* (one of the three most common protozoan causes of diarrheal disease worldwide, the other two being *Giardia* and *Entamoeba*).

To determine the maximum tolerable pathogen exposure resulting from working in wastewater-irrigated fields or consuming wastewater-irrigated crops, the tolerable additional disease burden of 10^{-6} DALY loss pppy is first "translated" into tolerable disease and infection risks as follows:

$$\text{Tolerable disease risk pppy} = \frac{\text{Tolerable DALY loss pppy}}{\text{DALY loss per case of disease}}$$

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

Box 1.1 Disability-Adjusted Life Years (DALYs)

DALYs are a measure of the health of a population or burden of disease due to a specific disease or risk factor. DALYs attempt to measure the time lost because of disability or death from a disease compared with a long life free of disability in the absence of the disease. DALYs are calculated by adding the years of life lost to premature death (YLL) to the years lived with a disability (YLD). YLL are calculated from age-specific mortality rates and the standard life expectancies of a given population. YLD are calculated from the number of cases multiplied by the average duration of the disease and a severity factor ranging from 1 (death) to 0 (perfect health) based on the disease (e.g., watery diarrhea has a severity factor from 0.09 to 0.12 depending on the age group; Murray and Lopez, 1996; Prüss and Havelaar, 2001). Thus, 1 DALY loss is equivalent to 1 year of illness or 1 YLL.

DALYs are an important tool for comparing health outcomes because they account for not only acute health effects but also for delayed and chronic effects, including morbidity and mortality (Bartram et al., 2001). Thus, when risk is described in DALYs, different health outcomes (e.g., cancer vs. giardiasis) can be compared and risk management decisions prioritized. Thus, the DALY loss per case of campylobacteriosis in Table 1.1 includes the appropriate allowance for the occurrence of Guillain-Barré syndrome (an inflammatory disorder of the peripheral nerves that may lead to paralysis and that occurs in around 1 in 1,000 cases of campylobacteriosis).

What does 10^{-6} DALY loss pppy mean?

The tolerable additional disease burden of 10^{-6} DALY loss pppy adopted in the guidelines means that a city of 1 million people collectively suffers the loss of 1 DALY per year. The highest DALY loss per case of diarrheal disease in Table 1.1 is 2.6×10^{-2}, for rotavirus disease in developing countries. Assuming that the recommendations in the guidelines are completely followed, this means that the tolerable number of cases of rotavirus disease, caused by the consumption of wastewater-irrigated food, in this developing-country city of 1 million people is:

$$\frac{1 \text{ DALY loss per year}}{2.6 \times 10^{-2} \text{ DALY loss per case}} = 38 \text{ cases per year}$$

The chance of an individual living in this developing-country city of 1 million becoming ill with rotavirus diarrhea in any one year is (38×10^{-6}) – i.e., 3.8×10^{-5}, which is the tolerable rotavirus disease risk per person per year in developing countries determined in Table 1.1.

Source (first two paragraphs): WHO (2006a).

Table 1.1 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 (there are no IC-DC differences for *Campylobacter* and *Cryptosporidium*).
[e]For developing counties, the DALY loss per rotavirus death has been reduced by 95% as ~95% 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 1.2 Diarrheal 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.

Table 1.1 gives the DALY losses per case of rotavirus diarrhoea, campylobacteriosis and cryptosporidiosis and the corresponding disease/infection ratios. From the data in Table 1.1, a value of 10^{-3} pppy was selected as the tolerable rotavirus *infection* risk to be used in the risk analyses in Sections 1.2.3 and 1.2.4; rotavirus was chosen as the overall index pathogen as its associated risks are higher than those for both *Campylobacter* and *Cryptosporidium*. The corresponding tolerable rotavirus *disease* risk is ~10^{-4} pppy, which is extremely safe as it is three orders-of-magnitude lower than the actual incidence of diarrheal disease in the world (Table 1.2), and thus there is a good level of inherent protection against disease outbreaks.

1.2.2. Quantitative Microbial Risk Analyses

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

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

$$P_1(d) = 1 - \exp(-rd) \quad (1)$$

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

$$P_1(d) = 1 - [1+(d/N_{50})(2^{1/\alpha} - 1)]^{-\alpha} \quad (2)$$

(c) annual risk of infection:

$$P_{1(A)}(d) = 1 - [1-P_1(d)]^n \quad (3)$$

where $P_1(d)$ is the risk of infection in an individual exposed to (here, following ingestion of) a single pathogen dose d (this "single pathogen dose d" is the number of pathogens ingested on 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 (i.e., the dose that causes infection in half the number of people exposed to it); 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; N_{50}, α and r are determined experimentally from human exposure trials).

Box 1.2 gives an example of how these equations are used. As shown in Box 1.2, the end result of the application of equations 1 to 3 is the required log unit reduction of pathogens that corresponds to the targeted rotavirus infection risk of 10^{-3} pppy and hence to the tolerable additional disease burden of 10^{-6} DALY loss pppy.

In combination with Monte Carlo risk simulations, quantitative microbial risk analyses (QMRA) can be used to generate numerical values of the median infection

Box 1.2 Use of the Quantitative Microbial Risk Analysis (QMRA) Equations for Unrestricted Irrigation

This example illustrates how the QMRA equations (equations 1–3) are used to determine the pathogen reduction (in log units[a]) required to protect human health in the case of unrestricted irrigation. The exposure scenario is the consumption of wastewater-irrigated lettuce.

1. **Tolerable risk of infection:** the "design" risk of rotavirus infection is taken as 10^{-3} pppy.
2. **Quantitative microbial risk analysis:** consumer exposure to pathogens is calculated by using the following illustrative parameter values in the QMRA equations:

5000 rotaviruses per liter of untreated wastewater
10 mL of treated wastewater remaining on 100 g lettuce after irrigation
100 g lettuce 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 dose is determined by QMRA as follows:
(a) Conversion of the tolerable rotavirus infection risk of 10^{-3} pppy ($P_{I(A)}(d)$ in equation 3) to the risk of infection per person per exposure event ($P_1(d)$ in

(continued)

Box 1.2 (continued)

equations 1 and 2; i.e., per consumption of 100 g lettuce, which takes place every two days throughout the year, so n in equation 3 is 365/2). Thus:

$$P_I(d) = 1-(1-10^{-3})^{[(1/365/2)]} = 5.5\times10^{-6}$$

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

$$P_1(d) = 1-[1+(d/N_{50})(2^{1/\alpha}-1)]^{-\alpha}$$

$$\text{i.e., } d = \{[1-P_1(d)]^{-1/\alpha}-1\}/\{N_{50}/(2^{1/\alpha}-1)\}$$

The values of the "infectivity constants" for rotavirus are N_{50} = 6.17 and α = 0.253. Thus:

$$d = \{[1-(5.5\times10^{-6})]^{-1/0.253}-1\}/\{6.17/(2^{1/0.253}-1)\} = 5\times10^{-5} \text{ per exposure event}$$

3. **Required pathogen reduction:** this dose d of 5×10^{-5} rotavirus, the maximum dose to keep within the maximum tolerable infection risk, 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 or 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[a] is:

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

[a]A 1-log unit reduction is a reduction of 90%, 2 log units a reduction of 99%, 3 log units a reduction of 99.9%, and so on (thus a "log unit" is strictly a "log10 unit"). Here, the required 6-log unit reduction is a reduction of 99.9999%, where each 9 is a significant figure.

risks related with wastewater irrigation for selected human exposure scenarios. Box 1.3 details how Monte Carlo simulations are made.

1.2.3. Assessing Median Infection Risks in Restricted Irrigation

Restricted irrigation refers to the irrigation of all crops except those eaten uncooked. The model scenario developed for assessing infection risks linked to 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 sce-

Box 1.3 Monte Carlo risk Simulations

The specimen calculations in Box 1.2 use "fixed" values for each parameter (e.g., 10 mL of wastewater remaining on 100 g of lettuce after irrigation; Shuval et al. [1997] measured a mean volume of 10.8 mL). 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 many times (a total of 10,000 times for the simulations reported herein) 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.

nario 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) 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 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.

Risk simulation for labor-intensive agriculture: The results of the Monte Carlo-QMRA risk simulations are given in Table 1.3 for various wastewater qualities (expressed as single log ranges of *E. coli* numbers per 100 mL, with 10^7–10^8 *E. coli* per 100 mL taken as the quality of untreated wastewater) and for 300 days exposure per year (the footnote to the table gives the range of values assigned to each parameter). From Table 1.3 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 can be achieved by a 4-log unit reduction (i.e., from 10^7–10^8 to 10^3–10^4 *E. coli* per 100 mL), so that the required wastewater quality is ≤10^4 *E. coli* per 100 mL (at this level the risk given in Table 1.3 is 4.4×10^{-3} pppy, which is slightly high; however, the risk is proportional to the number of days of exposure per year, here taken as 300; in practice the risk will be closer to 10^{-3} pppy).

Table 1.3 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[a]

Soil quality (*E. coli* per 100 g)[b]	Median infection risk per person per year		
	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}

[a]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;* $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$ for rotavirus; $N_{50} = 896 \pm 25\%$ and $\alpha = 0.145 \pm 25\%$ for *Campylobacter;* $r = 0.0042 \pm 25\%$ 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).
Note: the median risks for *Campylobacter* and *Cryptosporidium* are all lower than those for rotavirus
Source: WHO, 2006a and Mara et al., 2007

Table 1.4 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 (*E. coli* per 100 g)[b]	Median infection risk per person per year		
	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}
103–10^4	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]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;* $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$ for rotavirus; $N_{50} = 896 \pm 25\%$ and $\alpha = 0.145 \pm 25\%$ for *Campylobacter;* $r = 0.0042 \pm 25\%$ 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).
Source: WHO, 2006a and Mara et al., 2007

Risk simulation for highly mechanized agriculture: The simulated risks for various wastewater qualities and for 100 days exposure per year are given in Table 1.4, which shows that the median rotavirus infection risk is ~10^{-3} pppy for a wastewater quality of 10^5 *E. coli* per 100 mL. Thus, 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, and the required wastewater quality is $\leq 10^5$ *E. coli* per 100 mL.

1.2.4. Assessing the Median Infection Risks in Unrestricted Irrigation

Unrestricted irrigation refers to the irrigation of all crops, including those eaten uncooked. The exposure scenarios used for unrestricted irrigation are the consumption of wastewater-irrigated lettuce (Shuval et al., 1997) and the consumption of wastewater-irrigated onions; these crops were chosen as typical leaf and root vegetables commonly eaten uncooked, although it has not been determined whether the resulting health risks are actually typical for other leaf and root crops. The scenario also includes allowance for pathogen die-off between the last irrigation and consumption.

The results of the Monte Carlo-QMRA risk simulations are given in Table 1.5 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 1.5 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, so 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. Hence, the tolerable infection risk could be achieved by treatment to a wastewater quality of $\leq 10^4$ *E. coli* per 100 mL (at 10^4 per 100 mL the risk in Table 1.5 is 2.2×10^{-3} pppy, which is close enough to 10^{-3} pppy). This 4-log unit reduction by treatment would be supplemented by the 2–3 log unit reduction due to rotavirus die-off assumed in these risk simulations (see footnote to Table 1.5; this die-off would occur in warm climates in ~2 days; cf. Table 7), so giving a total pathogen reduction of 6–7 log units (cf. the specimen calculations in Box 1.2).

A 4-log unit reduction by treatment for unrestricted irrigation is also protective of the fieldworkers (see "Labor-intensive agriculture" in Section 1.2.3).

Table 1.5 Unrestricted irrigation: median infection risks from the consumption of wastewater-irrigated lettuce estimated by 10,000-trial Monte Carlo simulations[a]

Wastewater quality (*E. coli* per 100 mL)	Median infection risk per person per year		
	Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7–10^8	0.99	0.28	0.50
10^6–10^7	0.65	6.3×10^{-2}	6.3×10^{-2}
10^5–10^6	9.7×10^{-2}	2.4×10^{-3}	6.3×10^{-3}
10^4–10^5	9.6×10^{-3}	2.6×10^{-4}	6.8×10^{-4}
10^4	2.2×10^{-3}	1.3×10^{-4}	4.5×10^{-4}
10^3–10^4	1.0×10^{-3}	2.6×10^{-5}	3.1×10^{-5}
100–1000	8.6×10^{-5}	3.1×10^{-6}	6.4×10^{-6}
10–100	8.0×10^{-6}	3.1×10^{-7}	6.7×10^{-7}

[a]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 oocyst, per 10^5 *E. coli*; 10^{-2}–10^{-3} rotavirus and *Campylobacter* die-off, and 0–0.1 oocyst die-off, between last irrigation and consumption; $N_{50} = 6.7 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$ for rotavirus; $N_{50} = 896 \pm 25\%$ and $\alpha = 0.145 \pm 25\%$ for *Campylobacter; r* = 0.0042 ± 25% for *Cryptosporidium*.

Note: the median risks for *Campylobacter* and *Cryptosporidium* are all lower than those for rotavirus

Source: WHO, 2006a and Mara et al., 2007.

Table 1.6 Unrestricted irrigation: required pathogen reductions for various levels of tolerable risk of infection from the consumption of wastewater-irrigated lettuce and onions estimated by 10,000-trial Monte Carlo simulations[a]

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

[a]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 1–5 rotavirus per 10^5 *E. coli* for lettuce and onions, respectively; $N_{50} = 6.17 \pm 25\%$ and $\alpha = 0.253 \pm 25\%$.
[b]Assuming the raw wastewater quality to be 10^7–10^8 *E. coli* per 100 mL.
Source: WHO, 2006a.

Table 1.6 gives the required total log unit reductions for unrestricted irrigation of lettuce and onions for various levels of tolerable rotavirus infection risk: 10^{-2}, 10^{-3} and 10^{-4} pppy (these Monte Carlo simulations are the reverse of those in Tables 1.3 to 1.5 as they first set the risk and then determine the required total pathogen reduction). Table 1.6 shows that (a) the consumption of root crops requires a 1-log unit pathogen reduction greater than the consumption of non-root crops, and (b) the required pathogen reductions change by an order of magnitude with each order-of-magnitude change in tolerable risk.

In England, the guidelines for the microbiological quality of "ready-to-eat" foods (such as prepared sandwiches and salads on sale in local shops and supermarkets) state that up to 10,000 fecal coliforms per 100 g is "acceptable" (Gilbert et al., 2000). Lettuce is a common component of many ready-to-eat foods, so it makes little sense to irrigate lettuces with wastewater treated to a higher quality than that required of the lettuces themselves.

1.3. Achieving the Required Pathogen Reduction

The 2006 WHO guidelines allow health risks to be managed not only by wastewater treatment, crop restriction, irrigation techniques and human exposure control (as in the 1989 guidelines), but also by pathogen die-off before consumption and food preparation measures.

1.3.1. Wastewater Treatment

Probably the most obvious approach to reduce risk of infection from wastewater is the removal or inactivation of pathogens through wastewater treatment. Conventional treatment technologies, however, focus mainly on the removal of

suspended solids, organic matter and nutrients such as nitrogen and phosphorus, and not on the removal of pathogens. Water reclaimed through conventional treatment may therefore require further treatment such as filtration or disinfection to reduce the concentration of pathogens to an acceptable level. On the other hand, some unconventional wastewater treatment technologies have been shown to be more effective in removing pathogens.

In most situations in most developing countries, waste stabilization ponds are the most appropriate option for wastewater treatment (Mara, 2004; von Sperling and de Lemos Chernicharo, 2005). In warm climates, a series of ponds comprising an anaerobic pond, a secondary facultative pond and a single maturation pond can produce an effluent with $\leq 10^4$ *E. coli* per 100 mL (and also with ≤1 helminth egg per liter). (The anaerobic ponds can be covered and the biogas collected and used for such purposes as cooking or electricity generation [DeGarie et al., 2000], another form of wastewater use.)

1.3.2. Post-Treatment Health Protection Control Measures

There are various ways by which pathogen numbers are or can be reduced after treatment. The main post-treatment health protection control measures and the log unit pathogen reductions they achieve are listed in Table 1.7. These log unit reductions are extremely reliable: in essence they always occur. Hygiene education may be required in some societies to ensure that salad crops and vegetables when 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) are peeled before they are eaten. Post-treatment health protection control measures are only relevant for unrestricted irrigation, since in restricted irrigation the crops are cooked before consumption, leading to total pathogen inactivation.

In unrestricted irrigation, for a tolerable rotavirus infection risk of 10^{-3} pppy, the 4-log unit reduction by treatment must be supplemented by post-treatment control

Table 1.7 Post-treatment health protection control measures and corresponding pathogen reductions achieved

Control measure	Pathogen reduction (log units)	Notes
Drip irrigation	2–4	2-log unit reduction for low-growing crops, 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.

Source: WHO, 2006a.

measures totaling 2 log units for non-root crops and 3 log units for root crops (see Table 1.6). This could be achieved, for example, by a 1-log unit reduction due to die-off and a 1-log unit reduction by produce washing (or a 2-log unit reduction due to die-off) for non-root crops; and a 1-log unit reduction due to die-off and a 2-log unit reduction by produce peeling for root crops. This then gives the required total log unit reduction of 6 for non-root crops and 7 for root crops. However, it is likely that there will always be at least a 2-log unit reduction due to die-off in warm-climate countries (rather than the 1-log unit reduction assumed earlier), so that there will always be a factor of safety of at least one order-of-magnitude.

1.4. Reuse of Greywater

Unrestricted irrigation with greywater is beneficial as it increases crop yields and pathogen levels are low (Jackson et al., 2006; WHO, 2006b). The health risks are lower than those from domestic wastewater (i.e., grey and black waters combined), as pathogen numbers are much lower due to the much smaller fecal load in greywater (a cross-contamination load of ~0.04 g feces per person per day enters greywater, giving a greywater quality of ~10^4–10^5 *E. coli* per 100 mL, compared with 10^7–10^8 per 100 mL for domestic wastewater; WHO, 2006b). The QMRA studies reported in WHO (2006b) indicate that a 1.6- to 2.9-log unit reduction is required for protozoan pathogens (*Cryptosporidium, Giardia*) and a 2.3- to 3.3-log unit reduction for viral pathogens (rotavirus) so that the tolerable additional disease burden of 10^{-6} DALY loss pppy is not exceeded. These reductions can be achieved, as in the case of wastewater, by a combination of treatment and post-treatment health protection control measures (Table 1.7). But it will be apparent that little, if any, treatment is necessary as these pathogen reductions are achievable solely through pathogen die-off and produce washing/disinfection/peeling. Even so, retention in a tank for a few hours would be beneficial to remove scum and readily settleable solids.

1.5. Transposition of the Guidelines Into National Practice

The WHO 2006 guidelines are recommendations of good practice. In themselves they have no legal status in any jurisdiction. Governments can choose to adopt or adapt and adopt (or, of course, even ignore) the guidelines, and they can decide whether to transpose them into legally enforceable national standards or to keep them only as recommendations of good practice. The government departments normally involved in this decision-making process are Ministries or Departments of Health, Water, Environment and Finance, including the part of government responsible for food safety.
There are two basic decisions to be made, as follows:

1. Decision 1: are the Guidelines to be transposed into national standards or only endorsed as recommendations for good national practice?

2. Decision 2: Is the tolerable additional burden of disease of 10^{-6} DALY loss pppy appropriate for local conditions? This is an important decision as the value used for this controls the tolerable disease and infection risks pppy (Table 1.1) and thus the degree (and hence cost) of wastewater treatment needed to ensure that these risks are not exceeded. Is a value of 10^{-5} DALY loss pppy locally more appropriate?

The following points should be taken into consideration in making the second decision:

1. A stricter requirement would not normally be needed since, as noted earlier, a DALY loss of 10^{-6} pppy is the value used by WHO (2004) in its drinking water quality guidelines. Thus the consumption of wastewater-irrigated food is as safe as drinking fully treated drinking water if the recommendations in the 2006 guidelines are followed.
2. A less stringent requirement results in higher tolerable disease and infection risks pppy. For example, a tolerable additional disease burden of 10^{-5} DALY loss pppy would increase the disease and infection risks in Table 1.1 by a factor of 10, resulting in a tolerable rotavirus disease risk of 10^{-3} pppy, which is still two orders of magnitude lower than the current global incidence of diarrheal disease of 0.1 to 1 pppy (Table 1.2). The corresponding tolerable rotavirus infection risk is 10^{-2} pppy and therefore the required effluent qualities discussed earlier become one order-of-magnitude less stringent (for example, for restricted irrigation with labor-intensive agriculture, the required wastewater quality is $\leq 10^5$ *E. coli* per 100 mL, rather than $\leq 10^4$ per 100 mL). Governments may decide that this level of health protection (i.e., 10^{-5} DALY loss pppy) is sufficient if the local incidence of diarrhoeal disease is high (i.e., closer to 1 pppy than to 0.1 pppy). (Countries with a high diarrheal disease incidence include, of course, many developing countries, but also Australia [~0.9 pppy; Hall et al., 2006] and the United States [~0.8 pppy; Mead et al., 1999]).
3. An alternative basis for choosing 10^{-5} (rather than 10^{-6}) DALY loss pppy might be that the additional cost of wastewater treatment to meet the 10^{-6} DALY loss pppy is not affordable (or the extra money would be better spent on something else). This could be a decision for the medium-to-long term (especially if the local incidence of diarrhoeal disease is high), or for the short-to-medium term (unaffordable now, but the intention would be to upgrade treatment to meet the 10^{-6} DALY loss pppy in the not-too-distant future).
4. As treatment is required more to protect the fieldworkers (it is the only health protection measure available for restricted irrigation), a decision could be taken to adopt a 10^{-5} DALY loss pppy for the fieldworkers (for whom additional measures should be required, such as the provision by their employers of oral rehydration salts and access to medical assistance), whilst maintaining a 10^{-6} DALY loss pppy for unrestricted irrigation (i.e., adopting this level of health protection for consumers) by ensuring that an additional 1-log unit pathogen reduction is provided by the post-treatment health protection control measures listed in Table 1.7.

Thus there are three options and these are summarized in Table 1.8, together with their requirements for treatment and post-treatment health protection control

Table 1.8 Summary of requirements for wastewater treatment and post-treatment health protection control measures for restricted and unrestricted irrigation for health protection levels of 10^{-6} and 10^{-5} DALY loss per person per year[a]

Heath protection level	Irrigation and farming system	Wastewater treatment requirements	Post-treatment health protection control measures (Table 7)
1. 10^{-6} DALY loss pppy	(a) Restricted irrigation		
	(i) Labor-intensive agriculture	4-log unit pathogen reduction (i.e., to $\leq 10^4$ *E. coli* per 100 mL)	Not applicable
	(ii) Highly mechanized agriculture	3-log unit pathogen reduction (i.e., to $\leq 10^5$ *E. coli* per 100 mL)	Not applicable
	(b) Unrestricted irrigation		
	(i) Labor-intensive agriculture	4-log unit pathogen reduction (i.e., to $\leq 10^4$ *E. coli* per 100 mL)	Provision of additional 2-log unit pathogen reduction for non-root crops and 3-log unit reduction for root crops
	(ii) Highly mechanized agriculture	3-log unit pathogen reduction (i.e., to $\leq 10^5$ *E. coli* per 100 mL)	Provision of additional 3-log unit pathogen reduction for non-root crops and 4-log unit reduction for root crops
2. 10^{-5} DALY loss pppy	(a) Restricted irrigation		
	(i) Labor-intensive agriculture	3-log unit pathogen reduction (i.e., to $\leq 10^5$ *E. coli* per 100 mL)	Not applicable
	(ii) Highly mechanized agriculture	2-log unit pathogen reduction (i.e., to $\leq 10^6$ *E. coli* per 100 mL)	Not applicable
	(b) Unrestricted irrigation		
	(i) Labor-intensive agriculture	3-log unit pathogen reduction (i.e., to $\leq 10^5$ *E. coli* per 100 mL)	Provision of additional 2-log unit pathogen reduction for non-root crops and 3-log unit reduction for root crops
	(ii) Highly mechanized agriculture	2-log unit pathogen reduction (i.e., to $\leq 10^6$ *E. coli* per 100 mL)	Provision of additional 3-log unit pathogen reduction for non-root crops and 4-log unit reduction for root crops
3. 10^{-6} DALY loss pppy for consumers, and 10^{-5} DALY loss pppy for fieldworkers	Unrestricted irrigation: labor-intensive agriculture	3-log unit pathogen reduction (i.e., to $\leq 10^5$ *E. coli* per 100 mL)	Provision of additional 3-log unit pathogen reduction for non-root crops and 4-log unit reduction for root crops

[a]Based on the risk analyses summarized in Tables 3–6 and the values in Table 7.

measures. This table can easily be modified if the less stringent additional disease burden is 10^{-4} (rather than 10^{-5}) DALY loss pppy; this approach could be used as the first step in areas where there is currently extensive use of untreated wastewater for irrigation.

1.6. Conclusions

The 2006 WHO guidelines represent a radical departure from the 1989 guidelines, but they are much more soundly based on the protection of human health. The starting point is the acceptance of the tolerable additional burden of disease used in the 2004 WHO drinking water quality guidelines of $\leq 10^{-6}$ DALY loss per person per year that translates to a tolerable rotavirus infection risk of 10^{-3} pppy. The use of quantitative microbial risk analyses based on likely human exposure scenarios results in robust estimates of the risks to human health from, and the corresponding pathogen reductions required for, both restricted and unrestricted irrigation. National governments have to decide whether this baseline value of 10^{-6} DALY loss pppy is appropriate or whether to adopt, at least initially, a higher value (10^{-5} or even 10^{-4} DALY loss pppy). The recommendations in the 2006 guidelines can be confidently used without the general need in all cases to undertake case-specific estimates of the risks to human health resulting from the use of wastewater and greywater for crop irrigation.

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