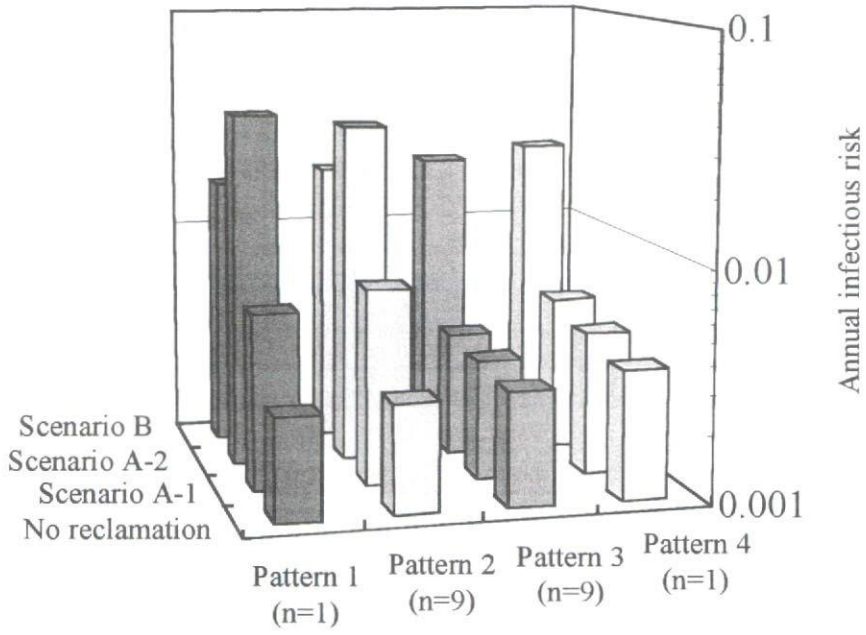
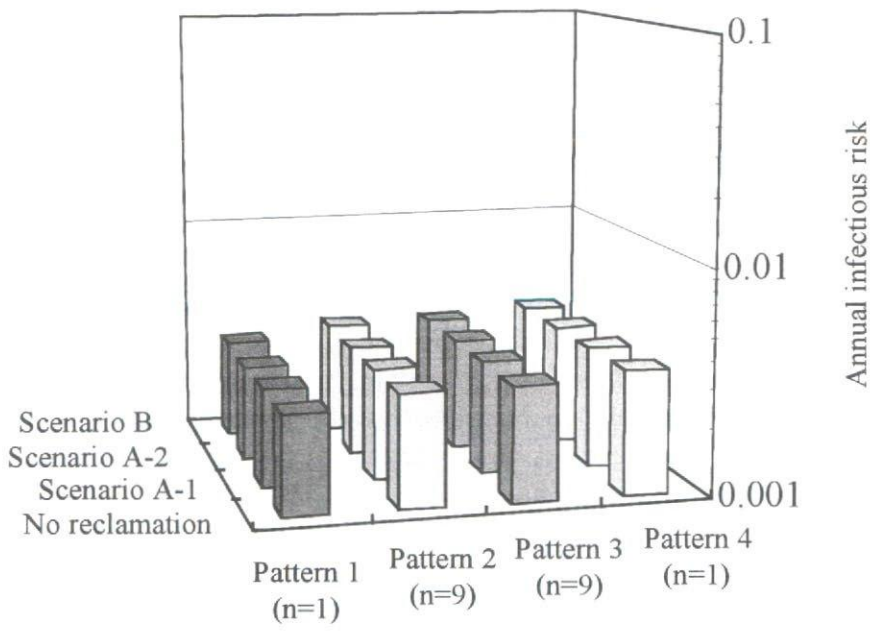
Figure 8 - Annual Infectious Risks by Poliovirus 1 in Cases of Reclaiming the Secondary Effluent and the Disinfected Effluent



(a) Case of reclaiming the secondary effluent without disinfection



(b) Case of reclaiming the disinfected secondary effluent

coliforms in the secondary effluent have been observed at the concentration between 10MPN/100mL and 850MPN/100mL. Although the observed concentration of total coliforms in the secondary effluent satisfied the standard for the wastewater reclamation, the disinfection of the secondary effluent would be recommended so as to avoid the increase of the viral infectious risk in

the reclamation. The standard for the wastewater reclamation as a drinking water (scenario A) has not been established in Japan. On the basis of the result shown in Figure 8, the sufficient disinfection of the secondary effluent is necessary for the reclamation.

Reduction of the Damage from the Water Shortage in the Wastewater Reclamation

The effect of the wastewater reclamation on reducing the damage from the water shortage was quantified in 20 trials of simulating the wastewater reclamation in Fukushima city. The average of the damage from the water shortage in 20 trials was 448%•day in case of no reclamation. In the scenarios A-2, the damage of 448%•day was perfectly reduced by replacing all of the water shortage with the reclaimed wastewater. A half of the damage (224%•day) was reduced in the scenario A-1.

The reduced damage from the water shortage in the scenario B reclaiming the wastewater for flush toilet was 354%•day. This reduced damage was equivalent to about 80% of the damage in case of no reclamation.

Trade-Off between the Infectious Risk and the Water Shortage

Figure 9 illustrates the relationship between the annual infectious risk and the reduced damage from water shortage in reclaiming the secondary effluent and the disinfected effluent, respectively.

In case of reclaiming the secondary effluent without disinfaction. In scenarios A-1 and A-2, the infectious risk by poliovirus 1 increased with the reduction of the damage from the water shortage when the reduced damage was higher than 300%•day. The wastewater reclamation for reducing the damage below 300%•day has a constant infectious risk (3.1×10^{-3}). The increase of the infectious risk was obvious especially when the higher damage than 400%•day was reduced in the scenario A-2. The increase could be described by the following exponential equation (R^2=0.97):

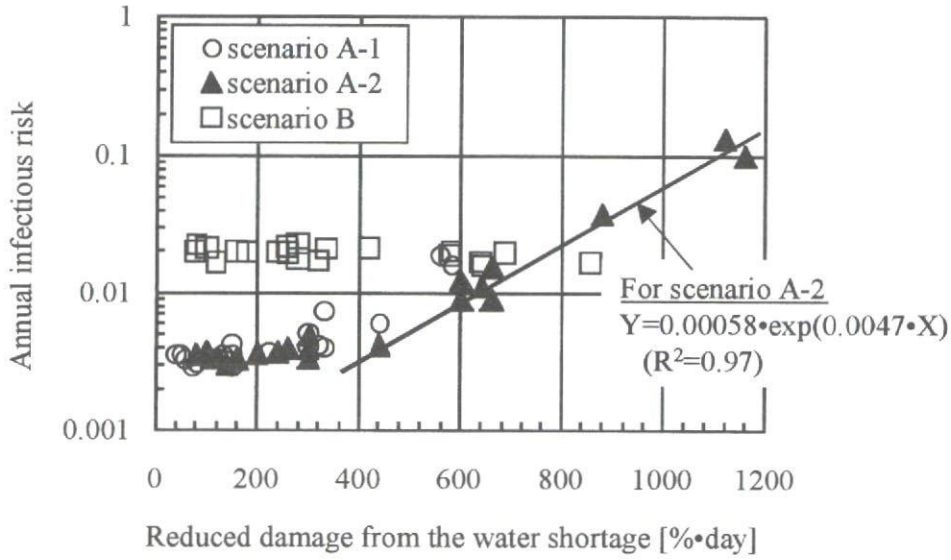
$Y=0.00058 \cdot \exp(0.0047 \cdot X)$, if $X > 400\%$•day

where, X was the reduced damage from water shortage [%•day] and Y was the infectious risk. On the basis of this equation, if the damage from the water shortage of 850%•day was reduced in the wastewater reclamation, the infectious risk would become ten times as high as that in case of no reclamation. In the scenario B, the annual infectious risk was almost constant (1.9×10^{-2}) regardless of the reduced damage from the water shortage.

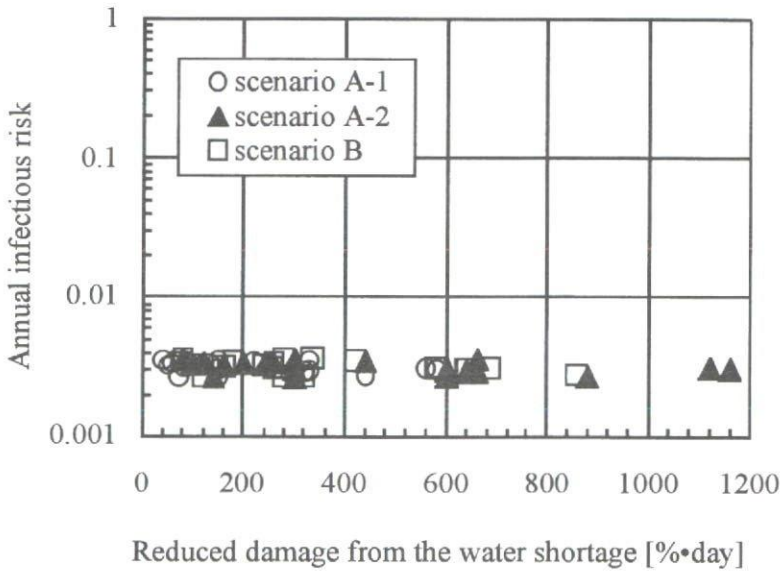
In case of reclaiming the disinfected secondary effluent. The annual infectious risk in the wastewater reclamation did not increased in every scenario. In the scenario B, the infectious risk decreased to 16% of that in reclaiming the secondary effluent without disinfection.

The damage from the water shortage could be reduced without any increase of infectious risk in the reclamation of the disinfected effluent. Therefore, if the secondary effluent was sufficiently disinfected by chlorine, its reclamation could be accepted as an effective countermeasure to the water shortage. In employing the wastewater reclamation in the water utilization system, it is necessary to evaluate potential risks by other pathogens and chemical substances such as disinfection by-products and to compare these risks with reduced damage from water shortage in the reclamation. The risk evaluation method proposed in this study will be applicable to various risk

Figure 9 - Relationships between the Annual Infectious Risk by Poliovirus 1 and the Reduced Damage from Water Shortage in Cases of Reclaiming the Secondary Effluent and the Disinfected Effluent



(a) Case of reclaiming the secondary effluent without disinfetion



(b) Case of reclaiming the disinfected secondary effluent

agents if the knowledges on these agents such as the dose-response relationship, the removal efficiencies in water and wastewater treatments are accumulated.

CONCLUSIONS

In order to predict the water shortage, the method to reproduce the river discharge was proposed using the matrix of probability. Based on the reproduced discharge, the infectious risk by poliovirus

1 and the reduced damage from the water shortage in the wastewater reclamation were evaluated in three scenarios. As the results, following conclusions were obtained:

- The infectious risk increased in reclaiming the undisinfected secondary effluent for a drinking water source or flush toilet. Especially, in the reclamation as a drinking water source (scenarios A-1 and A-2), the infectious risk was exponentially increased with the reduction of the damage from the water shortage when the damage of more than 300%•day was reduced.
- In the scenario A-2 replacing perfectly the shortage of a drinking water source with the undisinfected secondary effluent, the reclamation for reducing 850%•day of the damage from the water shortage brought ten times higher infectious risk than that in case of no reclamation.
- If 99.9% of poliovirus 1 was inactivated by the disinfection of the secondary effluent, its reclamation could reduce the damage from the water shortage without any increase of the infectious risk by poliovirus 1.
- The damage from the water shortage of 354%•day was reduced in the wastewater reclamation for flush toilet. This reduced damage was equivalent to 80% of the damage in Fukushima city.
- The proposed method can be applied to evaluate infectious risks by other pathogens in the wastewater reclamation.

ACKNOWLEDGMENTS

This study was partially supported by Japan Society for the Promotion of Science (JSPS), Grand-in-Aid for Scientific Research (C), 2001-2002 (Project No.: 13838002) and Grand-in-Aid for Young Scientists (B), 2002-2003 (Project No.: 14750455).

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RISK EVALUATION FOR VIRAL INFECTIOUS DISEASES THROUGH DRINKING WATER WITH THE SECONDARY INFECTION

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ABSTRACT

For discussing on viral infectious risks through the drinking water, not only the primary infection by viruses in the drinking water but also the secondary infection caused by the contact with infected persons should be taken into account because viral infectious diseases are easily spread from person to person. In this study, the methodology to evaluate the outbreak of viral infectious diseases through the drinking water with the secondary infection was proposed considering the geographic information system (GIS) on the population for estimating the contact opportunity with infected persons. The outbreak of infectious disease by rotavirus was simulated with the proposed method when its concentration in the drinking water was so low that the primary infectious risk could satisfy the acceptable annual risk of 10^{-4}.

In case that the infectious probability by a single contact with an infected person was lower than 10^{-5}, the infectious risk was almost same as that without the secondary infection. In other cases, outbreaks beyond the expectation occurred even if the viral concentration could be correctly managed on the basis of primary infectious risk. Therefore, the risk evaluation with the secondary infection was required for more effective management of infectious risk through the drinking water.

KEYWORDS

Viral infectious diseases; risk evaluation; drinking water; secondary infection; rotavirus; geographic information system (GIS)

INTRODUCTION

Many researchers reported that pathogenic viruses existed in the water environment such as river and coastal area (Morris, 1984; Havelaar *et al.*, 1993; Yano *et al.*, 1993). Sometimes pathogenic viruses were detected even in the drinking water (Rose *et al.*, 1986; Toranzos *et al.*, 1986). Actually, outbreaks of viral infectious diseases through the contaminated drinking water occurred all over the world (Morens *et al.*, 1979; Laursen *et al.*, 1994; Kukkula *et al.*, 1999). In order to prevent outbreaks of viral infectious disease, the concentration of pathogenic viruses in the drinking water should be regulated on the basis of the acceptable infectious risk.

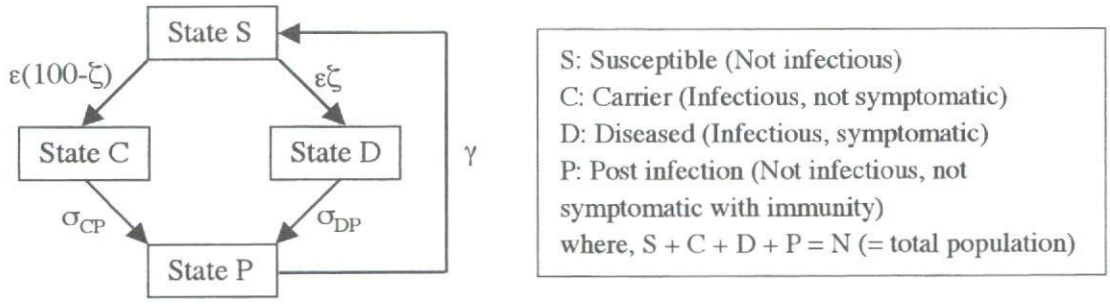
The concept of risk evaluation for the infection caused by waterborne pathogens is quite different from that for other health risks associated with carcinogenic substances and heavy metals. Because, in the case of infectious risk, there is the possibility of the secondary infection due to the contact with infected persons. Especially, viral infectious diseases are easily spread from person to person. Gerba (1999) reported secondary attack rates of 90% for poliovirus and about 30% for Norwalk virus. Therefore, the secondary infection is important to evaluate the viral infectious risk as well as the primary infection. Nevertheless, the effect of the secondary infection has been scarcely introduced in the risk evaluation.

The objective of this paper is to propose the methodology on the risk evaluation for viral infectious diseases through the drinking water considering both of primary and secondary infections. The geographic information system (GIS) on the population is adopted for estimating the contact opportunity with infected persons.

METHODS

States of persons with relation to infectious diseases

In order to describe the state of persons with relation to infectious diseases, persons are categorized into four states (S, C, D and P) as shown in Fig. 1. This categorization is based on Haas and Eisenberg (2001). State S means the susceptible persons who are not infected. Carriers and patients are included in States C and D, respectively. The infectious probability (ε) for persons in State S is calculated considering both of primary and secondary infections. The calculation procedure is explained below. The percentage (ζ) of the infected persons who develop the clinical illness widely ranged between 0.1% (for poliovirus 1) and 96% (for coxsackie B3) (Gerba, 1999). Persons recovered from States C and D will not be re-infected by the same virus for the certain period since they can get the immune system ($\sigma_{CP}=\sigma_{DP}=1$). Such persons who have the immune system are defined as State P. Although Haas and Eisenberg (2001) mentioned the possibility of infection for



- Explanation of parameters -

ε: the infectious probability in State S (considering both of primary and secondary infections).
ζ: the percentage of the individuals infected who develop clinical illness.
σ_{CP} and σ_{DP} : rates of recovery from States C and D to State P, respectively.
γ : the rate of movement from State P to State S.

Fig. 1. States of persons with relation to infectious diseases.

persons in State P, such an infection is neglected in this study for discussing on infectious risk.

Infectious probability considering both of primary and secondary infections

If the dosage of virus (x) through the drinking water is given, the primary infectious probability (P_p) can be evaluated with the following dose-response model:

$$P_p = 1 - \exp(\gamma \cdot x) \text{ (Exponential model) or } P_p = 1 - \left(1 + \frac{x}{\beta}\right)^{-\alpha} \text{ (Beta model)} \quad (1)$$

where, γ, α and β are parameters characterizing the infection by the causal virus. On the other hand, the secondary infectious probability (P_s) depends on the contact opportunity with infected persons in States C and D. The probability can be calculated by the following formula:

$$P_s = 1 - (1 - \mu)^{N_C + N_D} \quad (2)$$

where, μ is the infectious probability by a single contact with an infected person, N_C and N_D mean populations in States C and D, respectively. The infectious probability (ε) considering both of primary and secondary infections is calculated with the following formula:

$$\varepsilon = 1 - (1 - P_p)(1 - P_s) \quad (3)$$

Research area and contact opportunity

The infectious risk is evaluated in the area (40km x 20km) around Fukushima city, Japan. This area has about 0.43 million of population. In order to determine the opportunity of person-to-person contact for the evaluation of the secondary infectious probability, the research area is divided into 1km square meshes and the parameter F indicating the contact opportunity is proposed (Fig. 2). Everyone will contact with all infected persons within the mesh (F_0=1). If persons randomly decide whether they stay in the mesh or make trip to next meshes, the opportunity with infected persons in next meshes is one-fifth (F_1=1/5). Values of F for other meshes (F_2=1/25, F_3=1/125 and so on) are determined in the same manner. Carriers (State C) and patients (State D) during the incubation period as well as healthy persons (States S and P) can travel in the research area. On the other hand, patients in the duration of illness cannot make trip to other meshes.

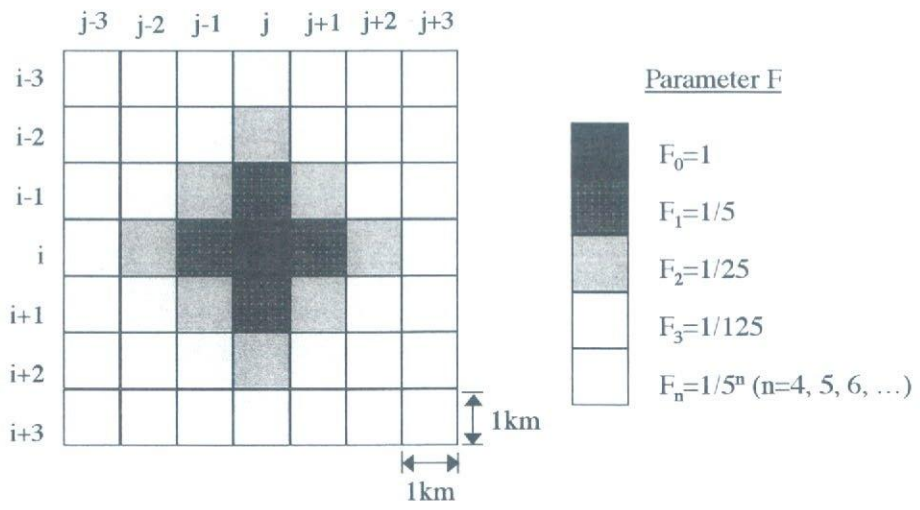


Fig. 2. Parameter F indicating the contact probability with infected persons in the mesh (i, j).

The secondary infectious probability in the mesh (i,j) could be evaluated by the following equation:

$$P_s(i,j) = 1 - (1-\mu)^{F_0\{N_C(i,j)+N_D(i,j)\}+F_1 N_{CD1}+F_2 N_{CD2}+\cdots} \quad (4)$$

where, N_{CD1} and N_{CD2} mean total populations (N_{CD}) of carriers and patients during the incubation period in surrounding meshes calculated by following equations, respectively:

$$N_{CD1} = N_{CD}(i-1,j)+N_{CD}(i+1,j)+N_{CD}(i,j-1)+N_{CD}(i,j+1)$$

$$N_{CD2} = N_{CD}(i-2,j)+N_{CD}(i+2,j)+N_{CD}(i,j-2)+N_{CD}(i,j+2)$$
$$+N_{CD}(i-1,j-1)+N_{CD}(i+1,j-1)+N_{CD}(i-1,j+1)+N_{CD}(i+1,j+1)$$

The contact with infected persons out of the research area is not considered in the simulation.

Assumptions for outbreak simulation

As an example for risk evaluation with the proposed method, we consider the infectious disease caused by rotavirus in the drinking water. Beta model (α=0.253 and β=0.427) is employed as the dose-response model for rotavirus (Haas *et al.*, 1999). Gerba (1999) reported that about sixty percents of adults infected by rotavirus develop the clinical illness (ζ=0.6). In addition, the following assumptions are employed.

1) Nobody in the research area has the immune system for rotavirus at the beginning of simulation, that is, everybody is belonging to State S.

2) The movement from State P to State S is not considered in the simulation (γ=0),

3) The occurrence probability of concentration of rotavirus in the drinking water is described by Poisson distribution (Haas and Rose, 1996).

4) The dosage of drinking water is two liters per day for all persons in the research area. This dosage is generally employed to establish standards in the drinking water.

5) If the acceptable annual risk for infection is 10^{-4}, the concentration of rotavirus in the drinking water is estimated as 2.31 x 10^{-7} PFU/L with the conventional risk evaluation method (for instance, Rose and Gerba, 1991). Therefore, the concentration of 2.31 x 10^{-7} PFU/L is employed as the average of viral concentration in the drinking water.

6) Infected persons in States C and D have the possibility of causing the secondary infection for a week. This period for rotavirus is assumed on the basis of the incubation period for 2 days and the duration of illness for 5 days (Haas *et al.*, 1999).

Under above assumptions, the outbreak of infectious disease by rotavirus in the drinking water is simulated with Monte Carlo method when the parameter μ is between 10^{-5} and 10^{-4} or zero (no secondary infection). The annual infectious risk is estimated as the ratio of the number of annual infected parsons to the population.

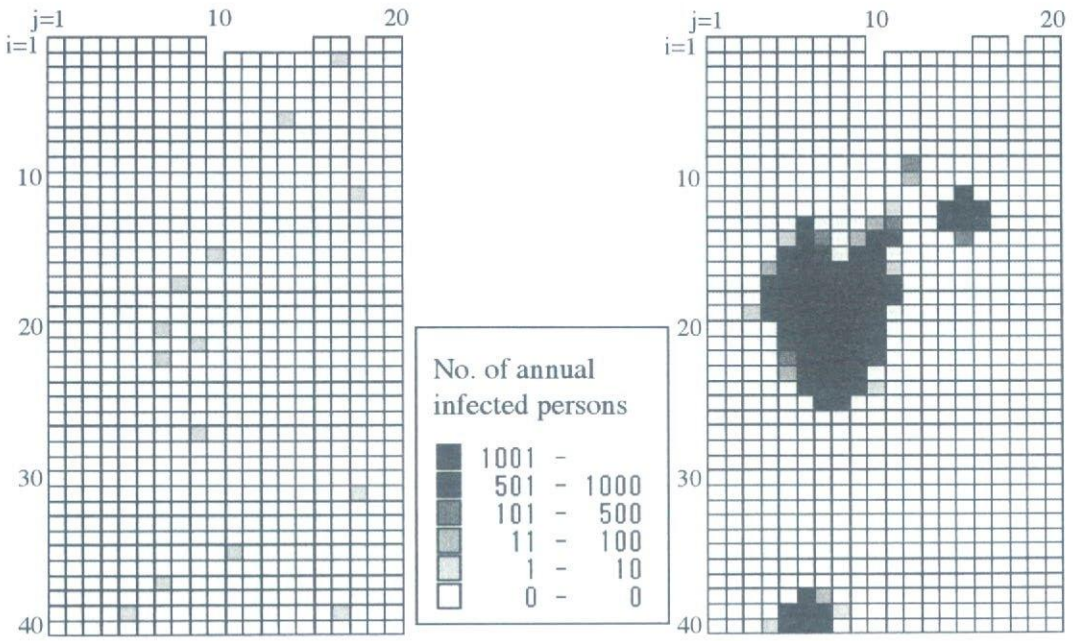
RESULTS AND DISCUSSIONS

Annual infectious risk without the secondary infection

The annual infectious risk without the secondary infection was between 1.4 x 10^{-5} and 3.7 x 10^{-5} from the result of simulation repeated for 24 times. The geometric mean was 2.5 x 10^{-5}. As above-mentioned, the annual infectious risk was estimated as 10^{-4} with the conventional method employing the constant concentration. The annual infectious risk of 2.5 x 10^{-5} obtained in this study

was only one-forth of this risk. In this simulation, Poisson distribution was taken into account for describing the occurrence probability of viral concentration in the drinking water. Fukushi *et al.* (1998) concluded that the infectious risk evaluated considering Poisson distribution was lower than that evaluated on the basis of the constant concentration.

Fig. 3 (a) illustrated a distribution of the number of annual infected persons without the secondary infection in the research area. In this case, only one or two persons were infected in one mesh through a year. And nobody was infected through 20 times of simulation in 446 meshes corresponding to 73% of meshes where at least one person was living. This means that sporadic outbreaks occurred in case of no secondary infection.



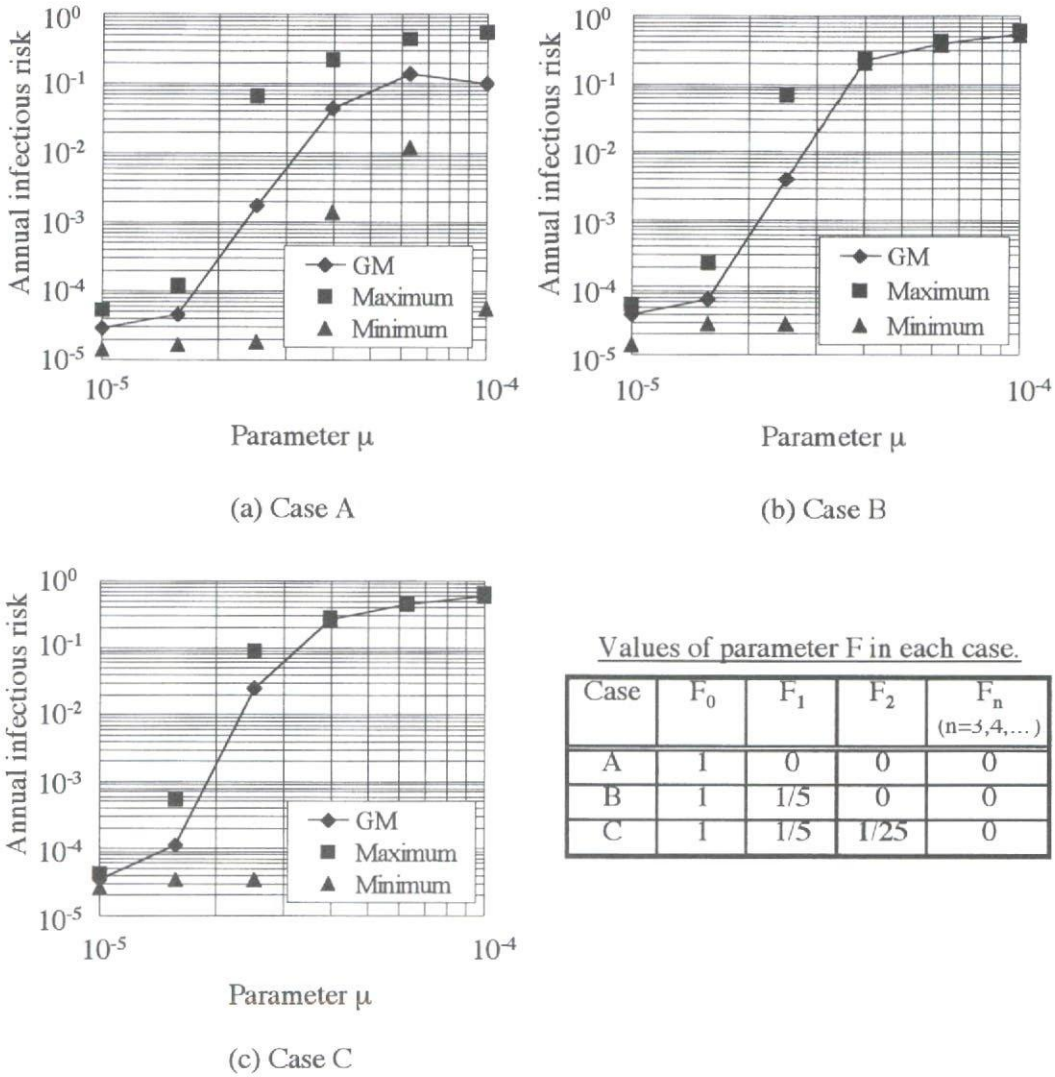
(a) No secondary infection.

(b) With the secondary infection. ($\mu = 4.0 \times 10^{-5}$)

Fig. 3. The distribution of the number of annual infected persons in the research area when the average concentration of rotavirus in the drinking water was 2.31×10^{-7} PFU/L.

Seriousness of secondary infection

Parameters μ and F are important to determine the seriousness of the secondary infection since the parameter F influences the contact opportunity with infected persons and the parameter μ is defined as an infectious probability in a single contact. Fig. 4 shows the annual infectious risk evaluated from outbreak simulations with both parameters. In order to evaluate the effect of the parameter F on the infectious risk, three cases (A, B and C) were investigated on the outbreak simulation. In the case A, the secondary infection was caused by the contact with infected persons only within one mesh. In the case B, the contact with infected persons in next meshes was taken into account. In the case C, the contact with infected persons in next next meshes was taken into account, too.



Values of parameter F in each case.

Case	F_0	F_1	F_2	F_n (n=3,4,...)
A	1	0	0	0
B	1	1/5	0	0
C	1	1/5	1/25	0

Fig. 4. The geometric mean (GM), maximum and minimum of annual infectious risks evaluated from 20 times of outbreak simulation in the research area.

When the parameter μ was 1.0×10^{-5}, geometric means of the annual infectious risk (3.2×10^{-5} – 3.8×10^{-5}) were almost same as that without the secondary infection in all cases shown in Fig. 4. Therefore, in the case that the parameter μ was lower than 10^{-5}, the secondary infection was neglected to evaluate the infectious risk in the research area. The geometric mean of the annual infectious risk increased with the increase of the parameter μ in every case. Especially, when the parameter μ was higher than 4.0×10^{-5}, the secondary infection was a key factor because over 10% of population were infected by rotavirus in cases B and C. In these cases, annual infectious risks were more than 4,000 times as great as that without the secondary infection. The parameter μ of 4.0×10^{-5} means that only one person was infected by contacts with twenty-five thousands of infected persons. It is of significance that such a low probability of secondary infection caused the accelerated spread of viral infectious diseases through the drinking water.

As shown in Fig. 4, the difference between maximum and minimum risks on the parameter μ in the case A was larger than those in other two cases. For example, when the parameter μ was 1.0×10^{-4}, the annual infectious risk ranged from 5.6×10^{-5} to 5.6×10^{-1}. Although the infectious probability

by a single contact with an infected person was constant, the maximum risk was 10,000 times greater than the minimum risk. In this case, the secondary infection was caused by the contact with infected persons only within one mesh. Therefore, the annual infectious risk became much higher when the primary infection for the drinking water occurred in the mesh with large population.

When the parameter μ was higher than 4.0×10^{-5}, infectious risks were not influenced by the position of meshes where the primary infection occurred because the outbreak was easily spread to neighbor meshes by the secondary infection. On the other hand, infectious risks widely ranged in cases of μ between 1.6×10^{-5} and 2.5×10^{-5} due to the low probability of the secondary infection. As shown in Fig. 4, the annual infectious risk in the case C was similar to that in the case B. This result indicated that the parameter F_2 of 1/25 was not effective to evaluate the infectious risk with the secondary infection using the proposed method (Fig. 2).

Fig. 3 (b) illustrated a distribution of the number of annual infected persons when the parameter μ was 4.0×10^{-5} in the case B. Compared with the distribution in Fig. 3 (a), it was found that a large scale of outbreak occurred around the mesh (20, 8). In this mesh, over 4,800 persons were infected among about six thousands of population. In addition, annual infectious risks in 108 meshes exceeded 10^{-2} and those in 55 meshes exceeded 10^{-1}.

Significance of the secondary infection for the evaluation of viral infectious risk

According to the above results, the viral infectious risk through drinking water is underestimated by the current methodology without the secondary infection. Therefore, the risk evaluation with the secondary infection is required for more effective management of infectious risk through drinking water.

CONCLUSIONS

In this study, the methodology to evaluate the outbreak of viral infectious diseases through the drinking water with the secondary infection was proposed considering the geographic information system (GIS) on the population for estimating the contact opportunity with infected persons. The outbreak of infectious diseases by rotavirus was simulated with the proposed method when its concentration in the drinking water was so low that the infectious risk without the secondary infection could satisfy the acceptable annual risk of 10^{-4}. Following conclusions were obtained from the result of outbreak simulation:

1) When the parameter μ indicating the infectious probability by a single contact with an infected person was lower than 10^{-5}, the infectious risk was almost same as that without the secondary infection. Therefore, the secondary infection was neglected for the risk evaluation in this case.

2) In the case that the parameter μ was higher than 4.0×10^{-4}, over 10% of population in the research area were infected by rotavirus. It is of significance that such a low probability of secondary infection caused the accelerated spread of viral infectious diseases through the drinking water.

3) The parameter F_2 of 1/25 was not effective to evaluate the infectious risk with the secondary infection using the proposed model.

ACKNOWLEDGEMENT

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