EVALUATION OF HEALTH RISKS IN THE WASTEWATER RECLAMATION IN THE ABUKUMA WATERSHED, JAPAN

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ABSTRACT

Wastewater reclamation is an effective countermeasure to the shortage of water. However, there is concern that the wastewater reclamation causes health risks of infection by pathogens and cancer by disinfection by-products such as trihalomethanes (THMs). Since it is difficult to discuss these risks together, the Disability-Adjusted Life Years (DALY) has been employed to integrate them with the unit of lost lifetime. Health risks of infection and cancer in Fukushima city with population of 0.3 million were evaluated with the DALY in the wastewater reclamation as a drinking water source. The damage [%•day] from the shortage of water was quantified by the product of the percent of deficiency to the water supply demand [%] and the period of deficiency [days]. In the current situation of water utilization without reclamation, the DALY for total population was about 11 years. The reclamation of the secondary effluent without disinfection brought no increase of DALY when the damage between 0 and 300 %•day was reduced. On the other hand, the DALY drastically increased when the reduction of the damage was over 300 %•day. If the secondary effluent was disinfected with chlorine, the maximum damage of 1200 %•day could be reduced by its reclamation without any increase of DALY.

KEYWORDS

Wastewater reclamation; shortage of water; health risks; pathogens; disinfection by-products; Disability-Adjusted Life Years (DALY)

INTRODUCTION

The shortage of water is recognized as one of the most serious problems on the global environment. United Nations (UN) reported that one third of the world population in 1995 was suffering from the shortage of water and two thirds in 2025 would be doing due to the increase of the water demand. For the countermeasure to the shortage of water, the wastewater reclamation has been introduced to the water utilization system for purposes of toilet flushing, car washing and irrigation in the urbanized area. In Singapore, the wastewater treated with membrane technologies has been provided for the drinking water named "newater". If the shortage of water becomes more serious, the wastewater reclamation as a drinking water source will be popular in the future.

Since pathogens are often detected from the secondary effluent (Omura *et al.*, 1989; Havelaar *et al.*, 1993; Yano *et al.*, 1993), an appropriate disinfection of the effluent is necessary before its reclamation to prevent the increase of the infectious risk. Watanabe *et al.* (2003) concluded that the infectious risk by poliovirus 1 did not increase in reclaiming the secondary effluent disinfected with chlorine as a part of the drinking water source. However, it is well-known that carcinogenic substances such as trihalomethanes (THMs) are produced when the secondary effluent is disinfected with chlorine. Therefore, the cancer risk as well as the infectious risk in the wastewater reclamation should be evaluated and decreased to the acceptable level.

The objective of this study is to evaluate both health risks of infection and cancer in the wastewater reclamation with a health index of the Disability-Adjusted Life Years (DALY). The DALY was developed by Murray and Lopez (1996) for the investigation on Global Burden of Disease (GBD) with World Health Organization (WHO). This index has the advantage to quantify the burden for population which will be evaluated from both of fatal diseases such as cancer and nonfatal diseases such as infectious diseases in the same unit of the lost lifetime [years]. The lifetime lost by nonfatal diseases is determined according to the disability caused by the diseases.

MATERIALS AND METHODS

Wastewater reclamation

Prediction of the river discharge at the intake point. The wastewater reclamation is simulated in Fukushima city located at the middle reach of the Abukuma river in Japan. In this city with the population of 0.3 million, the Abukuma river is used as a drinking water source. Fukushima city often suffer from the shortage of water due to low discharges of the Abukuma river, especially in summer season. In order to predict the shortage of water in this city, Watanabe *et al.* (2003) categorized the river discharge observed from 1980 to 1999 at the intake point of the water treatment plant into 20 levels and derived the matrix of simultaneous probability of discharge levels on consecutive two days from categorized data. With the derived matrix of probability, they proposed the method to predict the shortage of water by reproducing the river discharge level at the intake point day by day. In this study, the shortage of water in Fukushima city is predicted with the matrix of probability in the same manner.

Scenarios on the wastewater reclamation. The wastewater is reclaimed as a part of drinking water source. The daily dosage of the drinking water is assumed to be 2 L for all individuals in Fukushima city. According to the statistical analysis of river discharge at the intake point by the Ministry of Land, Infrastructure and Transportation in Japan, the discharge below 25 m^3/s is very rare. Therefore, this situation is regarded as the shortage of water. In such case, the intake from the Abukuma river is restricted by the river discharge level (Watanabe *et al.*, 2003), and the wastewater is reclaimed as a drinking water source in two scenarios A-1 and A-2. In scenario A-1, the wastewater reclamation covers a half of the shortage of drinking water source. In scenario A-2, all of the shortage is replaced by the reclaimed wastewater.

Damage from the shortage of water. The damage [%•day] from the shortage of water is quantified by the product of the percent of deficiency to the water supply demand [%] and the period of deficiency [days] (Ikebuchi, 2001).

Evaluation of the infectious risk

Pathogen and dose-response model. Rotavirus is employed for the evaluation of infectious risk in the wastewater reclamation. The infectious risk caused by rotavirus is evaluated with dose-response model proposed by Rose and Gerba (1991).

Assumptions for the evaluation of infectious risk. The concentration of rotavirus is assumed to be 50,000 times lower than that of total coliforms (Kaneko, 1997). The concentration of total coliforms in the river is predicted on the basis of the river discharge with the marix of probability (Watanabe *et al.*, 2003). Infected persons excrete rotavirus at the concentration of 10^6 PFU/g of feces for 30 days (Kaneko, 1997). The concentration of rotavirus in the wastewater is calculated from the number of infected persons and the discharge volume of wastewater (360 L/d/person). Ninety percents of rotavirus in the wastewater are removed by primary and secondary wastewater treatments (Kaneko, 1997). Moreover, 99.9% of rotavirus in the secondary effluent is inactivated by the chlorine disinfection (Vaughn *et al.*, 1986). The viral concentration in the drinking water source is calculated from those in the reclaimed wastewater and the river water. The removal efficiency of rotavirus by the conventional water treatment ranges from 1.7 to 2.9 log (Watanabe *et al.*, 2003). The inactivation efficiency of rotavirus in the drinking water by the chlorine disinfection after the water treatment is assumed to be 3log (Vaughn *et al.*, 1986).

Relative sensitivity to the infection. Figure 1 shows the relative sensitivity for Japanese to intestinal infectious diseases caused by pathogens including rotavirus (Watanabe *et al.*, 1999). The sensitivity for infants and children between 0 and 4 years old is quite higher than those for any other age groups. The sensitivity is considered in the evaluation of infectious risk (Watanabe *et al.*, 1999).

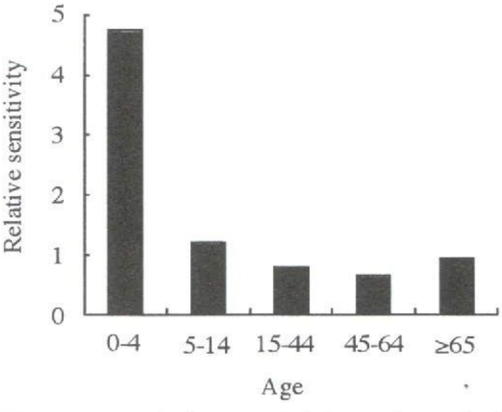


Figure 1. Relative sensitivity to intestinal infectious diseases for Japanese.

Evaluation of the cancer risk

Assumptions for the evaluation of cancer risk. Trihalomethanes (THMs) consisting of chloroform, bromodichloromethane (BDCM), dibromochloromethane (DBCM) and bromoform are employed as disinfection by-products causing cancer risk. Since it is known that THMs cause cancer in liver, the risk for the liver cancer is evaluated. The concentrations of THMs in the drinking water are calculated from THMs production capacities in the reclaimed wastewater and the river water. When the secondary effluent without disinfection in the wastewater treatment is reclaimed, THMs production capacity in the reclaimed wastewater is 333.0 μg/L (Table 1). On the other hand, if the reclaimed secondary effluent is disinfected in the wastewater treatment, the THMs production capacity is assumed to be 113.8 μg/L considering the volatilization of THMs during the storage of the wastewater before its reclamation. The THMs production capacity in the river water is determined with Monte Carlo method based on the observed data which is well-expressed by the lognormal distribution with the average of 107 μg/L. Moreover, it is assumed that 30% of THMs production capacity is reduced in the conventional water treatment process (Tambo, 1983).

Table 1. THMs production capacity in the secondary effluent [μg/L].

	Chloroform	BDCM	DBCM	Bromoform	Total THMs
With volatilization	47.1	37.5	24.1	5.1	113.8
Without volatilization	112.7	131.0	74.3	15.1	333.0

Calculation of cancer risk. According to Integrated Risk Information System (IRIS) published online by the U.S. EPA, cancer risks for lifetime exposure (70 years) to THMs except chloroform can be evaluated from the concentration in the drinking water with the slope factor. In case of chloroform, the U.S.EPA estimated the reference dose of 0.01mg/kg/d as a daily exposure that is likely to be without an appreciable risk of deleterious effects during a lifetime. If the person with the weight of 50 kg drinks 2 L of the water every day, the concentration in the drinking water should be lower than 0.25mg/L. The cancer risk for chloroform is evaluated on the basis of the occurrence probability of the concentration higher than 0.25mg/L.

Relative sensitivity to liver cancer. Figure 2 shows the relative sensitivity to the liver cancer for each age group. This sensitivity is calculated on the basis of the cases of liver cancer reported by Ministry of Health, Labor and Welfare in Japan. Unlike the sensitivity to the infection (Figure 1), senior people have the high sensitivity to the liver cancer. This sensitivity is considered in the evaluation of cancer risk in the same manner as the evaluation of infectious risk.

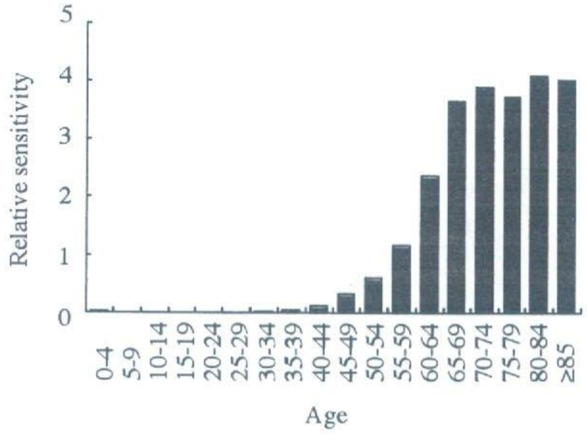


Figure 2. Relative sensitivity to liver cancer for Japanese.

Evaluation of health risks by the DALY

What is DALY? The Disability-Adjusted Life Years (DALY) is the sum of the Years of Life Lost (YLL) and the Years Lived with a Disability (YLD). The YLL indicating the lifetime lost by the fatal disease can be calculated on the basis of the life expectancy reported by Ministry of Health, Labor and Welfare in Japan. The disability caused by fatal or nonfatal disease is quantified with the YLD by decreasing the lifetime according to its severity proposed by Murrey and Lopez (1996).

Calculation of the DALY based on the infectious risk. It was reported by Gerba *et al.*(1996) that 60% of persons infected by rotavirus would be asymptomatic. The DALY is calculated only for symptomatic persons. Since Gerba *et al.* (1996) proposed 0.01% as the fatality ratio for rotavirus infection, the YYL for the infection is negligible. Symptomatic persons will suffer from the diarrhea for seven days (Gerba *et al.*, 1996). Since this duration of disability is quite lower than that for cancer, both of the time discounting rate and the age-weighting factor are not considered in the calculation of YLD. Number of symptomatic persons in an age group is calculated as the product of three valuables of the infectious risk, the relative sensitivity to intestinal infectious disease (Figure 1) and the population in the age group. The DALY lost by rotavirus infection is calculated by multiplying the YLD and total number of symptomatic persons.

Calculation of the DALY based on the cancer risk. The fatality rate for liver cancer was estimated as 84% from numbers of patients and deaths reported by the Ministry of Health, Labor and Welfare in Japan. Based on this fatality rate and the survival data observed in a Japanese hospital, the death rate (P_i) for liver cancer in the *i*th year after the medical treatment is calculated as shown in Figure 3. The symptom of liver cancer develops, the medical treatment is performed at the age of a, and then the expectation of DALY ($DALY_a$) lost by liver cancer for the individual (Figure 4) is calculated as by the following formula:

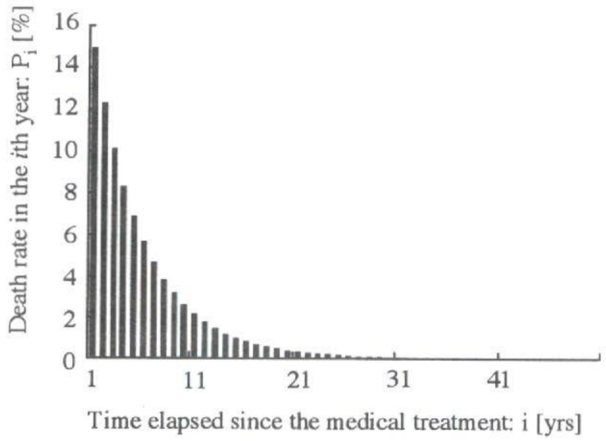


Figure 3. Death rate in the *i*th year after the medical treatment for liver cancer.

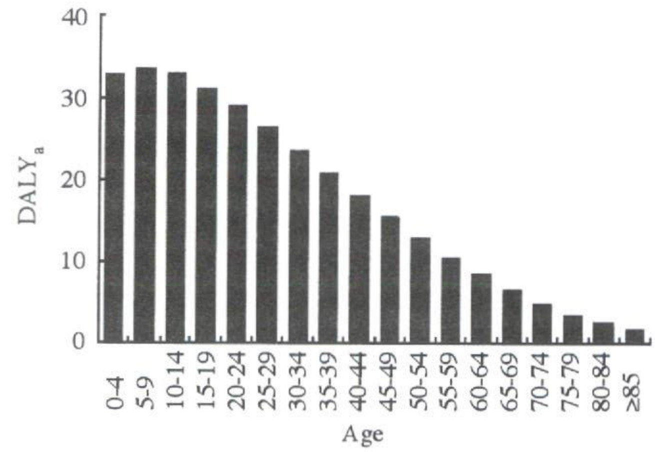


Figure 4. Expectation of DALY ($DALY_a$) lost by liver cancer for the individual.

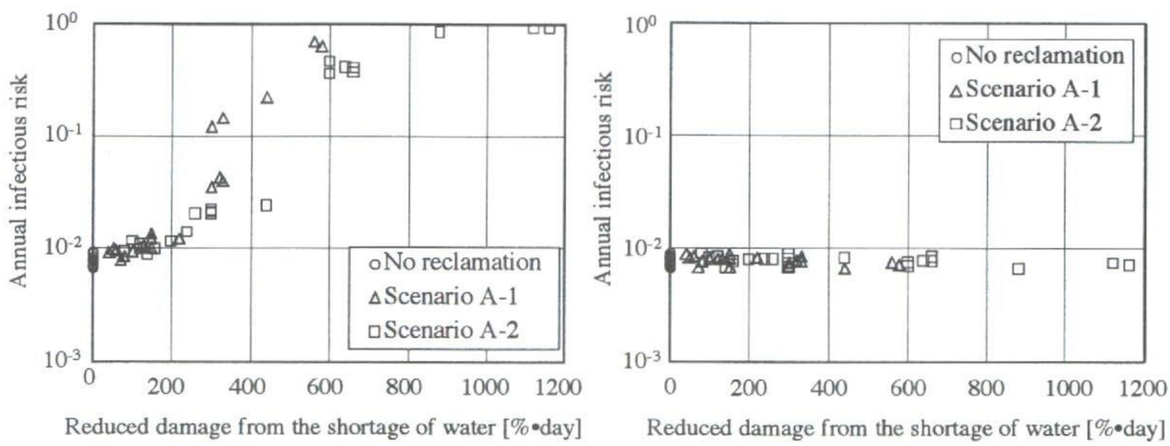
$$DALY_a = \sum_i P_i \left(YLL_i + YLD_i \right) \tag{1}$$

where, YLL_i is the YLL for the death at the age of *a+i* and YLD_i is the YLD during i years. The DALY lost by the liver cancer for the population is obtained by totalizing products of four valuables of the cancer risk, the relative sensitivity to liver cancer (Figure 2), the population and $DALY_a$ for all age groups.

RESULTS AND DISCUSSIONS

Health risks of infection and cancer in the wastewater reclamation

Infectious risk in the wastewater reclamation. Figure 5(a) shows the annual infectious risk in reclaiming the secondary effluent without disinfection. When the secondary effluent was not reclaimed, that is in



(a) Case of reclaiming the secondary effluent without disinfection

(b) Case of reclaiming the disinfected secondary effluent

Figure 5. Relationship between the annual infectious risk caused by rotavirus and the reduced damage from the shortage of water in the wastewater reclamation.

the current situation of water utilization, the infectious risk ranged from 6.0×10^{-3} to 1.0×10^{-2}. This infectious risk is higher than that (about 1.0×10^{-3}) generally reported (Kaneko, 1996). One of reasons for this high risk is that the actual dosage of drinking water may be lower than 2L. Another reasons is that rotavirus has the higher capacity of infection than any other viruses (e.g., poliovirus, coksackie virus, adenovirus). When the reduced damage from the shortage of water was over 200%•day, the infectious risk drastically increased. If the reduced damage was over 1000%•day, almost of all individuals was infected by rotavirus. Figure 5(b) shows the annual infectious risk in reclaiming the disinfected secondary effluent. In this case, the infectious risk did not increase regardless of the reduced damage from the shortage of water. It became obvious that the reclamation of the secondary effluent disinfected with chlorine brought no increase of infectious risk caused by rotavirus.

Cancer risk in the wastewater reclamation. Figure 6 illustrates the annual risk of cancer caused by chloroform in reclaiming the disinfected secondary effluent. The cancer risk was almost constant regardless of the reduced damage from the shortage of water. Annual cancer risks caused by other THMs were also constant. The average risk of cancer caused by chloroform (3.2×10^{-6}) was higher than those for other three substances (BDCM: 6.3×10^{-7}, DBCM: 6.8×10^{-7}, bromoform: 7.7×10^{-8}). When the secondary effluent without disinfection was reclaimed, the cancer risk was almost the same as that shown in Figure 6.

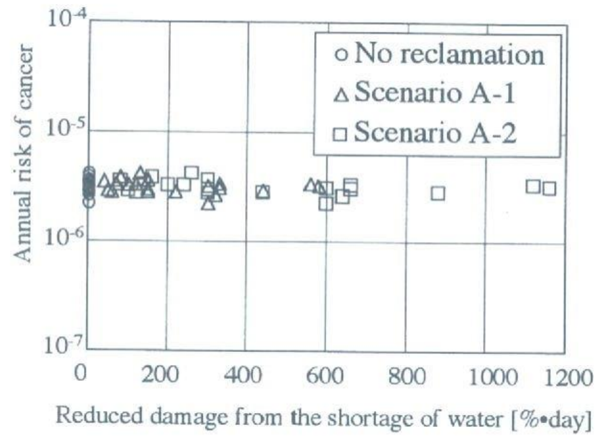
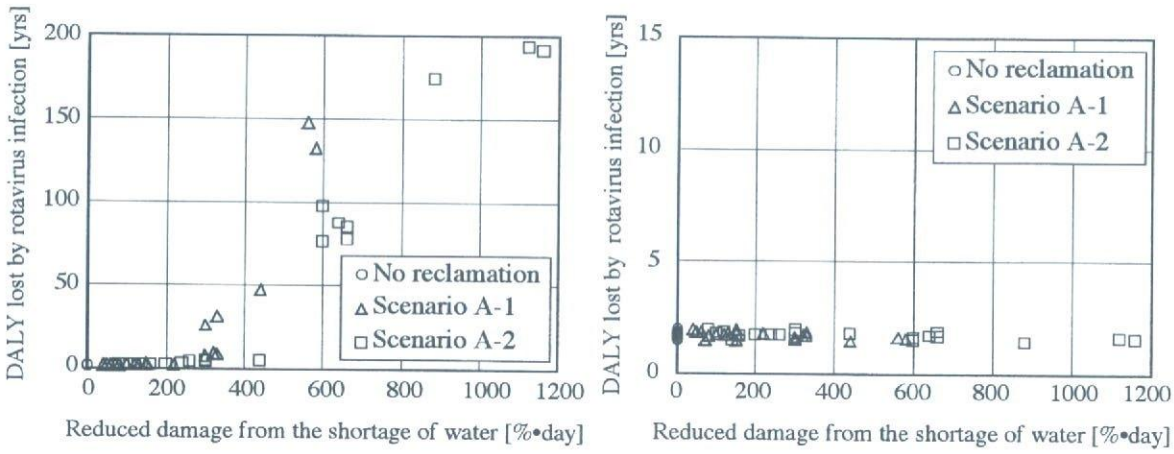


Figure 6. Relationship between the annual risk of liver cancer caused by chloroform and the reduced damage from the shortage of water in reclaiming the disinfected secondary effluent.

Evaluation of the wastewater reclamation with the DALY

DALY lost by rotavirus infection. Figure 7(a) shows the DALY lost by rotavirus infection for total



(a) Case of reclaiming the secondary effluent without disinfection

(b) Case of reclaiming the disinfected secondary effluent

Figure 7. Relationship between the DALY lost by rotavirus infection for total population and the reduced damage from the shortage of water in the wastewater reclamation.

population (0.3 million) when the secondary effluent without disinfection was reclaimed. The maximum DALY for total population was 194 years. In this case, The DALY for each individual was estimated as 5 hours and 40 minutes. In case of no reclamation, DALYs for total population and each individual were 1.7 years and 3 minutes, respectively. Therefore, more than 190 years of lifetime in Fukushima city would be lost by the wastewater reclamation. Figure 7(b) shows the DALY lost by rotavirus infection for total population in reclaiming the disinfected secondary effluent. The DALY in this case was the same as that in case of no reclamation.

DALY lost by cancer. Figure 8 illustrates the DALY lost by liver cancer in reclaiming the disinfected secondary effluent. Since the cancer risk did not increase in the wastewater reclamation as shown in Figure 6, the DALY lost by liver cancer was also constant (9.2 years). The similar result was obtained in case of reclaiming the secondary effluent without disinfection.

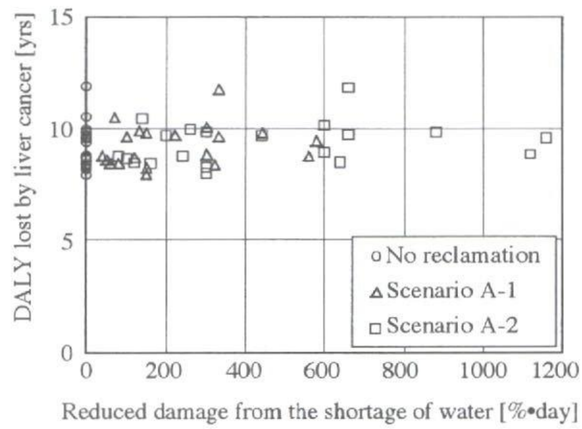
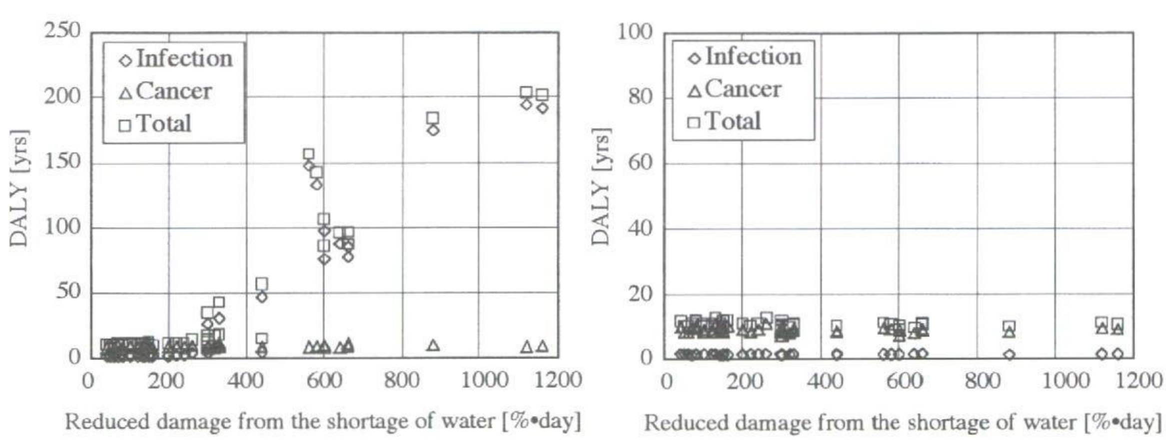


Figure 8. Relationship between the DALY lost by liver cancer for total population and the reduced damage from the shortage of water in reclaiming the disinfected secondary effluent.

Comparison of the DALY lost by infection with that lost by cancer. Figure 9(a) illustrates the comparison of the DALY lost by rotavirus infection with that lost by liver cancer for total population in reclaiming the secondary effluent without disinfection. The sum of these two DALYs is also illustrated in this figure. When the damage from the shortage of water between 0 and 300%•day was reduced, the sum of DALYs was constant (about 11 years). On the other hand, if the reduced damage was over 300%·day, the sum drastically increased corresponding to the increase of DALY lost by infection. Figure 9(b) shows DALYs lost by cancer and infection in reclaiming the disinfected secondary effluent. In this case, the maximum damage of 1200 %•day could be reduced by its reclamation without any increase of DALY. Therefore, if 99.9% of rotavirus in the secondary effluent is inactivated by chlorine disinfection, the same health risks as that in



(a) Case of reclaiming the secondary effluent without disinfection

(b) Case of reclaiming the disinfected secondary effluent

Figure 9. Comparison of the DALY lost by rotavirus infection with that lost by liver cancer for total population in the wastewater reclamation.

current situation of the water utilization could be maintained in the wastewater reclamation from the viewpoint of DALY.

CONCLUSIONS

Health risks for liver cancer and rotavirus infection in Fukushima city with the population with 0.3 million were evaluated in the wastewater reclamation as a drinking water source in case of the shortage of water. The shortage of water was predicted with the matrix of simultaneous probability of river discharge levels on consecutive two days at the intake point of the water treatment plant. DALYs lost by cancer and infection were calculated from evaluated risks. The following conclusions were obtained:

1) In the current situation of water utilization without reclamation, DALYs lost by cancer and infection in the city were 9.2 and 1.7 years, respectively.

2) The reclamation of the secondary effluent without disinfection brought no increase of DALY when the damage between 0 and 300 %•day was reduced. On the other hand, the DALY drastically increased when the reduction of the damage was over 300 %•day.

3) If 99.9% of rotavirus in the secondary effluent was inactivated by chlorine disinfection, the damage from the shortage of water could be reduced by its reclamation without any increase of DALY.

ACKNOWLEDGEMENT

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RISK EVALUATION OF PATHOGENS IN WASTEWATER RECLAMATION AS A DRINKING WATER SOURCE

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ABSTRACT

Urbanized areas in Japan have suffered from the water shortage in recent years. The water shortage will become more serious due to the increase of the water demand and the irregular rainfall. The wastewater reclamation is recognized as one of the most effective countermeasures for the water shortage. However, the wastewater reclamation has a high infectious risk because a number of pathogens may exist in the wastewater. It is essential to develop in advance the wastewater reclamation system able to make up for the water shortage and in parallel to minimize the infectious risk. In this study, infectious risks by poliovirus 1 in the wastewater reclamation of the Abukuma watershed, Japan, were evaluated in three scenarios A-1, A-2 and B. In scenarios A-1 and A-2, the wastewater was reclaimed as a part of the drinking water source. A half of the shortage in the water resource was replaced by the reclaimed wastewater in the scenario A-1. All of the shortage was replaced in the scenario A-2. The wastewater was reclaimed only for toilet flush in the scenario B. The effect of the wastewater reclamation on reducing the damage from the water shortage was also evaluated. The damage was quantified by the product [%•day] of the percentage of the water shortage [%] and the period of the water shortage [day].

The infectious risk did not increase in reclaiming the disinfected secondary effluent in all scenarios. When the secondary effluent without disinfection was reclaimed in the scenarios A-1 and A-2, annual infectious risks increased with the reduction of the damage from the water shortage. If more than 400%•day of the damage from the water shortage was reduced in the scenario A-2, the following relationship was obtained (R^2=0.97):

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

where, X was the reduced damage from the water shortage [%•day] and Y was the annual infectious risk. According to this equation, reducing the damage of 850%•day brought ten times higher infectious risk than that in case of no reclamation (3.1×10^{-3}).

In the scenario B, the infectious risk in reclaiming the secondary effluent without disinfection was about six times as high as that in reclaiming the disinfected effluent.

KEYWORDS

Risk evaluation, pathogens, infectious risk, virus, wastewater reclamation, water shortage, matrix of probability.

INTRODUCTION

Urbanized areas in Japan often have suffered from the water shortage since 1950s. It is why the water demand is increasing with the concentration of population and industries to the urbanized areas and the increase in amenity of life. Moreover, in recent years, irregular rainfalls that often occurred owing to the global climatic aberration have enhanced the water shortage. A lot of dams were constructed for the countermeasure to the water shortage in the 20th century. However, some plans of the dam construction have been reviewed from the viewpoint of various environmental problems such as the ecosystem preservation.

The wastewater reclamation is expected as the alternative water resource especially in the urbanized area from the following merits:
- The volume of wastewater is stable in comparison with other water resources.
- The wastewater is a water resource which can be easily accessed in the urbanized area.

Actually, the wastewater reclamation has been discussed and introduced to the water utilization system for the purposes of toilet flushing, car washing and irrigation in several large cities in Japan. When the water shortage become more serious in the future, the wastewater reclamation as a part of drinking water source will be needed as seen in Singapore.

Since many researchers have reported the existence of pathogens in the secondary effluent from the wastewater treatment plants (Omura *et al.*, 1989; Havelaar *et al.*, 1993; Yano *et al.*, 1993), there is the high infectious risk by pathogens in reclaiming the secondary effluent. Therefore, in order to introduce the wastewater reclamation to the water utilization system, the infectious risk have to be evaluated in advance and reduced to the acceptable level. Tanaka *et al.* (1998) evaluated viral infectious risks in the wastewater reclamation for the golf course irrigation, crop irrigation, recreational impoundment and groundwater recharge. In the wastewater reclamation for the golf course irrigation, the infectious risk by *Cryptosporidium parvum* was also evaluated by Jolis *et al.* (1999). Other researchers have reported infectious risks evaluated in various scenarios of the water reclamation (Rose *et al.*, 1996; Shuval *et al.*, 1997). However, the effect of the reclamation on reducing the damage from water shortage was not well-discussed in these previous studies.

The objective in this study is to evaluate infectious risks in the wastewater reclamation for a drinking water source and toilet flush, respectively. The effect of the reclamation on reducing the damage from the water shortage is also evaluated.

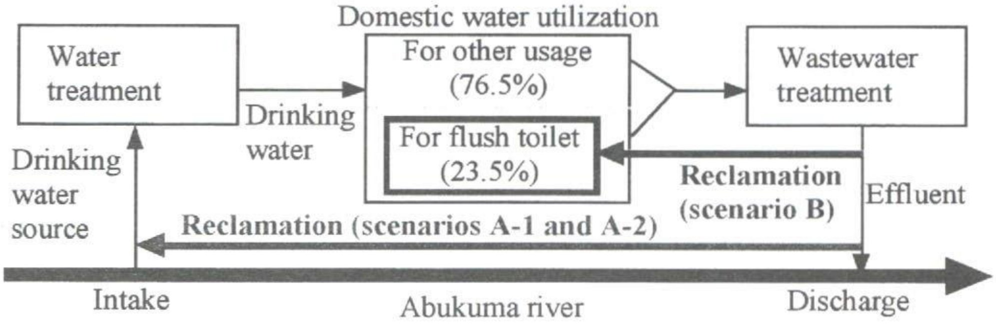
METHODOLOGY

Research Area and Water Utilization System

The wastewater reclamation is simulated in Fukushima city, Japan. This city is located at the middle reach of the Abukuma river. The area of the watershed of this river is 5,400km^2 and the length is 239km. The Abukuma watershed usually has annual rainfalls of 1,200-1,300mm in the field area and 1,500-1,800mm in the mountain area. These rainfalls are lower than the average (1800mm) in Japan. In this watershed, Fukushima city is the biggest city with the population of 0.3 million. Fukushima city often suffer from the water shortage, especially in summer season. In August 1994, the serious water shortage restricted the water supply in some parts of the city for two weeks. The effective countermeasure for avoiding the restriction of the water supply is required in Fukushima city.

A water utilization system involving the wastewater reclamation (Figure 1) is proposed for the evaluation of the infectious risk. The Abukuma river is used as a drinking water source in Fukushima city and receives the discharge from the wastewater treatment plant in the city. Citizens of the city usually utilize 360 liters of the drinking water per day. Then, the daily intake from the Abukuma river at the water treatment plant is estimated as 1.08 x $10^8 m^3$. The same volume of effluent is daily discharged from the wastewater treatment plant to the Abukuma river. According to the investigation on the domestic water usage in Japan, about a quarter (23.5%) of the water supply is utilized for flush toilet (The Japan Society of Civil Engineers, 1989).

Figure 1 - Water Utilization System in Fukushima City



Levels of the River Discharge and Definition of the Water Shortage

River discharges at the intake point of the water treatment plant are categorized into 20 levels shown in Table 1. Twenty-two percents of river discharge observed from 1980 to 1999 are included in level 19 with higher than $95m^3/s$. These high discharges have little meaning for the risk evaluation in the wastewater reclamation because the wastewater is reclaimed in case of low discharges. According to the statistical analysis by the Ministry of Land, Infrastructure and Transport in Japan, discharges below $27.68m^3/s$ are very rare (annual frequencies below $27.68m^3/s$ from 1980 to 1999 were in the range between 0 and 73 days). These discharges are corresponding to levels 0-4 in Table 1. This situation below level 4 is regarded as a water shortage.

Table 1 - River Discharge Levels at the Intake Point of the Water Treatment Plant in Fukushima City

Level	River discharge [m^3/s]	RF [%]*	Level	River discharge [m^3/s]	RF [%]
0	0 - 5	0.0	10	50 - 55	6.2
1	5 - 10	0.0	11	55 - 60	5.3
2	10 - 15	0.3	12	60 - 65	4.3
3	15 - 20	0.6	13	65 - 70	4.1
4	20 - 25	3.1	14	70 - 75	3.5
5	25 - 30	5.9	15	75 - 80	3.0
6	30 - 35	7.8	16	80 - 85	2.8
7	35 - 40	10.0	17	85 - 90	2.1
8	40 - 45	9.8	18	90 - 95	1.8
9	45 - 50	7.4	19	95 -	22.0

*Relative frequency of each river discharge level observed from 1980 to 1999

Reproduction of River Discharges at the Intake Point

In order to simulate the wastewater reclamation, it is necessary to predict the water shortage. The short-term fluctuation of the river discharge such as a flood is generally predicted on the basis of rainfall. On the other hand, the history of the fluctuation gives more valuable information than rainfall for the prediction of the long-term fluctuation such as the water shortage. Therefore, in this study, the matrix of simultaneous probability of discharge levels on consecutive two days are derived from discharges observed at the intake point of the water treatment plant in Fukushima city from 1980 to 1999 (n=7,290). The matrix can be expressed by the following formula:

$$P=[p_{ij}],\ p_{ij}=Pr[Q=j|Q_{-1}=i]$$

where, P is a matrix with elements of p_{ij}. This element means the conditional probability that the discharge level (Q) on a day will be j when the level (Q_{-1}) on the previous day is i.

Two matrices (P^+ and P^-) are developed for reproducing the smooth fluctuation of the river discharge. Matrix P^+ is used when the discharge was constant or increasing in the previous two days. Matrix P^- is used in the other cases. These matrices are expressed by the following formulas:

$$P^+=[p_{ij}^+],\ p_{ij}^+=Pr[Q=j|Q_{-1}=i,\ q_{-1}-q_{-2}\geq 0]$$
$$P^-=[p_{ij}^-],\ p_{ij}^-=Pr[Q=j|Q_{-1}=i,\ q_{-1}-q_{-2}<0]$$

where, q_{-1} and q_{-2} are discharges one day before and two days before, respectively. The occurrence probability of low discharges in August is quite higher than those in the rainy season. Twelve sets of matrices P^+ and P^- corresponding to each month were prepared to reflect the monthly characteristics to the prediction of river discharges.

Using the developed matrices, the river discharge is reproduced day by day. The discharge on the n th day (q_n) is determined by the following procedure:
(1) The discharge level of i on the previous day is determined from the discharge of q_{n-1}. Only the level on the 1st January is determined with Monte Carlo method based on the distribution of occurrence probability of river discharge in January.
(2) According to the level i, the distribution of occurrence probability of discharge level j on the n th day is prepared from developed matrices.
(3) The discharge level j is determined with Monte Carlo method using the prepared distribution.
(4) The discharge on the n th day (q_n) is estimated by the following formula:

$$q_n=5j+5\pi$$

where, π is the random variable from 0 to 1. As shown in Table 1, the discharge level is divided at the interval of $5m^3/s$. The above estimation is based on the uniform distribution of occurrence probability of discharge in each level. Only if the level j is 19, the discharge (q_n) is calculated by the following formula:

$$q_n=235.67+281.34(\pi-0.5)=95+281.34\pi$$

This formula is based on the assumption that expectation of q_n is $235.67m^3/s$ which is equivalent to the average of observed discharge when the discharge is higher than $95m^3/s$.

(5) The discharge on the (n+1) th day is determined by repeating procedures (1) - (4).

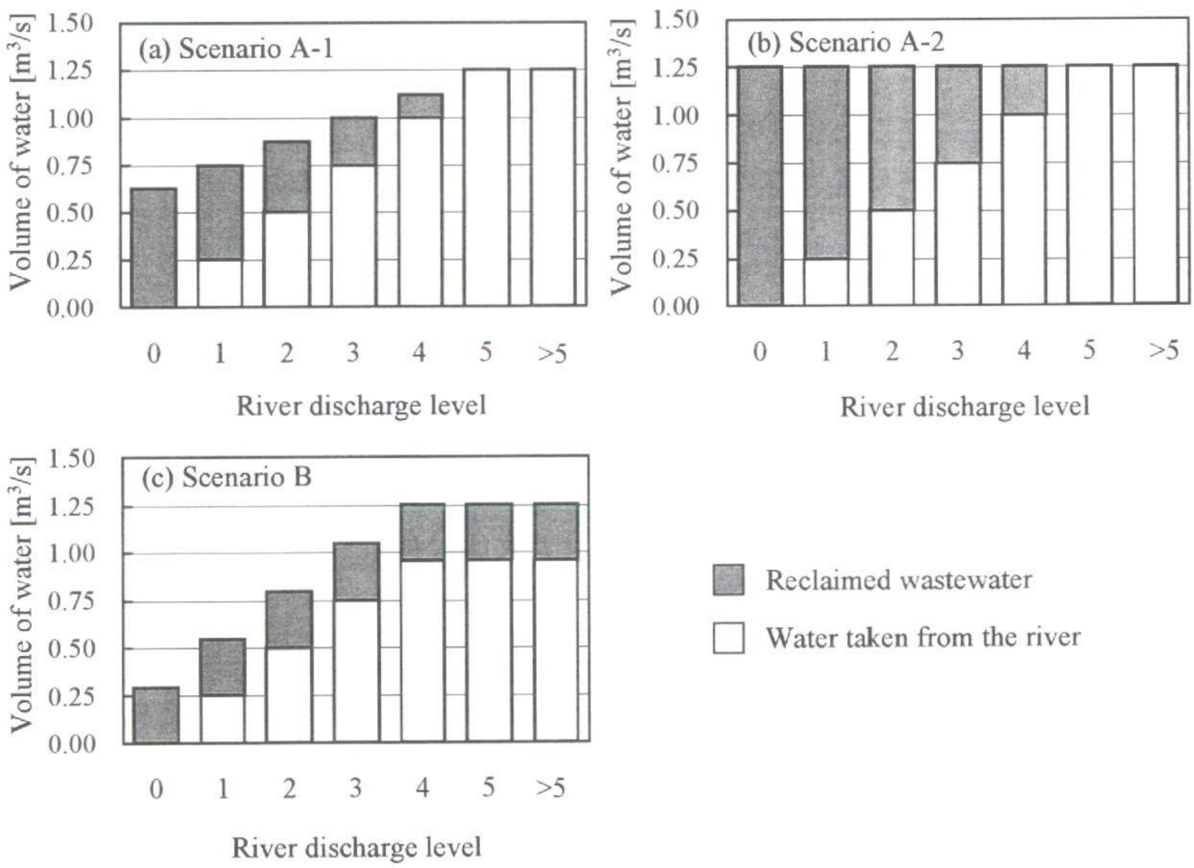
Scenarios on the Wastewater Reclamation

In order to evaluate infectious risks in the wastewater reclamation, the following scenarios are employed (Figure 1):

- Scenario A. The wastewater is reclaimed as a part of drinking water source. When the discharge level is less than level 4, the intake from the Abkuma river is restricted in consideration of water utilizations such as the irrigation and drinking water sources at other cities in the watershed. The wastewater reclamation covers a half of the shortage of drinking water source due to the restriction of intake in the scenario A-1. On the other hand, the shortage is perfectly replaced by the reclamation in the scenario A-2.
- Scenario B. Regardless of the river discharge, the wastewater is reclaimed only for flush toilet everyday. The daily intake at the water treatment plant can be decreased to 76.5% of present value.

Volumes of reclaimed wastewater in these scenarios are illustrated in Figure 2.

Figure 2 - Volumes of Water Taken from the River and Reclaimed Wastewater as a Drinking Water Source



Effect of the Wastewater Reclamation on Reducing the Damage from the Water Shortage

The seriousness of the water shortage is often quantified by the product [%•day] of the percentage of water shortage [%] and the period of water shortage [day] (Ikebuchi, 2001). The effect of wastewater reclamation on reducing the damage from the water shortage is evaluated as a decrease of the seriousness by the reclamation.

Evaluation of the Infectious Risk

Poliovirus 1 is employed for the evaluation of the infectious risk. This virus is selected as the representative virus from genus Enterovirus that often has caused waterborne infectious diseases. Infectious risk by poliovirus 1 is calculated with the following dose-response model (Rose and Gerba, 1991):

$$P(D) = 1 - \left[1 + \frac{D}{1.14}\right]^{-0.5}$$

where, D is the dosage of poliovirus 1 and P(D) is the infectious probability. The dosage of poliovirus 1 is calculated on the basis of the dosage of drinking water and the viral concentration. Since those who have recovered from the infection by poliovirus 1 cannot be re-infected due to the immune system, the number of infected persons on the t th day from the beginning of simulation can be calculated with the following formula:

$$I(t) = \left[N - \sum_{T=1}^{t-1} I(T)\right] \cdot P(D(t))$$

where, I(t) is the number of infected persons on the t th day and N is the population in Fukushima city (=0.3 million). If the calculated number of infected persons is including the decimal fraction, it is rounded to the integer. The annual infectious risk is evaluated as the ratio of total infected persons to the population.

Assumptions for Evaluating the Infectious Risk

There is a little information on virus concentration in the Abukuma river while the concentration of total coliforms are regularly monitored. Therefore, the viral concentration in the river is related to the concentration of total coliforms. Kaneko (1997) reported that the concentration ratio of virus to total coliforms was 1/50,000 in the river not polluted so heavily. He also mentioned that infected persons excreted 100-200g of feces including virus at the concentration of 10^6 particles/g in a day and the excretion of virus from infected persons continued in the period between several days and six weeks. Therefore, the feces weight of 200g and the excreting period of 30days are employed in this study. The viral concentration in the wastewater is calculated from the number of infected persons and the discharge volume (360L/day/person).

On viral removal efficiencies by typical water treatment (flocculation, sedimentation and sand filtration), Payment and Franco (1993) reported 3.2 $\log_{10}$ and 1.3 $\log_{10}$ for enteric viruses and Havelaar *et al.* (1995) reported 1.4 $\log_{10}$ for enterovirus. However, the viral behavior in the water treatment processes has not been sufficiently investigated. On the other hand, the removal efficiency of total coliforms by the water treatment has been well-investigated and reported as a value from 1.7Log_{10} to >2.9Log_{10} (Stetler *et al.*, 1992). According to reported data, it seems that viruses can be removed by typical water treatment as efficiently as total coliforms. The removal efficiency of poliovirus 1 is assumed in the range between 1.7 $\log_{10}$ and 2.9 $\log_{10}$. The viral removal efficiency in the water treatment depends on the operational situation. In general, low temperature and low suspended solids (SS) have negative effect on the water treatment because of the insufficient flocculation. Therefore, on the basis of the dataset on the water temperature and the SS concentration observed in the Abukuma river from 1980 to 1999, it is assumed that the minimum removal efficiency of poliovirus 1 ($1.7 Log_{10}$) is obtained when the product of the water temperature and the SS concentration is minimum. On the other hand, if the maximum of the product is observed, the viral removal efficiency becomes maximum ($2.9 Log_{10}$). In other cases, the removal efficiency (R) was estimated by assuming the linear relationship as shown in the following formula:

$$-Log_{10}R=0.0024 \cdot a \cdot b+1.7$$

where, a and b are the water temperature [°C] and the SS concentration [mg/L], respectively.

In the disinfection process after the water treatment, it is assumed that 99.9 percents of poliovirus 1 could be inactivated by free chlorine. Since there is little information on the inactivation of poliovirus 1 by free chlorine, the inactivation efficiency proposed by Vaughn *et al.* (1986) for rotavirus SA11 is employed. According to inactivation efficiencies for these viruses by chloramines and chlorine dioxide, poliovirus 1 and rotavirus SA11 have the similar tolerance against chlorine disinfectants (Sobsey, 1989).

Removal efficiencies of enteric viruses at the wastewater treatment plant have been reported in the range between 0 and 20 percents by the sedimentation and in the range between 75 and 99 percents by the activated sludge process (Kaneko, 1997). According to these reports, 90 percents are employed as the removal efficiency by wastewater treatment including the sedimentation and the activated sludge process. Moreover, it is assumed that 99.9 percents of poliovirus 1 in the secondary effluent can be inactivated by the chlorine disinfection.

Other assumptions employed in this study are as follows:
-All citizens in Fukushima city drink 2 liters per day of tap water and they ingest accidentally 0.001ml per day of the reclaimed wastewater for flush toilet.
-Nobody has the immune system to poliovirus 1 at the beginning of the simulation.

Prediction of Water Qualities Based on the River Discharge

As above-mentioned, concentrations of total coliforms and SS are needed in simulating the wastewater reclamation. It is said that some water qualities in the river are tightly related to the discharge. However, it is difficult to formulate the relationship between the concentration of total coliforms and the discharge observed in the Abukuma river (Figure 3). Therefore, in the same manner as the prediction of river discharges, the matrix of simultaneous probability between the concentration of total colifroms and the discharge is derived and then the concentration is predicted using this matrix. The SS concentration is also predicted using the matrix between SS concentration and the discharge. In order to derive matrices for total coliforms and SS, these concentrations are categorized into several levels shown in Table 2.

Figure 3 - Relationship between the River Discharge and the Concentration of Total Coliforms

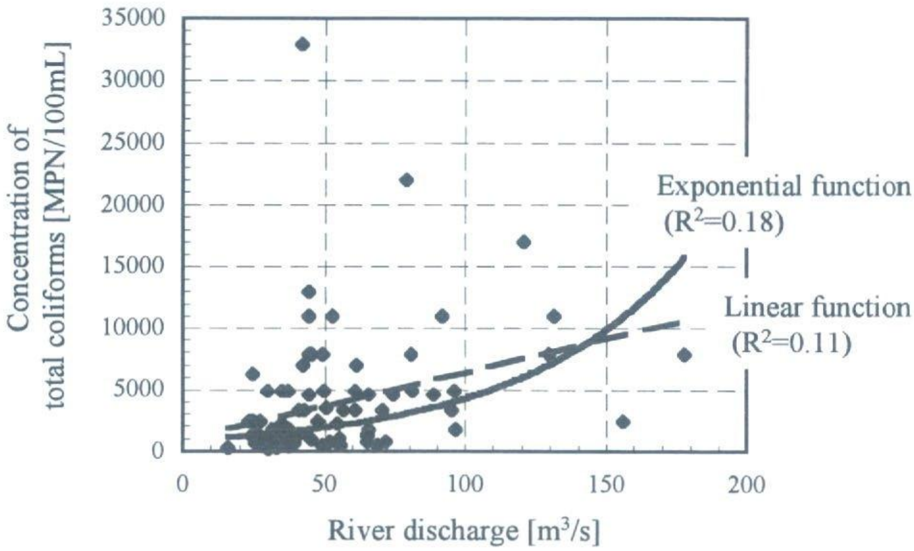


Table 2 – Concentration Levels of Total Coliforms and SS

Level	Total coliforms [MPN/100mL]	Frequency*
0	0 - $10^{1.5}$	0
1	$10^{1.5}$ - $10^{2.0}$	0
2	$10^{2.0}$ - $10^{2.5}$	4
3	$10^{2.5}$ - $10^{3.0}$	22
4	$10^{3.0}$ - $10^{3.5}$	30
5	$10^{3.5}$ - $10^{4.0}$	31
6	$10^{4.0}$ - $10^{4.5}$	7
7	$10^{4.5}$ - $10^{5.0}$	1
8	$10^{5.0}$ - $10^{5.5}$	0
9	$10^{5.5}$ -	0

* Frequency based on the observed data from 1980 to 1999.

Level	SS [mg/L]	Frequency*
0	0 - 2	0
1	2 - 4	0
2	4 - 6	5
3	6 - 8	1
4	8 - 10	7
5	10 - 12	9
6	12 - 14	14
7	14 - 16	10
8	16 - 18	10
9	18 - 20	6
10	20 - 22	11
11	22 - 24	3
12	24 - 26	3
13	26 - 28	6
14	28 - 30	3
15	30 - 32	1
16	32 - 34	2
17	34 - 36	1
18	36 - 38	1
19	38 -	8

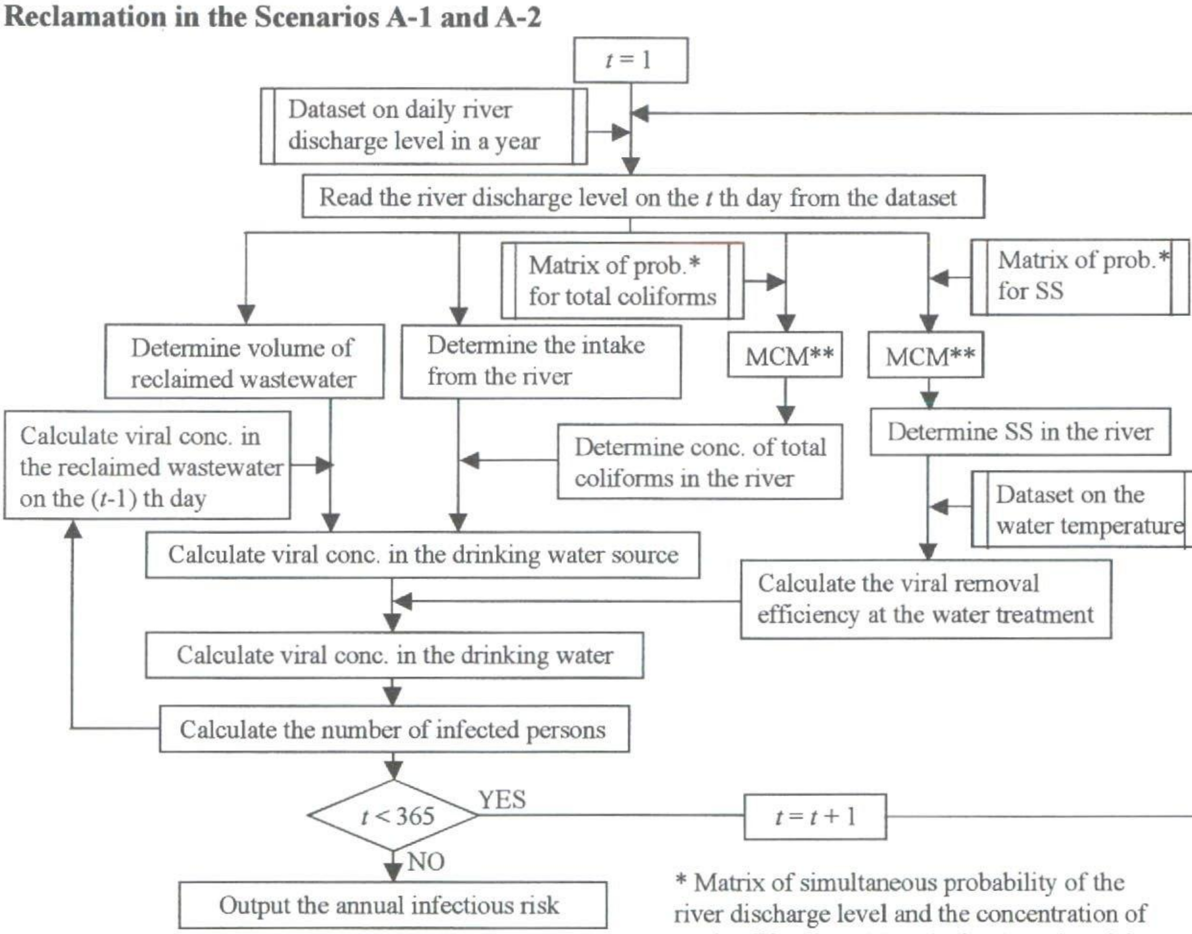
Procedures for Evaluating the Annual Infectious Risk

The flowdiagram for the evaluation of the annual infectious risk in wastewater reclamation in the scenarios A-1 and A-2 is illustrated in Figure 4. Each procedure is as follows:
(1) The river discharge on a day is read from the data file including reproduced discharges and the discharge level is determined.
(2) Concentration levels of total coliforms and suspended solids (SS) in the river are determined from the discharge level with developed matrices. These concentrations are predicted from the

determined levels with Monte Carlo method.
(3) The concentration of poliovirus 1 in the river is calculated from that of total coliforms.
(4) The removal efficiency of poliovirus 1 at the water treatment is estimated on the basis of the water temperature and the SS concentration.
(5) The volume of reclaimed wastewater is determined from the river discharge level.
(6) The viral concentration in the reclaimed wastewater is calculated from the number of infected persons on the previous day.
(7) The viral concentration in the drinking water source is calculated from those in the river and the reclaimed water.
(8) The viral concentration in the drinking water is calculated.
(9) The number of infected persons on a day is calculated employing the dose-response model.
(10) The annual infectious risk is evaluated by repeating procedures (1) - (9) for 365 times.

The annual infectious risk in wastewater reclamation in the scenario B is evaluated by the following procedures:
(1) The viral concentration in the wastewater is calculated from the number of infected persons on the previous day.
(2) The number of infected persons is calculated employing the dose-response model.
(3) The annual infectious risk is evaluated by repeating above two procedures for 365 times.

Figure 4 - Flowdiagram for Evaluating the Annual Infectious Risk in the Wastewater Reclamation in the Scenarios A-1 and A-2



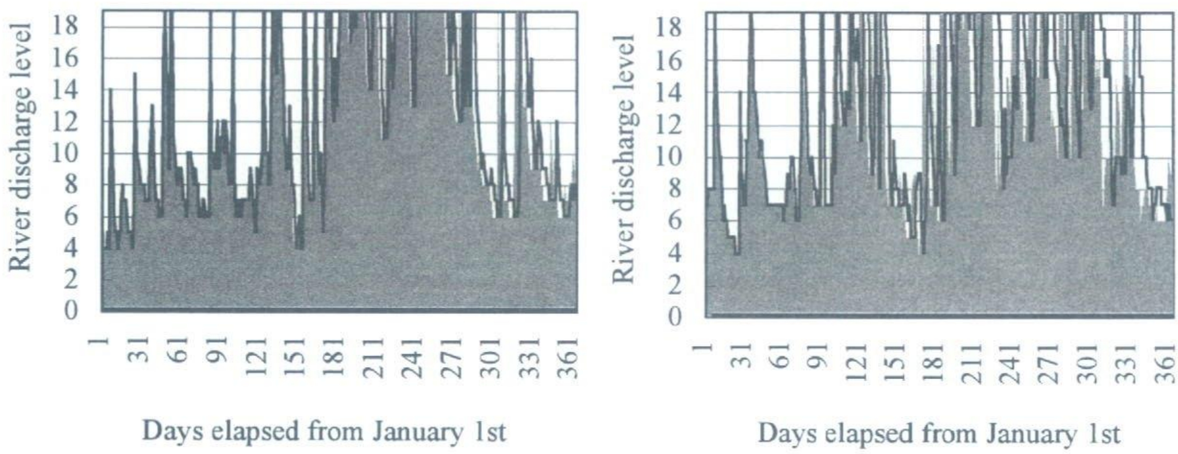
* Matrix of simultaneous probability of the river discharge level and the concentration of total coliforms or SS at the intake point of the water treatment plant.
** MCM (Monte Carlo Method).

RESULTS AND DISCUSSIONS

Reproduction of the River Discharge by the Matrix of Probability

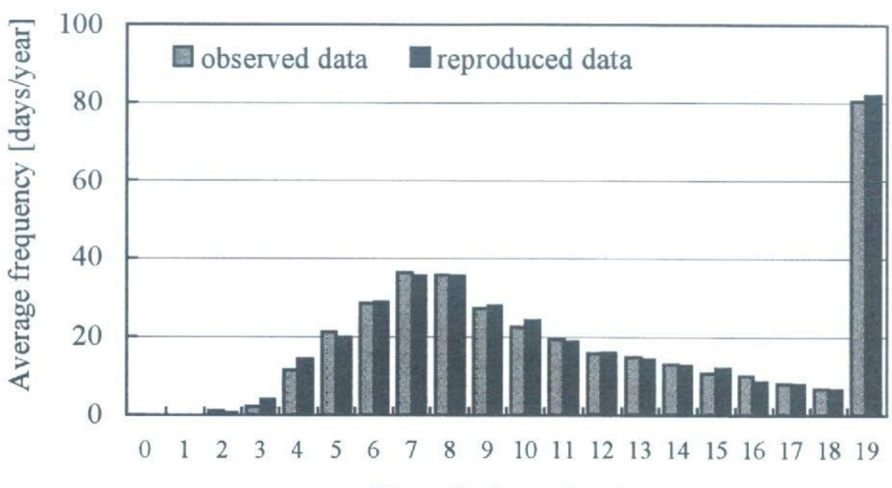
The river discharge at the intake point of the water treatment plant was reproduced 20 times using developed matrices of probability. Figure 5 illustrates observed and reproduced fluctuations in one case. The fluctuation of the river discharge could be well-reproduced throughout a year by the proposed method. High discharges in the rainy season of spring and low discharges in summer and winter could be also reproduced. In Figure 6, the frequency distribution of river discharge levels reproduced in 20 trials was compared with that of observed discharge levels. The chi-square goodness-of-fit test at the rejection level of 10% indicated that the reproduced frequency distribution was significantly fitted to the observed distribution.

Figure 5 - Observed and Reproduced Fluctuations of the River Discharge at the Intake Point of the Water Treatment Plant in Fukushima City



(a) Observed data (b) Reproduced data

Figure 6 - Frequency Distribution of Observed and Reproduced River Discharge Levels at the Intake Point of the Water Treatment Plant in Fukushima City



In order to investigate the influence of the frequency of the water shortage on the infectious risk, fluctuations of river discharge were categorized into four patterns on the basis of criteria shown in Table 3. Pattern 1 was the most serious case with the higher frequency of the water shortage than 40 days. In the pattern 2, the frequency of the water shortage was higher than the average frequency (14.8 days/year) observed from 1980 to 1999. In pattern 3 and 4, the frequency of water shortage was lower than the average. The water shortage was not serious in pattern 4 since river discharges in the highest level were observed more than 100 days. The typical frequency distribution of the reproduced river discharge in each pattern is illustrated in Figure 7.

Table 3 - Criteria for Categorization of the Fluctuation of the River Discharge

Patterns	Criteria	Water shortage
1	Discharges in levels 0-4 are observed more than 40 days.	Very serious
2	Discharges in levels 0-4 are observed between 15 and 39 days.	Serious
3	Discharges in levels 0-4 are observed less than 14 days and discharges in level 19 are observed less than 99 days.	Moderate
4	Discharges in levels 0-4 are observed less than 14 days and discharges in level 19 are observed more than 99 days.	Not serious

Figure 7 – Frequency Distribution of the Reproduced River Discharge Levels in Each Pattern

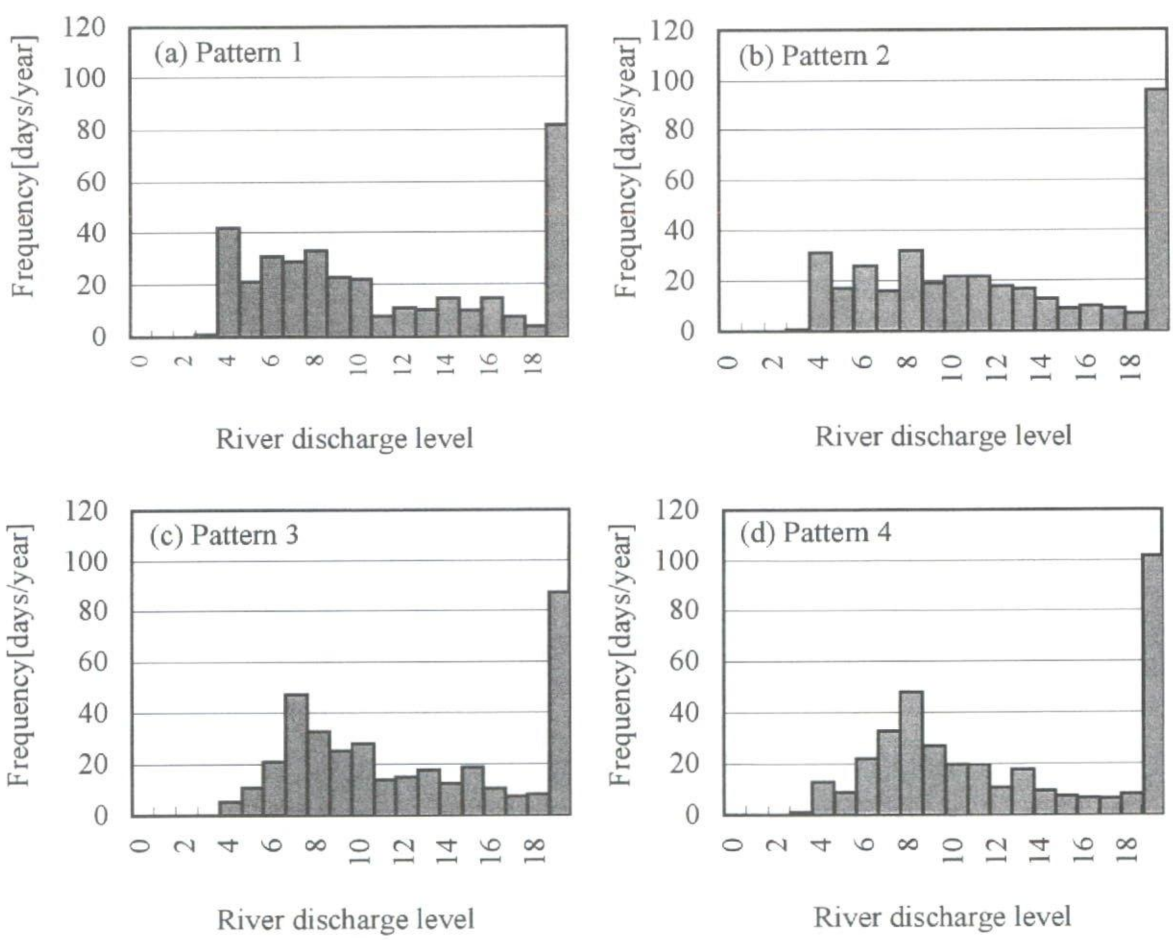


Table 4 shows frequencies of four patterns of the river discharge fluctuation in observed and reproduced data for 20 years. The ratio of frequency in the pattern 3 in the reproduced data was almost the same as that in observed data. The frequency distribution of the river discharge levels in this pattern 3 (Figure 7) was similar to the total frequency distribution of the river discharge level (Figure 6). It was difficult to reproduce an unusual fluctuation such as patterns 1 and 4 by the proposed method since the matrix of probability was derived from all observed data. For the prediction of the river discharge focusing on unusual patterns, it was necessary to derive the matrix from the dataset categorized into such patterns. Since four patterns of the river discharge were reproduced throughout a year, the annual infectious risk in the wastewater reclamation could be evaluated in all patterns of the river discharge.

Table 4 - Frequency of Each Patterns of the River Discharge Fluctuation

Pattern	Observed data		Reproduced data	
	Frequency	Ratio [%]	Frequency	Ratio [%]
1	3	15	1	5
2	4	20	9	45
3	8	40	9	45
4	5	25	1	5

Annual Infectious Risks in the Wastewater Reclamation

Annual infectious risks by poliovirus 1 in reclaiming secondary and disinfected effluents in each scenario were evaluated using twenty datasets of the reproduced river discharge. The risk evaluation was repeated 10 times using each dataset. Averages of annual infectious risks evaluated from categorized datasets of the river discharge are shown in Figure 8.

In case of reclaiming the secondary effluent without disinfection. In patterns 1 and 2, the infectious risk in the wastewater reclamation in every scenario was higher than that in case of no reclamation. Especially, the highest infectious risk of 3.8×10^{-2} was obtained in the scenario A-2 when the water shortage was very serious (pattern 1). This risk was more than ten times as high as that in case of no reclamation (2.8×10^{-3}). On the other hand, in the patterns 3 and 4, the increase of the infectious risk in scenarios A-1 and A-2 was slight in comparison with that in case of no reclamation. In the scenario B, almost the same infectious risk (1.7×10^{-2} - 2.3×10^{-2}) was obtained in all patterns. This infectious risk in the scenario B was about six times higher than that in case of no reclamation. The reclaimed wastewater of 0.001mL per day was ingested in this scenario. The infectious risk caused by such a low ingestion of the reclaimed wastewater has to be considered for the wastewater reclamation.

In case of reclaiming the disinfected secondary effluent. In all scenarios, the infectious risk did not increase in comparison with that in case of no reclamation regardless of the river discharge pattern. This result means that the concentration of poliovirus 1 in the reclaimed wastewater could be decreased by the chlorine disinfection to the almost same concentration in the river water.

The result of the risk evaluation indicated that the infectious risk increased in the reclamation of secondary effluent in comparison with the case of no reclamation. In Japan, the concentration of total coliform of 1,000CFU/100mL has been established as the standard in the wastewater reclamation for flush toilet (scenario B). At the wastewater treatment plant in Fukushima city, total