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Risk assessment of consuming agricultural products irrigated with reclaimed wastewater: An exposure model

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Abstract. This study assesses health risks to consumers due to the use of agricultural products irrigated with reclaimed wastewater. The analysis is based on a definition of an exposure model which takes into account several parameters: (1) the quality of the applied wastewater, (2) the irrigation method, (3) the elapsed times between irrigation, harvest, and product consumption, and (4) the consumers' habits. The exposure model is used for numerical simulation of human consumers' risks using the Monte Carlo simulation method. The results of the numerical simulation show large deviations, probably caused by uncertainty (impreciseness in quality of input data) and variability due to diversity among populations. There is a 10-orders of magnitude difference in the risk of infection between the different exposure scenarios with the same water quality. This variation indicates the need for setting risk-based criteria for wastewater reclamation rather than single water quality guidelines. Extra data are required to decrease uncertainty in the risk assessment, Future research needs to include definition of acceptable risk criteria, more accurate dose-response modeling, information regarding pathogen survival in treated wastewater, additional data related to the passage of pathogens into and in the plants during irrigation, and information regarding the behavior patterns of the community of human consumers.

1. Introduction

1.1. Treated Wastewater Utilization

Water scarcity in arid and semiarid regions has encouraged the search for additional sources currently not exploited intensively, such as treated domestic sewage. Treated wastewater is a relatively stable water source and can be utilized, mainly for agricultural irrigation. Disposal of treated wastewater for agricultural irrigation simultaneously solves water shortage problems and reduces potential environmental contamination. However, subject to distribution of waterborne disease, associated with treated wastewater reuse, a risk assessment of pathogen hazards, subject to diverse wastewater qualities utilization, as well as different irrigation technologies, is required.

Wastewater reclamation is the process of treating wastewater for beneficial uses, its transportation to demand sites, and its actual reuse [*Pettygrove and Asano*, 1985]. Reclamation of wastewater allows depletion of groundwater to be minimized and helps to prevent contamination of natural water sources, by reintroducing wastewater (even if only partly treated) as an alternative water source. Shortage of water has driven consumers in arid and semiarid areas around the world to reclaim municipal wastewater for diverse purposes, of which agricultural use is the main one.

Human communities consuming raw agricultural products (vegetables and fruits) irrigated with reclaimed wastewater ingest microbial pathogens (bacteria, viruses, and parasites). The ingestion of these pathogens *can* cause infection and illness. Health risk assessment allows the amount of ingested pathogens and the subsequent health effects of wastewater irrigation to be quantified and indicates the precaution phases that should be undertaken.

Consequently, one of the most important issues during wastewater reclamation is the protection of public health. Current health regulations governing wastewater reuse impose strict limitations. based on a "zero risk" alternative approach [*World Health Organization (WHO)*, 1989; *U.S. Environmental Protection Agency (EPA)*, 1992]. This approach can hardly be expected to emphasize economic benefits rather than health risks. Even so, it is now widely regarded as overcautious. Currently, almost no country or international body has yet set an acceptable risk criterion for wastewater reclamation. The EPA drinking water guideline for enteric viruses sets a limit of less than one infection per population of 10,000 per year ($<10^{-4}$). This drinking water guideline has been used for the evaluation of wastewater reclamation projects in the absence of a common acceptable risk criterion [*Asano et al.*, 1992; *Rose et al.*, 1996; *Shuval et al.*, 1997; *Tanaka et al.*, 1998]. The appropriateness level of the 10^{-4} risk standard as a measure of safety therefore needs further discussion.

1.2. Risks Associated With Effluent Reuse

Health risk assessment is the process through which toxicological data are combined with information concerning the degree of exposure to external risks. It is performed in order to quantitatively predict the likelihood that a particular adverse response will arise in a specific human population [*Paustenbach*, 1997]. Quantitative microbial risk assessment has recently been applied to estimate the risk of infection and illness from enteric pathogens in water and food. Several studies focus on health risk assessment of wastewater reuse in agriculture [*Asano and Sakaji*, 1990; *Asano et al.*, 1992; *Rose et al.*, 1996; *Shuval et al.*, 1997; *Tanaka et al.*, 1998].

Limited attention has been focused on exposure assessment

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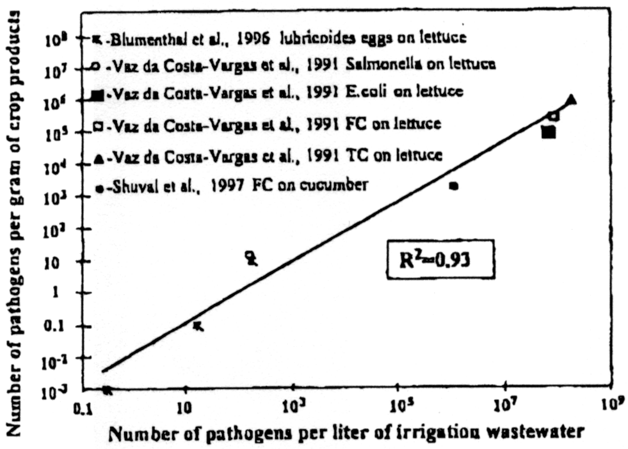

Figure 2. Expected crop contamination by pathogens, based on various studies on lumbricoides (helminth eggs), fecal coliforms (FC), salmonella, and total coliforms (TC), when 16 mL of reclaimed effluent per 100 g of crop remains on the crop.

dent action of single organisms forms the base for the βPM. The βPM was first used for drinking water and food technology and is considered an appropriate model for virus ingestion and infection probability assessment [*Rose and Gerba*, 1991; *Rose et al.*, 1996; *McNab*, 1997; *Tanaka et al.*, 1998].

$$P_i = 1 - (1 - D_i/\beta)^{-\alpha}, \tag{1}$$

where

P_i daily probability of infection by ingesting pathogens;
D_i daily consumed dose of contaminant, PFU d^{-1};
β the β Poisson distribution coefficient;
α a model parameter ($\alpha = 0.232$ and $\alpha = 0.247$ [*Haas*, 1983]).

Successively, the annual risk can be assessed from the daily risk, namely,

$$P_a = 1 - (1 - P_i)^{365}, \tag{2}$$

where P_a is the annual probability of infection by ingesting pathogens.

2.5. Wastewater Treatment Characteristics

Wastewater treatment systems consist customarily of a primary stage, secondary treatment, and tertiary phases. Usually, 5 days biological oxygen demand (BOD_5) and the suspended matter are common treatment efficiency parameters. In this analysis the virus content was used as the main removal efficiency measure:

$$E_R = 100(C_0 - C_{iw})/C_{iw}, \tag{3}$$

where E_R is the removal efficiency, percent; C_0 is the virus concentration in the raw sewage, PFU L^{-1}; and C_{iw} is the virus concentration in the irrigation reclaimed wastewater, PFU L^{-1}.

Primary treatment includes basic treatment such as screening of coarse solids and grit removal. The virus removal efficiency at the primary treatment stage is relatively low and is around 50% or 0.32 $\log_{10}$ [*Feachem et al.*, 1983]. In the secondary treatment stage (biological treatment process such as activated sludge) a higher removal is attained. The inclusive treatment removal efficiency of primary and secondary stages is estimated at 95% or 1.3 $\log_{10}$ [*Feachem et al.*, 1983].

Complete treatment consists of primary, secondary, and tertiary treatment phases. Tertiary treatment includes commonly chemical coagulation, sedimentation, and filtration or equivalent phases. The virus removal efficiency of a complete treatment is estimated at 99.9994% or 5.2 log 10 [*Asano and Sakaji*, 1990].

2.6. Irrigation Method, Wastewater Quality, and the Crop

Two major routes commonly contaminate agricultural crops and their products: (1) direct external contact of the applied wastewater with the surface of the plants' parts and (2) penetration of microorganisms through the root system into the plants' internal parts.

Direct contact of the fruits and vegetables with the reclaimed wastewater is associated with contamination by pathogens, which stick to the surface area of the plants' parts. Additional contamination is due to pathogens penetrating into the plant through injured surfaces. Contact contamination depends largely on the applied irrigation method. Relatively large amounts of wastewater and aerosols are in contact with the crop surface during SI, causing high contamination levels. Common DI provides wastewater to plants through on-surface laterals. Under DI, contamination of plants by direct contact with the irrigation wastewater can take place only if the foliage and fruits are almost entirely attached to the emitters. It includes mainly low-spreading plants like cucumber and tomato. However, the extent of the contamination is lower than in the case of SI, since no aerosols are distributed. Data regarding pathogen level in crops under DI are scarce and frequently inconsistent. Measurements of soil and plants, which were carried out in the past, demonstrate contamination levels that are at least 2 orders of magnitude lower than under SI [*Shuval*, 1980; *Oron et al.*, 1990].

In high-erecting plants like corn, grapes, and most deciduous orchards there is a low probability that their lower parts will be contaminated. Under SDI the direct surface contamination is eliminated entirely.

Previous works made it evident that contamination through direct uptake by the roots is almost impossible and can be considered negligible in comparison with contamination by direct contact [*Sadovski et al.*, 1978; *Shuval*, 1980; *Katzenelson and Mills*, 1984; *Oron et al.*, 1991, 1995]. The soil surrounding the subsurface emitters and plant roots performs as a complementary removal phase for viruses [*Oron*, 1996].

The main mechanism for contamination through SI is by direct contact of the effluent with the plant foliage and fruits. Measurements of different pathogens' presence on various plants show that a constant volume of wastewater and its microorganisms remain attached to the plant after irrigation. *Shuval et al.* [1997] found in their studies that only an amount of 10.8 mL of wastewater remained on every 100 g of lettuce plants. This is lower by ~40% than findings in other works. Taking data from various works reveals a linear relationship between the content of pathogens in the irrigation wastewater and their related concentration on the plant (Figure 2). The linearity verifies that contamination by direct contact is a physical process and does not depend on the type of microorganism.

In order to be able to compare the SI, the DI, and the SDI methods the effluent equivalent volume (EEV) concept was adapted. The EEV approach is used for DI, with a triangular

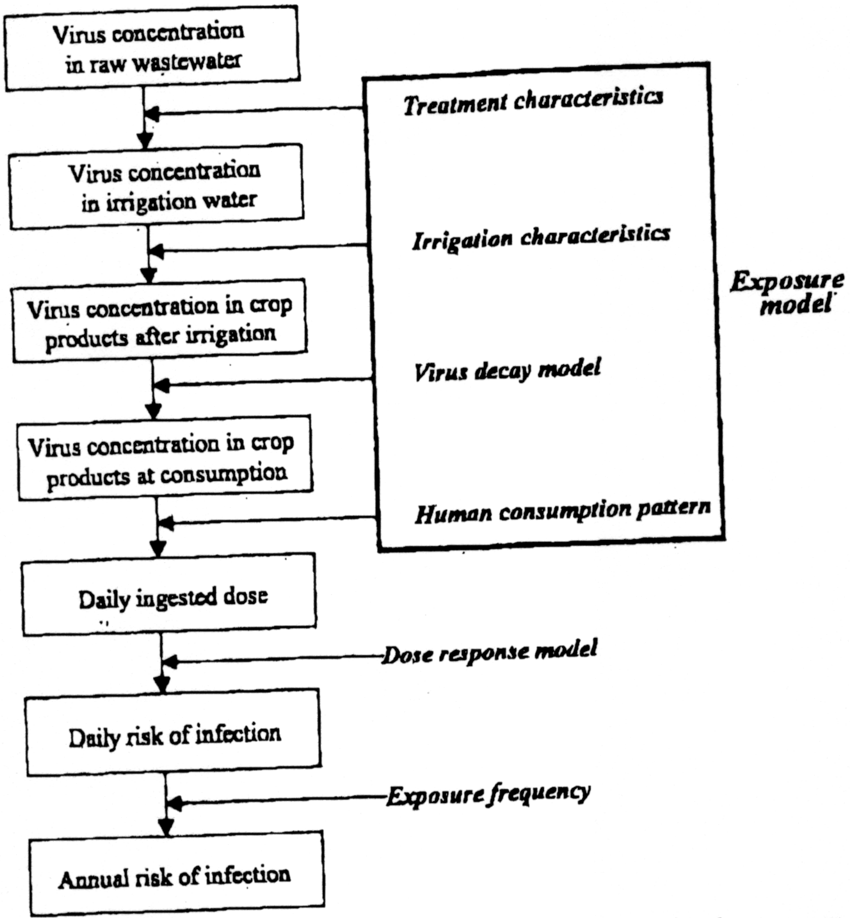

Figure 1. The procedure for determining the expected annual infection risk due to consumption of agricultural products irrigated with effluent.

(between 0 $\log_{10}$ and 6 $\log_{10}$), the irrigation method (SI, DI, or SDI), and the elapsed time between irrigation and consumption (between 0 and 30 days). The detailed input for the various scenarios is given in Table 1.

2.4. Dose-Response Model (DRM)

A dose-response model (DRM) was developed in order to examine the effect of consumption of agricultural products irrigated by effluent on human health. The DRM shows the relationship between the rate of exposure (virus dose) and the rate of effect on the consuming human community (response). Commonly, DRMs are based on animal behavior or data obtained from controlled experiments in which adult healthy humans consume pathogens. Consequently, the data related to DRMs regarding human reaction are limited, and they are generally considered to be among the most uncertain health risk analysis models [*McNab*, 1997; *Paustenbach*, 1997].

The β Poisson model (βPM) for rotaviruses is used dominantly as a DRM. Rotaviruses are the type of enteric viruses with the lowest infectious dose. The hypothesis of an indepen-

Table 1. Summary of Input Data for Monte Carlo Simulation

Variable	Symbol	Dimensions	Mean Value	Distribution
Virus concentration in raw sewage	C_0	PFU L^{-1}[a]	1000	lognormal; $\sigma = 300$
Kinetic decay constant	k	d^{-1}	0.69	...
Daily vegetable and fruit consumption	M_l	g (kg ca d)$^{-1}$	7.7	step; Figure 4
Human body weight	M_{body}	kg	71	normal; Figure 4
Percent of vegetables and fruits consumed raw	f_{raw}	...	50	triangular; Figure 4
Model				
Parameter β-Poisson model	α	...	0.247	...
Parameter β-Poisson model	α	...	0.232	...
Equivalent volume				
spray irrigation	$V_{eq,si}$	g^{-1}	1.6×10^{-4}	...
Drip irrigation	$V_{eq,di}$	g^{-1}	1.6×10^{-6}	triangular; Figure 3
Subsurface drip irrigation	$V_{eq,sdi}$	g^{-1}	1.6×10^{-7}	triangular; Figure 3
$\log_{10}$ removal wastewater treatment	E_r	$\log_{10}$		range: 0–6 $\log_{10}$
Period between irrigation and consumption	t_d	days		range: 0–30 days

[a] PFU, plaque forming unit. Here, ca, per capita.

and health risk analysis due to consumption of agricultural products irrigated with reclaimed wastewater. The exposure of consumers to contaminants due to wastewater irrigation depends on several factors: (1) the quality of the applied wastewater, (2) the irrigation method, (3) the elapse time between irrigation, harvest, and subsequent product consumption, and (4) consumers' habits. Previous works deal only roughly with the effect of the irrigation method, which is, in practice, one of the key issues for their exposure estimate [*Shuval et al.*, 1997; *Tanaka et al.*, 1998]. Other sources estimate an accidental ingestion of 100 mL of irrigation water per year, without specifying whether this concerns consumers or workers [*Rose et al.*, 1996].

The present study focuses on the risk to consumers of using agricultural products irrigated with reclaimed domestic wastewater. Risks for farmers and workers are not in the scope of this work. The risks associated with microbial aerosol dispersion and the related impact on adjacent living communities have been reported elsewhere [*Applebaum et al.*, 1984; *Ward et al.*, 1989].

2. Implication of the Risk Assessment Approach

2.1. Exposure Model Features

Exposure consists of a series of events in which a person (or a community) is in a close contact with a biological, chemical, or physical agent [*Hammad and Manocha*, 1995]. The prevailing route of exposure to reclaimed wastewater for human consumers is primarily through ingestion. When modeling exposure of a community to a specific phenomenon, regarding wastewater, the following should be considered: (1) wastewater treatment characteristics, (2) the route of virus migration from the irrigation wastewater into and within the plant, (3) virus die-off during the period between last irrigation and agricultural raw product consumption, and (4) the consumption pattern of the population.

The exposure route is commonly based on a human adult whose dietary intake of fruits and vegetables is based entirely on crops irrigated with effluent. The corresponding assumptions are as follows: (1) Only exposure through ingestion is considered. (2) The virus concentration in raw sewage is log-normally distributed. The arithmetic mean is 1000 plaque forming units per liter (PFU L^{-1}), and the standard deviation is 300 PFU L^{-1} [*Rose et al.*, 1996; *Tanaka et al.*, 1998]. (3) The decay of pathogens during storage of effluent before irrigation is part of the treatment system. (4) The total period between final irrigation and consumption equals the time between final irrigation and harvest and the period that the fruits and vegetables are stored between harvest and consumption. (5) No cross-contamination of fruits and vegetables after harvesting is considered. (6) Consumers eat 50% of their diet uncooked, unpealed, and unwashed. A triangular distribution (minimum is 25%; maximum is 75%) is used to express the uncertainty of this estimate (Figure 3).

An exposure model (EM) for assessing the risk associated with consuming agricultural products irrigated with wastewater was developed. The developed EM is based on previous literature data and various field measurements. The EM quantifies the relationship between irrigation wastewater quality and the daily virus dose that consumers ingest. The expected annual risk of infection is estimated stochastically by numerical simulation using the Monte Carlo simulation method (MCSM) and the developed EM. The outcomes of the numerical computations are compared, including the given and obtained risks.

Numerical simulation of exposure scenarios provides the means to express uncertainty and variability of the model input parameters by characterizing them with a distribution pattern. Variability is the impreciseness that occurs because of actual differences among segments of a population. Although the variability is not reduced, it provides additional data, thus increasing the accuracy of the analysis. Uncertainty stems from the limitation in the thoroughness of the measurement of the specific factor [*Finley et al.*, 1994].

The numerical simulation combines treatment characteristics and effluent quality, thus yielding the irrigation quality. The irrigation wastewater quality and the exposure model lead concurrently to the daily virus dose that consumers ingest. The daily risk of infection is then calculated using a dose response model implementing data from literature. Finally, the daily risk of infection is converted into an annual risk of infection taking into account the exposure frequency. The general modeling layout and data-processing procedure are described in Figure 1.

2.2. Monte Carlo Simulation Method (MCSM)

The Monte Carlo simulation method (MCSM) builds up successive scenarios using input values that are randomly selected from probability distributions, commonly utilizing the pertinent computer software. For each run, the software draws one random variable from the distribution for each of the model input variables and computes a single result. A large number of repeated computations produce a complete distribution of the modeled results [*Thompson et al.*, 1992].

The MCSM produces a complete distribution of output variables, of which the arithmetic mean, the standard deviation, the 95% lower confidence limit (LCL), and the 95% upper confidence limit (UCL) are calculated. The expected value is a probability-weighted average of the results generated during a simulation run and equals the average (arithmetic mean) of the generated results. The calculations can be carried out using appropriate software such as the RiskMaster for Windows program (V.1.0C) as an add-on to a Microsoft Excel™ spreadsheet [*RiskMaster*, 1995].

Each simulation is carried out for approximately 12,000 computer runs to guarantee convergence and to make up a representative sample of the near infinite number of combinations of possible input variables. The stability and convergence of the simulation are tested by running two independent simulations of 12,000 runs. The estimated mean, LCL, and UCL agree within 1%. From this it was concluded that 12,000 runs are sufficient to ensure convergence and stability of the output distribution [*Thompson et al.*, 1992].

2.3. Examined Scenarios

The nine initially examined scenarios combine treatment options (primary treatment, secondary treatment, or complete treatment) and a specific irrigation technique (spray irrigation (SI), drip irrigation (DI), or subsurface drip irrigation (SDI)). The elapsed time between irrigation and harvest is assumed to be constant at 15 days.

The combined simulations of the initial nine scenarios with a range of exposure scenarios was conducted in order to analyze the influence of wastewater treatment efficiency, irrigation method, and elapsed time between irrigation and agricultural product consumption on the resulting human health risk. Each scenario is a combination of wastewater treatment efficiency distribution to express variability and uncertainty. The triangular distribution is a conservative characterization of a normal distribution and takes into account a high level of uncertainty [*Finley et al.*, 1994]. Figure 3 shows the distribution diagram of the equivalent volume which has an average virus content of 0.16 mL in the irrigation wastewater penetrating into 100 g of plant matter (minimum is 0.016 mL/100 g; maximum is 1.6 mL/100 g).

Under SDI the risk of crop contamination is further reduced by minimizing the direct contact between the upper parts of the plant or the soil surface and contaminated wastewater. The two main mechanisms of contamination under SDI are either by overirrigation, causing the effluent to reach the soil surface, or through penetration via the root system and internal migration to the upper parts of plants. The limited data regarding SDI revealed that very small amounts or no viruses can penetrate into the plants [*Shuval*, 1980; *Katzenelson and Mills*, 1984; *Oron et al.*, 1995, 1997]. The EEV concept was as well applied for SDI and a triangular distribution (Figure 3). Under SDI and for a triangular distribution the average EEV was 0.016 mL/100 mL, the minimum was 0.0016 mL/100 g, and the maximum was 0.16 mL/100 g. Comparisons with on-surface conventional DI irrigation demonstrate that at least 2 orders of magnitude reduction in pathogen levels in soil and crops can be attained under SDI [*Campos et al.*, 1998].

2.7. Effect of Irrigation, Harvesting, and Consumption Timing on Virus Die-Off

Under adequate environmental conditions the viruses can survive for extended periods of several months [*Feachem et al.*, 1983]. Virus survival depends on surrounding conditions, however, and their multiplication needs a suitable host. Natural decay processes of viruses depend on moisture, salinity, temperature, pH, and radiation intensity. The fate of pathogens in the environment is usually represented by a first-order rate die-off kinetics (equation (4)). A decay constant in the range of 0.65–0.73 d^{-1} is often used for viruses [*Asano and Sakaji*, 1990; *Shuval et al.*, 1997; *Tanaka et al.*, 1998]:

$$C_c = C_{iw}\,[\exp(-kt_d)], \tag{4}$$

where

C_c virus concentration at elapsed time t_d after irrigation or at consumption, PFU L^{-1};
C_{iw} initial virus concentration of irrigation water, PFU L^{-1};
k kinetic decay constant, d^{-1};
t_d elapsed time between final irrigation and consumption, days.

2.8. Agricultural Products Consumption Pattern

Fruits and vegetables are the major parts of the human diet which are affected by irrigation with reclaimed wastewater. The *EPA* [1997] investigated the daily intake of fruits and vegetables per body weight in the United States. The EPA analysis is based on a mean common body weight of approximately 71 kg [*Finley et al.*, 1994]. The fraction of fruits and vegetables that is consumed uncooked, unpealed, and unwashed can be described by a triangular distribution pattern (average 50%; minimum 25%; maximum 75%). The combination of these data leads to a daily per capita consumption of raw fruits and vegetables that is affected by wastewater application (Figure 4).

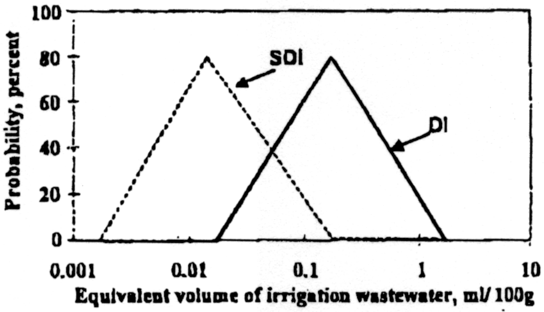

Figure 3. The distribution of the equivalent effluent volume for drip irrigation (DI) and subsurface drip irrigation (SDI) which are used in the Monte Carlo simulation (the x axis is logarithmic; the mean value for DI is 0.16 mL/100 g and for SDI is 0.016 mL/100 g).

2.9. Exposure Model (EM)

Subject to the above considerations, the EM was defined and examined. The exposure due to ingestion of contaminated food can be estimated as the product of contaminant concentration in the consumed food and the amount of food consumed per day [*Hammad and Manocha*, 1995]:

$$D_i = f_{\mathrm{raw}} M_{\mathrm{body}} M_i c_{iw} V_{\mathrm{eq}} \exp(-kt), \tag{5}$$

where

D_i daily dose of contaminant, PFU per capita per day, PFU $(\mathrm{ca\ d})^{-1}$;
f_{raw} fraction of fruits and vegetables eaten raw;
M_{body} human body weight, kg;
M_i daily consumption per capita per kg of body weight, g $(\mathrm{kg\ ca\ d})^{-1}$;
c_{iw} virus concentration of irrigation water, PFU L^{-1};
V_{eq} equivalent volume of irrigation water present in the crop, g^{-1};
k kinetic decay constant, d^{-1};
t time, days.

The above expression allows us to examine the combined effects of human consumption habits for vegetables and fruits as related to the applied wastewater quality and application method.

3. Results

3.1. Results of Monte Carlo Simulation

The EM was examined for various situations and conditions. A sample result for one scenario, C/si/15 (Table 2: complete treatment effluent applied through SI, with 15 days elapsed time between irrigation and consumption), is presented in Figure 5. The results (Figure 5) exemplify the outcome of one numerical simulation of 12,000 computer runs. The frequency distribution diagram shows the number of computer runs that result in an annual risk of infection for various intervals. That preliminary stage is required primarily to assess the approximate number of computer runs which are employed for the entire examination of the EM for all other scenarios.

3.2. Scenarios of Risks

The EM was further examined for various hypothetical situations which might be faced in practice in agricultural fields. These scenarios are combinations of irrigation methods, efflu-

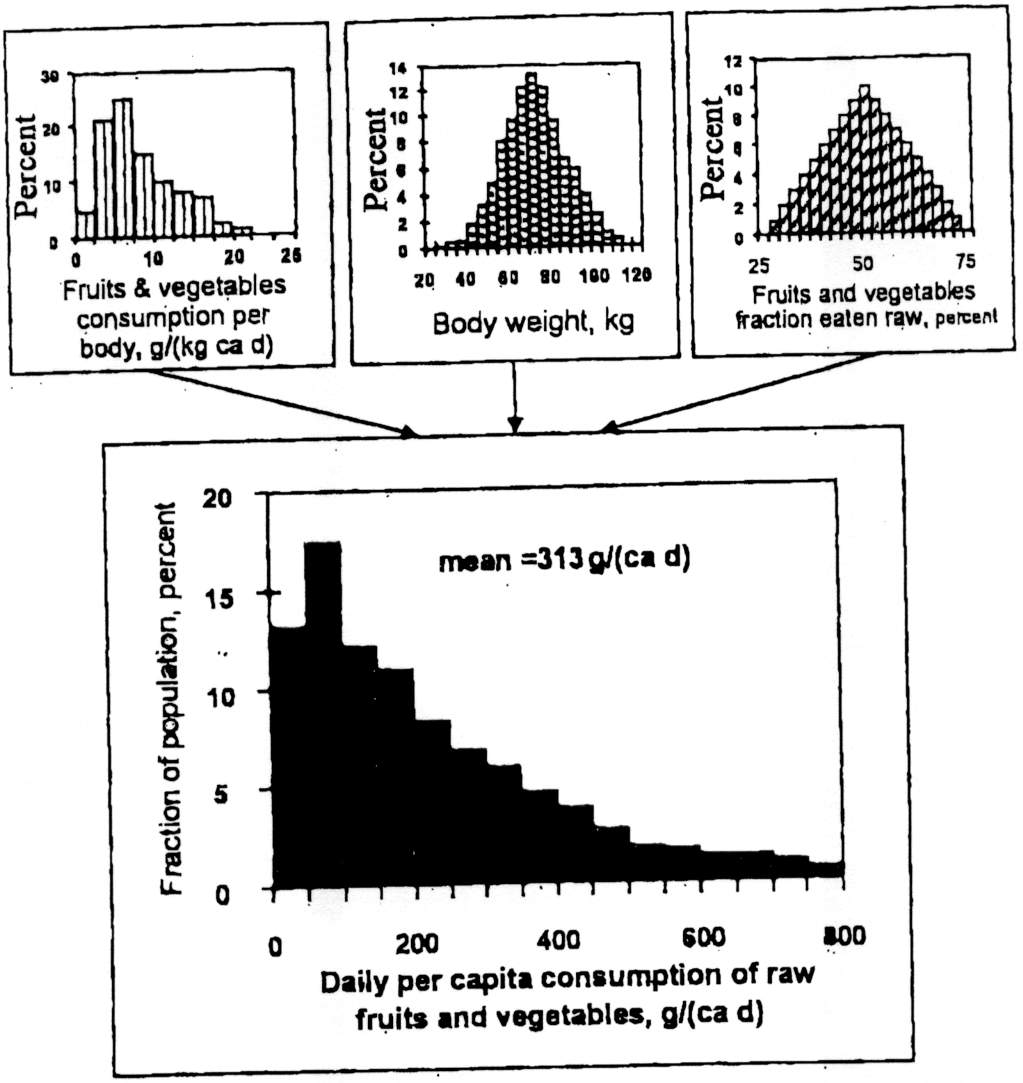

Figure 4. The daily per capita consumption distribution of raw fruits and vegetables as a combined function of body weight, fruits, and vegetables consumption pattern (modified from *EPA* [1997] and *Finley et al.* [1994]).

ent qualities, and various elapsed times. The sample results include the mean annual risks and related standard deviations, and lower and upper confidence limits (Table 2). Consequently, some conclusions can be drawn: (1) The range between the LCL and UCL is 2 orders of magnitude for SI and 3 orders of magnitude for DI and SDI. (2) The UCL for all scenarios with complete wastewater treatment is well below the EPA drinking water guideline. The only other scenario meeting the guideline is the SDI with secondary effluent. (3) Secondary treatment prior to the application for irrigation reduces

Table 2. Annual Risk of Infection for Nine Scenarios Based on 12,000 Computer Runs

Scenario			Annual Risk of Infection			
Code*	Effluent Type	Irrigation Method	Average	Standard Deviation	LCL	UCL
P/si/15	primary	spray	10^{-1}	10^{-1}	10^{-2}	10^{-1}
S/si/15	secondary	spray	10^{-2}	10^{-2}	10^{-3}	10^{-2}
C/si/15	complete	spray	10^{-6}	10^{-6}	10^{-7}	10^{-5}
P/di/15	primary	on-surface drip	10^{-3}	10^{-2}	10^{-5}	10^{-2}
S/di/15	secondary	on-surface drip	10^{-4}	10^{-3}	10^{-6}	10^{-3}
C/di/15	complete	on-surface drip	10^{-8}	10^{-7}	10^{-10}	10^{-7}
P/sdi/15	primary	subsurface drip	10^{-4}	10^{-3}	10^{-6}	10^{-3}
S/sdi/15	secondary	subsurface drip	10^{-5}	10^{-4}	10^{-7}	10^{-4}
C/sdi/15	complete	subsurface drip	10^{-9}	10^{-8}	10^{-10}	10^{-8}

All scenarios are based on an elapsed time between irrigation and consumption of 15 days.

*P, primary; S, secondary; C, complete.

the health risk of wastewater reuse by at least 1 order of magnitude. (4) Complete treatment of effluent prior to the application for irrigation reduces the health risk of wastewater reuse by nearly 4 orders of magnitude. (5) Drip irrigation involves a health risk that is lower by nearly 2 orders of magnitude in comparison with SI. (6) Subsurface irrigation further reduces health risks by at least 1 order of magnitude compared to conventional drip irrigation.

The results obtained from this model show that several practical operational measures should be changed in order to reduce the annual risk of infection in a wastewater reclamation project. Risk analysis only quantifies the health benefits of every operational change. The decision to take one operational measure can also be based on a socioeconomic analysis [*Haruvy*, 1997].

3.3. Virus Removal Efficiency of the Wastewater Treatment System

Several simulation scenarios were examined for varying virus removal treatment efficiencies. Increasing the virus removal efficiency decreases the annual risk (UCL) of infection (Figure 6). For an elapsed time of 15 days between irrigation and consumption the virus removal efficiency must be 4 $\log_{10}$ for SI, 3 $\log_{10}$ for DI, and 2 $\log_{10}$ or less for SDI in order to comply with the EPA guideline ($<10^{-4}$).

3.4. Elapsed Time Between Final Irrigation and Agricultural Product Consumption

A range of scenarios was examined for various elapsed periods between irrigation and consumption, while virus removal efficiency in the wastewater treatment system remained constant at 2 $\log_{10}$. By augmenting the time between the last irrigation and consumption it is possible to decrease the UCL of the annual risk of infection (Figure 7). For a set treatment efficiency of 2 $\log_{10}$ and the conditions set, the elapsed time must be 20 days for SI, 13 days for DI, and approximately 11 days for SDI, according to the calculations, in order to comply with the EPA guideline ($<10^{-4}$).

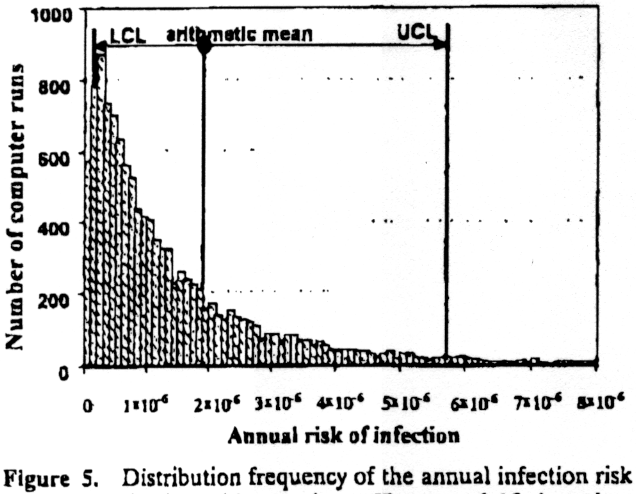

Figure 5. Distribution frequency of the annual infection risk for spray irrigation with complete effluent and 15 days time between harvest and consumption (C/si/15 scenario, based on 12,000 computer runs). UCL and LCL, upper and lower confidence limits.

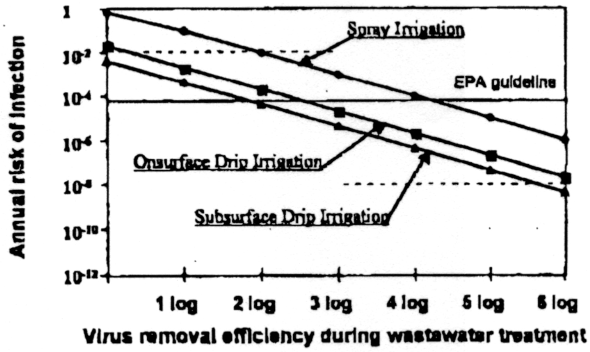

Figure 6. The relationship between annual risk of infection (UCL) and wastewater treatment efficiency (based on 12,000 computer runs). The elapsed time between irrigation and consumption is 15 days for all cases.

3.5. Combining Treatment Efficiencies and Elapsed Times

The concluding modeling was used to examine a broad range of combinations of removal efficiencies in the treatment facilities and elapsed times. These were examined for the three main irrigation methods (Figure 8). One simulation was run for each combination of a virus removal efficiency between 0 $\log_{10}$ and 6 $\log_{10}$ (intervals of 1 $\log_{10}$) and an elapsed time between 0 and 30 days (intervals of 5 days). The results of the numerous simulations show the UCL of the annual risk of infection for SI, DI, and SDI.

4. Discussion and Conclusions

This study assesses the consumers' health risks due to use of agricultural products irrigated with reclaimed wastewater by numerical simulation with the MCSM. It focuses on the influence of wastewater treatment level, application method, irrigation timing, and consumers' behavior on the exposure to enteric viruses.

A model for the assessment of risk of infection associated with wastewater irrigation of edible plants was developed. The model takes into account several criteria: (1) the quality of the applied wastewater, (2) the irrigation method, (3) the time between irrigation, harvest, and subsequent consumption, and (4) consumers' behavior.

Risk assessment is a useful tool to upgrade reclamation

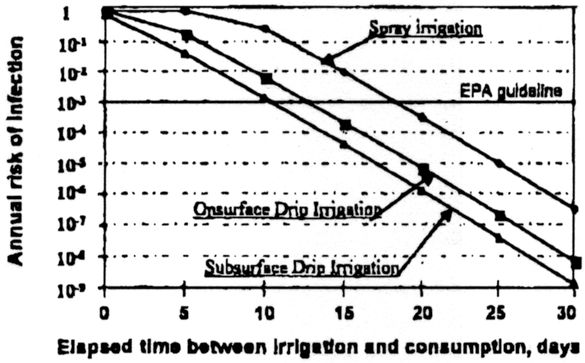

Figure 7. The relationship between annual risk of infection (UCL) and elapsed time between irrigation and agricultural product consumption (based on 12,000 computer runs). The wastewater treatment efficiency is constant at 2 $\log_{10}$.

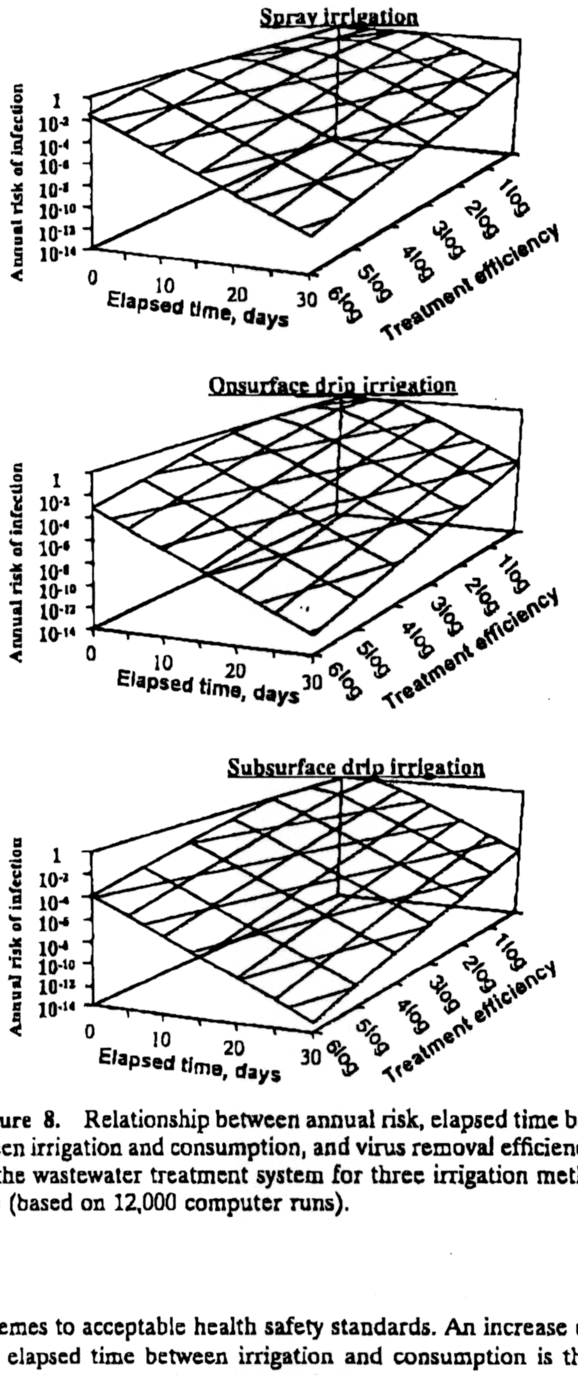

Figure 8. Relationship between annual risk, elapsed time between irrigation and consumption, and virus removal efficiency of the wastewater treatment system for three irrigation methods (based on 12,000 computer runs).

schemes to acceptable health safety standards. An increase of the elapsed time between irrigation and consumption is the most effective operational change (1 order of magnitude per 5 extra days). Other operational improvements are increasing the virus removal efficiency of the wastewater treatment (1-order of magnitude risk reduction for each extra log of removal), and a switch from spray to DI and, primarily, to SDI (2–3-orders of magnitude risk reduction).

There is a 10-order of magnitude difference in the risk of infection between the different exposure scenarios with the same water quality. The large differences in risk of infection between exposure scenarios indicate the need for setting risk-based criteria for wastewater reclamation, rather than a single water quality guideline. Operational practice plays an important role in reducing risk by limiting exposure to pathogens.

The annual risks of infection show large deviations. These broad ranges are probably due to a mix of uncertainty and variability of data. Extra data are required to increase the quality of the input parameters to decrease uncertainty. The distribution of the output parameters then represents the diversity of the populations.

The application of sophisticated mathematical modeling frequently provides some levels of uncertainty. The outcome of a simulation can provide guidelines, which, however, can only seldom be more accurate than the input data. Virus concentrations in wastewater vary from one site to another. The EEV approach for the uptake of viruses tries to bypass this limitation along with the scarce available data. In addition, the information related to human behavior and immunity is also scarce.

The exposure estimate contains less uncertainty than other phases of the risk assessment, especially dose-response modeling. Frequently, the dose-response models may not be very representative for less advanced communities, such as infants and the elderly. These models, however, can be transferable to different private locations after adequate modifications, taking into account immunity and disease tolerance characteristics of the community.

There is currently a trend toward downgrading the risks associated with highly treated wastewater for irrigation of crops, particularly those to be consumed raw. The results of the model point out that even with few $\log_{10}$ reductions, if the irrigation method is such that it leads to a high level of contamination, without adequate lag times between watering and harvesting, then the risks are apparent. Implementing a lag time between effluent application and harvesting is an additional barrier, confirming risk reduction, and should be recommended as a mandatory assessment for all food crops by state federal agencies, thus restricting spray irrigation of reclaimed wastewater and certain crops. This approach certainly could be used by Codex when examining the risks associated with imported agricultural products that are likely to be irrigated with low-quality treated wastewater.

The risk comparison in this study provides information regarding the relative risks. However, it does not provide a standard for risk acceptability. Setting acceptable risk limits that will ensure adequate public health protection is a much more complex task that also includes socioeconomic considerations.

Future related research associated with pathogen risk assessment should include the following: (1) defining the acceptable risk levels, (2) defining dose-response models considering the influence of local circumstances such as immunity on the human response to pathogens, (3) obtaining additional information regarding occurrence and prevalence of pathogens in wastewater and their removal in wastewater treatment, and (4) obtaining additional information regarding the paths of pathogens into and onto the crop through spray irrigation, onsurface drip irrigation, and subsurface drip irrigation.

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and health risk analysis due to consumption of agricultural products irrigated with reclaimed wastewater. The exposure of consumers to contaminants due to wastewater irrigation depends on several factors: (1) the quality of the applied wastewater, (2) the irrigation method, (3) the elapse time between irrigation, harvest, and subsequent product consumption, and (4) consumers' habits. Previous works deal only roughly with the effect of the irrigation method, which is, in practice, one of the key issues for their exposure estimate [*Shuval et al.*, 1997; *Tanaka et al.*, 1998]. Other sources estimate an accidental ingestion of 100 mL of irrigation water per year, without specifying whether this concerns consumers or workers [*Rose et al.*, 1996].

The present study focuses on the risk to consumers of using agricultural products irrigated with reclaimed domestic wastewater. Risks for farmers and workers are not in the scope of this work. The risks associated with microbial aerosol dispersion and the related impact on adjacent living communities have been reported elsewhere [*Applebaum et al.*, 1984; *Ward et al.*, 1989].

2. Implication of the Risk Assessment Approach

2.1. Exposure Model Features

Exposure consists of a series of events in which a person (or a community) is in a close contact with a biological, chemical, or physical agent [*Hammad and Manocha*, 1995]. The prevailing route of exposure to reclaimed wastewater for human consumers is primarily through ingestion. When modeling exposure of a community to a specific phenomenon, regarding wastewater, the following should be considered: (1) wastewater treatment characteristics, (2) the route of virus migration from the irrigation wastewater into and within the plant, (3) virus die-off during the period between last irrigation and agricultural raw product consumption, and (4) the consumption pattern of the population.

The exposure route is commonly based on a human adult whose dietary intake of fruits and vegetables is based entirely on crops irrigated with effluent. The corresponding assumptions are as follows: (1) Only exposure through ingestion is considered. (2) The virus concentration in raw sewage is log-normally distributed. The arithmetic mean is 1000 plaque forming units per liter (PFU L^{-1}), and the standard deviation is 300 PFU L^{-1} [*Rose et al.*, 1996; *Tanaka et al.*, 1998]. (3) The decay of pathogens during storage of effluent before irrigation is part of the treatment system. (4) The total period between final irrigation and consumption equals the time between final irrigation and harvest and the period that the fruits and vegetables are stored between harvest and consumption. (5) No cross-contamination of fruits and vegetables after harvesting is considered. (6) Consumers eat 50% of their diet uncooked, unpealed, and unwashed. A triangular distribution (minimum is 25%; maximum is 75%) is used to express the uncertainty of this estimate (Figure 3).

An exposure model (EM) for assessing the risk associated with consuming agricultural products irrigated with wastewater was developed. The developed EM is based on previous literature data and various field measurements. The EM quantifies the relationship between irrigation wastewater quality and the daily virus dose that consumers ingest. The expected annual risk of infection is estimated stochastically by numerical simulation using the Monte Carlo simulation method (MCSM) and the developed EM. The outcomes of the numerical computations are compared, including the given and obtained risks.

Numerical simulation of exposure scenarios provides the means to express uncertainty and variability of the model input parameters by characterizing them with a distribution pattern. Variability is the impreciseness that occurs because of actual differences among segments of a population. Although the variability is not reduced, it provides additional data, thus increasing the accuracy of the analysis. Uncertainty stems from the limitation in the thoroughness of the measurement of the specific factor [*Finley et al.*, 1994].

The numerical simulation combines treatment characteristics and effluent quality, thus yielding the irrigation quality. The irrigation wastewater quality and the exposure model lead concurrently to the daily virus dose that consumers ingest. The daily risk of infection is then calculated using a dose response model implementing data from literature. Finally, the daily risk of infection is converted into an annual risk of infection taking into account the exposure frequency. The general modeling layout and data-processing procedure are described in Figure 1.

2.2. Monte Carlo Simulation Method (MCSM)

The Monte Carlo simulation method (MCSM) builds up successive scenarios using input values that are randomly selected from probability distributions, commonly utilizing the pertinent computer software. For each run, the software draws one random variable from the distribution for each of the model input variables and computes a single result. A large number of repeated computations produce a complete distribution of the modeled results [*Thompson et al.*, 1992].

The MCSM produces a complete distribution of output variables, of which the arithmetic mean, the standard deviation, the 95% lower confidence limit (LCL), and the 95% upper confidence limit (UCL) are calculated. The expected value is a probability-weighted average of the results generated during a simulation run and equals the average (arithmetic mean) of the generated results. The calculations can be carried out using appropriate software such as the RiskMaster for Windows program (V.1.0C) as an add-on to a Microsoft Excel™ spreadsheet [*RiskMaster*, 1995].

Each simulation is carried out for approximately 12,000 computer runs to guarantee convergence and to make up a representative sample of the near infinite number of combinations of possible input variables. The stability and convergence of the simulation are tested by running two independent simulations of 12,000 runs. The estimated mean, LCL, and UCL agree within 1%. From this it was concluded that 12,000 runs are sufficient to ensure convergence and stability of the output distribution [*Thompson et al.*, 1992].

2.3. Examined Scenarios

The nine initially examined scenarios combine treatment options (primary treatment, secondary treatment, or complete treatment) and a specific irrigation technique (spray irrigation (SI), drip irrigation (DI), or subsurface drip irrigation (SDI)). The elapsed time between irrigation and harvest is assumed to be constant at 15 days.

The combined simulations of the initial nine scenarios with a range of exposure scenarios was conducted in order to analyze the influence of wastewater treatment efficiency, irrigation method, and elapsed time between irrigation and agricultural product consumption on the resulting human health risk. Each scenario is a combination of wastewater treatment efficiency