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 water shortage. However, there is a concern that wastewater reclamation causes health risks of infection by pathogens and cancer by disinfection by-products such as trihalomethanes (THMs). To discuss these risks, the Disability-Adjusted Life Years (DALY) has been employed and integrated with the unit of lost lifetime. Health risks such as infection and cancer in Fukushima city with population of 0.3 millions were evaluated using the DALY in the wastewater reclamation as a drinking water source. The damage [%•day] from the shortage of water was quantified using the product of the percentage deficiency to 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. Reclamation of 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 [%•days]. 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

Disability-Adjusted Life Years (DALY), health risks, wastewater reclamation

INTRODUCTION

Water shortage is recognized as one of the most serious problems in the global environment. The United Nations (UN) reported in 1995 one third of the world population suffered from water shortage and in 2025 two thirds of the population is expected to experience the same problem due to the increase of water demand. To solve the problem, the wastewater reclamation has been introduced into water utilization system for the purposes of toilet flushing, car washing and irrigation in urbanized area. In Singapore, wastewater treated with membrane technologies has been provided as the drinking water
known as “Newater”. If water shortage becomes a more serious problem, wastewater reclamation as a source of drinking water will be popular in the future.

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

The objective of this study is to evaluate both the health risks of infection and cancer in the wastewater reclamation using the 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 is evaluated from fatal diseases such as cancer and nonfatal diseases such as infectious diseases in the same unit of the lost lifetime [years]. 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 water shortage caused by low discharges of the Abukuma river, especially during the 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 the categorized data. With the derived matrix of probability, they proposed a 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 this method sufficiently validated for its rationality (Watanabe et al., 2003).

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 statistical analysis of river discharge at the intake point by the Ministry of Land,
Infrastructure and Transportation in Japan, 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 half of the shortage of drinking water source. In scenario A-2, all of the shortage of water 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 based on the river discharge with the matrix 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 of Japanese to intestinal infectious diseases caused by pathogens including rotavirus (Watanabe et al., 1999). The sensitivity for Japanese infants and children between 0 and 4 years old is higher than those on any other age groups. The sensitivity is considered in the evaluation of infectious risk with the reliable method proposed by Watanabe et al. (1999).
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 causes 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, the 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 using the 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 the THMs production capacity is reduced in the conventional water treatment process (Tambo, 1983).

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

<table>
<thead>
<tr>
<th></th>
<th>Chloroform</th>
<th>BDCM</th>
<th>DBCM</th>
<th>Bromoform</th>
<th>Total THMs</th>
</tr>
</thead>
<tbody>
<tr>
<td>With volatilization</td>
<td>47.1</td>
<td>37.5</td>
<td>24.1</td>
<td>5.1</td>
<td>113.8</td>
</tr>
<tr>
<td>Without volatilization</td>
<td>112.7</td>
<td>131.0</td>
<td>74.3</td>
<td>15.1</td>
<td>333.0</td>
</tr>
</tbody>
</table>

Calculation of cancer risk. According to the 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 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 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), older people have higher sensitivity to 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.](image)

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 based on the life expectancy reported by Ministry of Health, Labor and Welfare in Japan. The disability caused by fatal or nonfatal disease is quantified using the YLD by decreasing the lifetime according to its severity as 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 diarrhea for seven days (Gerba et al., 1996). Since the duration of disability is lower than that of cancer, both the time discounting rate and
the age-weighting factor were not considered in the calculation of YLD. The 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. When the symptoms of liver cancer develops, the medical treatment is performed at the age of $a$, and then the expectation of DALY ($\text{DALY}_a$) lost by liver cancer for the individual (Figure 4) is calculated using the formula:

$$\text{DALY}_a = \sum_i P_i (\text{YLL}_i + \text{YLD}_i)$$

(1)

where, $\text{YLL}_i$ is the YLL for death at the age of $a+i$ and $\text{YLD}_i$ is the YLD during $i$ years. The DALY lost by the liver cancer for the population is obtained by summing up the products of four valuables of the cancer risk, the relative sensitivity to liver cancer (Figure 2), the population and $\text{DALY}_a$ 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 the current situation of water utilization, the infectious risk ranged from $6.0 \times 10^{-3}$ to $1.0 \times 10^{-2}$. This
infectious risk is higher than that (about $1.0 \times 10^{-3}$) generally reported (Kaneko, 1996). One of the reasons for this high risk is that the actual dosage of drinking water may be lower than 2L. Another reason is that rotavirus has the higher capacity of infection than any other viruses (e.g., poliovirus, coxsackie 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 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.

![Figure 5](image.png)

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

![Figure 6](image.png)

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.

*Cancer risk in the wastewater reclamation.* Figure 6 illustrates the annual risk of cancer caused by chloroform in reclaiming the disinfected secondary effluent. 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 x 10^{-6}) was higher than those in other three substances (BDCM: 6.3 x 10^{-7}, DBCM: 6.8 x 10^{-7}, bromoform: 7.7 x 10^{-8}). When the secondary effluent without disinfection was reclaimed, the cancer risk was almost the same as that shown in Figure 6.

**Evaluation of the wastewater reclamation with the DALY**

*DALY lost by rotavirus infection.* Figure 7(a) shows the DALY lost by rotavirus infection for the total 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 the case of no reclamation, DALYs for the total population and each individual were 1.7 years and 3 minutes, respectively. Therefore, more than 190 years of lifetime in Fukushima city will be lost by the wastewater reclamation. Figure 7(b) shows the DALY lost by rotavirus infection for the total population in reclaiming the disinfected secondary effluent. The DALY in this case was the same as in case of no reclamation.

![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.](image)

*DALY lost by cancer.* Figure 8 illustrates the DALY lost by liver cancer in reclaiming the disinfected secondary effluent. Since 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). Similar result was obtained in the case of reclaiming the secondary effluent without disinfection.

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

![Figure 8](image1.png)

**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.

![Figure 9](image2.png)

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

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

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

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

4) Health risk evaluation based on DALY would contribute to policy making for the introduction of the wastewater reclamation into the water utilization system in the watershed.

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