DEVELOPMENT OF A RISK ASSESSMENT APPROACH FOR EVALUATING WASTEWATER REUSE STANDARDS FOR AGRICULTURE

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ABSTRACT
A risk assessment approach was developed to arrive at a comparative risk analysis of the various recommended wastewater irrigation microbial health guidelines for unrestricted irrigation of vegetables normally eaten uncooked. The guidelines compared are those of the WHO and the USEPA/USAID. The laboratory phase of the study determined the degree of contamination of vegetables irrigated by wastewater. Based on these estimates of the risk of ingesting pathogens, it is possible to estimate the risk of infection/disease based on the risk of infection and disease model developed for drinking water by Haas et al. (1993). For example, the annual risk of infectious hepatitis from regularly eating vegetables irrigated with raw wastewater is shown to be as high as $10^{-3}$. The study indicates that the annual risk of succumbing to a virus disease from regularly eating vegetables irrigated with effluent meeting WHO guidelines (1,000 FC/100mL) is negligible and of the order of $10^{-6}$ to $10^{-7}$. The risk of the more infectious, but less serious, rotavirus is $10^{-3}$ to $10^{-6}$. The USEPA considers an annual risk of $10^{-4}$ to be acceptable for microbial contamination of drinking water. The additional health benefit that might result from a further reduction of risk gained by adhering to the USEPA/USAID Reuse Guidelines (1992), which require no detectable faecal coliforms/100mL, appears to be insignificant in relation to the major additional costs associated with the expensive technology required to treat effluent to such a rigorous standard. Our preliminary estimates show that meeting the USEPA Guidelines would result in an extra expenditure of $3-30$ millions/case of disease prevented. © 1997 IAWQ. Published by Elsevier Science Ltd

KEYWORDS
Wastewater irrigation standards/guidelines; risk analysis; cost/effectiveness; WHO; USEPA.

INTRODUCTION
This study aimed at developing a risk assessment approach, based on a mathematical model and experimental data, to arrive at a comparative risk analysis of the various recommended wastewater irrigation microbial health guidelines for unrestricted irrigation of vegetables normally eaten uncooked. The guidelines evaluated are those recommended by WHO (1989) and USEPA/USAID (1992). Health regulations, aimed at providing protection to the health of the public that consume crops irrigated by wastewater, were initiated by the California State Board of Health which established in 1933 the first microbial effluent standards for the "irrigation of garden truck produce eaten raw" at a coliform concentration equivalent to that required for drinking water (then 2.2 MPN/100mL) (Ongerth and Jopling, 1977). This standard became widely accepted by other states in the US and after WWII was copied by many newly established countries interested in
promulgating health regulations to cover the ever growing practice of wastewater recycling and reuse in agriculture. In 1982 the World Bank and WHO embarked on a broad spectrum scientific study involving three teams of independent scientists to review the epidemiological and technological evidence available concerning health risks associated with wastewater irrigation so as to provide a rational health basis for the revaluation of microbial guidelines for wastewater irrigation (Feachem et al., 1983; Shuval et al., 1986; Strauss and Blumenthal, 1989). These studies resulted in 1989 in the WHO "Health Guidelines for the Use of Wastewater in Agriculture and Aquaculture" which, based on the new epidemiological and technological evidence, recommended the microbial guidelines for wastewater irrigation of vegetables eaten raw of a mean of 1,000 faecal coliforms (FC)/100mL and <1 helminth egg/L in effluent. These new guidelines have become widely accepted by the international agencies, including the FAO, UNDP, UNEP and World Bank, and have been adopted by a number of developing as well as developed countries. In 1992 the USEPA together with the USAID published their own "Guidelines for Water Reuse" intended both for internal use in the US and for use by the USAID missions working in developing countries. These new guidelines, for irrigation of crops eaten uncooked, are even stricter than the original California standards and called for no detectable FC/100mL, a BOD of ≤10mg/L, turbidity of ≤2NTU and a chlorine residual of 1mg/L. In addition, the guidelines called for rigorous engineering requirements for biological treatment, sand filtration, chemical disinfection and various fail-safe, redundancies and back-up equipment facilities.

RISK ASSESSMENT MODEL

For the purposes of this study, the risk assessment model estimating the risk of infection and disease from ingesting microorganisms in drinking water, developed by Haas et al (1993) was selected. However, certain modifications where required since we are estimating the risk of infection associated with eating vegetables irrigated with wastewater of various microbial qualities. The basic model of Haas et al (1993) for the probability of infection (P₁) from ingesting pathogenic microorganisms in water is:

\[ P₁ = 1 - (1 + \frac{N}{N_{50}}(2^{1/a} - 1))^a \]

P₁ = The risk of infection by ingesting pathogens in drinking water; N = Number of pathogens ingested; N_{50} = Number of pathogens that will infect 50% of the exposed population; a = The ratio N/N_{50} and P₁.

Various studies have shown a wide variation in the probability of infected persons becoming ill with morbidity rates varying between 1-97% depending on the virulence of the pathogen, age, nutritional and general health status of the subjects. Since not every person infected by the ingestion of pathogens becomes ill, an independent estimate is made of \( P_D \) -the probability of contracting a disease (formula 2):

\[ P_D = P_{D:1} \times P₁ \]

P_D = The risk of an infected person becoming diseased or ill; P_{D:1} = The probability of an infected person developing clinical disease.

DETERMINING THE NUMBER OF PATHOGENS INGESTED

In order to make an estimate of the number of pathogens ingested from eating wastewater irrigated vegetables we first had to determine through laboratory experiments the amount of liquid that might cling to vegetables irrigated with wastewater. It was then possible to estimate the concentration of indicator organisms and pathogens that might remain on such wastewater irrigated vegetables and be ingested by subjects eating such vegetables. In doing this we assumed that any microorganisms contained in the residual wastewater remaining on the irrigated vegetables would cling to the vegetables even after the wastewater itself evaporated. This was achieved by simulating the worst case conditions by totally immersing pre-weighed cucumbers and heads of long leaf lettuce in water for varying periods of time and determining the amount of weight increase which provided an estimate of water clinging to the vegetables. It was found that cucumbers absorb increasing quantities of water over periods of immersion <4h. In this series of experiments, not reported here in detail, there was no bacterial uptake into the tissue of the vegetable
resulting from the absorption of liquid and such vegetables are entirely free of internal contamination. Based on the laboratory determinations we have estimated that the amount of wastewater of varying microbial qualities that that would cling to the outside of wastewater irrigated cucumbers \( n = 26 \) would be \( 0.36 \text{mL/100g} \) (or one large cucumber) and \( 10.8 \text{mL/100g} \) long leaf lettuce (about three leaves of lettuces) \( n = 12 \). Based on these measurements it is possible to estimate the amount of indicator organisms that might remain on the vegetables if irrigated with raw wastewater and with wastewater meeting the WHO Guidelines. In the case of irrigation with raw wastewater we estimated that the FC concentration was \( 10^7/100 \text{mL} \). In the case of irrigation with wastewater meeting the WHO Guideline the concentration of FC would be \( 1,000/100 \text{mL} \). We then estimated that the enteric virus:FC ratio in wastewater, based on various studies (e.g. Schwartzbrod, 1995), is \( 1:10^5 \). For this preliminary risk estimate all enteric viruses were treated as a single pathogen, such as infectious hepatitis or poliovirus, so that it will be possible to make certain assumptions as to median infectious dose and infection to morbidity ratios.

It was also assumed that under actual field conditions there would be a certain degree of indicator and pathogen dieaway and/or removal from the wastewater source until the final ingestion by the subject in the home. These factors include, settling, adsorption, desiccation, biological competition, UV irradiation from sunlight and a degree of removal and/or inactivation by washing of the vegetables in the home. A number of studies have indicated that there is rapid dieaway/removal of indicators as well as pathogens in wastewater irrigated soil and on crops, < 5 logs in 2d under field conditions (Rudolfs et al., 1951; Berger-Rabinowitz, 1956; Sadovski et al., 1978; Armon et al., 1994). Armon et al (1994) also suggested possible regrowth of bacteria on vegetables contaminated with wastewater but presented no data to support this hypothesis. In any event, human enteric viruses cannot multiply under environmental conditions. Asano and Sakaji (1990) have determined virus dieaway in the environment under field conditions of wastewater reuse, finding that in two weeks the total virus inactivation reaches some 99.99% while in 3d there is a 90% reduction of virus concentration. Even superficial washing of vegetables in the home can remove an additional 99-99.9% of the virus contamination. Schwartzbrod (1995) has estimated that there would be < 6 log reduction of virus levels between irrigation with wastewater and consumption of the crops if the total time elapsed reached 3 weeks. To be on the conservative side we have estimated that the total virus inactivation/removal from the wastewater source until ingestion results in a reduction in virus of 3 logs, although a 99.99% loss is not unreasonable and might occur in most cases.

ESTIMATES OF RISK OF INFECTION AND DISEASE

Based on the above tests and assumptions we now can estimate the number of pathogens ingested by a subject who eats a 100g cucumber or 100g (three leaves) of long lettuce irrigated with wastewater of various qualities. In this preliminary risk estimate we have selected hepatitis A, which can result in serious disease sequelae, which has had a clear epidemiological record indicating the possibility of it being environmentally transmitted and waterborne (Schwartzbrod, 1995). We have assumed that the median infectious dose for 50% of the exposed subjects to become infected \( (N_{50}) \) could range between 30-1,000PFU. We have also assumed that while the ratio of infections to clinical disease is often as low a 100:1 we shall estimate, as a worst case, that 50% of those infected will succumb to clinical disease \( (P_{D1} = 0.5) \). We also assumed, based on vegetable consumption patterns in Israel, that on an annual basis a subject would consume 100g lettuce or cucumbers/d for 150d \( (P_{D2} = 0.25) \) We have assumed that \( a = 5 \); however, even assuming \( a = 0.2 \) does not lead to a significantly increased risk. First, as a positive control test of the model, we have estimated the risk of infection and disease from consuming vegetables irrigated with raw wastewater with an estimated initial FC level of \( 10^7 \). Based on the above assumptions, including a 3 log dieaway, it is estimated that under such conditions a 100g cucumber or 100g (three leaves) lettuce irrigated with raw wastewater will have a final level of contamination of \( 10^1-10^2 \) FC. Based on that level of contamination and a virus:FC ratio of \( 1:10^5 \) it can be estimated that there is a probability, that 1/10,000 cucumbers and 1/1,000 leaf lettuce will carry a single enteric virus. Based on these estimates of ingesting enteric viruses, the risk of infection/disease that might result has been determined where lettuce carries a higher risk than cucumbers (Table 1).
Table 1. Risk of infection and disease by hepatitis A from eating 100g (3 leaves) of long leaf lettuce irrigated with raw wastewater

<table>
<thead>
<tr>
<th>Median infectious dose</th>
<th>One time risk of eating 100g</th>
<th>Annual risk of eating 100g/d for 150d</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$P_t$</td>
<td>$P_D$</td>
</tr>
<tr>
<td>$N_{90} = 30$</td>
<td>$4.6 \times 10^{-4}$</td>
<td>$2.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>$N_{90} = 1,000$</td>
<td>$1.5 \times 10^{-5}$</td>
<td>$7.5 \times 10^{-6}$</td>
</tr>
</tbody>
</table>

However, if the effluent is treated to meet the WHO Guideline for irrigation of vegetables to be eaten uncooked of 1,000 FC/100mL the risk of infection and disease estimates for lettuce are those shown in Table 2.

Table 2. Risk of infection and disease by hepatitis A from eating 100g (3 leaves) of long leaf lettuce irrigated with wastewater effluent meeting the WHO Guidelines for unrestricted irrigation of vegetables at 1,000 FC/100mL

<table>
<thead>
<tr>
<th>Median infectious dose</th>
<th>One time risk of eating 100g</th>
<th>Annual risk of eating 100g/d for 150d</th>
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<td>$1.5 \times 10^{-6}$</td>
<td>$7.5 \times 10^{-10}$</td>
</tr>
</tbody>
</table>

The risk assessment of consuming cucumbers irrigated with effluent meeting the WHO Guidelines is in the range of $10^{-7}$ to $10^{-8}$/year, while in the case of lettuce (Table 2) it is in the range of $10^{-6}$ to $10^{-8}$. Is this a high or low level of risk? In order to shed some light on what are considered reasonable levels of risk for communicable disease transmission from environmental exposure, it should be noted that the USEPA has determined that guidelines for drinking water microbial standards should be designed to ensure that human populations are not subjected to the risk of infection by enteric disease greater than $10^{-5}$ (or 1 case/10,000 persons/year) (Regli et al., 1995). We have also calculated the annual risk of disease from the more infectious, but less severe, rotavirus as $10^{-5}$ to $10^{-6}$. Compared to the USEPA estimates of reasonable acceptable risks for waterborne disease associated microbial standards for drinking water, the WHO Wastewater Reuse Guidelines appear to be some 1-2 orders of magnitude more rigorous, if not more.

Table 3. The risk of infection and disease from cholera from eating 100g of cucumbers or 100g of long leaf lettuce (3 leaves) irrigated with raw wastewater or treated wastewater effluent meeting the WHO Guidelines for unrestricted irrigation

<table>
<thead>
<tr>
<th>Type of wastewater</th>
<th>Type of vegetable</th>
<th>Risk of infection $P_t$</th>
<th>Risk of disease $P_D$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw</td>
<td>Cucumber</td>
<td>$1.5 \times 10^{-6}$</td>
<td>$7.5 \times 10^{-7}$</td>
</tr>
<tr>
<td>Raw</td>
<td>Lettuce</td>
<td>$1.5 \times 10^{-4}$</td>
<td>$7.5 \times 10^{-3}$</td>
</tr>
<tr>
<td>Treated1</td>
<td>Cucumber</td>
<td>$1.5 \times 10^{-10}$</td>
<td>$7.5 \times 10^{-11}$</td>
</tr>
<tr>
<td>Treated1</td>
<td>Lettuce</td>
<td>$1.5 \times 10^{-8}$</td>
<td>$7.5 \times 10^{-9}$</td>
</tr>
</tbody>
</table>

1treated to the WHO Guideline of 10000FC/100ml

VALIDATION OF THE MODEL FOR A CHOLERA EPIDEMIC

In 1970 an epidemic of cholera occurred in Jerusalem. Our investigation and analysis provided strong evidence that the main route of transmission was through the irrigation of vegetables, including lettuce and cucumbers illegally irrigated with raw wastewater from Jerusalem, which the villagers sold door to door throughout Jerusalem (Fattal et al., 1986). Since we had at our disposal considerable detailed evidence concerning that epidemic we felt it might provide an opportunity to test and validate the risk assessment model against real world data. Based on microbial testing carried out during the epidemic and other studies
we have estimated that the concentration of cholera vibrios in the raw municipal wastewater was $10^5$ to $10^6/100$ mL. We have also assumed, based on the literature (Feachem et al., 1983) that the median infectious dose ($N_{50}$) for cholera in Jerusalem under conditions of good health and nutrition was $10^4$ vibrios. Table 3 shows the theoretical risk of infection and disease from cholera based on the risk assessment model.

The total number of cases of disease reported in Jerusalem was 200 and we have estimated that some 1-200,000 persons purchased the contaminated vegetables and were exposed to risk. It is estimated that the case rate in Jerusalem was in the order of $10^4$ which falls in the range of the theoretical risk of disease for cucumbers and lettuce irrigated with raw wastewater calculated by the risk assessment model of $10^{-4}$ to $10^{-5}$. It can also be assumed that, had the Jerusalem wastewater been treated to the WHO effluent guideline, the risk of disease transmission by wastewater irrigation would have been essentially negligible, even if the concentration of cholera vibrios in the wastewater had reached the levels it did during the epidemic.

**COST/EFFECTIVENESS ANALYSIS**

At this stage of our study we have made only some very preliminary estimates of the costs and benefits/effects associated with meeting the various wastewater effluent guidelines. As an example we shall present the hypothetical case of a third world city of 1 million population about to build a wastewater treatment plant to assure safe utilisation of the effluent for agricultural irrigation of vegetable crops including those eaten uncooked which would serve the population of the city. It is assumed that they have opted for a pond treatment system that will meet the WHO Guidelines. They want to compare the cost and risks at that level of treatment to the cost and risks if they had adopted the USEPA/USAID recommended guidelines for vegetables eaten uncooked. We have assumed, for the purposes of this illustration only, that the unit cost of treatment of wastewater to meet the various guidelines can roughly be estimated at:

| WHO Guideline ($1,000$ FC/100mL) | $0.10/M^3$ |
| Person/Year (assume 100m$^3$/person/year) (in ponds) | $10.00/P/yr$ |
| USEPA/USAID Guideline- 0 FC/100mL | $0.45/M^3$ |
| Person/year (assume 100m$^3$/person/year) | $45.00/P/yr$ |

To meet the WHO guidelines will cost the city some $10,000,000/yr in wastewater treatment costs but the USEPA/USAID guidelines would cost some $45,000,000/yr or $35,000,000 a year more. Let us assume that half the population consumes wastewater irrigated vegetables on a regular basis and that the degree of annual risk of contracting a case of hepatitis A (associated with the use of irrigating vegetables eaten uncooked with wastewater meeting WHO guidelines) is in the worst case $1.7 \times 10^{-6}$ (or about 1 case/year/500,000 exposed persons) as estimated in this study (Table 2.). If it is assumed that USEPA/USAID guidelines will achieve an essentially zero risk of disease, then we can estimate that the one case of infectious hepatitis/year would have been prevented. The additional cost of treatment would result in a cost of about $35,000,000 for each case of disease prevented or $3,500,000/rotavirus case prevented. If, however, the true level of risk associated with the WHO guidelines is closer to the $10^{-7}$ level estimated by the less conservative interpretation of the results of this study, then no detectable reduction of risk would be gained by the additional investment of $35,000,000 required to meet the stricter, more expensive USEPA/USAID guidelines. It is questionable whether additional treatment associated with major additional expenditures is justified to further reduce the already negligibly low levels of risk of infection/disease that our estimates indicate are associated with the new WHO Guidelines.

**DISCUSSION AND CONCLUSIONS**

A preliminary model for the assessment of risk of infection and disease associated with wastewater irrigation of vegetables eaten uncooked has been developed based on a modification of the Haas et al. (1993) risk assessment model for drinking water. The modifications include determining the amount of wastewater that would cling to irrigated vegetables such as cucumbers and lettuce and estimates of the concentration of pathogens that would be ingested by consuming vegetables irrigated with wastewater of different standards. Our validation of the model with data from the Jerusalem cholera epidemic, which was caused primarily by...
the consumption of wastewater irrigated vegetables, lend support to our assumptions that the risk assessment model provides a reasonable approximation of the levels of disease that really can and have occurred in the case of irrigation with poor quality wastewater. The risk assessment, using this model, of irrigation with treated wastewater effluent meeting the WHO guidelines (1,000 FC/100mL) indicates the annual risk of contracting a virus disease is about $10^{-6}$ to $10^{-7}$ and rotavirus disease is about $10^{-5}$ to $10^{-6}$. The USEPA has determined that guidelines for drinking water standards should be designed to ensure that human populations are not subjected to the risk of infection by enteric disease $>10^{-4}$ for a yearly exposure (Regli et al., 1995). Thus, this preliminary study suggests that the WHO guidelines provide a factor of safety some 1-2 orders of magnitude greater than that called for by the USEPA for microbial standards for drinking water. While our cost effectiveness analysis is still very preliminary, the data suggests that the additional degree of risk reduction that might be attained by meeting the USEPA/USAID guidelines would, under the most conservative estimate, result in expenditures of some $3-30$ million dollars per case of disease prevented. It is questionable whether such additional investments in high technology wastewater treatment facilities to meet the USEPA/USAID guidelines, rather than the WHO guidelines which provide a very low level of risk, are justifiable considering the small degree of additional health protection they might provide.

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REFERENCES


