Estimating the safety of wastewater reclamation and reuse using enteric virus monitoring data

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ABSTRACT: The reliability of wastewater reclamation and reuse to meet a given annual risk of infection, considering the variability of enteric virus concentrations, has been investigated. Two concepts related to the reliability and safety of wastewater reclamation and reuse are presented. The first is *reliability*, defined as the probability that the risk of infection from enteric viruses in reclaimed wastewater does not exceed an acceptable risk. The second is based on the *expectation* of the acceptable annual risk in which the exposure to enteric viruses may be estimated stochastically by numerical simulation.

To assess the potential risks associated with the use of reclaimed wastewater in various reuse applications, four exposure scenarios were tested: golf course irrigation, food crop irrigation, recreational impoundments, and groundwater recharge. Past monitoring data on enteric virus concentrations in unchlorinated secondary effluents in California were used. Because enteric virus concentrations in unchlorinated secondary effluents were found to vary over a wide range, characterizing their variability was found to be extremely important. The reliability criterion of meeting the less than 10^{-4} annual risk of infection (less than or equal to one infection per 10 000 population per year) at least 95% of the time was used to assess the safety of using reclaimed wastewater in the four different exposure scenarios. The methodologies used in this study should be refined, based on a larger enteric virus database developed using standardized field and laboratory protocols. *Water Environ. Res.*, **70,** 39 (1998).

KEYWORDS: enteric viruses, monitoring, inactivation efficiency, reclamation, reuse, risk assessment.

One of the most important issues in wastewater reclamation and reuse is the protection of public health. For this reason, special emphasis is placed on reducing concentrations of pathogenic organisms, including bacteria, parasites, and enteric viruses, in reclaimed wastewater. The need for research, especially on the efficacy of enteric virus inactivation/removal, has been recognized because of these constituents' low-dose infectivity, their long-term survival in the environment, difficulties in monitoring them, and their low removal efficiency in conventional wastewater treatment (Asano and Sakaji, 1990; Dryden *et al.*, 1979; and Gerba and Rose, 1993). The possibility exists that failure may occur with wastewater treatment systems and that enteric viruses may be present even in tertiary-treated effluents. Thus, the proper design and operational reliability of wastewater treatment facilities are of paramount importance to wastewater reclamation and reuse practice.

The objectives of this paper are to investigate: (1) methods that can be used to evaluate the reliability of wastewater reclamation and reuse to meet a given annual risk of infection, considering the variability of virus concentrations; and (2) the comparative safety of various wastewater reuse applications, using the U.S. Environmental Protection Agency's (U.S. EPA's) Surface Water Treatment Rule (SWTR) for domestic water supply as the baseline acceptable risk. The SWTR acceptable risk criterion is interpreted as being equal to or less than one infection per 10 000 population per year (that is, 10^{-4}) from enteric viruses (U.S. EPA, 1989).

Study Approach

In the following analysis, two concepts related to the safety of wastewater reclamation and reuse are considered. The first is *reliability*, defined as the probability that the risk of infection from enteric viruses in reclaimed wastewater does not exceed an acceptable risk. The second concept is based on the *expectation* of the acceptable annual risk, in which the exposure to enteric viruses may be estimated stochastically by numerical simulation. Thus, central to the safety of wastewater reclamation and reuse is the ability to estimate the overall reliability of a given treatment process and related environmental factors as well as the expectation of the acceptable risk under varying enteric virus concentrations.

To determine the concentration and variability of enteric viruses in municipal wastewater, virus monitoring data for unchlorinated secondary effluents from four wastewater treatment plants in California were analyzed, using a log-normal distribution model. The assumption that observed data follow the log-normal distribution was tested by the Kolmogorov–Smirnov goodness-of-fit test. The reliability of wastewater reclamation and reuse was analyzed with respect to the enteric virus inactivation/removal capabilities of various treatment systems. The expectation of annual risk was simulated using Monte Carlo methods (MCMs) and compared with the results of the virus inactivation/removal calculations using four different unchlorinated secondary effluents.

To assess potential risks associated with the use of reclaimed wastewater in various reuse applications, four exposure scenarios (Asano and Sakaji, 1990, and Asano *et al.*, 1992) were tested. The four exposure scenarios—golf course irrigation (scenario I), food crop irrigation (scenario II), recreational impoundments (scenario III), and groundwater recharge (scenario IV)—are summarized in Table 1 and discussed in detail later in the text. Finally, the safety of wastewater reclamation and reuse is compared using two scoring systems, derived from the reliability assessment and the expectation of meeting the SWTR criterion for enteric viruses. However, assessing the appropriateness of the 10^{-4} risk of infection implied in the SWTR criterion document as a measure of safety was beyond the scope of this paper.

Table 1—Summary of exposure scenarios used in the risk assessment.[a]

Application purposes	Risk group receptor	Exposure frequency	Amount of water ingested in a single exposure, mL	Reduction in the environment
Scenario I, golf course irrigation	Golfer	Twice per week	1	Stop irrigation 1 day before playing
Scenario II, crop irrigation	Consumer	Everyday	10	Stop irrigation 2 weeks before harvest and shipment; viral reduction resulting from sunlight
Scenario III, recreational impoundment	Swimmer	40 days per year—summer season only	100	No virus reduction
Scenario IV, groundwater recharge	Groundwater consumer	Everyday	1 000	3 m vadose zone and 6 month retention in aquifer; virus inactivation coefficient = 0.69/d

[a] Adapted from Asano *et al.* (1992).

Background Information

The enteric virus database used in this study, and the virus removal capabilities in various tertiary treatment systems, are summarized in this section.

Enteric Virus Concentrations and Their Variability In Unchlorinated Secondary Effluents. Estimation of the risk of infection, based on grab samples from tertiary-treated effluents, whose enteric virus concentrations are almost always below the detection limit, cannot be used to quantify the safety of wastewater reclamation and reuse (Asano *et al.*, 1992). Thus, the enteric virus database used in this study included 377 unchlorinated secondary effluent samples in which 242 samples (64%) were positive, as reported in Table 2. The main purpose of virus monitoring at the four facilities was to ensure that virtually no enteric viruses could be found in the tertiary effluents to be used for unrestricted wastewater reuse. The effluents were to be in compliance with the most stringent requirements for the total coliform group of bacteria specified in the California Wastewater Reclamation Criteria (State of California, 1978).

Quantifying virus concentrations is necessary for estimating the risk of infection resulting from exposure to reclaimed wastewater. All of the observed data in Table 2 are plotted in Figure 1. The distributions of many pollutants in wastewater treatment plant effluents have been found to follow the normal distribution or the log-normal distribution (Asano and Wassermann, 1979; Dean, 1981; Dean and Forsythe, 1976; and Niku *et al.*, 1982). The statistical models considered in this study were the normal distribution and the log-normal distribution. The data reported as negative values were estimated, as they are below the detection limits. Although these data points cannot be plotted on the graph, they were used to calculate the empirical cumulative density function (CDF). The goodness-of-fit of the hypothesized distribution was evaluated using the nonparametric Kolmogorov–Smirnov test (Benjamin and Cornell, 1970; Hogg and Tanis, 1988; and Niku and Schroeder, 1981). At the 10% significance level (Benjamin and Cornell, 1970), it was found that the empirical CDFs followed the log-normal rather than the normal distribution. Thus, the log-normal distribution was

Table 2—Summary of the enteric virus data used in this study (unchlorinated secondary effluents).

California agency	Facility	Study period	Type of secondary treatment	Samples, no.	Positive samples, no.
Orange County Water District[a] (OCSD TF)	County Sanitation Districts of Orange County, plant no. 1	1975–1978	Trickling filter	145	109
Orange County Water District[a] (OCSD AS)	County Sanitation Districts of Orange County, plant no. 1	1978–1981	Activated sludge	105	53
County Sanitation Districts of Los Angeles County[b] (Pomona AS)	Pomona	1975	Activated sludge	60	27
Monterey Regional Water Pollution Control Agency[c] (MRWPCA AS)	Castroville	1980–1985	Activated sludge	67	53
Total				377	242

[a] Adapted from McCarty *et al.* (1978, 1980, and 1982).
[b] Adapted from CSDOLAC (1977).
[c] Adapted from Engineering-Science (1987).

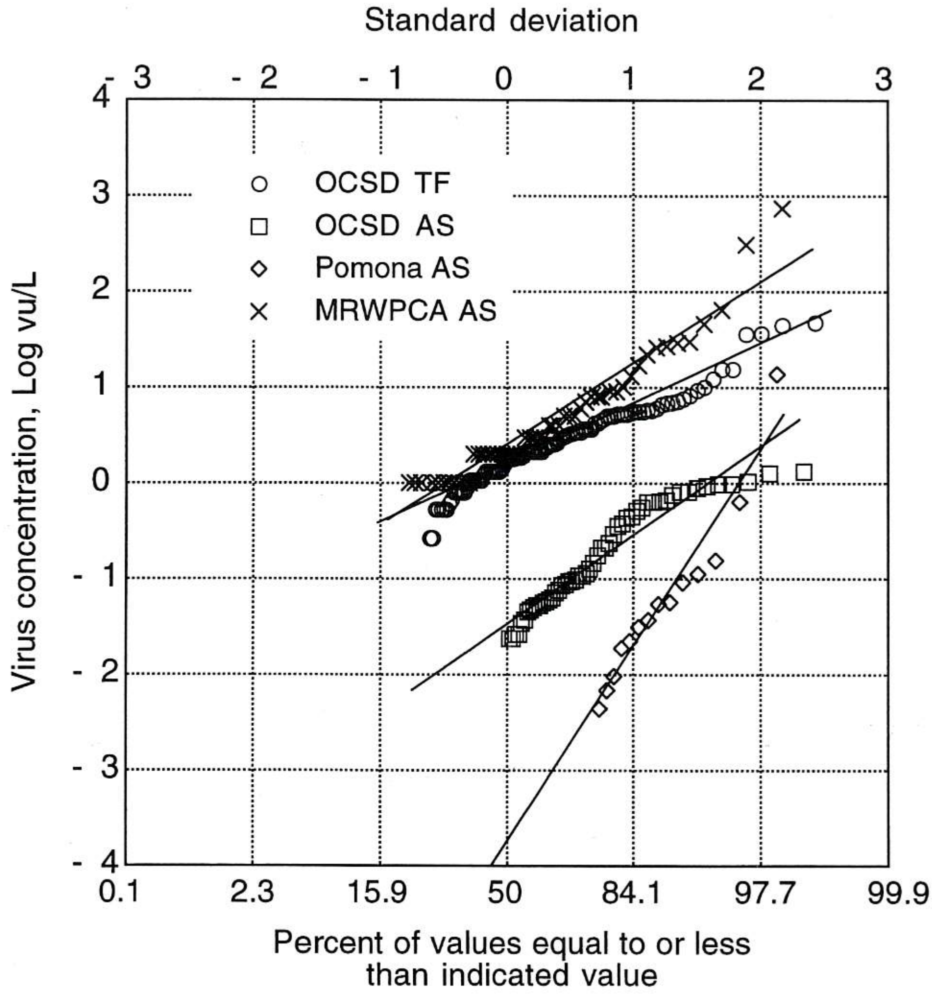

Figure 1—Cumulative distribution function of virus concentrations in unchlorinated secondary effluents.

used in this study as the statistical model for virus concentrations in unchlorinated secondary effluents. The estimated parameters for the log-normal distribution model of the enteric virus concentrations, obtained using regression analysis, are reported in Table 3.

Based on the results of the analyses, presented in Table 3 and Figure 1, it can be concluded that the virus concentrations vary over a wide range in unchlorinated secondary effluents. Furthermore, virus concentrations in different wastewater treatment plants varied widely. For example, the geometric means of the virus concentrations ranged over four orders of magnitude (10^{-4} to 10^{0} vu/L), and the spread factors ranged approximately from 4 to 115. Thus, consideration of the variability of enteric virus concentrations, as well as the site-specific nature of the distribution of viruses in unchlorinated secondary effluent, is extremely important in virus risk analysis.

Virus Inactivation/Removal Capabilities in Various Treatment Systems. To protect public health, considerable effort has been invested since the 1960s to establish baseline conditions and regulations that would allow for the safe use of reclaimed wastewater. One of the landmark studies conducted to verify the efficacy of wastewater treatment systems was the Pomona Virus Study (CSDOLAC, 1977; Dryden *et al.*, 1979; and Miele and Selna, 1977). In this study, the performances of tertiary treatment processes consisting of coagulation, flocculation, sedimentation, filtration, and disinfection (designated as full-treatment in this paper), and the alternative, contact filtration, were evaluated as summarized in Table 4. When the residual chlorine concentration was 10 mg/L, both treatment processes removed approximately 5.2 logs of seeded poliovirus. When residual chlorine was approximately 5 mg/L, the full treatment still removed 5.2 logs, but contact filtration removed approximately 4.7 logs. When secondary effluent was chlorinated, the inactivation/removal efficiency of secondary treatment alone was 3.9 logs at a 9-mg/L residual chlorine dose (CSDOLAC, 1977). In all cases, the chlorine contact time was 2 hours.

Performance and Reliability Analyses

As noted in the previous section, the variability of virus concentrations in unchlorinated secondary effluent is large; thus, it becomes difficult to select appropriate virus concentrations to use in the subsequent risk calculations. The geometric means of the observed virus data have been reported in several earlier studies (Haas, 1983b; McCarty *et al.*, 1978; and Olivieri *et al.*, 1989). If the distributions of virus concentrations are assumed

Table 3—Estimated parameters for the log-normal distribution of virus concentrations in unchlorinated secondary effluent.[a]

		California agencies[a]			
Estimated parameters	**Symbols**	**OCSD TF**	**OCSD AS**	**Pomona AS**	**MRWPCA AS**
Arithmetic mean[b] of log C	μ	0.15	−1.47	−3.81	0.37
Standard deviation of log C	σ	0.63	0.91	2.06	0.86
Geometric mean[c] of C	m_g	1.4	0.034	0.000 2	2.32
Spread factor[d] of C	S	4.27	8.13	114.82	7.24
Correlation factors	R^2	0.963	0.962	0.934	0.940
Number of samples used for regression analysis		99	52	14	53
Number of samples used for calculation of empirical CDF		135	105	60	67
Estimated C in given percentile	50%	1.4	0.034	0.000 2	2.3
	90%	8.9	0.5	0.34	29
	95%	15	1.1	3.0	59

[a] Refer to Table 2.
[b] C denotes enteric virus concentrations expressed as viral units per litre (vu/L).
[c] Geometric mean, m_g, is defined as $m_g = 10^{\mu}$.
[d] Spread factor, S, is defined as $S = 10^{\sigma}$.

to follow the log-normal distribution, their geometric means are equal to the 50th percentile. However, the 50th percentile value in the probability analysis may not be acceptable with respect to public health protection, given the knowledge that any risk of infection derived from this value will be exceeded 50% of the time. Risk estimated from the observed maximum concentration would be conservative. However, it should be noted that the maximum value may depend on sample size and time of observation.

Estimation of Reliability. Several researchers have attempted to estimate the effectiveness of pathogen inactivation/removal in water and wastewater treatment processes and the fate of pathogens in the environment, using risk assessment methodologies (Asano and Sakaji, 1990; Asano *et al.*, 1992; Gerba and Haas, 1988; Gerba and Rose, 1993; Haas, 1983b; Hutzler and Boyle, 1980 and 1982; Olivieri *et al.*, 1989; and Rose and Gerba, 1991). One method of determining the relative safety of wastewater reclamation and reuse is to estimate the time during which a risk of infection from enteric viruses in reclaimed wastewater does not exceed an acceptable level. Niku and Schroeder (1981) applied the concept of reliability to the operation of wastewater treatment plants. They defined the reliability of operation as the probability of time when a failure does not occur. Using similar reasoning, failure in this study is defined as the time during which the risk of infection from enteric viruses in reclaimed wastewater exceeds an acceptable level (that is, 10^{-4}), and the reliability of wastewater reclamation and reuse is the probability of time when the failure does not occur. In this context, the reliability of wastewater reclamation and reuse is defined as the probability that the risk of infection resulting from the ingestion of enteric viruses in reclaimed wastewater does not exceed the acceptable level. To estimate the reliability of wastewater reclamation and reuse, a three-step process is involved, as outlined below.

Step 1. The first step is to determine the concentration of enteric viruses that constitutes an acceptable risk in the use of reclaimed wastewater. The acceptable annual risk of infection, Pa, can be estimated using Equation 1, where Pa^* is the acceptable daily risk and n denotes number of exposure events in a year.

$$Pa = 1 - (1 - Pa^*)^n \tag{1}$$

Solving Equation 1 for Pa^*, the acceptable daily risk, yields

$$Pa^* = 1 - (1 - Pa)^{1/n} \tag{2}$$

When a person ingests a volume, V (L), of reclaimed wastewater containing an enteric virus concentration C (vu/L), a single exposure dose, D, for this event is

$$D = CV \tag{3}$$

Table 4—Comparison of full treatment and direct filtration in the Pomona Virus Study (CSDOLAC, 1977).

Treatment process	**Full treatment (Title 22)**	**Contact filtration**
Coagulation	Alum: 150 mg/L Anionic polymer: 0.2 mg/L	Alum: 5 mg/L Anionic polymer: 0.06 mg/L
Flocculation	1 hour	—
Sedimentation	Conventional	—
Filtration	Granular medium	Granular medium
Disinfection	Chlorine: 10 and 5 mg/L residual with 2-h contact time	Chlorine: 10 and 5 mg/L residual with 2-h contact time

Two dose-response relationships used commonly to estimate the acceptable daily exposure virus concentration, Ca^*, associated with the given acceptable daily risk, Pa^*, are as follows:

Single-hit exponential model: $Ca^* = -\ln(1 - Pa^*)/\gamma V$ (4)

Beta-distributed probability model:

$$Ca^* = [(1 - Pa^*)^{-1/\alpha} - 1]\beta/V \quad (5)$$

where α, β, and γ are model parameters estimated from actual infection data when actual pathogens are administered.

A similar methodology was used to estimate *Giardia* cyst density in domestic water supply systems complying with the SWTR (Gerba and Haas, 1988; Gerba and Rose, 1993; Regli *et al.*, 1991; and Rose and Gerba, 1991). The beta-distributed probability model was chosen for use in this study because it best represented the frequency distribution of infection for enteric viruses (Asano and Sakaji, 1990; Haas, 1983a; and Rose and Gerba, 1991)

Step 2. In the second step, the probability that the daily risk resulting from exposure to reclaimed wastewater in various applications satisfies the acceptable daily risk is estimated. Using the log-virus removal during tertiary treatment, R, the virus concentration, Ct, in the tertiary-treated reclaimed wastewater can be calculated from the enteric virus concentration, Cs, in the unchlorinated secondary effluent:

$$Ct = Cs10^{-R} \quad (6)$$

If Cs follows a log-normal distribution, as shown in Figure 1 and summarized in Table 3, and R is constant, Ct also follows a log-normal distribution.

The ultimate enteric virus concentration in reclaimed wastewater to be ingested will be affected by environmental factors such as dilution, sorption, and die off. These environmental factors are lumped together, and the environmental inactivation/removal efficiency for enteric viruses, E, is defined as a fraction of enteric viruses remaining after the environmental exposure. Thus, the virus concentration in the ingested wastewater, C^*, in various reclaimed wastewater applications, is calculated as follows:

$$C^* = CtE = Cs10^{-R}E \quad (7)$$

If the distribution of virus concentrations in unchlorinated secondary effluents is known, the probability of time when the observed virus concentration in reclaimed wastewater does not exceed a given virus concentration can be determined. For the log-normal distribution, the probability that a virus concentration in the reclaimed wastewater does not exceed a given virus concentration, Co, can be calculated using Equation 8:

$$\text{Prob}\ [C^* \le Co] = \text{Prob}\ [Cs \le Co10^{R}/E] = \Phi\{[\log\ (Co10^{R}/E) - \mu]/\sigma\} \quad (8)$$

where Φ is the standardized normal function (Hogg and Tanis, 1988).

The probability of time that the risk of infection from enteric viruses in reclaimed wastewater is less than acceptable has been defined previously as the reliability p. Thus, the probability of ingesting a virus concentration, C^*, that is smaller than the acceptable virus concentration, Ca^*, is equivalent to the reliability of wastewater reclamation and reuse, p, which can be expressed as follows:

$$p = \text{Prob}\ [P \le Pa] = \text{Prob}\ [C^* \le Ca^*] \quad (9)$$

where P is an annual risk resulting from the exposure to reclaimed wastewater.

Using Equations 6 and 7, the reliability of wastewater reclamation and reuse, p, can be determined from the distribution of virus concentrations in unchlorinated secondary effluent, Cs.

$$p = \text{Prob}\ [Cs \le Ca^*10^{R}/E] \quad (10)$$

Reliability p is computed using the following relationship:

$$p = \Phi[(\log\ (Ca^*10^{R}/E) - \mu)/\sigma] = \Phi[(\log Ca^* + R - \log E - \mu)/\sigma] \quad (11)$$

Step 3. The third step involves the selection of an acceptable risk of infection. The reference used in this study, as noted previously, is the U.S. EPA's SWTR for domestic water supply. If the reliability of wastewater reclamation and reuse is the same as the reliability of domestic water supply in meeting the enteric virus removal criterion and the risk of infection, reclaimed wastewater is deemed to be as safe as drinking water.

Relationships between Reliability and Virus Inactivation/ Removal Efficiency. By substituting the acceptable daily virus exposure concentration, Ca^*, the values of μ and σ from Table 3, and the environmental inactivation/removal efficiency of enteric viruses, E, into Equation 11, the relationship between the log-virus removal during tertiary treatment, R, and the reliability of wastewater reclamation and reuse, p, can be established. The relationship between R and p for scenarios I, II, and III, identified in Table 1, has been determined, and the results are plotted in Figure 2. The rotavirus model with dose-response model parameters ($\alpha = 0.232$, $\beta = 0.247$), used by Rose and Gerba (1991), was also used for this calculation. The reliability of wastewater reclamation and reuse with scenario IV, groundwater recharge with reclaimed wastewater, is not shown in Figure 2 because the reliability requirement is always met without tertiary treatment for all effluents from the treatment facilities reported in Table 1.

If wastewater reclamation and reuse is implemented with unchlorinated secondary effluents without tertiary treatment ($R = 0$, that is, no log removal), the reliability is so low that additional on-site mitigation measures will be required, even for golf course irrigation (scenario I). If the inactivation/removal efficiency in tertiary treatment is increased to 5 logs (that is, 99.999% removal), wastewater reclamation and reuse with all exposure scenarios (scenarios I through IV) will become as safe as the use of domestic water supply because the reliability is essentially 100%.

If using reclaimed wastewater is to be as safe as using a domestic water supply, with respect to the risk of enteric virus infection, the required virus removal efficiency in tertiary treatment is determined in the reverse way to how reliability is calculated, using Equation 12, the rearranged form of Equation 11:

$$R = \sigma\Phi^{-1}(p) + \mu + \log E - \log Ca^* \quad (12)$$

where Φ^{-1} represents the inverse standardized normal function. The procedure necessary to determine the required inactivation/ removal efficiency is illustrated in Figure 3.

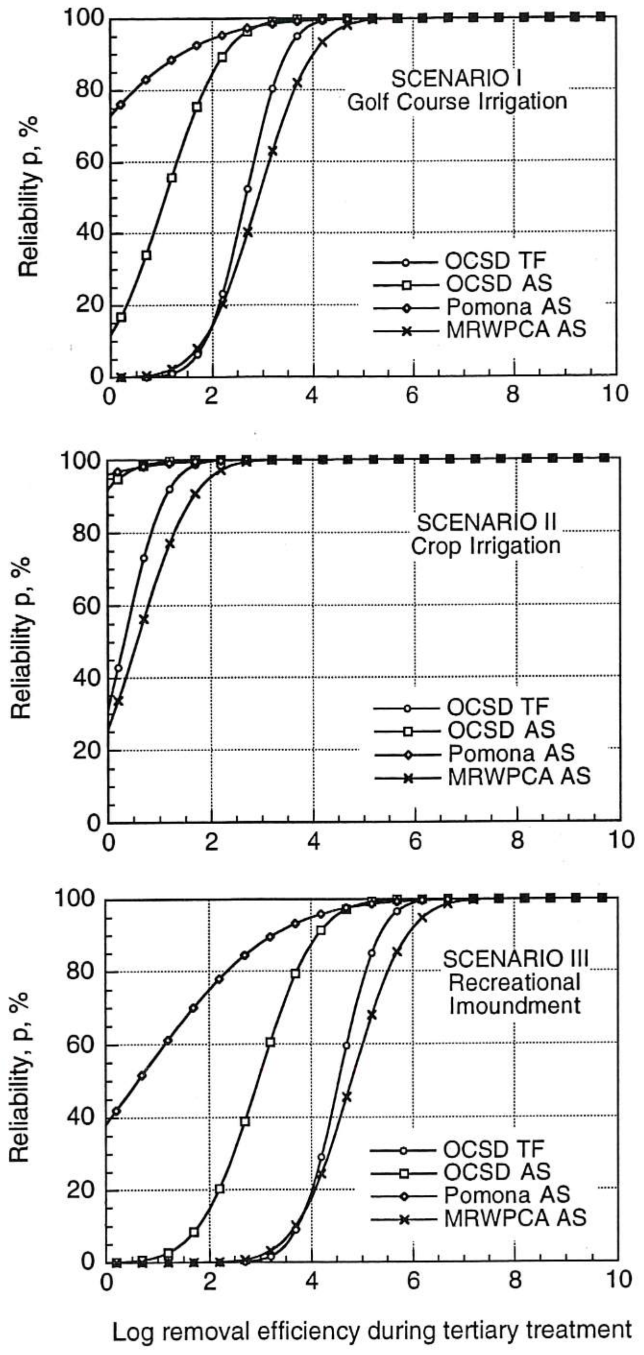

Figure 2—Relationships between reliability and removal efficiency for tertiary treatment for various exposure scenarios.

Reliability Requirements in Wastewater Reuse

Exposure dose (intake volume times the concentration of enteric virus in the ingested water), frequency of exposure, and environmental decay/fate are assessed for each exposure scenario in this section (see Table 1).

Virus Inactivation/Removal Efficiency Required in Tertiary Treatment. If the acceptable annual risk of infection from enteric viruses in reclaimed wastewater is on the order of 10^{-4} at least 95% of time, acceptable virus concentration Ca^* can be calculated using Equations 2 and 5. If reclaimed wastewater is to be as safe as a domestic water supply that meets the SWTR for enteric viruses, the required virus inactivation/removal in tertiary treatment can be calculated using Equation 12. A summary of calculations for the reliability requirement by tertiary treatment (for example, filtration and disinfection), if 1 enteric virus infection per 10 000 population per year is met 90 or 95% of the time, is presented in Table 5.

Reliability of Meeting California's Wastewater Reclamation Criteria (Title 22). If inactivation/removal efficiencies are applied to the unchlorinated secondary effluents given in Tables 2 and 3, the distribution of virus concentrations in reclaimed wastewater after full treatment and contact filtration can be predicted. The reliability of wastewater reclamation and reuse when the specific inactivation/removal capabilities of the tertiary treatment used in the Pomona Virus Study are applied has been simulated, and the results are given in Table 6, assuming that the exposure scenarios remain the same as those reported in Table 1. For golf course irrigation (scenario I), food crop irrigation (scenario II), and groundwater recharge (scenario IV), the reliability of wastewater reclamation and reuse is such that more than 95% of the time the SWTR criterion is met for systems I and III (see Table 6) for all of the effluents studied. However, for recreational impoundments (scenario III), the reliability of wastewater reclamation and reuse is not as high as with the use of domestic water supplies complying with the SWTR criterion even for systems I and III. It is noted that maintaining a high-quality secondary effluent equivalent to the Orange County Sanitation District activated-sludge (OCSD AS) and the Pomona AS is necessary for recreational impoundments

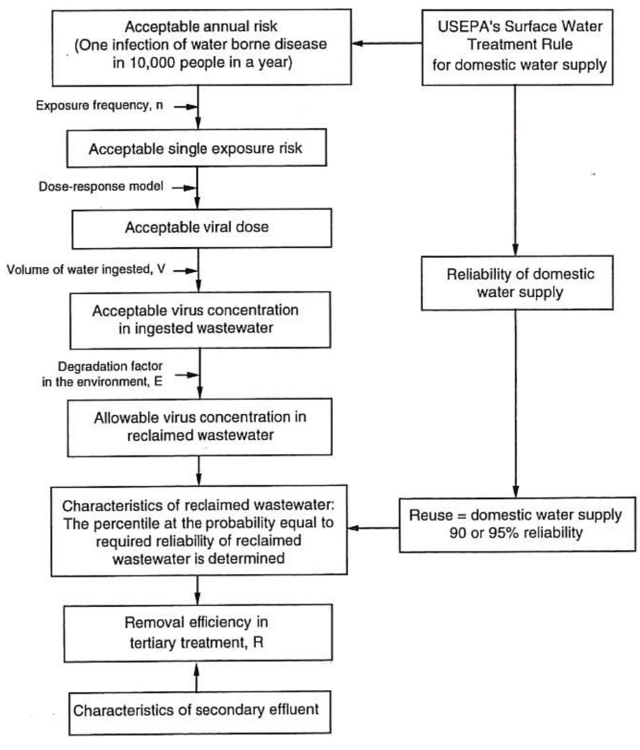

Figure 3—Procedures for determining required virus removal efficiency in tertiary treatment that is comparable in safety to domestic water supply.

Table 5—Required log removal of enteric viruses by tertiary treatment (filtration and disinfection) if one enteric virus infection per 10 000 population per year is met 90 or 95% of the time.

Treatment process	Reliability, % of time							
	Scenario I, golf course irrigation		Scenario II, crop irrigation		Scenario III, swimming		Scenario IV, groundwater recharge	
	90	95	90	95	90	95	90	95
OCSD TF	3.6	3.9	1.3	1.5	5.5	5.8	0.0	0.0
OCSD AS	2.4	2.7	0.0	0.4	4.3	4.6	0.0	0.0
Pomona AS	1.5	2.3	0.0	0.0	3.4	4.2	0.0	0.0
MRWPCA AS	4.2	4.5	1.8	2.1	6.0	6.4	0.0	0.0

where full-body contact such as swimming may take place. Otherwise, more efficient treatment than full treatment or a contact filtration system with a high chlorine dosage may be necessary. In contrast to recreational impoundments, where full-body contact may take place, risk of infection from enteric viruses in the groundwater recharge application (scenario IV) is still negligible, even if secondary effluent without chlorination is used.

The effects of failure in achieving the prescribed removal efficiency in tertiary treatment, as shown in Table 6, can be examined by referring to Figure 2. If systems I, II, and III failed in their respective removal efficiencies, the effect of not achieving the prescribed removal efficiency is not the same among the four exposure scenarios. For example, the geometric mean of the removal efficiency for system I was 5.2 logs. If the removal efficiency were reduced by 1 log to 4.2 logs because of inefficient operation of coagulation or disinfection, the reliability for the Monterey Regional Water Pollution Control Agency (MRWPCA) AS process, for example, may be reduced from nearly 100% to 90% for golf course irrigation (scenario I), while the reliability in recreational impoundments (scenario III) may drop to as low as 25%. Thus, failure of the treatment system would have more serious consequences for recreational impoundments where full-body contact could occur.

Variation in Virus Concentrations and Expected Risk of Infection

The preceding risk assessment method was used to evaluate reliability compliance with different exposure scenarios (see Tables 5 and 6) using the enteric virus data reported in Table 3. The risk evaluation method, however, does not describe the extent of risk associated with wastewater reclamation and reuse when the risk actually exceeds the acceptable annual risk of infection. Theoretically, the risk of virus infection might occur, even if the reliability of wastewater reclamation and reuse is extremely high, because the virus concentrations in reclaimed wastewater can take any value between zero and infinity, owing to the characteristics of the log-normal distribution. Although

Table 6—Reliability of wastewater reclamation and reuse when Pomona Virus Study results are applied to various unchlorinated secondary effluents.

Treatment process	Secondary effluent	Reliability, %			
		Scenario I	Scenario II	Scenario III	Scenario IV
System I					
Full-treatment/contact filtration with high chlorine (5.2 logs)	OCSD TF	100	100	77	100
	OCSD AS	100	100	99	100
	Pomona AS	100	100	98	100
	MRWPCA AS	99	100	62	100
System II[a]					
Direct chlorination of secondary effluent (3.9 logs)	OCSD TF	95	100	10	100
	OCSD AS	100	100	81	100
	Pomona AS	99	100	93	100
	MRWPCA AS	84	100	11	100
System III					
Contact filtration with low chlorine (4.7 logs)	OCSD TF	100	100	48	100
	OCSD AS	100	100	96	100
	Pomona AS	100	100	97	100
	MRWPCA AS	97	100	39	100

[a] System II is an application of chlorinated secondary effluents in various wastewater reuse applications, where 3.9 logs of enteric viruses are inactivated/removed.

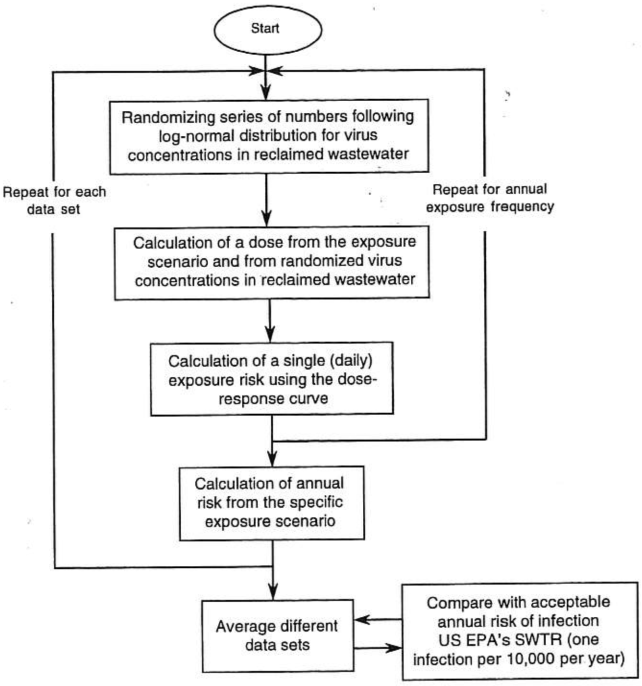

Figure 4—Schematic diagram for simulation of annual risk of infection using MCM.

the likelihood of events exceeding the established acceptable annual risk of infection might be small in the case of relatively high reliability, the risk might be extremely high compared to the acceptable risk. In other words, the annual risk of infection might exceed the established acceptable risk by a large extent because of a small number of extraordinary events.

To assess the effects of variations in enteric virus concentrations, an expected value (expectation) is computed using MCMs to quantify how often, and to what extent, the risk of infection exceeds the acceptable annual risk. Because concentrations of enteric viruses in unchlorinated secondary effluents, *Cs*, follow a log-normal distribution (see Figure 1 and Table 3), log-normally distributed virus concentrations in secondary effluents are simulated using the MCM, and the expected values of the annual risk of infection are computed. A schematic diagram depicting the procedure followed in the risk calculations using the MCM is shown in Figure 4.

Expectation of Annual Risk. *Expectation* is defined in this paper as an average value of the risks for many exposure events, considering their frequencies. As reported previously in Table 3, the log-normal distribution of enteric virus concentrations in unchlorinated secondary effluents was determined with corresponding parameters μ and σ. By randomly selecting from a pool of numbers that follow a log-normal distribution (Devroye, 1986, and Newman and Odell, 1971), a typical daily virus concentration in unchlorinated secondary effluent, *Cs*, can be computed. Using the computed value, a single-exposure risk of infection caused by enteric viruses, $P^*(D)$, can be determined using Equations 3 and 6 and the following beta-distributed dose–response relationship (Haas, 1983a):

$$P^*(D) = 1 - (1 + D/\beta)^{-\alpha} \qquad (13)$$

Annual risk Pa is calculated with variable daily risks, where D_i represents the ingested dose in the ith exposure event:

$$Pa = 1 - \prod_{i=1}^{n} [1 - P^*(D_i)] \qquad (14)$$

The expected value of Pa changes depending on the single exposure risk of infection caused by enteric viruses, $P^*(D)$, and the exposure frequency, n, used in the simulation as given by Equation (15):

$$E(Pa) = E\left[1 - \prod_{i=1}^{n} [1 - P^*(D_i)\right]$$
$$= 1 - E\left[\prod_{i=1}^{n} [1 - P^*(D_i)\right] \qquad (15)$$

where n is the frequency of exposures in a year.

Using MCM, the expected annual risk is calculated in the following steps: (1) simulate an enteric virus concentration in reclaimed wastewater by random number generation, (2) calculate a single-exposure risk caused by the reclaimed wastewater using the dose–response curve, (3) repeat the previous two steps for each exposure occurring in a year, (4) calculate annual risk of infection based on the calculated single-exposure risk, and (5) repeat these steps in a number of different data sets and take an arithmetic mean of Pa. The generated virus concentrations using a random number generator and MCM (500 trials were run for each wastewater treatment plant) are plotted in Figure 5. As an example, the result for golf course irrigation using tertiary treatment effluent from OCSD trickling filter (TF) is illustrated in Figure 6, in which the frequency distribution for the annual risk of infection and the 95% lower confidence limit (LCL) and upper confidence limit (UCL) are shown. Although the expected value in this case is 1.1×10^{-6}, the calculated risks are distributed in the range of 8.0×10^{-7} to 1.7×10^{-6}. Ideally, the variation of the simulated annual risk of infection should also be considered in the assessment of the reliability of wastewater reclamation and reuse.

The expectations for the annual risk of infection from wastewater reclamation and reuse in various exposure scenarios are summarized in Table 7. If the reliability of wastewater reclamation and reuse is determined by whether the expected value of the annual risk is equal to or less than 10^{-4} 95% of the time (the SWTR criterion), the wastewater reuse practices are deemed to be as safe as using the domestic water supply. The expectations of annual risk with full treatment or contact filtration and high chlorine dose (system I) are less than 10^{-4} in golf course irrigation, food crop irrigation, and groundwater recharge (exposure scenarios I, II, and IV), regardless of the quality of secondary effluent. For unrestricted recreational impoundment where swimming may take place, the expectation of an annual risk slightly exceeding the risk requirement imposed in this study may exist, as shown in Table 7. If unchlorinated secondary effluent without any further treatment is used for the variety of wastewater reuse applications, the expected annual risk, as might be expected, is much higher than the acceptable annual risk, except for groundwater recharge. The ranges of simulated annual risk are tabulated in Table 8 with respect to 95% UCL.

Discussion

From the results of the analyses presented in Tables 7 and 8, the reliability or relative safety of wastewater reclamation

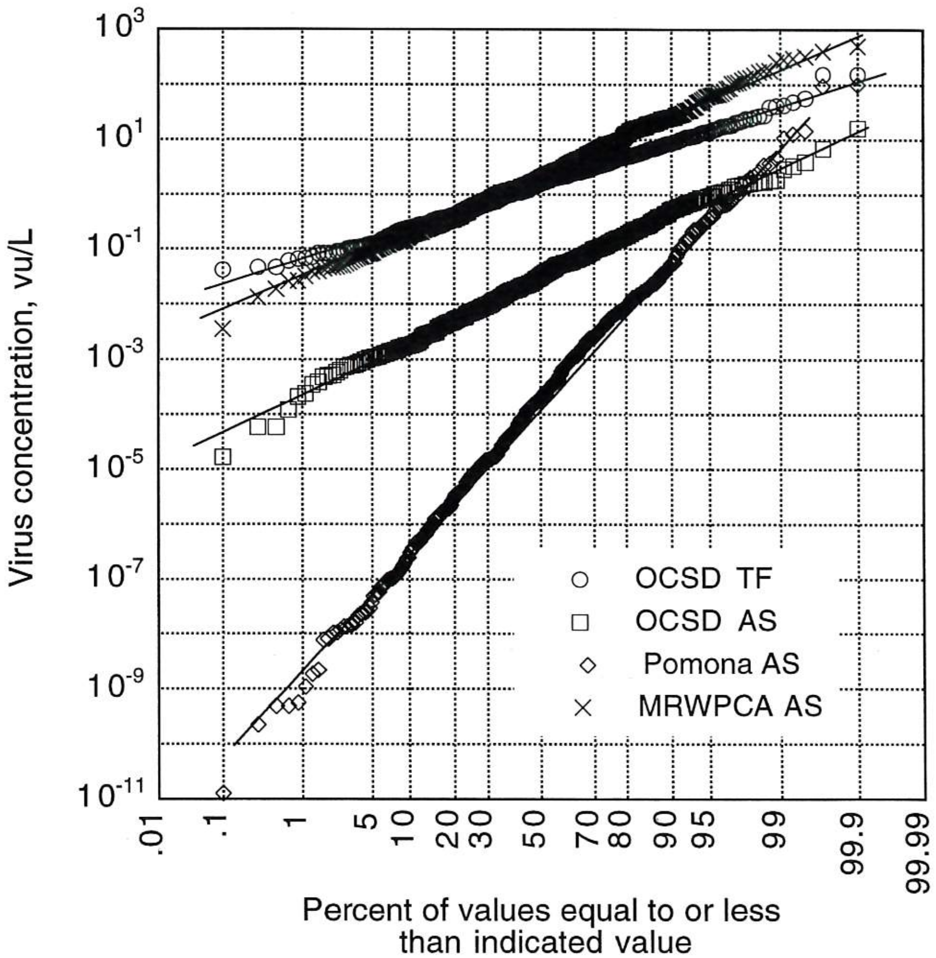

Figure 5—Generated virus concentrations using a random number generator and MCM simulation (based on 500 trials).

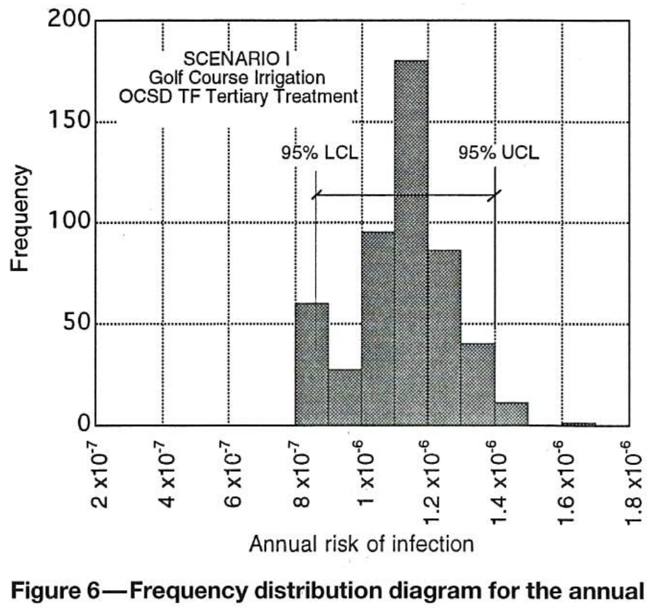

Figure 6—Frequency distribution diagram for the annual risk of infection for golf course irrigation using tertiary treatment effluent (based on 500 trials).

and reuse can be assessed using a combination of scoring systems derived from the reliability measures (Table 9, A) and the expectation (B) of the acceptable annual risk of infection from enteric viruses in reclaimed wastewater. Such a scoring system is shown in Table 9. If the acceptable annual risk of infection is 1 infection per 10 000 population (that is, 10^{-4}), the reliability of four different exposure scenarios can be evaluated by using a simple scoring system consisting of very good, O; good, ∅; unsatisfactory, △; and risky, X, corresponding to reliability values of greater than or equal to 95, 90, 85, and less than 85%, respectively. For annual expectation estimates, simulated by MCM, the scoring system consisting of expectation values of less than or equal to 5×10^{-5} risk of infection is denoted with O; less than or equal to 10^{-4} is denoted with ∅; up to 5×10^{-4} is denoted with △; and more than 5×10^{-4} is denoted with X.

When the full-treatment effluent from OCSD TF and the chlorinated secondary effluent from Pomona AS are used for recreational impoundment (scenario III), assessments based on the reliability and the expectation estimates resulted in different conclusions. For unrestricted recreational impoundments (scenario III) using system I effluents, the OCSD TF and the MRWPCA AS effluent could not meet the acceptable risk of infection criterion based on either reliability or expectation (see Table 9). To protect public health, the 95% UCL may be used

Table 7—Expectations of annual risk of infection simulated using a Monte Carlo simulation (n = 500 trials).

Tertiary treatment		Treatment system: OCSD TF	OCSD AS	Pomona AS	MRWPCA AS
System I					
Full treatment (5.2-log inactivation/removal)	Scenario I	1.1×10^{-6}	7.8×10^{-8}	2.9×10^{-7}	4.3×10^{-6}
	Scenario II	5.0×10^{-9}	3.5×10^{-10}	1.3×10^{-9}	1.9×10^{-8}
	Scenario III	8.6×10^{-5}	5.9×10^{-6}	2.2×10^{-5}	3.3×10^{-4}
	Scenario IV	1.0×10^{-59}	7.3×10^{-61}	2.1×10^{-60}	4.1×10^{-59}
	Scenario IV	7.1×10^{-13} [a]	4.3×10^{-14} [a]	1.8×10^{-13} [a]	2.7×10^{-12} [a]
System II					
Direct chlorination of secondary effluent (3.9-log inactivation/removal)	Scenario I	2.3×10^{-5}	1.6×10^{-6}	5.7×10^{-6}	8.7×10^{-5}
	Scenario II	1.0×10^{-7}	6.9×10^{-9}	2.5×10^{-8}	3.9×10^{-7}
	Scenario III	1.7×10^{-3}	1.2×10^{-4}	4.3×10^{-4}	6.6×10^{-3}
	Scenario IV	2.1×10^{-58}	1.9×10^{-59}	4.3×10^{-59}	8.1×10^{-58}
	Scenario IV	1.4×10^{-11} [a]	9.7×10^{-13} [a]	3.6×10^{-12} [a]	5.4×10^{-11} [a]
System IV					
Unchlorinated secondary effluent (0-log inactivation/removal)	Scenario I	1.6×10^{-1}	1.2×10^{-2}	3.8×10^{-2}	4.4×10^{-1}
	Scenario II	8.0×10^{-4}	5.5×10^{-5}	2.0×10^{-4}	3.1×10^{-3}
	Scenario III	1.0×10^{0}	4.6×10^{-1}	3.2×10^{-1}	1.0×10^{0}
	Scenario IV	3.2×10^{-57}	2.2×10^{-58}	6.5×10^{-58}	1.3×10^{-56}
	Scenario IV	1.1×10^{-7} [a]	7.7×10^{-9} [a]	2.8×10^{-8} [a]	4.3×10^{-7} [a]

[a] Virus inactivation/removal coefficient of 0.1/d is assumed in this case, instead of 0.69/d.

for the discussion of safety. Following the same method used to develop Table 9, the 95% UCL's annual risks based on expectation have been determined and are given in Table 10.

In assessing the reliability of wastewater reclamation and reuse, the SWTR criterion was used as a reference. Although there was no clear definition of reliability requirement in the SWTR for domestic water supplies regarding the inactivation/removal of *Giardia* and enteric viruses, the turbidity requirement in finished water is stated to be below the maximum concentration *at least 95% of time*. Thus, the reliability criterion of meeting the less than 10^{-4} annual risk of infection at least 95% of time was adopted in this study to assess the safety of reclaimed wastewater application in a given exposure scenario. It may be argued, however, that the reliability criterion used in this study was too stringent. In fact, Regli *et al.* (1988) reported that the annual risk of infection from swimming in natural waters ranged from 8×10^{-4} to 1.5×10^{-2}. Cabelli *et al.* (1979 and 1982) also reported that a risk more than one order of

Table 8—Expectations of the annual risk of infection for the upper 95% confidence limit (UCL) using a Monte Carlo simulation (n = 500 trials).

Tertiary treatment		Treatment system: OCSD TF	OCSD AS	Pomona AS	MRWPCA AS
System I					
Full treatment (5.2-log inactivation/removal)	Scenario I	1.4×10^{-6}	1.1×10^{-7}	5.5×10^{-7}	6.0×10^{-6}
	Scenario II	5.3×10^{-9}	3.7×10^{-10}	1.5×10^{-9}	2.1×10^{-8}
	Scenario III	1.3×10^{-4}	1.3×10^{-5}	1.0×10^{-4}	6.8×10^{-4}
	Scenario IV	1.2×10^{-59}	9.6×10^{-61}	4.2×10^{-60}	5.3×10^{-59}
	Scenario IV	7.4×10^{-13} [a]	4.7×10^{-14} [a]	2.1×10^{-13} [a]	2.9×10^{-12} [a]
System II					
Direct chlorination of secondary effluent (3.9-log inactivation/removal)	Scenario I	2.8×10^{-5}	2.2×10^{-6}	1.1×10^{-5}	1.2×10^{-4}
	Scenario II	1.0×10^{-7}	7.5×10^{-9}	2.9×10^{-8}	4.1×10^{-7}
	Scenario III	2.6×10^{-3}	2.6×10^{-4}	2.1×10^{-3}	1.3×10^{-2}
	Scenario IV	2.4×10^{-58}	1.9×10^{-59}	8.4×10^{-59}	1.0×10^{-57}
	Scenario IV	1.5×10^{-11} [a]	1.0×10^{-12} [a]	4.1×10^{-12} [a]	5.8×10^{-11} [a]
System IV					
Unchlorinated secondary effluent (0-log inactivation/removal)	Scenario I	1.9×10^{-1}	1.7×10^{-2}	7.3×10^{-2}	5.3×10^{-1}
	Scenario II	8.3×10^{-4}	5.9×10^{-5}	2.3×10^{-4}	3.3×10^{-3}
	Scenario III	1.0×10^{0}	6.2×10^{-1}	6.7×10^{-1}	1.0×10^{0}
	Scenario IV	3.8×10^{-57}	3.0×10^{-58}	1.3×10^{-57}	1.6×10^{-56}
	Scenario IV	1.1×10^{-7} [a]	8.3×10^{-9} [a]	3.3×10^{-8} [a]	4.6×10^{-7} [a]

[a] Virus inactivation/removal coefficient of 0.1 d is assumed in this case, instead of 0.69/d.

Table 9—Scoring system for safety of reclaimed water in various exposure scenarios when full treatment or contact filtration is used (system I) or chlorinated secondary effluent is used (system II).

Treatment system	Secondary effluent	Scenario I, golf course irrigation A	Scenario I, golf course irrigation B	Scenario II, crop irrigation A	Scenario II, crop irrigation B	Scenario III, recreational impoundment A	Scenario III, recreational impoundment B	Scenario IV, groundwater recharge A	Scenario IV, groundwater recharge B
		A, reliability[a]; B, expectation[b]							
System I									
Full treatment or	OCSD TF	O	O	O	O	X	Ø	O	O
contact filtration	OCSD AS	O	O	O	O	O	O	O	O
with high	Pomona AS	O	O	O	O	O	O	O	O
chlorine dose	MRWPCA AS	O	O	O	O	X	Δ	O	O
(5.2-log removal)									
System II									
Secondary effluent	OCSD TF	O	O	O	O	X	X	O	O
with high	OCSD AS	O	O	O	O	X	Δ	O	O
chlorine dose	Pomona AS	O	O	O	O	Ø	Δ	O	O
(3.9-log removal)	MRWPCA AS	X	Ø	O	O	X	X	O	O

[a] Scoring system based on reliability (O = very good, annual risk of infection equal to or less than 10^{-4} at ≥95% of time; Ø = good, ≥90%; Δ = unsatisfactory, ≥85%; and X = risky, <85%.

[b] Scoring system based on expectation using a Monte Carlo simulation of not exceeding the 10^{-4} annual risk of infection criterion (O ≤ 5×10^{-5}; Ø ≤ 10^{-4}; Δ ≤ 5×10^{-4}; and X > 5×10^{-4}).

magnitude larger is acceptable to voluntary swimmers. Haas (1996) argued that the benchmark of 1 in 10 000 as an acceptable level of risk associated with drinking water must be reconsidered, stating that an annual risk of infection of 1 in 1 000 (or even a less stringent risk level) is more appropriate than the current approach.

The purpose of this paper, however, has been to investigate (1) the methods of evaluating the reliability of wastewater recla-

Table 10—Scoring system for safety of reclaimed water in various exposure scenarios based on 95% UCL of expectation when full treatment or contact filtration is used (system I) or chlorinated secondary effluent is used (system II).[a]

Treatment system	Secondary effluent	Scenario I, golf course irrigation A	Scenario I, golf course irrigation B	Scenario II, crop irrigation A	Scenario II, crop irrigation B	Scenario III, recreational impoundment A	Scenario III, recreational impoundment B	Scenario IV, groundwater recharge A	Scenario IV, groundwater recharge B
		A, reliability[a]; B, expectation[b]							
System I									
Full treatment or	OCSD TF	O	O	O	O	X	Δ	O	O
contact filtration	OCSD AS	O	O	O	O	O	O	O	O
with high	Pomona AS	O	O	O	O	O	Δ	O	O
chlorine dose	MRWPCA AS	O	O	O	O	X	X	O	O
(5.2-log removal)									
System II									
Secondary effluent	OCSD TF	O	O	O	O	X	X	O	O
with high	OCSD AS	O	O	O	O	X	Δ	O	O
chlorine dose	Pomona AS	O	O	O	O	Ø	X	O	O
(3.9-log removal)	MRWPCA AS	X	Δ	O	O	X	X	O	O

[a] Scoring system based on reliability (O = very good, annual risk of infection equal to or less than 10^{-4} at ≥95% of time; Ø = good, ≥90%; Δ = unsatisfactory, ≥85%; and X = risky, <85%.

[b] Scoring system based on expectation at the 95% UCL using a Monte Carlo simulation of not exceeding the 10^{-4} annual risk of infection criterion (O ≤ 5×10^{-5}; Ø ≤ 10^{-4}; Δ ≤ 5×10^{-4}; and X > 5×10^{-4}).

mation and reuse to meet a given annual risk of infection considering the variability of virus concentrations in wastewater, and (2) the comparative safety of different wastewater treatment systems in combination with the different exposure scenarios in meeting U.S. EPA's SWTR for domestic water supplies. Thus, discussions on the appropriateness of the 10^{-4} risk of infection as a measure of safety from enteric viruses are beyond the scope of this study.

Conclusions

The principal conclusions derived from this study to assess the reliability and the safety of wastewater reclamation and reuse are:

- The observed enteric virus concentrations in undisinfected secondary effluent from municipal wastewater treatment plants are highly variable. Thus, in assessing the risk of infection caused by viruses, the variability in their occurrence must be considered.
- Risk assessment methodologies were developed to assess the safety of reclaimed wastewater in four different applications subject to the frequency and dose of reclaimed wastewater, and the reliability of wastewater treatment systems.
- Two concepts proposed to assess the safety of reclaimed wastewater are (1) *reliability*, which is defined as a measure of safety expressed in terms of the probability of meeting an acceptable risk, and (2) *expectation*, which is defined as the average risk for many exposure events based on MCMs for the analysis. The acceptable risk criterion used was based on U.S. EPA's SWTR for enteric virus removal. The acceptable level of annual risk of infection from enteric viruses in four different reclaimed wastewater applications was compared to the 10^{-4} (1 infection per 10 000 persons) criterion. The safety of using treated wastewater of varying quality was evaluated for golf course irrigation, recreational impoundment, crop irrigation, and groundwater recharge.
- The reliability of wastewater reclamation and reuse, when the specific inactivation/removal capabilities of the tertiary treatment used in the Pomona Virus Study (systems I and III) are applied, has been simulated. For golf course irrigation, food crop irrigation, and groundwater recharge, the reliability of wastewater reclamation and reuse is such that more than 95% of time, the SWTR criterion is met for systems I and III for all of the effluents studied. However, for recreational impoundments, the reliability of wastewater reclamation and reuse is not as high as for domestic water supplies complying with the SWTR criterion, even for systems I and III.
- The expectations of annual risk with full treatment or contact filtration and high chlorine dose (system I) are less than 10^{-4} even at 95% UCL in golf course irrigation, food crop irrigation, and groundwater recharge, regardless of the quality of secondary effluent. For unrestricted recreational impoundment where swimming may take place, the expectation of annual risk slightly exceeding the risk requirement imposed in this study may exist. If unchlorinated secondary effluent without any further treatment (system IV) is used for a variety of wastewater reuse applications, the expected annual risk, as might be expected, is much higher than the acceptable annual risk, except for groundwater recharge.
- This paper should be viewed as a first step in the application of quantitative microbiological risk assessment to wastewater reclamation and reuse. The methodologies used should be refined, using a larger enteric virus database developed with standardized field and laboratory protocols. Additional studies covering more comprehensive methods and criteria for evaluating the risk of infection from enteric viruses are needed and may include natural immunity, the relationship of conventional environmental virus assays and human infection doses, secondary infections, and the possibility that secondary viral infections could be more virulent than primary infections.

Notations

α, β	Parameters of the beta-distribution model
γ	Parameter of the single-hit exponential model
μ	Geometric mean of the log-normal distribution whose random variable is logarithmically transformed with respect to enteric viruses in unchlorinated secondary effluent
σ	Standard deviation of the log-normal distribution whose random variable is logarithmically transformed with respect to enteric viruses in unchlorinated secondary effluent
C	Enteric virus concentration in ingested reclaimed wastewater
C^*	Virus concentration in the ingested reclaimed wastewater
Ca^*	Acceptable daily (single) exposure virus concentration in ingested reclaimed wastewater
Cs	Virus concentration in unchlorinated secondary effluent
Ct	Virus concentration in tertiary effluent
D	Single-exposure dose
Di	*i*th value of a daily exposure dose
E	Environmental reduction factor of viruses
$E[\ ]$	Expectation
mg	Geometric mean of the log-normal distribution with respect to enteric viruses in unchlorinated secondary effluent
n	Number of exposure events in a year
p	Probability of time when a virus concentration exceeds a given concentration, or when the risk of infection caused by viruses exceeds a given acceptable risk level (that is, reliability)
P	Annual risk of infection caused by exposure to reclaimed wastewater
$\Pi[\ ]$	Multiple product
$P^*(D_i)$	Single-exposure risk caused by a single-exposure dose, D_i
Pa	Acceptable annual risk caused by enteric viruses
Pa^*	Acceptable daily (single) exposure risk caused by viruses
R	Log-virus removal during tertiary treatment; that is, absolute value of the logarithmic ratio of residual virus concentration to entering virus concentration during tertiary treatment
S	Spread factor of the log-normal distribution with respect to enteric viruses in unchlorinated secondary effluent: $S = 10^{\sigma}$

V	Ingested amount of reclaimed wastewater containing enteric viruses
vu/L	Viral unit per litre

Acknowledgments

Credits. Special credit goes to the Japan International Cooperation Agency and the Japan Ministry of Construction for enabling the senior author's study abroad at the University of California at Davis. Richard A. Mills, Richard H. Sakaji, and Rafael Mujeriego provided valuable advice and suggestions.

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Submitted for publication March 29, 1996; revised manuscript submitted January 3, 1997; accepted for publication January 7, 1997.

References

Asano, T., and Wassermann, K.L. (1979) Water Reclamation Plants Need Complete Reliability. *Water Sew. Works,* **126,** 9, 88.

Asano, T., and Sakaji, R. (1990) Virus Risk Analysis in Wastewater Reclamation and Reuse. In *Chemical Water and Wastewater Treatment.* H.H. Hahn and R. Klute (Eds.), Springer Verlag, Berlin, Heidelberg, Ger., 483.

Asano, T.; Leong, L.Y.C.; Rigby, M.G.; and Sakaji, R.H. (1992) Evaluation of the California Wastewater Reclamation Criteria Using Enteric Virus Monitoring Data. *Water Sci. Technol.,* **26,** 1513.

Benjamin, J.R., and Cornell, C.A. (1970) *Probability, Statistics, and Decision for Civil Engineers.* McGraw-Hill, Inc., New York, N.Y.

Cabelli, V.J.; Dufour, A.P.; Levin, M.A.; McCabe, L.J.; and Haberman, P.W. (1979) Relationship of Microbial Indicators to Health Effects at Marine Bathing Beaches. *Am. J. Public Health,* **69,** 690.

Cabelli, V.J.; Dufour, A.P.; McCabe, L.J.; and Levin, M.A. (1982) Swimming-Associated Gastroenteritis and Water Quality. *Am. J. Epidemiol.,* **115,** 606.

County Sanitation Districts of Los Angeles County (1977) *Pomona Virus Study, Final Report.* Prepared for Calif. State Water Resour. Control Board, Sacramento, Calif., and U.S. EPA, Washington, D.C.

Dean, R.B., and Forsythe, S.L. (1976) Estimating the Reliability of Advanced Waste Treatment, *Water Sew. Works,* **123,** 6, 87, and **123,** 7, 57.

Dean, R.B. (1981) Use of Log-Normal Statistics in Environmental Monitoring. In *Chemistry in Water Reuse.* W.J. Cooper (Ed.), Ann Arbor Science Publishers, Inc., Mich.

Devroye, L. (1986) *Non-Uniform Random Variate Generation.* Springer-Verlag, New York, N.Y.

Dryden, F.D.; Chen, C.L.; and Selna, M.W. (1979) Virus Removal in Advanced Wastewater Treatment Systems. *J. Water Pollut. Control Fed.,* **51,** 2098.

Engineering-Science (1987) *Monterey Wastewater Reclamation Study for Agriculture.* Prepared for Monterey Regional Water Pollution Control Agency, Berkeley, Calif.

Gerba, C.P., and Haas, C (1988) Assessment of Risks Associated with Enteric Viruses in Contaminated Drinking Water. In *Chemical and Biological Characterization of Sludges, Sediments, Dredge Soils, and Drilling Muds.* ASTM STP 976, J.J. Lichtenberg, J.A. Winter, C.I. Weber, and J. Fradkin (Eds.), Am. Soc. Testing Mater., Philadelphia, Pa., 489.

Gerba, C.P., and Rose, J.B. (1993) Estimating Viral Disease Risk from Drinking Water. In *Comparative Environmental Risk Assessment.* C.R. Cothern (Ed.), Lewis Publishers, Boca Raton, Fla.

Haas, C.N. (1983a) Estimation of Risk Due to Low Doses of Microorganisms: A Comparison of Alternative Methodologies. *Am. J. Epidemiol.,* **118**, 573.

Haas, C.N. (1983b) Effect of Effluent Disinfection on Risks of Viral Disease Transmission via Recreational Water Exposure. *J. Water Pollut. Control Fed.,* **55**, 8, 111.

Haas, C.N. (1996) Acceptable Health Risk. Viewpoint. *J. Am. Water Works Assoc.,* **18**, 8.

Hogg, R.V., and Tanis, E.A. (1988) *Probability and Statistics Inference.* 3rd Ed., Macmillan Publishing Co., New York, N.Y.

Hutzler, N.J., and Boyle, W.C. (1980) Wastewater Risk Assessment. *J. Environ. Eng.,* **106**, EE5, 919.

Hutzler, N.J., and Boyle, W.C. (1982) Risk Assessment in Water Reuse. In *Water Reuse.* E.J. Middlebrooks (Ed.), Ann Arbor Science Publishers, Inc., Mich.

McCarty, P.L.; Reinhard, M.; Dolce, C.; and Argo, D.G. (1978) *Water Factory 21: Reclaimed Water, Volatile Organics, Virus, and Treatment Performance.* EPA-600/2-78-076, U.S. EPA, Cincinnati, Ohio.

McCarty, P.L.; Reinhard, M.; Graydon, J.; Schreiner, K.; Sutherland, J.; Everhart, T.; and Argo, D.G. (1980) *Wastewater Contaminated Removal for Groundwater Recharge at Water Factory 21.* EPA-600/2-80-114, U.S. EPA, Cincinnati, Ohio.

McCarty, P.L.; Mortelmans, K.E.; Argo, D.G.; and English, J.N. (1982) *Advanced Treatment for Wastewater Reclamation at Water Factory 21.* Technical Report No. 267, Stanford University, Calif.

Miele, R.P., and Selna, M.W. (1977) Virus Sampling in Wastewater-Field Experiences. *J. Environ. Eng. Div.*, **103**, EE4, 693.

Newman, T.G., and Odell, P.L. (1971) *The Generation of Random Variates.* Charles Griffin & Company Limited, London, G.B.

Niku, S., and Schroeder, E.D. (1981) Factors Affecting Effluent Variability from Activated Sludge Processes. *J. Water Pollut. Control Fed.,* **53**, 5, 646.

Niku, S.; Schroeder, E.D.; and Haugh, R.S. (1982) Reliability and Stability of Trickling Filter Process. *J. Water Pollut. Control Fed.,* **54**, 2, 129.

Olivieri, A.W.; Cooper, R.C.; and Danielson, R. (1989) Risk of Waterborne Infectious Illness Associated with Diving in the Point Loma Kelp Bed, San Diego, CA. In *Proceedings of the Environmental Engineering Specialty Conference.* J.F. Marina *et al.* (Eds.), Am. Soc. Civil Eng., New York, N.Y.

Regli, S.; Amirtharajah, A.; Borup, B.; Hibler, C.; Hoff, J.; and Tobin, R. (1988) Panel Discussion on the Implication of Regulatory Changes for Water Treatment in the United States. In *Advances in Giardia Research.* P.M. Walls *et al.* (Eds.), Univ. Calgary Press, Alb., Can., 275.

Regli, S.; Pore J.B.; Haas, C.N.; and Gerba, C.P. (1991) Modeling the Risk from *Giardia* and Viruses in Drinking Water. *J. Am. Water Works Assoc.,* **83**, 11, 76.

Rose, J.B., and Gerba, C.P. (1991) Use of Risk Assessment for Development of Microbial Standards. *Water Sci. Technol.,* **24**, 2, 29.

State of California (1978) Administrative Code, Title 22, Division 4, Environmental Health. Chapter 3, *Wastewater Reclamation Criteria.* Dep. Health Serv., Berkeley, Calif., 1557.

U.S. Environmental Protection Agency (1989) National Primary Drinking Water Regulations: Filtration, Disinfection; Turbidity, *Giardia Lamblia*, Viruses, Legionella and Heterotrophic Bacteria; Final Rule. *Fed. Regist.*, **54**, 124, 27486.