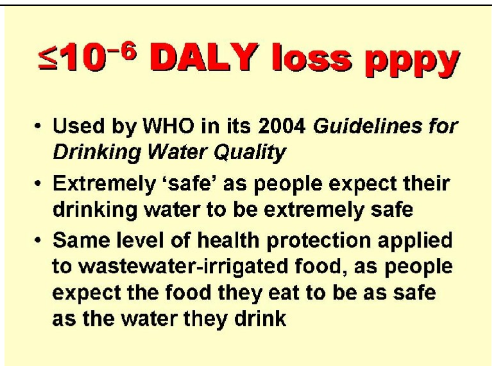
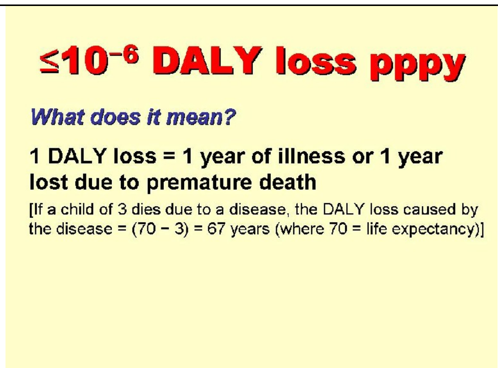
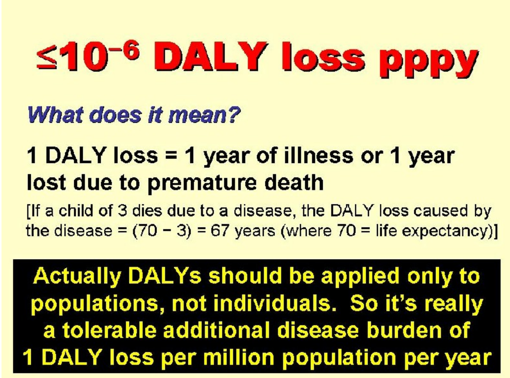
WASTEWATER REUSE 4
Health protection

1.		The last of these four presentations on wastewater use in agriculture is concerned with the protection of human health.
2.		The 2006 Guidelines of the World Health Organization are based on a ‘tolerable additional disease burden’ of no more than 10^{-6} DALY loss per person per year, where DALY stands for **d**isability-**a**djusted **l**ife **y**ear, and we’ll come to this in a moment. The new WHO Guidelines don’t contain any guideline values for viral, bacterial or protozoan pathogens, only for helminth eggs.
3.		This ‘tolerable additional disease burden’ of no more than 10^{-6} DALY loss per person per year was used by WHO in the 2004 edition of its *Guidelines for Drinking Water Quality*, and it’s extremely ‘safe’ as people expect their drinking water to be extremely safe. This same level of health protection is applied to wastewater-irrigated foods as people expect the food they eat to be as safe as the water they drink.
4.		OK, but what does a 10^{-6} DALY loss per person per year actually mean? Well, a 1 DALY loss equals 1 year of major illness or 1 year lost due to premature death. For example, if a child of 3 dies due to some disease, then the DALY loss caused by that disease is 70 minus 3, or 67 years, where 70 is the child’s life expectancy.

5.

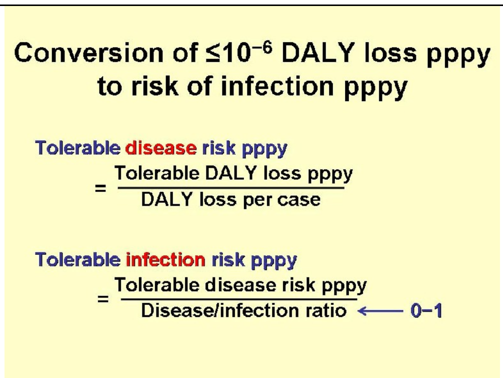
Now, 10^{-6} DALY loss per person per year equals (365 × 24 × 60 × 60), that's the number of seconds in a year, × 10^{-6}, which is a loss of about 32 disability-adjusted life *seconds*, or 'DALseconds', per person per year. So, it's OK if you're ill for 32 seconds a year.

6.



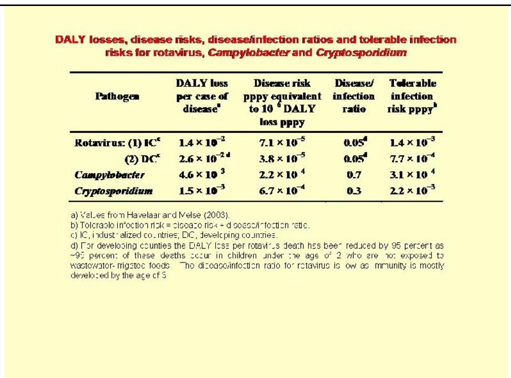
In point of fact, DALY losses should only be applied to populations, and not to individuals; so really this 10^{-6} DALY loss per person per year is really a tolerable disease burden of 1 DALY loss per million people per year.

7.



Now we have to convert this 10^{-6} DALY loss per person per year to something we can use. First we determine the tolerable disease risk by dividing the 10^{-6} DALY loss per person per year by the DALY loss per case of the disease in question; and then we calculate the tolerable infection risk by dividing the tolerable disease risk that we've just determined by the disease/infection ratio, which is somewhere between 0 and 1, as not everybody who is infected becomes ill.

8.



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

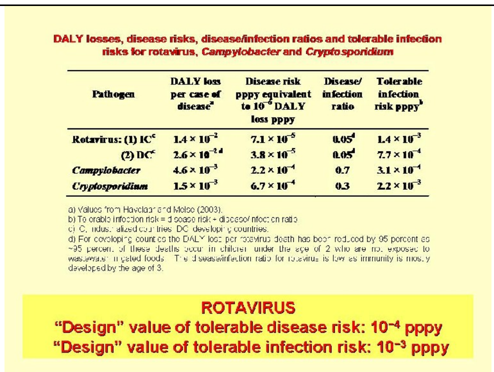
Pathogen	DALY loss per case of disease[a]	Disease risk pppy equivalent to 10^{-6} DALY loss pppy	Disease/ infection ratio	Tolerable infection risk pppy[b]
Rotavirus: (1) IC[c]	1.4×10^{-2}	7.1×10^{-5}	0.05[d]	1.4×10^{-3}
(2) DC[c]	2.6×10^{-2} [d]	3.8×10^{-5}	0.05[d]	7.7×10^{-4}
Campylobacter	4.6×10^{-3}	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 infection risk = disease risk ÷ disease/infection ratio.
c) IC, industrialized countries; DC, developing countries.
d) For developing counties the DALY loss per rotavirus death has been 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.

This table lists the index pathogens used: rotavirus, the bacterium *Campylobacter*, and *Cryptosporidium*, a protozoon. The table also gives the DALY loss per case of disease caused by them; this can be thought of the disease 'cost' in DALYs per disease episode. There's a slight difference in rotavirus 'costs' in industrialized and developing counties, but not for the other two.

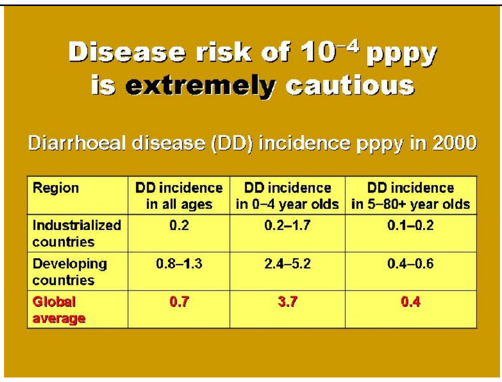
The table gives, for each pathogen, the tolerable disease risk per person per year ['pppy'] for the 10^{-6} DALY loss per person per year; the disease/infection ratio; and the resulting tolerable infection risk per person per year, using the equations on the previous slide.

9.



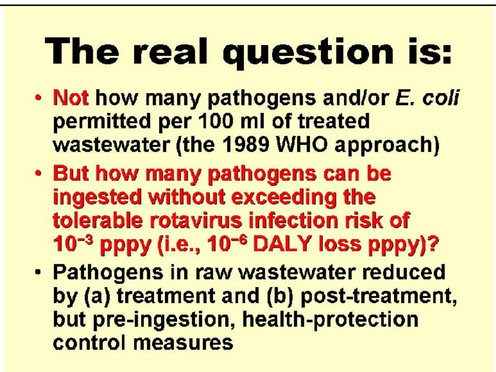
These values tell us that a reasonable *design* risk for rotavirus disease is 10^{-4} per person per year, and for rotavirus infection risk 10^{-3} per person per year.

10.



However, this design rotavirus disease risk of 10^{-4} per person per year is extremely cautious, given the much, much higher actual incidence of diarrhoeal disease, which in the world as a whole is 0.4 per person per year for the over-fives. That’s roughly 10^{-1} per person per year, so our ‘design’ rotavirus disease risk of 10^{-4} per person per year is some three orders of magnitude **lower** than the actual incidence of diarrhoeal disease in the world today.

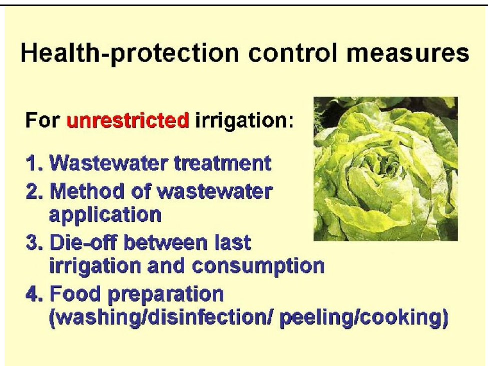
11.



Now, the real question is not how many pathogens or *E. coli* are permitted in the treated wastewater (this was the approach adopted in the 1989 WHO Guidelines), but how many pathogens can be ingested without exceeding the tolerable rotavirus infection risk of 10^{-3} per person per year.

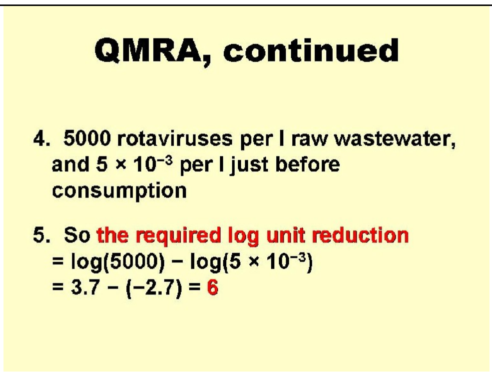
Pathogens in the raw wastewater are reduced by treatment, but also, and this is very important, by post-treatment health-protection control measures.

12.



These health-protection control measures, apart from wastewater treatment, are: the method of wastewater application, and this refers specifically to drip irrigation; the pathogen die-off that occurs between the last irrigation and consumption; and how food that is eaten uncooked, such as salads and some vegetables, is prepared; and this includes washing with clean water, disinfecting, and peeling.

13.	**What total log unit reduction of pathogens required?**	So the key question is: **What is the total log unit pathogen reduction required, so that the tolerable rotavirus infection risk of 10^{-3} per person per year is not exceeded?**
14.	**What total log unit reduction of pathogens required?** **The answer comes from** **QMRA**	and **the answer comes from QMRA**, quantitative microbial risk analysis. Ideally it should come from epidemi-ological data, but we don't have sufficient good-quality data to allow us to do this.
15.	**Example calculation** Assume: 1. 5000 rotaviruses/litre raw wastewater 2. 10 ml of treated w'w remaining on 100 g lettuce after irrigation 3. 100 g lettuce eaten per person every 2 d Dose *d* rotaviruses = no. of rotaviruses on 100 g lettuce at time of consumption	We'll now illustrate the QMRA approach by means of an example set of calculations. First we have to make some **reasonable** assumptions − for example, let's assume that the raw wastewater contains 5000 rotaviruses per litre; that 10 ml of treated wastewater remain on 100 g of lettuce after irrigation; and that people eat 100 g of lettuce every second day. The pathogen dose *d* in the QMRA equations is, in this case, the number of rotaviruses on 100 g of lettuce at the time of consumption.
16.	**Determine *d* by QMRA** 1. Risk of infection per exposure event – $P_I(d)$: $P_I(d) = 1 - (1 - 10^{-3})^{[1/(365/2)]} = 5.5 \times 10^{-6}$ 2. β-Poisson dose-response model: $d = \{[1 - 5.5 \times 10^{-6}]^{-1/0.253} - 1\}/\{6.17(2^{1/0.253} - 1)\}$ $= 5 \times 10^{-5}$ rotaviruses per exposure 3. The required no. of rotaviruses is 5×10^{-5} per 10 ml (vol. on lettuce) = 5×10^{-3} per litre ——————— **Note:** the audio recording says "… the pathogen dose to the pathogen dose *d*, is 5.5 × 10^{-5}", but it should be "5.5 × 10^{-6}" (as shown in the slide).	So we have to determine *d* by QMRA and we do this as follows: We know $P_{I(A)}(d)$, the annual risk of infection from *n* exposures per year to the pathogen dose *d*, because this is the tolerable rotavirus infection risk of 10^{-3} per person per year; and *n* is 365/2 as people eat wastewater-irrigated lettuce every second day. So we can calculate, as shown in the first equation on the slide, that $P_I(d)$, an individual's risk of infection from a single exposure to the pathogen dose *d*, is 5.5 × 10^{-6}. We now use the β-Poisson dose-

		response model to calculate *d* for this value of $P_I(d)$ and, as shown on the slide, *d* is 5×10^{-5} rotaviruses, and this is the number of rotaviruses per 10 ml (the volume of treated wastewater remaining on 100 g of lettuce), or 5×10^{-3} rotaviruses per **litre**.
17.		So, there are 5000 rotaviruses per litre of raw wastewater and 5×10^{-3} per litre just before consumption; therefore the required log unit reduction is: $$\log(5000) - \log(5 \times 10^{-3})$$ which equals 6.
18.		Now the above set of calculations used 'fixed' parameter values − for example, exactly 10 ml of wastewater remaining on 100 g of lettuce after irrigation. But really we can't be so certain: it might be a little more or a little less, or even a lot more or a lot less. To overcome this 'uncertainty' we can assign a **range** of reasonable values to each parameter, so we could say, for example, that somewhere between 10 and 15 ml of wastewater remains on 100 g of lettuce after irrigation. We assign a range of values for each parameter in the QMRA equations, although we can assign a 'fixed' value to any particular parameter if we want to − for example, everyone eats essentially exactly 100 g of lettuce every 2 days. We then use a computer program that randomly selects a value for each parameter from within the range specified for it, and it then calculates the resulting risk per person per year. It then repeats this single calculation for a total of usually 10,000 times, and calculates median infection risks, or 95-percentile risks, or whatever we want. This reiteration is called a multi-trial, in our case a 10,000-trial, Monte Carlo simulation, and in our case it's a simulation of the health risks associated with wastewater irrigation.

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[Slide repeated for convenience]</td>
<td>In the work we did here in Leeds, with colleagues from the London School of Hygiene and Tropical Medicine, we considered both ‘restricted’ and ‘unrestricted’ irrigation. Restricted irrigation is the term used for the irrigation of all crops except salad crops and vegetables that may be eaten uncooked, such as cabbage, carrots and onions; and unrestricted irrigation is used for the irrigation of everything including salad crops and vegetables that may be eaten uncooked.
We used two exposure scenarios: lettuce consumption for unrestricted irrigation; this scenario had been developed in the mid-1990s by Professor Shuval of the Hebrew University of Jerusalem, and we extended it a little by including a root crop, onions.
For restricted irrigation we developed the scenario of ‘involuntary soil ingestion’. People working in wastewater-irrigated fields inevitably get some contaminated soil on their fingers and from time to time, and without thinking about it, they put a finger or two on their lips or in their mouth and some of the soil particles from their fingers are ingested as a result.</td>
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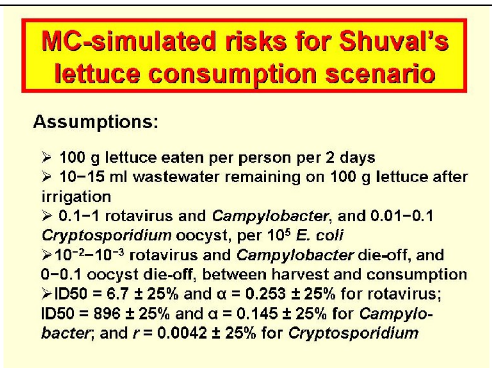
<td>19.</td>
<td>
</td>
<td>So, first, unrestricted irrigation, and the slide shows the range of values we chose for each parameter in the QMRA calculations. There was one fixed value, 100 g of lettuce per person per 2 days; and the range of values for the others was 10−15 ml of wastewater remaining on 100 g lettuce after irrigation; for every 10^5 E. coli in the wastewater there were 0.1−1 rotavirus and Campylobacter, and 0.01−0.1 Cryptosporidium oocyst; there was a die-off between harvest (actually the last irrigation) and consumption of 10^{-2}–10^{-3} for rotavirus and Campylobacter, and 0−0.1 for the oocysts; and finally we allowed the ‘pathogen constants’ in the dose-response equations to vary by ±25%.</td>
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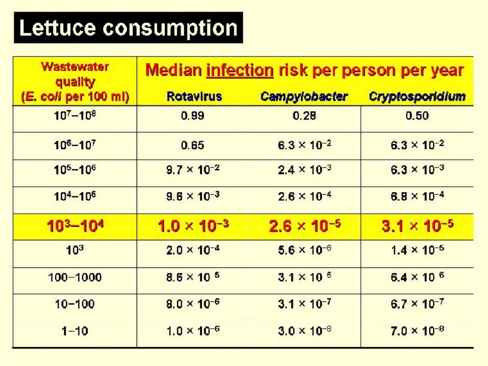
20.



Lettuce consumption

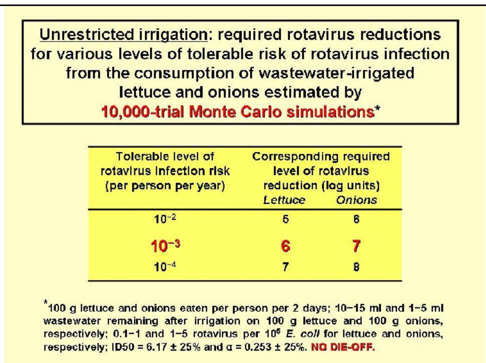
Wastewater quality (*E. coli* per 100 ml)	Median infection risk per person per year: Rotavirus	*Campylobacter*	*Cryptosporidium*
10^7–10^8	0.99	0.28	0.50
10^6–10^7	0.65	6.3×10^{-2}	6.3×10^{-2}
10^5–10^6	9.7×10^{-2}	2.4×10^{-3}	6.3×10^{-3}
10^4–10^5	9.6×10^{-3}	2.6×10^{-4}	6.8×10^{-4}
10^3–10^4	**1.0×10^{-3}**	**2.6×10^{-5}**	**3.1×10^{-5}**
10^3	2.0×10^{-4}	5.6×10^{-6}	1.4×10^{-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}
1–10	1.0×10^{-6}	3.0×10^{-8}	7.0×10^{-8}

These are the results of the 10,000-trial Monte Carlo simulations for the lettuce consumption scenario. We calculated median infection risks for the three index pathogens for various wastewater qualities, defined as single-log ranges of *E. coli* numbers per 100 ml. Thus 10^7−10^8 *E. coli* per 100 ml represents untreated wastewater and, at the other extreme, 1−10 per 100 ml is getting close, bacteriologically speaking, to drinking water.

As you can see in the table on the slide, for a wastewater quality of 10^3–10^4 *E. coli* per 100 ml the resulting median rotavirus infection risk is 10^{-3} per person per year, which is the design value that relates back to the 10^{-6} DALY loss per person per year. And it's good to note that the corresponding risks for *Campylobacter* and *Cryptosporidium* are two orders-of-magnitude lower.

The table also confirms that the risks from using untreated wastewater are very high, practically a certainty for rotavirus infection, and not much lower for the other two. The table also tells us that it's not really worth irrigating with a wastewater of better quality than 10^3–10^4 *E. coli* per 100 ml as the resulting median infection risks are much lower than 10^{-3} per person per year.

21.



Unrestricted irrigation: required rotavirus 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***

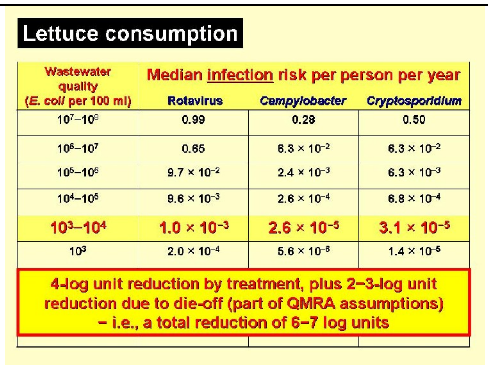
Tolerable level of rotavirus infection risk (per person per year)	Corresponding required level of rotavirus reduction (log units): *Lettuce*	*Onions*
10^{-2}	5	6
10^{-3}	**6**	**7**
10^{-4}	7	8

*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; ID50 = 6.17 ± 25% and α = 0.253 ± 25%. **NO DIE-OFF.**

This slide gives the results of Monte Carlo risk simulations that were done the reverse way to those on the previous slide − that is to say, we fixed the rotavirus infection risk at 10^{-2}, 10^{-3} and 10^{-4} per person per year and then, for each of these values, the computer program determined the required rotavirus reduction in log units. In this case no die-off between the last irrigation and consumption was considered and the footnote to the table gives the ranges of parameter values that we used for both lettuce and, as a root crop, onions.

The table shows that, for the design rotavirus infection risk of 10^{-3} per person per year, we need to get a 6-log unit reduction for lettuce and 7 for onions. These are the total reductions from raw wastewater to consumption.

22.



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10^4–10^5	9.6×10^{-3}	2.6×10^{-4}	6.8×10^{-4}
10^3–10^4	**1.0×10^{-3}**	**2.6×10^{-5}**	**3.1×10^{-5}**
10^3	2.0×10^{-4}	5.6×10^{-6}	1.4×10^{-5}

4-log unit reduction by treatment, plus 2–3-log unit reduction due to die-off (part of QMRA assumptions) – i.e., a total reduction of 6–7 log units

Going back to the previous slide, we can see that to get to the design rotavirus infection risk of 10^{-3} per person per year, we need to have a 4-log unit reduction by treatment; that is to say from 10^7–10^8 *E. coli* per 100 ml to 10^3–10^4 per 100 ml. But the assumptions we made for these Monte Carlo-QMRA calculations included, for rotavirus, a 2–3 log unit reduction due to die-off between the last irrigation and consumption. Therefore the total log unit reduction required is 4 from treatment plus 2–3 from die-off – that is, 6–7 log units.

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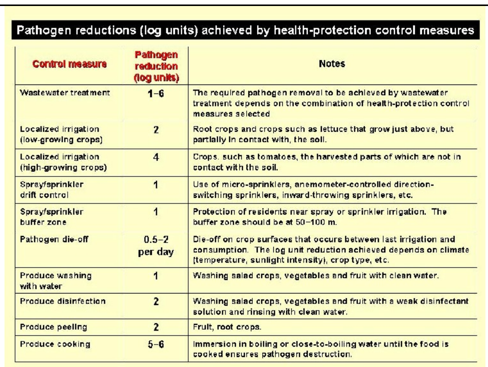
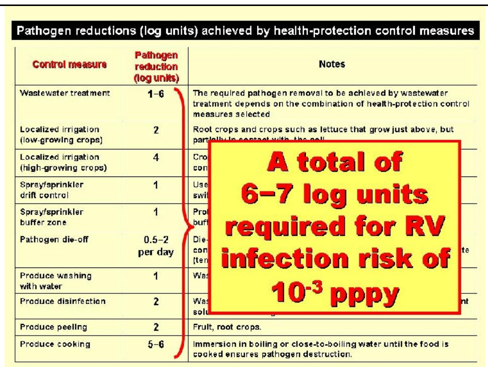


Pathogen reductions (log units) achieved by health-protection control measures

Control measure	Pathogen reduction (log units)	Notes
Wastewater treatment	1–6	The required pathogen removal to be achieved by wastewater treatment depends on the combination of health-protection control measures selected
Localized irrigation (low-growing crops)	2	Root crops and crops such as lettuce that grow just above, but partially in contact with, the soil.
Localized irrigation (high-growing crops)	4	Crops, such as tomatoes, the harvested parts of which are not in contact with the soil.
Spray/sprinkler drift control	1	Use of micro-sprinklers, anemometer-controlled direction-switching sprinklers, inward-throwing sprinklers, etc.
Spray/sprinkler buffer zone	1	Protection of residents near spray or sprinkler irrigation. The buffer zone should be at 50–100 m.
Pathogen die-off	0.5–2 per day	Die-off on crop surfaces that occurs between last irrigation and consumption. The log unit reduction achieved depends on climate (temperature, sunlight intensity), crop type, etc.
Produce washing with water	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	Fruit, root crops.
Produce cooking	5–6	Immersion in boiling or close-to-boiling water until the food is cooked ensures pathogen destruction.

In point of fact, die-off is just one of several post-treatment health-protection control measures. This table lists all these and the log unit pathogen reduction achieved by each of them.

24.



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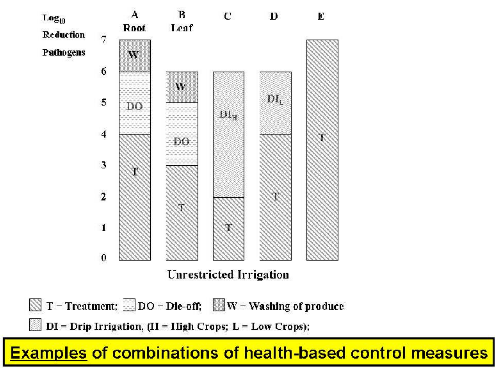
Localized irrigation (low-growing crops)	2	Root crops and crops such as lettuce that grow just above, but
Localized irrigation (high-growing crops)	4	
Spray/sprinkler drift control	1	
Spray/sprinkler buffer zone	1	
Pathogen die-off	0.5–2 per day	
Produce washing with water	1	
Produce disinfection	2	
Produce peeling	2	Fruit, root crops.
Produce cooking	5–6	Immersion in boiling or close-to-boiling water until the food is cooked ensures pathogen destruction.

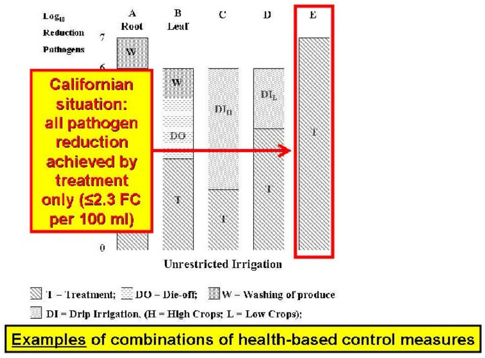
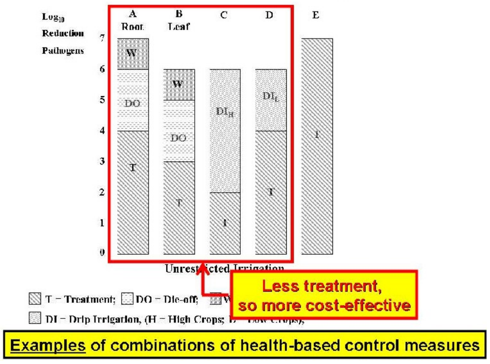
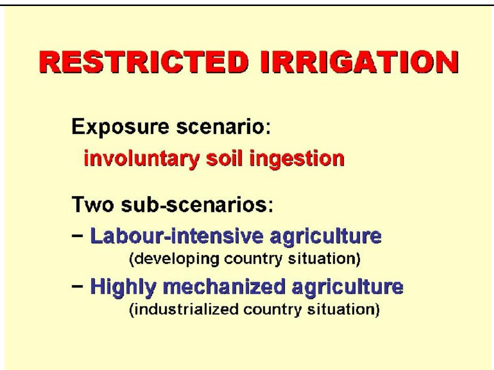
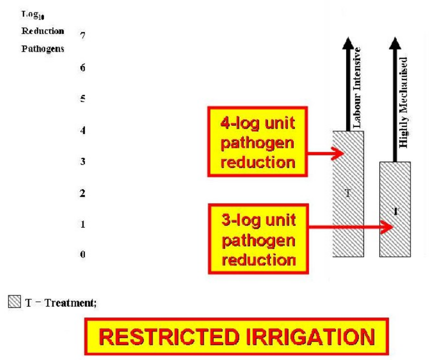
The point is that there has to be a total 6–7 log unit reduction which is partially achieved by treatment, with the balance made up by some combination of post-treatment control measures,

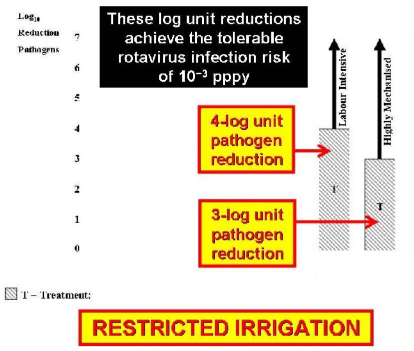
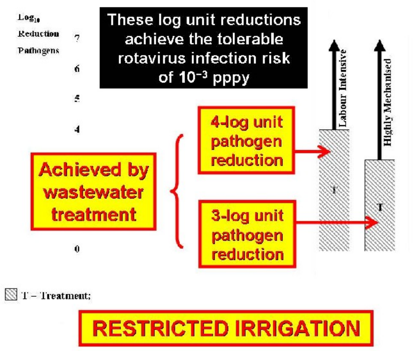
25.



Examples of combinations of health-based control measures

like the examples shown here, and it's worth stressing that these are only examples. One of these combinations, the one on the far left, for root crops like onions, is a 4 log unit reduction by treatment, 2 due to die-off and 1 due to produce washing in clean water. Really the design engineer can choose any combination he or she chooses, and the ones shown here are not the only ones, nor necessarily the most common ones. You design, you choose!

26.		The Californians chose to get the required 6–7 log unit reduction by treatment alone, by using advanced quaternary wastewater treatment techniques. But for most people this is just too expensive, and so …
27.		it's really better to use some combination of treatment and post-treatment control measures, like the ones shown here. This is a much more cost-effective approach and, given that pathogen die-off *always* occurs, to ignore it is simply to waste money on unnecessary treatment.
28.		For restricted irrigation we used the exposure scenario of involuntary soil ingestion, with two sub-scenarios: 'labour-intensive agriculture' with exposure for 300 days a year, to represent a typical developing-country situation; and 'highly mechanized agriculture' to represent what happens in industrialized countries: farmers driving tractors and wearing protective clothing such as gloves and boots, for 100 days a year, so the amount of soil ingested would be a lot less than in the first case.
29.	 —————————— **Note:** the audio track says "…**3** log units for labour-intensive agriculture, and **2** log units for highly mechanized…", but it should be **4** and **3** log units, respectively, as shown in the slide.	A series of 10,000-trial Monte Carlo risk simulations was done, essentially as for unrestricted irrigation but with ranges of parameter values more appropriate for the exposure scenario of involuntary soil ingestion. The resulting required pathogen reductions were 4 log units for labour-intensive agriculture, and 3 log units for highly mechanized (and so less exposed) agriculture.

30.		These log unit reductions achieve the tolerable rotavirus infection risk of 10^{-3} per person per year, for the fieldworkers.
31.		And, because they're for the fieldworkers, they have to be achieved solely by wastewater treatment, because the fieldworkers are directly exposed to the wastewater-contaminated soil.
32.	**HELMINTH EGGS** • For both restricted and unrestricted irrigation: ≤1 egg per litre – except in case of drip irrigation of high-growing crops: *no recommendation* • When children under 15 exposed, use additional control measures (eg, antihelminthic chemotherapy) • Based on epidemiology, not QMRA	Finally, we come to helminth eggs, the eggs of *Ascaris*, *Trichuris* and the human hookworms, *Ancylostoma* and *Necator*. To protect the health of both the fieldworkers and the crop consumers WHO recommends a maximum count of 1 egg per litre of treated wastewater, although in the case of drip irrigation of high-growing crops, like tomatoes, no recommendation is necessary. This guideline value of ≤1 egg/l doesn't, however, protect children under the age of 15, so when these are exposed by working in, or playing in, wastewater-irrigated fields, additional control measures are needed – for example, regular deworming, either at home or at school. This helminth egg guideline is based on epidemiological data, mainly from studies in Mexico; so it wasn't necessary to use QMRA to derive the guideline.