

# Health impact assessment of wastewater reuse for replenishing an urban landscape lake by disability-adjusted life year

Rong Chen, Tingting Gao, Xiaochang Wang, Jinhong Zhou and Limei Xu

## ABSTRACT

Wastewater reuse for landscape water replenishment has raised severe public concerns over potential health hazards. Thus, this study aims to quantify the health impacts due to the replenishment of Lake Cui in Kunming with reclaimed water. Based on experimental analyses, *Escherichia coli* and norovirus were determined as the major pathogens in Lake Cui. Three typical exposure routes, namely river cleaning, boating and road flushing were identified during a field investigation. The disease burden, expressed by disability-adjusted life year (DALY) was evaluated and compared with the infection risk obtained by quantitative microbial risk assessment. Findings showed that the disease burden due to road flushing was highest compared to the other pathways. For the different pathogens, *E. coli* was the leading cause of DALYs. As well, infection risk for the two pathogens exceeded the United States Environmental Protection Agency (USEPA) risk level of  $10^{-4}$ , while the disease burdens were below the WHO threshold of  $10^{-6}$  DALYs. Thus, infection risk should not be regarded as the endpoint for health impact assessment. By contrast, the disease burden is much more suitable for quantifying the health hazard due to environmental pollution. The methodology introduced in this study provides new directions for the evaluation of health impacts related to water reuse for landscape ecology.

**Key words** | DALY, health impact, landscape replenishment, pathogen, reclaimed water

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## INTRODUCTION

Landscape water bodies are essential parts of urban eco-environments. In recent years, the demand for water supply has expanded, whereas the amount of water available for replenishing landscape water bodies from the traditional sources are decreasing. Thus, several alternative water sources, such as reclaimed water, have become a major source of landscape water replenishment (Dorevitch *et al.* 2012). However, the health risk attributed to reclaimed water replenishment has caused widespread concerns. Pathogens that are possibly existing in reclaimed water, such as bacteria (e.g., *Escherichia coli*), viruses (e.g., enterovirus), protozoa (e.g., cryptosporidium), etc., can cause various extents of health hazards to human populations exposed to recreational landscape water bodies replenished

with reclaimed water (Ferley *et al.* 1989). Studies show that recreational activities such as boating and fishing in microbial-contaminated water bodies are likely to cause acute gastrointestinal, respiratory, and skin diseases, as well as aural region infections, ocular region discomfort, etc. (Dufour 1984). As a result, quantitative health impact evaluation is conducted for landscape water bodies replenished with reclaimed water in densely inhabited regions. On this basis, providing effective measures for health risk control and management is of great practical significance.

This study takes Lake Cui in Kunming, Yunnan Province, China as a case study. Lake Cui, which is located in the center of Kunming city, is a major site for residents to carry out daily entertainment activities. The lake is small

and shallow, with a water area of  $15 \times 10^4 \text{ m}^2$  and an average depth of 1.2 m. In addition to a small amount of rainfall as a supplementary water source, the major water source for replenishing the lake is reclaimed water from the fourth wastewater treatment plant in Kunming, China. Previous field surveys indicate that the lake water can not only be ingested by tourists via recreational water activities, such as boating, fishing, and swimming, etc., but park staff are also exposed during river cleaning and road flushing. Thus, pathogenic microorganisms existing in the lake water can be easily transferred to humans, and finally lead to different extents of health damage.

The traditional method for health impact assessment is mainly based on the quantitative microbial risk assessment process (QMRA). This method is conducted by applying a dose–response relationship to quantifying the risk of infection due to ingesting a certain dose of a pathogen (Haas *et al.* 1999). For this method, the annual risk standard for pathogenic microorganisms is recommended as  $10^{-4}$  by the United States Environmental Protection Agency (USEPA), which is explained as one infection case out of every 10,000 individuals, whereby only an infection risk below this standard value is defined as safe (Hu *et al.* 2011). However, the infection risk obtained from QMRA can only be used for evaluating the probability of a health hazard occurring, such as an infection. This method cannot, however, be used to describe any further and quantify the severity of a particular health damage or the resulting health loss. These problems can all be overcome by expressing the health impacts in disability-adjusted life years (DALYs) (Murray & Lopez 1996). The DALY is a measure of the overall disease burden, expressed as the number of healthy years lost due to ill-health, disability, or early death. The DALY has been adopted as a new technique for the quantification of health impacts due to environmental pollution, because this indicator can provide a comprehensive evaluation of the magnitude of particular health damage (Dorota *et al.* 2006). On this basis, the health impact caused by pathogenic microorganisms due to water reuse in Lake Cui was evaluated by the DALY method in this study. By this method, the major risk factors leading to the largest disease burden can be confirmed, and instructive measures for health impact control can be made.

## MATERIALS AND METHODS

### Exposure characterization

#### Identification of waterborne pathogens

Waterborne diseases are widely prevalent and there are frequent outbreaks in China. Among all diseases, typhoid and paratyphoid, caused by *Salmonella typhi* and paratyphoid *Salmonella* are major intestinal infectious diseases that are especially severe in Guizhou, Guangxi, Yunnan, and Zhejiang provinces. According to the statistics for outbreaks in Guizhou province during 1951–2001, 445,261 accumulated cases of typhoid and paratyphoid were reported, leading to  $34.82 \times 10^5$  annual morbidity from *Salmonella* infections. About 3,515 cases of death were reported, with a case fatality rate (CFR) of 0.79% (Tao *et al.* 2003). *E. coli* usually exists in the human intestinal tract in large numbers and is regarded as normal enteric flora, which may not cause health damage. However, a few strains, such as enterohemorrhagic *E. coli*, enterotoxigenic *E. coli*, and enteropathogenic *E. coli* can cause acute intestinal diseases such as diarrhea, or even death after dehydration (Bitton 2005). According to epidemiological reports, a waterborne outbreak event caused by *E. coli* contamination occurred in Chongqing province in 1997, which led to a total of 985 diarrhea cases. Bacillary dysentery due to *Shigella* infection is also one of the typical intestinal infectious diseases with a high prevalence rate in most cities and rural regions of China. Statistically, the annual morbidity from bacillary dysentery reported for Zhaotong city in Yunnan province is  $3.43 \times 10^7$ , and the fatality rate is reported to vary between  $0.04 \times 10^5$  and  $1.95 \times 10^6$  (Zhang & Zeng 2007). Also, the annual average morbidity of bacillary dysentery of  $4.09 \times 10^6$  was reported for Hubei province during 1996–2005, with a CFR of 0.06%, and a death rate of  $0.02 \times 10^5$ .

Enterovirus is also regarded as one of the common pathogens that cause waterborne viral infections. Detection of enterovirus in surface water, drinking water, and wastewater has been widely reported (Vantarakis & Parapetropoulou 1999). For example, during the outbreak of herpangina caused by enterovirus-71, which occurred in

Taiwan in 1998, a total of 129,106 cases of illness and 78 cases of death were reported, whereby most patients were children under five years old (Ho et al. 1999). In addition, other species of enterovirus, including echovirus-19 and echovirus-30, caused an outbreak of child viral encephalitis (Xie & Zheng 2006). Rotavirus infection is a leading cause of child diarrhea, which mainly occurs among children under three years of age. Nearly 50% of the infected children may develop severe diarrhea. Rotavirus can be transmitted via the fecal–oral route, and has been detected in surface water, tap water, groundwater, and urban wastewater, according to previous reports. Infectious diarrhea in adults caused by rotavirus can also lead to the outbreak and prevalence of viral gastroenteritis (Gerba et al. 1985). Norovirus is a common pathogen causing viral gastroenteritis. Contact with norovirus-contaminated food or water can eventually lead to the occurrence of acute viral diarrhea. According to statistics, almost 19–42% of nonbacterial diarrhea outbreak incidents that occurred in the 1970s and 1980s worldwide can be attributed to norovirus infection, and such outbreaks also occurred in the Hebei, Sichuan and Gansu provinces of China (Hu et al. 2011).

### Detection of selected pathogens

In this study, *E. coli*, *Salmonella*, *Shigella*, rotavirus, enterovirus and norovirus were determined as typical pathogens causing a potential health hazard. Two parallel tests were conducted under the same conditions and by referring to the same methods to predict the exposure concentrations of the above pathogens. Experimental analysis of bacteria and viruses were based on real-time quantitative polymerase chain reaction (PCR) techniques. For *E. coli*, *Salmonella*, and *Shigella* detection, water samples were first filtered through a mixed cellulose ester membrane with a pore

size of 0.22  $\mu\text{m}$ , and then eluted with 30 mL of 3% beef extract solution (at pH 9.5), which was finally centrifuged at 1,100 rpm for 30 min at 4 °C. From the concentrates, DNA was extracted for PCR detection following the manufacturer's instructions. For rotavirus, enterovirus and norovirus detection, viral particles were concentrated by membrane filtration combined with polyethylene glycol (PEG) precipitation when turbidity was low, or PEG precipitation only when turbidity was high. Concentrates of virus particles were then used to extract the viral genomic RNA before PCR analysis following the manufacturer's instructions (Zheng et al. 2014).

Experimental analysis results showed that *Salmonella*, *Shigella*, rotavirus and enterovirus were not detected in lake water (Table 1). In contrast, the average concentrations of *E. coli* and norovirus were 2.89 CFU/mL and 1.45 CFU/mL, respectively. In Table 1, the numbers 1–5 represent the different sampling points, among which sampling point 1 is located in the lake center, sampling point 2 is beside the lake bank, sampling point 3 is in the plant covering area, sampling point 4 is near to the inflow point, and sampling point 5 is close to the discharging point. All of the five sampling points are marked in Figure 1. Based on the above analysis and results, *E. coli* and norovirus were finally determined as the major pathogenic factors in the Lake Cui water reuse system. The subsequent analysis and discussion were conducted mainly to focus on these two types of pathogens.

### Determination of exposure route and exposure dose

According to field investigations, the major exposure routes for water reuse in Lake Cui include: (1) skin contact with lake water by park staff while river cleaning; (2) inhalation and skin contact with reclaimed water by gardeners while road flushing; and (3) skin contact with water splashes by

**Table 1** | Average concentration of *E. coli* and norovirus detected in reclaimed water (CFU/L)

Pathogen	Sample label					Average
	1	2	3	4	5	
<i>E. coli</i>	$5.72 \times 10^5$	$9.94 \times 10^1$	N/A <sup>a</sup>	$2.85 \times 10^3$	N/A <sup>a</sup>	$2.89 \times 10^3$
Norovirus	N/A <sup>a</sup>	N/A <sup>a</sup>	$1.45 \times 10^3$	N/A <sup>a</sup>	N/A <sup>a</sup>	$1.45 \times 10^3$

<sup>a</sup>Not detected.

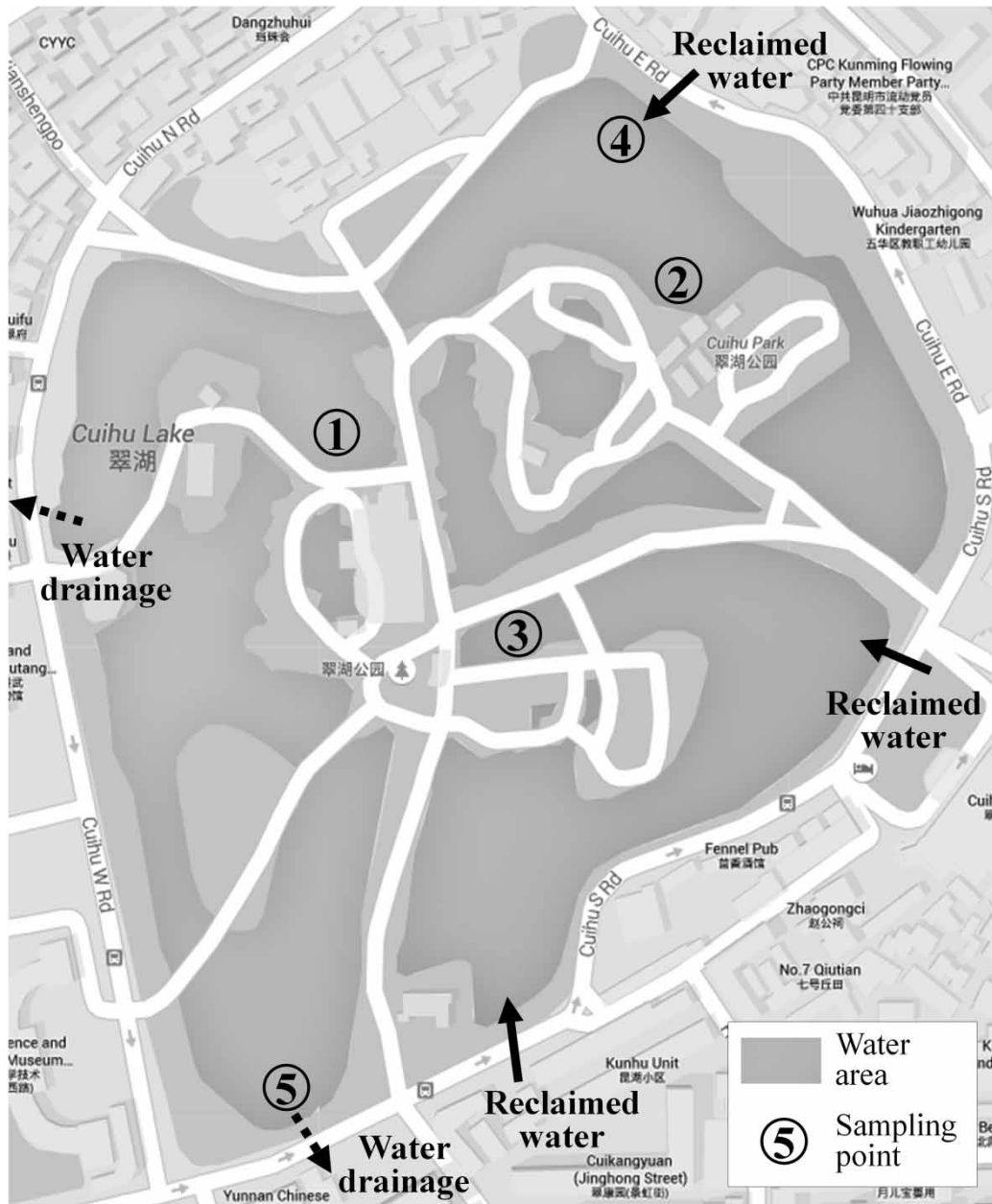


Figure 1 | Sampling points in Lake Cui.

tourists while boating. Exposure dosages for the above three pathways were calculated by Equation (1) (Hu *et al.* 2011):

$$D = C \times V \quad (1)$$

where  $D$  represents a single exposure dose of reclaimed water for a particular exposure route, CFU/y;  $C$  is the

exposure concentration of a specific pathogen detected in the reclaimed water, CFU/L; and  $V$  is the single ingestion volume of reclaimed water per route, L/y.

The ingestion volumes of reclaimed water ( $V$ ) relating to river cleaning and boating were determined by referring to research conducted by Samuel *et al.* (2011) on the estimation of water consumption during various activities. In that

research, studies were conducted to estimate water ingestion during boating, fishing, swimming, etc. by using a mass-balance approach, as described by Dufour *et al.* (2006), according to the characterized self-reported estimates of water ingestion among 3,367 participants. For road flushing,  $V$  was recommended by He *et al.* (2006) according to a field investigation of exposure-related factors such as respiratory rate, skin surface area, exposure duration, etc. for wastewater reclamation and utilization in Beijing. The annual exposure frequency ( $n$ ) for each route was determined based on field investigations of Lake Cui. Details of the parameter values are summarized in Table 2.

## Dose–morbidity analysis

### Basic consideration

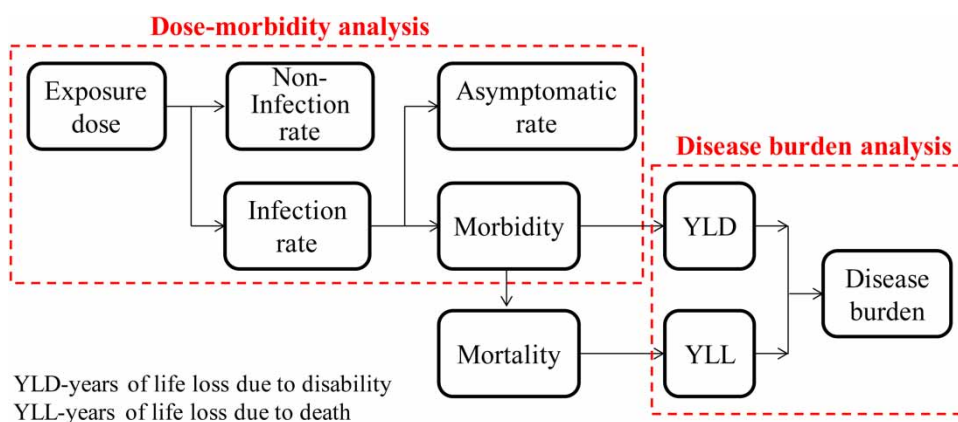
To assess the burden of disease related to exposure to microbiological contaminants or conversely, to apply a reference threshold of tolerable disease burden, the health outcomes following each specific exposure or ingestion have to be

defined, and models of disease process have to be collected or designed, as shown in Figure 2. Either infection or non-infection may occur after exposure to the microbiological contaminants. The infection cases do not necessarily imply illness symptoms. It is only when pathogenic microorganisms do cause damage to human cells, tissues, or organs that symptoms of illness may develop, and even death may occur. For the development of various disease outcomes from exposure to microbiological contaminants, transition probabilities between each step must be established and calculated before the evaluation of disease burden. In other words, the relation between an exposure dose of a pathogen and morbidity for a certain disease outcome needs to be constructed. This process enables the partitioning of an exposed population over different stages of disease development and the calculation of a burden of disease including all relevant health outcomes.

As illness is conditional to infection, the probability of becoming ill ( $P_{ill}$ ) can be calculated as a product of infection rate ( $P_{inf}$ ) and the probability of illness, given infection ( $P_{ill/inf}$ ), as shown in Equation (2). Therefore,  $P_{inf}$  and  $P_{ill/inf}$

**Table 2** | Exposure parameters and associated values for different exposure routes

Exposure route	Ingestion volume of reclaimed water ( $V$ ) (mL/time)	Exposure frequency ( $n$ ) (times/year)	Reference
River cleaning	3.7 ml/time	40 times/y	Samuel <i>et al.</i> (2011)
Boating	3.7 ml/time	14.9 times/y	Sun <i>et al.</i> (2013)
Road flushing	60 ml/time	164.8 times/y	He <i>et al.</i> (2006)



**Figure 2** | Process of disease development from exposure to disease burden.

are middle steps for establishing the relation between exposure dose and morbidity:

$$P_{ill} = P_{inf} \times P_{ill/inf} \quad (2)$$

### Dose–response for infection ( $P_{inf}$ )

For pathogenic microorganisms, infection rate due to single exposure can often be described adequately by the single-hit model (Haas et al. 1999). For this model, in the case of ‘ $m$ ’ successive human body barriers, the probability that any single organism successfully passes all these barriers is defined as  $P_m$ . Thus, the probability that at least one of the ingested organisms survives and infects the host is calculated by Equation (3). In this equation,  $P_{inf/time}$  represents the probability of infection per time,  $D$  is exposure dose, and  $P_m$  is a dose–response parameter:

$$P_{inf/time}(D) = 1 - e^{-P_m D} \quad (3)$$

However, the susceptibility of a human host to infection generally depends on a number of recognized and unrecognized factors. In the traditional single-hit model, the characterization of these factors was not involved. Thus, for further application of this model to the DALY calculation, modifications with various factors reflecting the variation in  $P_m$  between hosts were needed. Two well-documented factors are immune status and age. For the description of immune status, human antibody level, which reflects the protection by the humoral immune system, is used. In this condition, the higher the human antibody level is, the greater the defensive ability of the exposed population will be. To represent the age effect, an age weight function ‘ $Cxe^{-\beta x}$ ’ is adopted by referring to the WHO method for calculating the DALY. According to this age weight function, newborns (<2 years old) as well as the older exposed population (>60 years old) are much more susceptible to infection by pathogen compared with younger adults. This is because the resistance of the immune system to external disturbances for the middle-aged group is comparatively stronger. On the other hand, for neonatal populations, the mucosal immune system is immature and inactive, and for the older age group, the immune system

has declined. On this basis, the modeling of  $P_m$  using a logit function is shown in Equation (4), and the modified single-hit model based on the characterization of immune status and age between hosts is shown in Equation (5). In these two equations,  $x$  represents the human antibody level and  $y$  represents average age. Other parameters such as  $a$ ,  $b$ ,  $c$ , and  $\beta$  are dose–response coefficients:

$$\log\left(\frac{P_m}{1 - P_m}\right) = a + bx + cye^{-dy} \quad (4)$$

$$P_{inf/time}(D, x, y) = 1 - e^{-DP_m(x,y;a,b,c,\beta)} \quad (5)$$

As limited by the available data, human antibody levels ( $x$ ) for *E. coli* and norovirus in the general population were determined as the recommended values for the anti-cryptosporidium antibody level investigated in a previous study by analyzing the serum banks (Teunis et al. 2002). The average age of the exposed population ( $y$ ) was determined as 40 years old, according to field investigation within the region of Lake Cui. Other parameters such as  $a$  and  $b$  were suggested by a previous study on cryptosporidium dose–response relation (Teunis et al. 2002), while WHO recommended values of  $c$  and  $\beta$  were used for calculating the DALY, as shown in Table 3.

### Dose–response for illness resulting from infection ( $P_{ill/inf}$ )

The only morbidity response we considered was acute gastroenteritis. According to Teunis et al. (1999), the modeling of  $P_{ill/inf}$  mainly depends on three components: (1) an infected host, defined as many living pathogens present in (parts of) the gut; (2) a hazard of illness, defined as a certain nonzero hazard of becoming ill during infection; and (3) the duration of infection, defined as the length of the period that colonization persists. As illness is conditional on infection, the infection duration is the key variable used to construct the dose–morbidity relationship. A host with strong defenses

**Table 3** | Parameter values for modified dose–infection relationship

Parameter	a	b	c	k	x	y
Suggested value	3.56	−53.2	−0.1658	0.04	0.64	40

against the pathogen is assumed to clear infection rapidly, while a pathogen that is highly virulent is assumed to sustain intra-intestinal growth for a long period, namely, to induce a long duration of infection. Thus the probability of illness, given infection, is calculated by Equation (6):

$$P_{ill/inf}(D) = 1 - (1 + \gamma D)^{-\delta} \quad (6)$$

where  $D$  represents exposure dose, and  $\gamma$  and  $\sigma$  are scale and shape parameters, respectively, for the gamma distribution of infection duration (Teunis et al. 1999). The parameters involved in Equation (6) were determined by fitting the dose–illness data obtained from several human volunteer experiments, as shown in Table 4.

On this basis, the probability of illness can be calculated by Equation (7) according to the modified single-hit model (Equation (5)) for calculating infection rate and the suggested function (Equation (6)) for calculating the probability of illness, given infection. However, for the DALY calculation, the annual probability of illness is an essential input variable. Thus, according to the annual exposure frequency ( $n$ ) summarized in Table 2, the annual morbidity is calculated by Equation (8):

$$P_{ill/time}(D, x, y) = P_{inf/time}(D, x, y) \times P_{ill/inf}(D) \quad (7)$$

$$P_{ill/y}(D, x, y) = 1 - (1 - P_{ill/time}(D, x, y))^n \quad (8)$$

## Disease burden analysis by DALY method

### DALY method

Disease burden is defined as a quantitative description of health loss due to a disease outbreak. For the assessment of disease burden attributed to environmental pollutants, the DALY method suggested by the WHO is adopted.

**Table 4** | Parameter values for dose–morbidity relationship

Pathogen	$\lambda$	$R$
<i>E. coli</i>	$2.28 \times 10^{-2}$	$2.46 \times 10^{-2}$
Norovirus	$8.73 \times 10^{-4}$	$9.50 \times 10^{-2}$

According to the WHO definition of the DALY, this indicator takes time as a metric and is used to quantify the healthy life lost under a disabled condition and death outcomes by taking comprehensive consideration of the impact of disease severity, duration, and early death on human health (Wei et al. 2012). For environmental health impact assessment, the disease burden (DALY) caused by pollutants can be calculated by the sum of years of life lost due to disability (YLD) and years of life lost due to premature death (YLL), according to specific disease outcomes, including morbidity and mortality (Havelaar & Melse 2003), shown in Equation (9). YLD can be calculated as a product of the annual probability of illness ( $P_{ill/y}$ ), disability weight ( $W$ ), and disease duration ( $T$ ), shown as Equation (10) (WHO 2013). For a death outcome, YLL can be calculated as the product of the annual probability of illness ( $P_{ill/y}$ ), CFR, and average standard life expectancy ( $L$ ), considering a specific age of death, shown in Equation (11):

$$DALY = YLD + YLL \quad (9)$$

$$YLD = P_{ill/y}(D, x, y) \times W \times T \quad (10)$$

$$YLL = P_{ill/y}(D, x, y) \times CFR \times L \quad (11)$$

### Determination of disease parameters

The parameters used for the DALY calculation, including disability weight ( $W$ ), disease duration ( $T$ ), and expected life loss due to premature death ( $L$ ) were determined according to national or regional disease burden studies. As for the value of  $W$ , disability weight of watery diarrhea for *E. coli* infection was determined by Murray & Lopez (1996), while for bloody diarrhea and acute gastroenteritis, the disability weight was obtained from the disability weight table constructed for Shanghai residents by Gu et al. (2002). Disability weight for the death outcome was determined as 1, explained as the complete loss of healthy life. Disease duration ( $T$ ) was obtained from clinical survey results of various intestinal infectious diseases investigated by the China Center for Disease Control and Prevention. For *E. coli* infection, the duration of watery diarrhea was suggested as 2–3 days (with an average of 2.5 days), and

duration of bloody diarrhea was recommended as 5–7 days (with an average of 6 days). For norovirus infection, the duration of acute gastroenteritis was suggested as 0.5–2.5 days (with an average of 1.5 days).

To estimate healthy life loss due to premature death,  $L$  was calculated as life expectancy minus death age. According to the census results of 2010 for Yunnan province, the life expectancy for residents was estimated as 69.54 years. However, due to the uncertainty of age distribution of the exposed population, a worse case assumption was adopted, whereby death occurs at one year old (Machdar et al. 2013). On this basis, the expected life loss due to premature death ( $L$ ) can be calculated as 68.54 years.

The parameters and associated values for the DALY calculation are summarized in Table 5.

## RESULTS AND DISCUSSION

### Exposure dose calculation

The results of a single exposure dose for *E. coli* and norovirus are summarized in Table 6. The total exposure dose for *E. coli* was estimated at  $1.95 \times 10^2$  (CFU/time), which is much higher than the exposure dose for norovirus. This difference may be explained by the higher concentration of *E. coli* detected in the reclaimed water.

From the results of the exposure–dose for the different exposure routes, it can be noticed that the ingestion dose of pathogens through road flushing was among the highest.

Table 5 | Values of disease parameters for the DALY calculation

Pathogen	Disability weight	Disease duration (days)	Expected life loss (years)	Likelihood of health outcomes
<i>E. coli</i>				
Watery diarrhea	0.067	2.5	29.54	$5.30 \times 10^{-1}$
Bloody diarrhea	0.440	6.0	29.54	$4.70 \times 10^{-1}$
Death	1.000		29.54	$2.70 \times 10^{-4}$
<i>Norovirus</i>				
Acute gastroenteritis	0.740	1.5		1.00
Death	1.000		29.54	0.00

Table 6 | Results of single exposure dose, CFU/time

Dose	<i>E. coli</i>	Norovirus	Total
River cleaning	$1.07 \times 10^1$	5.37	$1.61 \times 10^1$
Boating	$1.07 \times 10^1$	5.37	$1.61 \times 10^1$
Road flushing	$1.73 \times 10^2$	$8.97 \times 10^1$	$2.60 \times 10^2$
Total	$1.95 \times 10^2$	$9.77 \times 10^1$	

This result can be interpreted by the higher ingestion volume of reclaimed water through road flushing.

### Morbidity calculation

The results for the daily probability of illness are calculated according to Equation (7). Moreover, the annual probability of illness is calculated according to Equation (8). The results are summarized in Table 7. The average probability of illness per time ( $P_{ill/time}$ ) for *E. coli* and norovirus was estimated at  $3.42 \times 10^{-14}$  and  $3.05 \times 10^{-15}$ , respectively, morbidity for *E. coli* being slightly higher than for norovirus. By comparison of the different exposure routes, road flushing caused the highest morbidity due to microbial contamination. The prevalence of waterborne disease through river cleaning and boating were relatively low. Results for the annual probability of illness ( $P_{ill/y}$ ) were similar to the prediction of single morbidity ( $P_{ill/time}$ ). The average probability of illness of  $5.55 \times 10^{-12}$  per year was estimated to be attributed to *E. coli*, which was slightly higher than for norovirus. The annual morbidity due to road flushing was estimated at

Table 7 | Results of morbidity calculation

	<i>E. coli</i>	Norovirus	Average
$P_{ill/time}$			
River cleaning	$8.61 \times 10^{-16}$	$3.59 \times 10^{-17}$	$4.48 \times 10^{-16}$
Boating	$8.61 \times 10^{-16}$	$3.59 \times 10^{-17}$	$4.48 \times 10^{-16}$
Road flushing	$1.01 \times 10^{-13}$	$9.08 \times 10^{-15}$	$5.49 \times 10^{-14}$
Average	$3.42 \times 10^{-14}$	$3.05 \times 10^{-15}$	
$P_{ill/y}$			
River cleaning	$3.55 \times 10^{-14}$	0	$1.78 \times 10^{-14}$
Boating	$1.32 \times 10^{-14}$	0	$6.61 \times 10^{-15}$
Road flushing	$1.66 \times 10^{-11}$	$1.50 \times 10^{-12}$	$9.06 \times 10^{-12}$
Average	$5.55 \times 10^{-12}$	$5.00 \times 10^{-13}$	



$9.06 \times 10^{-12}$ , which was much higher than the values estimated for the other two pathways.

### The DALY calculation

The disease burden attributed to *E. coli* and norovirus was calculated based on Equations (9)–(11), and the results are summarized in Table 8. A total disease burden of  $2.40 \times 10^{-11}$  DALYs per person per year (pppy) was estimated. *E. coli* made the largest contribution of  $2.23 \times 10^{-11}$  DALYs pppy, accounting for 93.05% of the total disease burden estimation. The contribution of norovirus was estimated at  $1.67 \times 10^{-12}$  DALYs pppy, accounting for 6.95% of the total disease burden. Thus, for a decrease in total disease burden, the concentration of *E. coli* needs to be significantly further reduced.

The disease burden from road flushing was estimated at  $2.39 \times 10^{-11}$  DALYs pppy, accounting for 99.73% of the total disease burden. The disease burden for river cleaning and boating was  $4.75 \times 10^{-14}$  DALYs pppy and  $1.77 \times 10^{-14}$  DALYs pppy, respectively, which accounted for 0.20% and 0.07% of the total disease burden. Thus, for further disease burden control, contact with reclaimed water through road flushing should be strictly limited.

### Comparison of risk (QMRA) with disease burden (DALY)

Compared with the DALY method, the extent of the health impact evaluated by the traditional QMRA method is specified as a probability of infection due to exposure to microbiological contaminants. For QMRA, the infection risk is generally calculated by either an exponential model or beta-Poisson model, which is simplified from the single-hit model mentioned before. Accordingly, the beta-Poisson

model was used to calculate the infection risk for *E. coli* and norovirus in Lake Cui. The expression for the beta-Poisson model is shown in Equation (12) (Haas et al. 1999):

$$P_{time} = 1 - \left( 1 + \frac{D}{D_{50}} \times (2^{\frac{1}{\alpha}} - 1) \right)^{-\alpha} \quad (12)$$

where  $P_{time}$  represents the infection risk caused by a selected pathogen,  $D$  represents the exposure dose,  $D_{50}$  represents the half infection dose, and  $\alpha$  represents the dose–response factor.

The parameters involved in this equation were obtained from the recommendations of previous studies (Teunis et al. 2008). The  $D_{50}$  of  $8.60 \times 10^7$  and  $\alpha$  of  $1.78 \times 10^{-1}$  were suggested for *E. coli*, while the  $D_{50}$  of  $1.64 \times 10^{-9}$  and  $\alpha$  of  $4 \times 10^{-2}$  were suggested for norovirus. For further comparison of infection risk obtained by QMRA with the USEPA recommended risk level for microbial contamination, the annual infection risk was estimated by using Equation (13) based on the annual exposure frequencies summarized in Table 2:

$$P_y = 1 - (1 - P_d)^n \quad (13)$$

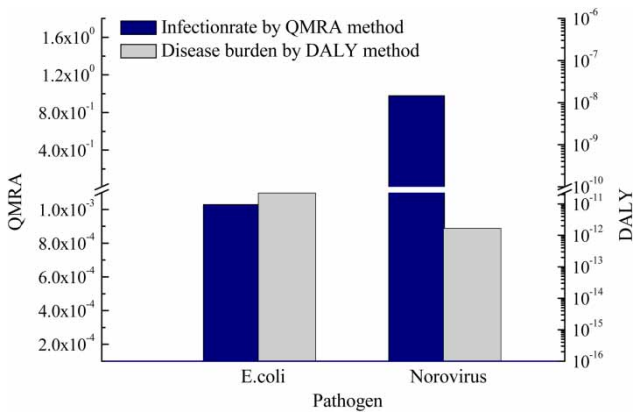
Results for the infection risks obtained by the QMRA method are summarized in Table 9. The average annual infection rate for river cleaning, boating, and road flushing was estimated at  $5.00 \times 10^{-1}$ ,  $4.68 \times 10^{-1}$ , and  $5.02 \times 10^{-1}$ , respectively, of which exposure through road flushing led to the highest infection risk for water reuse in Lake Cui. This finding was consistent with that for the disease burden calculations. Norovirus had the highest infection risk of  $9.78 \times 10^{-1}$  compared with that of  $1.03 \times 10^{-3}$  for *E. coli*. This result was inconsistent with the result of the disease burden evaluation shown in Figure 3. Thus, we

**Table 8** | Results of disease burden calculation

DALY (pppys)	<i>E. coli</i>	Norovirus	Total	Percentage
River cleaning	$4.75 \times 10^{-14}$	0	$4.75 \times 10^{-14}$	0.20%
Boating	$1.77 \times 10^{-14}$	0	$1.77 \times 10^{-14}$	0.07%
Road flushing	$2.22 \times 10^{-11}$	$1.67 \times 10^{-12}$	$2.39 \times 10^{-11}$	99.73%
Total	$2.23 \times 10^{-11}$	$1.67 \times 10^{-12}$	$2.40 \times 10^{-11}$	
Percentage	93.05%	6.95%		

**Table 9** | Results of infection risks obtained by QMRA

Pathway	<i>E. coli</i>	Norovirus	Average
River cleaning	$4.53 \times 10^{-5}$	$9.99 \times 10^{-1}$	$5.00 \times 10^{-1}$
Boating	$1.69 \times 10^{-5}$	$9.35 \times 10^{-1}$	$4.68 \times 10^{-1}$
Road flushing	$3.02 \times 10^{-5}$	1.00	$5.02 \times 10^{-1}$
Average	$1.03 \times 10^{-5}$	$9.78 \times 10^{-1}$	

**Figure 3** | Comparison of infection risk obtained by QMRA with disease burden obtained by DALY.

may conclude that a higher infection risk may not necessarily indicate a greater disease burden. On the other hand, the average infection risk per year for *E. coli* and norovirus for river cleaning, boating, and road flushing exceeded the USEPA reference risk level of  $10^{-4}$ . Thus, the infection risk obtained from QMRA was regarded as unacceptable. When compared with the WHO recommended threshold of  $10^{-6}$  DALYs pppy for disease burden estimation, the total disease burden estimated for these two pathogens from all pathways was below the WHO standard shown in Figure 3. Thus, the disease burden obtained by the DALY was regarded as acceptable. Therefore, infection should not be regarded as the end point of a certain health damage due to environmental pollution. In addition, the infection risk should not be determined as the only prediction of health impact according to QMRA. Compared with the infection risk obtained from the traditional QMRA, the DALY is much more suitable for use in comprehensively describing and quantifying the health impact caused by microbiological contaminants due to water reuse.

## CONCLUSIONS

This study was conducted to assess the health impact caused by microbiological contaminants due to water reuse in Lake Cui, Kunming, quantitatively. By combining an epidemiological investigation of significant waterborne diseases with a field survey of local exposure characteristics and experimental analysis of typical pathogens, the DALY was applied for evaluating the health impacts. The infection risk obtained by the traditional QMRA was assessed in terms of microbiological contamination. Comparisons and discussions were made according to the results obtained from the different methods. We draw the following conclusions:

1. According to epidemiological investigation, *E. coli* and norovirus are the major pathogens originating from water reuse in Lake Cui. By combining field investigation with the analysis of local water reuse characteristics, the major exposure pathways, including river cleaning, boating, and road flushing, were also determined. Results obtained by DALY analysis indicated that *E. coli* was the major microbiological contaminant, and road flushing was the major exposure route in causing the largest disease burden.
2. Compared with the traditional QMRA method, the DALY takes full consideration of the disease characteristics, severity, duration, etc. when quantifying the health impact due to environmental pollution. The infection rate obtained by QMRA cannot be directly used to determine the occurrence and extent of a particular health damage after infection occurs. The health hazard evaluated in terms of DALY is not only complete and able to verify the results of the infection risk assessment, but also provides an understanding of the ultimate health impact due to environmental contamination. The results obtained in this study can provide guidance on effective pollution control and prevention.

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