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Estimating disease burden of rotavirus in floodwater through traffic in the urban areas: A case study of Can Tho city, Vietnam

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Abstract

Microbial pathogens in urban floodwaters pose risks to human health, potentially causing diseases such as diarrhea. However, the disease burden related to urban traffic exposure from citizens passing through floodwaters is not easily quantified and therefore not included in many studies. Notably, this problem has received little attention in low-to-middle-income countries, with frequent flood events and the heavy diarrheal disease burden. This article calculates the infection risks and disease burden, considering traffic associated with exposure to floodwater contaminated with rotavirus for the first time in Ninh Kieu District, Can Tho city. Can Tho city in the Vietnamese Mekong Delta is well known to have many flood events every year, with many diarrheal cases during the flood season. The methodology comprises two steps. First, we applied quantitative microbial risk assessment that proposes the inclusion of exposure to traffic due to rotavirus in floodwater. Second, the disease burden was expressed in disability-adjusted life years (DALYs). The exposed groups are child pedestrians, adult pedestrians, motorcyclists, and cyclists. We used video footage to monitor the traffic. The results show that total DALYs per flood event were 1.35×10^4 for 63,390 exposed people (i.e., 2129 DALYs per 10,000 cases). Motorcyclists are the strongest contributors to the DALYs (95%), followed by cyclists (2.8%), adult pedestrians (2%), and child pedestrians (0.2%). The population in Ninh Kieu District may suffer from waterborne diseases

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through traffic activities during flooding times. Our approach can be applied in other areas worldwide and helps identify main risk groups and focus areas for interventions.

KEYWORDS

health risk assessment, Mekong Delta, rotavirus A, traffic activity, urban floodwater, waterborne disease burden

1 | INTRODUCTION

Microbial pathogens significantly impact human health, as demonstrated by the coronavirus pandemic. Therefore, identifying the health risks related to pathogens is essential. One of the most common hazards of exposure to waterborne pathogens is flooding (Ahern et al., 2005; Cann et al., 2013). Urban flooding trends to increase caused by extreme rainfall events due to climate change and high imperviousness areas due to the rapid growing population (van Aalst, 2006). Microbial health impact during the post-flooding period was linked to the flood water diluted sewer water (Cook et al., 2008). It poses disease risk through direct or indirect contact such as waterborne diseases (e.g., diarrhea), vector-borne diseases (e.g., malaria and dengue fever), and rodent-borne diseases (e.g., leptospirosis) (Lau et al., 2010). In developed countries, such as England and the Netherlands, the importance of health risk assessment (HRA) related to waterborne pathogens in urban flood risk management has been emphasized (Fewtrell, Kay, et al., 2008; Hammond et al., 2013; WHO, 2017). The infection risks caused by waterborne pathogens in floodwater help urban authorities to understand the safety of floodwater and develop risk mitigation strategies (Sales-Ortells & Medema, 2014).

In low and middle-income countries (LMICs), the urban floodwater quality is more significant due to fast-growing urban populations and inadequate drainage systems (Luo et al., 2019). Various epidemiological studies have indicated increased waterborne disease cases during the flooding period (Phung et al., 2014; Phung et al., 2017; Thompson et al., 2015). While direct exposure to polluted urban floodwater, such as through traffic activities or cleaning up inundated houses, seems unavoidable, these activities may cause public health issues related to waterborne disease (Few et al., 2013; Few & Tran, 2010). Infectious diseases are one of the most pressing health issues during flooding. For instance, diarrhea is the second most common communicable disease associated with mortality in Vietnam (MOH, 2018). It is also one of the most common diseases in the flood season of Can Tho city (Vietnam) (Preventive Medical Center in Can Tho, 2016b). Can Tho city is a major urban center in the Vietnamese part of the Lower Mekong Delta. This city is exposed to increased flooding due to rapid urbanization, especially in the urban area called Ninh Kieu District (Leloup et al., 2013; Pham et al., 2010). In addition to flooding, water pollution is also considered a severe problem in this area. For example, Nguyen et al. (2017) identified total coliform concentrations in floodwaters comparable to those in sewage concentrations. During flooding, total coliforms in surface waters were up to 70 times higher than those suggested by Vietnamese surface water standards (Salingay et al., 2014). Notably, *Escherichia coli* and rotavirus A were prevalent in floodwater in 2016 in Ninh Kieu (Huynh et al., 2020). Nguyen et al. (2017) indicated that direct exposure to floodwater is a potential cause of gastrointestinal infection due to *E. coli* and *Salmonella*. The exposed people through traffic activity are the majority in the case study. Like many other cities in Vietnam and other LMICs, riding and walking through floodwater is unavoidable for a large proportion of the citizens in Can Tho City. Motorcycles are the primary mode of transportation on urban streets (Hung et al., 2010). Consequently, the residents may have microbial health risks when experiencing traffic through flooded streets.

The health risks of gastrointestinal infection have been widely studied using quantitative microbial risk assessment (QMRA) (Haas et al., 2014). However, the health impacts specifically for traffic have thus far not been fully quantified (Jalilov et al., 2018). First attempts include Veldhuis et al. (2010), who evaluated the health risks for pedestrians splashed by passing traffic in the Netherlands, and Mark et al. (2015), who studied the health risks for adults wading through floodwater to work and (upper) middle-class children going to school in Dhaka, Bangladesh. However, such analyses are difficult, because information on the behavior of people during flooding is hardly ever reported. Veldhuis et al. (2010) and Mark et al. (2015) quantified the health risks for different exposed groups. The infection probability can also be combined with exposed population data to get a better understanding of the disease burden (expressed in disability-adjusted life years [DALYs]) that will help to find focus areas for intervention (Gao et al., 2015). However, simulating the disease burden for traffic during

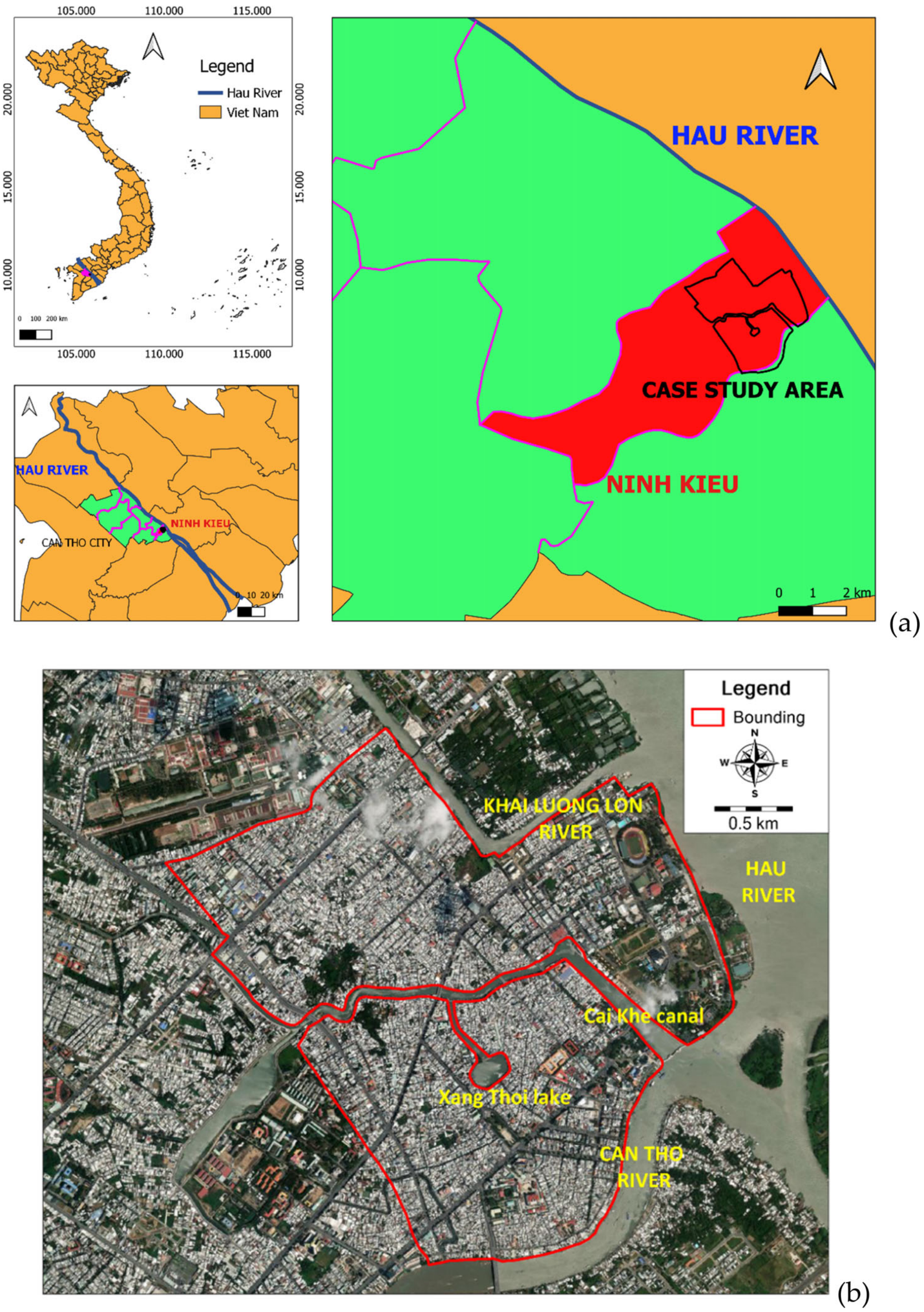

FIGURE 1 Maps of (a) Vietnam, Can Tho city, and case study area (bounded by the black line) within Ninh Kieu district (b) Study area (bounded by the red line) in Ninh Kieu district, and the main rivers, canals (Background Google™ satellite data).

floods has thus far not been the focus of research. In particular, in LMICs, this disease burden can be significant. Therefore, this article aims to assess the health risks and disease burden for traffic associated with exposure to floodwater contaminated with enteric pathogens.

Understanding public health vulnerability and in particular, the relationship between health risk and waterborne pathogens in floodwater is essential to healthy and resilient cities. Our case study is in the Ninh Kieu District of Can Tho City. This city is a Rockefeller Foundation's 100 Resilient Cities Network (100R) member. The concentration of rotavirus A in floodwater in the study area is high (Huynh et al., 2020). In this study, we conducted a two-step approach. First, we estimated infection and illness risk per person exposed to floodwater using QMRA (Haas et al., 2014; Medema & Ashbolt, 2006). Second, we calculated the health impact or disease burden per flood event caused by microbial pathogens. We incorporated the population directly exposed to floodwater through traffic activities, such as riding motorbikes, bicycles, and walking. To the best of our knowledge, this study was the first to quantify both the infection risk and the disease burden of waterborne pathogens for those exposed to floodwater through traffic activity in a developing country.

2 | CASE STUDY

Ninh Kieu District (Can Tho City, Vietnam) is located on the western side of the Hau River, a Mekong tributary (Figure 1). The monsoon season dominates this Lower Mekong River Basin from June to November with heavy rainfall. Besides, the high sea level and flows of upstream areas (i.e., Myanmar, Thailand, Laos) affect the high river water level on the Mekong River in the beginning and middle of the lunar calendar. The high tide period occurs twice a day, in the morning and afternoon. The average maximum daily river water level in the period 1978–2018 was 0.7–1.75 m at high tide. River water is usually at its highest level in September, October, and November which can reach up to 2.25 m (Kingston et al., 2011). This city faces pluvial and fluvial flooding, and sometimes both. Pluvial floods occur due to inadequate drainage networks during heavy rainfall events. The average annual rainfall in the period 1985–2019 was about 1376.6—1792.6 mm which was 90% that occurred in rainy season months (June–November). Rainfall peaked in August–October with 15–25 rainy days per month with an average monthly rainfall of about 140.8–240.5 mm (Can Tho's People Committee, 2019). The fluvial floods are caused by overtopping the river bank; the river water enters the drainage systems at the outlets and then exits on streets through sewer pipes. According to local reports, inundation happens an average of four to five times a year in the city. Flood usually occurs in the inner city due to heavy rainfall, while the area near the river is inundated due to the upstream flow and high tide twice a day (Huong & Pathirana, 2013). Untreated wastewater in the combined sewer system backs up and pollutes the floodwater during the flooding period. During high tide periods, the flooding period usually coincides with the starting/closing time of offices and schools in the case study areas (5:00–7:00 and 17:00–19:00) (Figure S4, Supplement). Thus, exposure to polluted floodwater in the streets is unavoidable. Ninh Kieu is the densest urban center in Can Tho with 10,400 people/km^2, while the average population density for Can Tho is 859 people/km^2 (GSO, 2019). Many residents, therefore, face a risk of infection and loss of health due to waterborne pathogens in floodwater (Nguyen et al., 2017).

3 | MATERIALS AND METHODS

In this study, we first used the QMRA approach to assess infection probability and illness probability for exposure per person per flood event. Then, we evaluated the disease burden by DALYs. The data on floodwater was based on our previous study (Huynh et al., 2020).

3.1 | Data description

Surface water (rivers/canals/lakes) and sewer water samples were available from the research work presented by Huynh et al. (2020). This part summarizes the flood event and sampling campaign on October 17, 2016. On this day, high river water levels and rain were observed (Figure S2, Supplement). However, the main cause of the inundation was attributed to high river water levels of 2.03 m (Figure S1, Supplement). The inundation was explained by the river water entering the combined sewer systems through the pipes at the outlets and flowing later out to the streets in the morning and afternoon/evening. Therefore, the events were expected to carry a high concentration of pathogens. The sampling process aimed to evaluate the different stages of the flood. During the event, in one of the selected locations, three moments were identified and used for the sampling, the rising stage, the peak stage, and the receding stage of the floodwater. We sampled floodwater at eight locations (Figure 2). The sampling sites, sampling time, and microbial concentration in the floodwater samples at the flooded streets are shown in Table S1 (Supplement).

3.2 | Quantitative microbial risk assessment

Haas et al. (2014) introduced the microbial risks based quantitatively on a dose–response equation to assess microbial hazards. This methodology uses measurements of microbial pathogens to identify harm and estimate the risk they pose to people. For example, QMRA has been applied to determine the risk related to waterborne pathogens for domestic applications such as drinking water sources (George et al., 2015; Lim et al., 2015; Yapo et al., 2013) or agricultural uses (Kouamé et al., 2017), recreation water (Schets et al., 2008; Sunger & Haas, 2015), and floodwater (Nguyen et al., 2017; Sales-Ortells & Medema, 2015; Veldhuis et al., 2010). QMRA involves four steps: (i) hazard identification, (ii) dose–response assessment, (iii) exposure assessment, and (iv) risk characterization. This study applied the QMRA approach to calculate two results: the infection rate and the illness risk per person per flood event (Figure 3). We explained in detail these steps in the following parts.

3.2.1 | Hazard identification

The flood-related water samples were analyzed in our previous study. We considered several microbial pathogens, including *E. coli, Salmonella, Campylobacter* spp.,

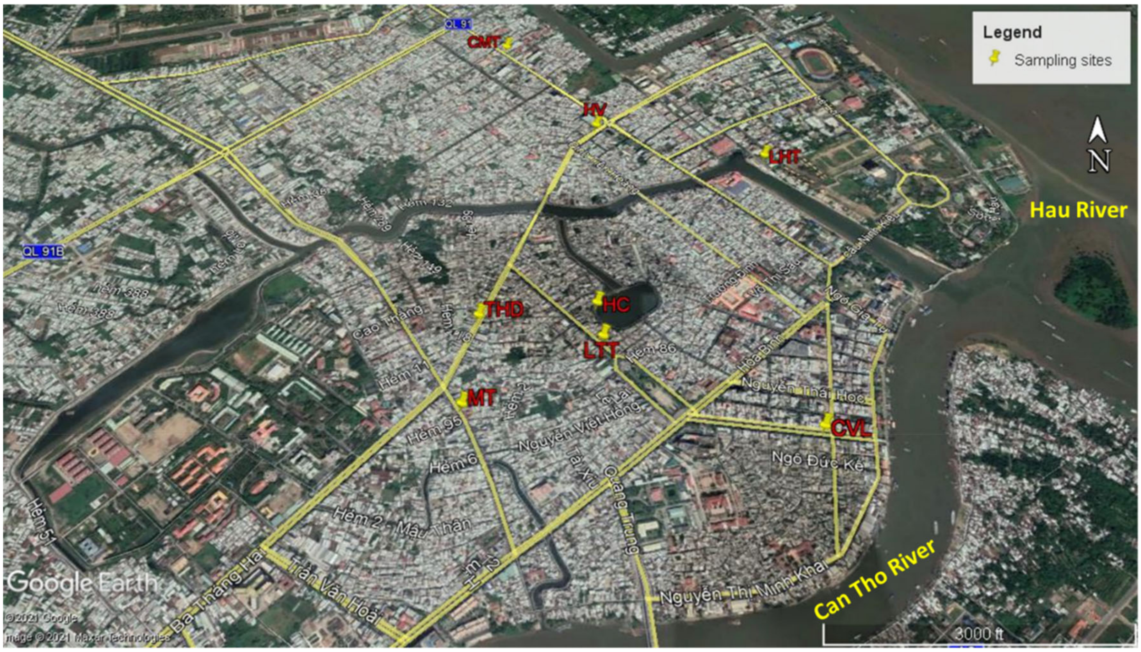

FIGURE 2 Eight floodwater sampling sites in Ninh Kieu District on 11 September and 16–19 October 2016. The initials correspond to the sampling sites in Table S1 (Supplement) (background Google Earth™ satellite data).

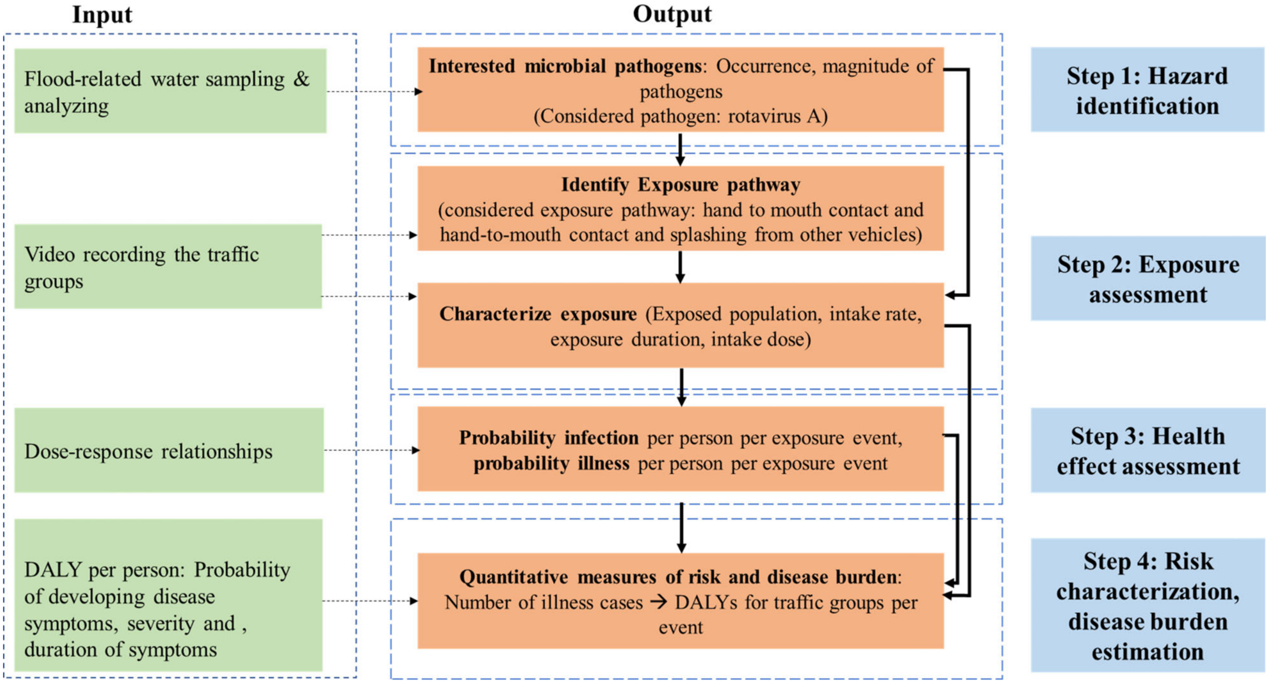

FIGURE 3 Methodology framework for health risk assessment and disease burden estimation due to microbial pathogens in urban floodwater for traffic exposure.

Shigella/EIEC, *Giardia* spp., *Cryptosporidium* spp., norovirus, and rotavirus (Huynh et al., 2020). However, only *E. coli* and rotavirus A were detected in the floodwater samples, while the other pathogens were not detected. Since we analyzed total *E. coli* and not the pathogenic *E. coli*, we only assessed human health risks related to rotavirus A in this study. Rotavirus A is the primary cause of viral gastroenteritis in humans, especially for children and the elderly (Atmar & Estes, 2006; Sattar et al., 2018). Over two decades in Vietnam, rotavirus has been one of the predominant pathogens that cause diarrhea in children (Doan et al., 2003; Huyen et al., 2018;

Man et al., 2005; Nguyen et al., 2001; Thompson et al., 2015). The measurement procedure for rotavirus A, the pathogen of interest and other pathogens, is described by Huynh et al. (2020). From here, we use "rotavirus" to mean "rotavirus A" in our study.

3.2.2 | Exposure assessment

The exposure analysis presented here is evaluated at the individual (person) level. These involve the exposure pathway, duration, and ingested volume (Fewtrell, Smith, et al., 2008). Besides, the number of exposed people was estimated.

a. Exposure pathways and exposure groups

The QMRA only considered accidental ingestion of contaminated flood water through traffic activities as the exposure pathway in this study. Ingesting water by hand-to-mouth contact and splashing from other vehicles were common exposure pathways of these groups. We did not consider bathing in floodwater or washing/cooking/drinking contaminated water since they are unusual activities in this local area. Child and adult pedestrians, motorcyclists, and cyclists are often observed in flooded streets and directly exposed to floodwater in the streets (Figure S4, Supplement). Therefore, we selected these four groups of exposed people. The motorbike and bike groups included pillion riders.

In this study, the intake volume (mL) of floodwater for an individual per flood event is defined by the intake rate and exposure duration. The intake rate (units of mass/time) is the amount of contaminated food/water ingested by an individual during a specific period (EPA, 2011b). The exposure duration is when a person is in contact with the hazard.

i. Intake rate

- *Child pedestrians and adult pedestrians*: These can ingest water when wading through floodwater on their way to and from schools/offices. No estimates for ingestion during wading existed. Intake volumes from the literature included 30–50 mL and 01–30 mL for children and adults, respectively, per incident, such as playing and bathing (Donovan et al., 2008; Veldhuis et al., 2010). However, these studies did not incorporate exposure duration per incident. Besides, bathing and playing in floodwater are uncommon in urban settings in Vietnam. Dorevitch et al. (2011) showed the average intake volumes were 3.5 mL for walking/splashing in pool water for 60 min. We, therefore, used 3.5 mL/h as the intake rate for children and adult pedestrians with lognormal (3.5, 3.6) (mL) distribution.
- *Motorcyclists and cyclists*: No intake rates or intake volumes have been reported in the literature for motorcyclists or cyclists through floodwater. However, Dorevitch et al. (2011) identified that motorboat drivers ingested 3.7 mL in 1 h. Therefore, we assumed the ingested volume for these two groups was 3.7 mL/h.

ii. Exposure duration

Since we considered the exposure through traffic activity, the exposure duration (i.e., the time spent in inundated areas) depends on the length of the flooded street and the speed of vehicles. Thus, we expressed the exposure duration (t_e) on the flooded road as:

$$t_e = l/v \tag{1}$$

where l (m) is the length of the flooded street and v (m/h) is the velocity of the individual. l in the flood event in the afternoon of October 17, 2016 ranged from 85 to 925 m. We used the average length of all the flooded streets to calculate the average exposure duration (Table 2). We assumed that the individual kept the same speed when traveling through a flooded street. Tang et al. (2020) identified the traffic flow speeds (i.e., motorcycles, cars, and buses) in an arterial road in Hanoi (Vietnam) to be 9–14 km/h during the rush hour in the morning (7:00–9:00) and afternoon (17:00–19:00), increasing to more than 30 km/h during the non-rush hours. Therefore, we assumed that the velocity was 14 km/h as the study took place during rush hour. Several studies have determined that the average speeds of cyclists were 10 km/h in China (Cherry & He, 2009) and 13.5 km/h in France (Jensen et al., 2010). We assumed a speed of 10 km/h for our case study, which seemed more suitable for Vietnamese people. For pedestrians, the average speeds were 70 and 80 m/min for children and adults, respectively (Waters e al. 1983).

Additionally, the difference in flood inundation depths of the streets in the study area was small (0.2–0.4 m, SD = 0.06) (Table S2, Supplement). Besides, there is a lack of reliable information about the association between flood depth, intake rate, and exposure duration. Thus, we assumed that the variability of flood depth did not affect the intake rate or the exposure duration.

b. Number of exposed people in a flood event

Since it was difficult to count all the exposed people in the flooded streets, we recorded video and counted for one street, then extrapolated for the other flooded streets. We assumed that the total number of exposed people in all the flooded streets was the multiple of the exposed people density (exposed people per square meter) and the total inundated areas of flooded streets (square meters).

First, to estimate the exposed population density, we recorded a video of an inundated street segment. We used the manual counting method to count the number of people passing through that street segment. This manual counting method is used in transportation studies to analyze traffic flow (Iowa State University, 2002; Pande & Wolshon, 2003). We chose Chau Van Liem Street to record the video covering 30 min of inundation (Figure S3, Supplement). We then calculated the exposed people density (d_e, people/m^2) based on the number of exposed people that we recorded (n_{str}, people) and inundation area that we observed (a_{str}, 10 m × 100 m) at Chau Van Liem Street (Equation 2). The description and the recording at Chau Van Liem Street are shown in the Supplement section:

$$d_e = \frac{n_{str}}{a_{str}} \tag{2}$$

Second, we calculated the total flooded areas in all the flooded streets as Equation (3):

$$N_e = d_e \times A \times \mathrm{sf} \tag{3}$$

where A(m^2) is the sum of the inundated area of all the flooded streets and sf is the scale factor to correct the traffic density in each flooded street. A (36,880 m^2) was calculated based on the widths and the lengths of the inundated roads (Table S2, Supplement). Since there was a lack of information about the flooded streets in the morning of October 17, 2016, we referenced data for the flooded streets in the afternoon of this day reported by the Can Tho Drainage and Sewage Company. The flooded streets, inundated duration, floodwater level, and lengths and widths of the inundated areas were shown in Table S2 (Supplement) (CanThoWassco, 2017). We focused on the flooded streets with inundated areas exceeding 200 m^2 and flood depths higher than 0.2 m and ignored small inundations.

The scale factor (sf) is included because larger streets may be more crowded than small streets. We determined the scale factor based on the widths of the streets. Chau Van Liem Street, which is 10 m wide, was considered the "base" street with a scale factor of 1.0. Scale factors were 0.8 and 1.2 for those streets with smaller (<10 m) and larger (>10 m) widths, respectively (Table S1, Supplement).

In reality, the number of exposed people and inundated areas in each street are variable during floods. However, we assumed that the traffic density and traffic flow velocity were constant during the flood to simplify the calculation. Since the flood duration was variable among flooded streets (from 1 to 2 h), we assumed an average of 1 h for the flood event in the case study. Besides, we did not observe the variation of the inundated area during the flooding period. Thus, we assumed that the extent and depth of the inundated area did not change during the 1-h flood event.

3.2.3 | Risk assessment

In the final step, the steps mentioned above are combined to estimate the risk probability per person per exposure (i.e., exposure to floodwater). To show the health risk with the best available data, we quantified the infection risk and disease burden for one street (i.e., Chau Van Liem Street) based on the measured concentrations and exposed people on this street. Then, we extrapolated the risk assessment of all the flooded roads. The equations for the intake dose, infection probability, illness probability, and the DALYs are described below. Table 1 shows the critical input for the QMRA approach.

Intake dose

The intake dose (μ) is the dose of pathogens that exposed people ingested when they contacted floodwater (Equation 4) (EPA, 2011a):

$$\mu = c \times \mathrm{IR} \times t_e \tag{4}$$

where c is the concentration of the microbial pathogens; in this study, the pathogen is rotavirus A (genome of copies/mL). We detected rotavirus A in 21/37 (57%) of the floodwater samples, and it ranged from 2.27×10^3 to 2.96×10^6 genome copies/mL (Huynh et al., 2020).

IR is the intake rate (mL/h), which is the ingested volume per hour of exposure; and $t_e$is the exposure duration (hour), which is the exposure time in the flood event.

Dose–response relationships

A dose–response model describes the risk response (infection, illness, or death) for a given dose of a specific pathogen. The recommended dose–response model for rotavirus is hypergeometric (Teunis & Havelaar, 2000; Ward et al., 1986). This study used a simplified version, the beta-Poison model (Equation 5). This model is used regularly in the literature to estimate the infection

TABLE 1 Input data for the QMRA model to calculate the infection probability and illness probability per person per event.

Inputs	Units	Values and/(or) distribution	References
α (rotavirus)		0.253	(Haas et al., 1999)
β (rotavirus)		0.4220	
Concentrations			
The average value for all floodwater samples	(gc/mL)[a]	5.89×10^5 (mean, 95% CI 2.3×10^5–9.5×10^5) Lognormal (11.9, 2.11, 0)	(Huynh et al., 2020)
95th percentile concentration for all floodwater samples		2.56×10^6	
The average value for floodwater samples at Chau Van Liem Street		1.02×10^6	
Intake rates			
Child pedestrians	(mL/h)	3.7 Lognormal (3.7, 3.8)	(Dorevitch et al., 2011)
Adult pedestrians		3.5 Lognormal (3.6, 3.7)	
Motorcyclists			
Cyclists			
Speeds			
Child pedestrians	m/h	4200	(Waters et al., 1983)
Adult pedestrians		4800	
Motorcyclists		14,000	(Tang et al., 2020)
Cyclists		10,000	(Cherry & He, 2009)
Flooded lengths	m	300 (mean, 95% CI 0–1488) Lognormal (5.4, 0.787, 0)	This article
Risk of illness given infection of rotavirus P(ill|inf)		0.5	(WHO, 2016)

Abbreviation: QMRA, quantitative microbial risk assessment.

[a] gc/mL: genome of copies per milliliter.

probability (P_{inf}) for rotavirus (Gerba et al., 1996; Machdar et al., 2013; Mcbride et al., 2013):

$$P_{\text{inf}} = 1 - \left(1 + \frac{\mu}{\beta}\right)^{-\alpha} \tag{5}$$

where $\alpha$and β have been estimated as 0.253 and 0.422, respectively (Haas et al., 2014); μ is the ingested dose of rotavirus in genome copies (gc), which was calculated by Equation (4).

The probability of developing illness after infection (P_{ill}) was estimated by Equation (6):

$$P_{\text{ill}} = P_{\text{inf}} \times P_{\text{ill}|\text{inf}} \tag{6}$$

where $P_{\text{ill}|\text{inf}}$ is the risk of illness given infection (the likelihood that an infected person develops symptoms of acute illness), which is 0.5 for rotavirus A (WHO, 2016). Other studies also applied this value to the community exposed to wastewater (Fuhrimann et al., 2017), and water supply (Machdar et al., 2013).

The distribution of infection probability was simulated using Monte Carlo simulations with a random sampling of 10,000 iterations from the distributions of intake rate, flood length, and rotavirus concentration (Table 1). We used RiskAMP software version 5.4.1, an add-in package in Microsoft Excel, to simulate the distribution (Structured Data LLC, 2005).

3.3 | Disease burden

We calculated the disease burden by DALY metrics for the exposed people. DALY consists of the years of life lost (YLL) and years lived with disability (YLD) (Fewtrell & Bartram, 2001; Machdar et al., 2013). For rotavirus A, the standard DALY value of low-income countries is 482 DALYs per 1000 cases (YLL = 480, YLD = 2.2). The YLL is based on life expectancy at the age of death (WHO, 2016). Since the life expectancy at birth to calculate YLL is dependent on age at the time of death, we calculated a new value for YLL, using the average life

TABLE 2 Probability of developing negative outcome ($P_{\text{outcome}|\text{ill}}$), severity (s), and duration of symptoms (d) to calculate DALYs per case caused by rotavirus (Havelaar & Melse, 2003).

Symptoms	Probability (%)	Severity	Duration (year)
Mild diarrhea	88	0.1	0.02
Severe diarrhea	11.4	0.23	0.02
Death	0.6	1	72.6

expectancy at birth of Vietnamese people (73.6 years) (GOPFP, 2019). The average age at death of 1 due to rotavirus was assumed (Havelaar & Melse, 2003), which means the loss is 72.6 years. We considered the YLD due to rotavirus A with mild and severe diarrhea symptoms (Table 2). The disease burden of each illness case (DALYs per case, DALY_{pc}) for rotavirus (Equation 7) involves the YLL and YLD with the probability (%) of developing a negative health outcome (disease symptoms) given by an illness ($P_{\text{outcome}|\text{ill}}$); the severity of symptoms (s); and the duration of symptoms (d, year):

$$\text{DALY}_{\text{pc}} = P_{\text{outcome}|\text{ill}} \times s \times d \tag{7}$$

Then, from Equation (9), the disease burden per flood event was determined for each exposure group based on DALYs per illness case $\left(\text{DALY}_{\text{pc}}\right)$ and the number of illness cases in each group (N_{ill}). N_{ill} (Equation 8) was the product of exposed people in each group (N_{e}, from Equation 3) and P_{ill} (from Equation 6). Finally, the total DALYs provided the disease burden due to rotavirus for the four exposure groups through traffic activities (Equation 10).

The number of illness cases in each exposure group per flood event is

$$N_{\text{ill}} = N_{\text{e}} \times P_{\text{ill}} \tag{8}$$

The disease burden for each exposure group per flood event is

$$\text{DALYs}_{\text{pe}} = \text{DALY}_{\text{pc}} \times N_{\text{ill}} \tag{9}$$

The total DALYs of all exposure groups per flood event is

$$\text{Total DALYs} = \sum_{i} \left(\text{DALYs}_{\text{pe}}\right)_{i} \tag{10}$$

3.4 | Sensitivity analysis and uncertainty analysis for parameters

3.4.1 | Sensitivity analysis

Sensitivity analysis is used to measure the uncertainty of the proposed parameters since they are taken from the literature. The nominal range sensitivity analysis (NRSA) method was used to assess the sensitivity of the result due to the variability in the input parameters and variables (Cullen & Christopher Frey, 1999). It is used to evaluate the sensitivity of the model by changing the variables one at a time while maintaining other parameters. These changes are made across a range of plausible values with base, low, and high values (Table 3). We called the DALYs calculating with these values baseline, scenario 1, and scenario 2, respectively. We considered the influence of exposure duration, intake rate, and concentration on the infection probability and disease burden. The exposure duration depends on the speed of the exposed people and the lengths of flooded streets (Equation 1). The mean speeds of the motorcycle were estimated as 9 km/h in the rush hours (7:00–9:00 and 17:00–19:00) and 30 km/h in the non-rush hours (Tang et al., 2020). We used these data as the low and high values of the motorcycle speed. In contrast, during non-rush hours, the pedestrians tended to walk 4% slower than during rush hours. Hence, this percentage was used to calculate the low value for the speed of pedestrians (Bosina & Weidmann, 2017). The base value for the speed of pedestrians was 1.34 and 1.16 m/s for adults and children, respectively (Waters et al., 1983). We did not consider the high value of speed for pedestrians due to a lack of data. We assumed 9 km/h (Cherry & He, 2009) and 13.5 km/h (Langford et al., 2015) for the low value and high value of cyclist speeds, respectively. For the intake rates, the high values for child pedestrians and adult pedestrians/motorcyclists/cyclists by wading through surface water were 50 and 10 mL/h, respectively (EPA, 2011b). The low value was 1.4 mL/h, applied to all the exposed groups (Dorevitch et al., 2011). We fixed the low and high lengths of the inundated streets and measured rotavirus concentration at its 25th and 95th percentiles, respectively. Besides, we evaluated the sensitivity of the rotavirus concentration by using the ratio between the indicator *E. coli* and the rotavirus (*E. coli*: rotavirus = 10^5:1) to calculate the low value of the rotavirus concentration. Some recent studies have assumed the association between *E. coli* and rotavirus by this ratio to calculate the rotavirus concentration in drinking water and floodwater (Fuhrimann et al., 2016; Labite et al., 2010). Our previous study used the *E. coli* concentration in floodwater (average concentration 7.17×10^3 CFU/mL) analysis (Huynh et al., 2020) to estimate the

TABLE 3 Inputs of sensitivity analysis for QMRA and disease burdens with low values, high values, base values, and percentage changes compared to base values. A negative (−) indicates a decrease.

		Low		**High**		**Base**
Inputs	**Units**	**Values**	**Changes (%)**	**Values**	**Changes (%)**	**Values**
Rotavirus A concentration (measured)	gc/mL	5.3×10^3	−35%	2.6×10^6	11%	5.9×10^5
Rotavirus A concentration (ratio)		7.17×10^{-2}	−120%	—		
Intake rate						
Child pedestrians	mL/h	1.4	−60%	50	1329%	3.5
Adult pedestrians			−60%	10	186%	3.5
Motorcyclists			−62%	10	170%	3.7
Cyclists			−62%	10	170%	3.7
Lengths of flooded streets	m	85	−254%	689	130%	300
Flooded areas on streets	m^2	16,700		143,000		36,880
Speed						
Child pedestrians	m/h	4000	−4%	4800	14%	4200
Adult pedestrians		4600	−4%	5200	8%	4800
Motorcyclists		9000	−36%	30,000	114%	14,000
Cyclists		9000	−10%	13,500	35%	10,000

Abbreviation: QMRA, quantitative microbial risk assessment.

rotavirus concentration. The ratio concentration of rotavirus (3.9×10^{-2} CFU/mL) was 7 log10 lower than the average measured concentration (5.9×10^5 gc/mL).

Additionally, we evaluated the number of exposed people by considering the density of the exposed people. The people density during rush hours (base value) was 2.5 times higher than during non-rush hours (low value) (Tang et al., 2020). Therefore, the low value of the exposed people density was 2.5 times lower than the base value shown in Table 3. For the low value of DALYs per case, we assumed the standard DALYs due to rotavirus (0.014) were used for developed countries (Havelaar & Melse, 2003). Furthermore, we considered the influence of flooded areas (m^2) on disease burden. In 5 years (2013–2017), the Ninh Kieu districts experienced 24 flood events (CanThoWassco, 2017) (Table S2, Supplement). The flooded areas of these events ranged from 6400 to 252,000 m^2 (SD = 55,288, 95%CI mean 29,647–73,885). In our sensitivity analysis, we used the 25th and 95th percentiles of flood areas as low and high values. There were limited available $P_{\text{ill|inf}}$, α, and β parameters in the beta-Poison model to study; thus, we did not include these in the sensitivity analysis.

3.4.2 | Uncertainty analysis

To determine the uncertainty of which parameter is more important than the others, we used the Spearman test to find the correlation coefficient (rho) between the input and the output (i.e., infection risk) (Gurian, 2015; Haas et al., 2014). We simulated the distributions of intake volume, concentration, flood length (Table 1), and infection risk by Monte Carlo with 10,000 iterations in the software RiskAMP Monte Carlo Add-In Library version 5.4.1. Personal & Learning Edition.

4 | RESULTS

4.1 | QMRA and disease burden in a flood event

The number of exposed people in Chau Van Liem Street during a 1-h flood event was assumed to be twice as many as the exposed people counted in the video covering 30 min of inundation. Motorcycles were prevalent on the roads (95%). Of these, a quarter was shared motorcycles with two persons. Cyclists, adult pedestrians, and child pedestrians were the minority with 2.8%, 2%, and 0.1%, respectively. The gastroenteritis cases caused by rotavirus A in a flood event were 30,831 among the 63,390 exposed people in the four groups (Table 4).

The average infection risk per person per exposure (pppe) (i.e., exposure to floodwater) in Chau Van Liem Street and all the flooded streets were highest for child pedestrians at 9.6×10^{-1} and 9.7×10^{-1}, respectively. The infection probability of adult pedestrians,

TABLE 4 Exposed people density, ingested dose, average infection probability per person per exposure (pppe), illness cases, and disease burden for the four exposure groups due to rotavirus infection in a flood event in Chau Van Liem Street and all the flooded streets.

			Exposure groups				
	Units		**Child pedestrians**	**Adult pedestrians**	**Motorcyclists**	**Cyclists**	**Total**
Exposed people density	People/1000 m^2		2	34	1632	48	
Number of exposed people	People per (1 h) flood event	Chau Van Liem Street	2	34	1632	48	1716
		All the flooded streets	75	1274	61,143	899	63,390
Ingested doses	gc/pppe	Chau Van Liem Street	3.65×10^6	6.39×10^5	2.19×10^5	3.07×10^5	
		All the flooded streets	2.1×10^6	3.68×10^5	1.26×10^5	1.76×10^5	
(Average) infection probability	pppe	Chau Van Liem Street	9.8×10^{-1}	9.7×10^{-1}	9.6×10^{-1}	9.7×10^{-1}	
		All the flooded streets	9.8×10^{-1}	9.7×10^{-1}	9.6×10^{-1}	9.6×10^{-1}	
Illness cases	Illness people/event	Chau Van Liem Street	1.0	17	787	23	828
		All the flooded streets	37	617	29,312	865	30,831
Disease burden	DALYs/event	Chau Van Liem Street	0.4	7	345	10	3.62×10^2
		All the flooded streets	16	270	12,835	379	1.35×10^4

Abbreviation: DALYs, disability-adjusted life years.

motorcyclists, and cyclists was correspondingly 9.6×10^{-1}–9.7×10^{-1} (Table 4). Figure 4 indicates a similar percentile distribution among the four groups. The infection risk distribution in Figure 5 showed that pedestrians had highest likely to be infected than other groups. This means that the infection risk of pedestrians is highest and that value had the highest probability to happen than other groups. For all exposure groups, the high values of infection risk had a higher probability to happen. For example, at an infection risk of 0.96, the probability to happen is 31%, 26%, 15%, and 18% for child pedestrians, adult pedestrians, cyclists, and motorcyclists. At an infection risk of 0.98, the probability to happen is 53%, 37%, 36%, and 30% for child pedestrians, adult pedestrians, cyclists, and motorcyclists, respectively.

The DALYs from all the exposure groups in a flood event at Chau Van Liem Street were 3.62×10^2. The total DALYs for all the roads were 1.35×10^4. Motorcyclists are the main contributor to the total DALYs, followed by cyclists, adult pedestrians, and child pedestrians (Table 4).

4.2 | Sensitivity analysis and uncertainty analysis

According to the NRSA results (Figure S5 and Table S4, Supplement), the most influential variable in health outcomes was flooded areas (337%) followed by the (measured) concentration of rotavirus (11%–15%). Increasing the flooded areas by 290% (i.e., four times higher than the base value) resulted in the most significant change in disease burden (approximately 282% higher). For concentration, increasing the (measured) rotavirus concentrations

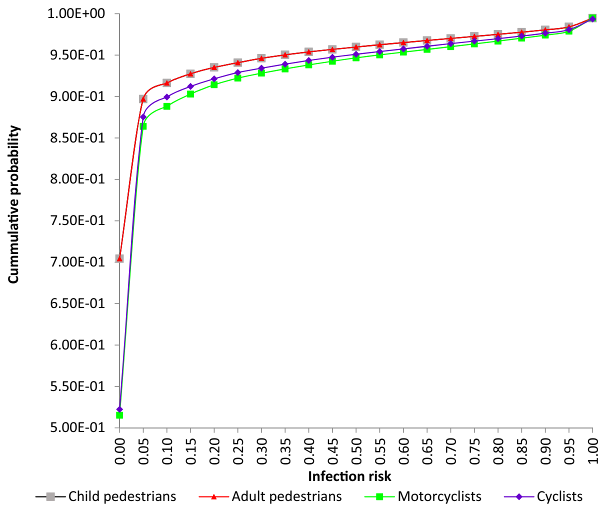

FIGURE 4 The cumulative probability distribution for the probability of infection from Monte Carlo simulation for four traffic groups.

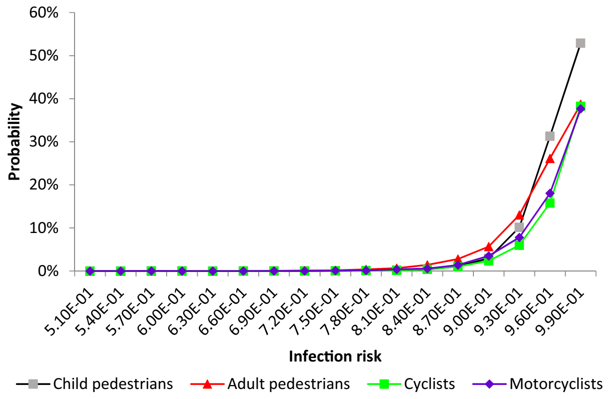

FIGURE 5 The probability distribution of infection risk per person per exposure caused by rotavirus A in floodwater for the four exposure groups through traffic activities in Ninh Kieu District of Can Tho City.

by 1 log (i.e., 11% higher than the base value) increased the infection risk and DALYs by 0.6%, 1.0%, 1.3%, and 1.2% for child pedestrians, adult pedestrians, motorcyclists, and cyclists, respectively. With a reduction of two log10 in the rotavirus concentration (i.e., 35% lower than the base value), these health outcomes were reduced by 4.7%, 7.4%, 9.9%, and 9% for these exposure groups, respectively. Notably, using the ratio between *E. coli* and rotavirus, the rotavirus concentration was seven log10 lower than the base value (i.e., 120% lower than the base value). This caused a significant reduction in the infection risk and disease burden of child pedestrians, cyclists, and motorcyclists/adult pedestrians by 88%, 97%, and 99%, respectively.

Besides, the reduction of DALYs per case and density resulted in a considerable decrease in negative health outcomes. If the exposed people density was 2.5 times less crowded on roads, the DALYs decreased by 61% (i.e., 2.5 times less than the DALYs calculated by the base value). Decreasing the DALYs per case by 32 times (i.e., 97%) reduced the disease burden by 97%. Since the plausible high values of the concentration (ratio), DALYs per case, and people density were not available, we did not consider the NRSA of these parameters in the health outcomes.

The speed, flooded street lengths, and intake rate only contributed to the outcome by less than 3%, except for the speed of pedestrians by 9%. Reducing the velocity of child and adult pedestrians, motorcyclists, and riders by 4%, 36%, and 10%, respectively, caused an increase of 0.02%, 1.11%, 0.45%, and 0.1% in the health outcomes. However, increasing the speed by double and one-third for motorcyclists and cyclists reduced the infection risk and disease burden by 1% and 0.3%, respectively. When the length of the inundation area increased by two times longer than the base value, the health outcomes increased by 0.4%, 0.6%, 0.8%, and 0.7% for child pedestrians, adult pedestrians, motorcyclists, and cyclists, respectively. By traveling along an inundated street that was 3.5 times shorter, the health risk and disease burden were reduced by 0.8%, 1.2%, 1.6%, and 1.5% for the four groups, respectively. Changing the water intake (Table 3) had a limited effect on the health outcome (1.1%–1.4% lower or 1%–2% higher).

The uncertainty of the input had a weak impact on the infection risk (rho <0.3). The correlation coefficient of flood length and infection risk of the four exposure groups was 0.24–0.27, followed by concentration (0.14–0.22) and intake rate (0.08–0.14) (Table S5, Supplement).

5 | DISCUSSION

5.1 | Quantitative microbial risk assessment

This study demonstrates the health risk of enteric pathogens due to exposure to urban floodwater through traffic activities in developing countries. In terms of average infection risk, the result confirms the findings of previous similar studies that children have the highest potential risk of infection, followed by adults (Man et al., 2014; Sterk et al., 2008; Veldhuis et al., 2010). However, the infection risk distribution showed that children had lowest likely to be infected than motorcyclists, cyclists, and adult pedestrians. The infection probability in our study was 1–4 orders of magnitude higher than those in previous studies. For example, according to Veldhuis et al. (2010), the infection probabilities for adult and child pedestrians were 5×10^{-5}–0.2 and 10^{-4}–0.3, respectively. Man et al. (2014) identified infection risks for children to be 0.33, 0.23, and 0.035, while the infection risks for adults were 0.039, 5.8×10^{-3}, and 3.9×10^{-4} in the Netherlands. In the case study Dhaka (Bangladesh), Mark et al. (2015) indicated infection risks caused by *Vibrio cholera* in floodwater for children and adults in low- and middle-class areas were 52×10^{-5}–5.6×10^{-3} and 1.5×10^{-6}–5.5×10^{-4}, respectively. The reason is that the concentration of rotavirus in our case was 2–7 log10 higher than the pathogen concentrations in the other studies. When we used the ratio between *E. coli* and rotavirus ($1{:}10^{-5}$) to calculate the rotavirus concentration (Table 3), the estimated concentration of rotavirus was seven log10 smaller than the base value (i.e., the measured concentration). It resulted in the infection risks calculated for child pedestrians, adult pedestrians, motorcyclists, and cyclists in the same range as other previous studies with 0.1, 0.03, 8.9×10^{-3}, and 0.013, respectively.

Some uncertainties may affect the infection probability. The first is whether it is appropriate to use dose–response models undertaken with adults in developed countries for case studies in developing countries (Mills et al., 2018). The dose–response relationship of rotavirus was formed for male volunteers ranging from 18 to 45 years old (Teunis et al., 1996). Hence, it does not represent children. Moreover, it may not accurately reflect the actual dose–response relationship of the case study, which may have different degrees of immunity. Second, in our research, rotavirus was analyzed by qPCR, which only detected the genetic material, not the active status of the virus. To the best of our knowledge, there is a lack of research mentioning the rotavirus concentration in sampling floodwater. Only one study detected rotavirus in floodwater (9%, 9/100 samples) in Thailand but did not analyze the concentration (Ngaosuwankul et al., 2013). Fuhrimann et al. (2017) estimated the rotavirus concentration based on *E. coli* concentration and the ratio between *E. coli* and rotavirus. Rotavirus concentrations in the river and sewer water in the Netherlands were 57–5386 PDU/L (PCR-detectable units) and 339–55,000 PDU/L (Lodder & de Roda Husman, 2005). These results were much lower than our study, by between 3 and 6 orders of magnitude. Since the water quality in developed countries may be better than in developing countries, analyzing enteric pathogens such as rotavirus in floodwater in developing countries needs to consider other similar research in the future. Moreover, for future research, it may be helpful to test the virus's live (or infective) nature in floodwater, for example, by cultures (Arnold et al., 2012).

5.2 | Disease burden

Our study conducted an experiment to identify the number of people exposed to traffic during flooding. Motorcyclists were prevalent in the streets during this time. This result was similar to previous studies about the high predominance of personal transport vehicles, such as motorcycles, in Vietnam's urban streets. For example, the number of motorcycles per hour contributed 93.4%–96.5% (i.e., 13,600 ± 3170) in arterial roads in Hanoi and Ho Chi Minh City (Hung et al., 2010; Kim et al., 2012; Tang et al., 2020). However, the number of vehicles in our study was less than in the previous study since Can Tho city is less crowded than these other two cities. Also, the estimated illness cases per flood event in our study (Table 4) was 20 times higher than the gastrointestinal cases reported by the local preventive medical center. According to epidemiological data in Ninh Kieu, there were 1550 diarrhea cases in 2014, 774 cases in 2015, and 757 cases in 2016 (Preventive Medical Center in Can Tho, 2016a). One reason might be ill people buy medicine at a pharmacy store without visiting doctors or hospitals, which is a common habit (Preventive Medical Center in Can Tho, 2016b). Therefore, the epidemiological data may not cover all real illness cases in Ninh Kieu. Another reason was that we might have overestimated the illness cases due to the high infection probability based on the high rotavirus concentration. The third reason was that the risk of illness given infection usually comes from indirect sources since it is ethically inconceivable to conduct human trials to establish this. Therefore, the risk of illness given infection ($P_{\text{inf|ill}}$) may have been under/overestimated when it was studied for volunteers in developed countries (Teunis & Schijven, 2017). The $P_{\text{inf|ill}}$ value should receive more attention for people in developing countries, especially for adults who have a better immune system. Besides, we suggested a further study on collecting information about self-medication patients at local pharmacies, for example by a questionnaire survey, to overcome the under-reporting data (Brata et al., 2013; Astrid Mukemo et al., 2020).

We compared our DALY values with DALYs in other daily life activities to assess the severity of health risks related to the waterborne pathogen. The motorcyclists contributed the highest disease burdens to total DALYs (12,835, 95%), followed by adult pedestrians, cyclists, and child pedestrians. In our study, the total DALYs per flood event (with one exposure per flood event) were 13,500 DALYs for 63,390 exposed people (i.e., 2129

DALYs/10,000 cases). This result was much greater than DALYs caused by rotavirus in river water in Germany through one-off swimming events (6.4 DALYs/10,000 cases in seven exposures per year) (Timm et al., 2016). Our disease burden is respectively two and three times lower than the disease burden due to microbial pathogens in drinking water in Ghana (5000 DALYs/10,000 cases per year) (Machdar et al., 2013) and Uganda (10,172 DALYs for 15,015 people, 6775 DALYs/10,000 cases) (Katukiza et al., 2013). Our result exceeded by four to five log10 of the tolerable burden of disease related to the drinking water according to WHO (0.1–0.01 DALY/10,000 per year) (WHO, 2003). Since we calculated the DALYs per flood event, the DALYs for people exposed to floodwater more than once per year could be higher than this standard.

5.3 | Sensitivity analysis

Our sensitivity analysis first highlights the influence of flooded areas on disease burden. Investing in reducing inundation can reduce the disease burden and infection risk for local people. Second, the infection risk and disease burden were sensitive to the concentration of rotavirus. Sales-Ortells and Medema (2015) reported a similar result about the more significant influence of concentration on infection risk than other input parameters. Additionally, in our study, when applying the ratio (i.e., ratio between *E. coli* and rotavirus) to calculate the rotavirus concentration, the infection risk and disease burden showed a noticeable difference compared to the base value (i.e., measured concentration). Our previous study observed a weak association between *E. coli* and rotavirus in flood-related waters (Huynh et al., 2020). Another study indicated the rare correlation of fecal indicators such as *E. coli* with other pathogens in sewer and surface water (Payment & Locas, 2011). Therefore, in future studies, care should be exercised using the ratio of *E. coli* and rotavirus in specific case studies to assess the health risk since it may underestimate the health risk.

Since decreasing the exposed people density caused a significant reduction in health outcomes, we indicated the importance of controlling the number of people in the streets during flooding. Moreover, we stated the importance of DALYs per case since reducing DALYs per case resulted in a significant decrease in disease burden. Besides, more awareness is needed when applying an appropriate standard from case to case. For example, using standard DALYs per case due to rotavirus in water was inconsistent in Kampala City, Uganda. Katukiza et al. (2013) applied the standard DALY value due to the rotavirus for developing countries (3.69×10^{-1} DALYs per case) (Katukiza et al., 2013). In contrast, for the same area, Fuhrimann et al. (2017) used a much lower DALY (3.22×10^{-3} DALYs per case) referencing a study estimating for all Australians. These two different DALYs led to significant differences in assessing the disease burden for the community. More research into standard DALYs may be needed to have a plausible range, especially LMICs. In contrast, the intake rates, the length of flooded streets, and the speed of exposed people mostly had a minimal effect on health outcome change. Limaheluw et al. (2019) also indicated less impact of ingesting volume to disease burden for consuming polluted surface water in sub-Saharan Africa (Limaheluw et al., 2019). In addition, the uncertainty of concentration and the length of flooded streets showed more importance to the infection risk than intake rates, although the correlations were weak.

According to the best of our knowledge, this is the first study that calculates the disease burden caused by microbial pathogens in urban floodwater with sampling data for exposure through traffic activities. Although infection risk and disease burden may over/underestimate the risk due to uncertainties, we highlight the risk from microbial pathogens through traffic activity during a flood event. Our study provides quantitative evidence that may help manage the health impacts. With the support of the hydrodynamic model, applying the appropriate mitigation measures can reduce microbial health risk, for example, low-impact development or natural-based solutions (Ishaq et al., 2022; Oral et al., 2020). While improving floodwater quality and reducing inundation play an essential role in reducing the risk, actions could also reduce the exposure. For example, the local authorities could give an early warning of flooding. Alternative routes/means could be provided to reduce the number of people wading through floodwaters. Awareness programs on the infection risk of floodwaters can also help. In urban areas of LMICs countries like Vietnam, besides taking care of children, riders, especially motorcyclists, should have more awareness during flooding. Riders were the most exposed population to traffic activities. If they knew about the reality of the likelihood of infection and health loss, they might avoid highly flooded streets, delay traveling in periods of high floods or use public transport on flooding days. Moreover, after exposure to floodwater, people should be aware of washing their hands and clothes. Recently, some studies show the positive of coronavirus 2 (SARS-CoV-2 virus) in untreated wastewater (Elsamadony et al., 2021; Ihsanullah et al., 2021) and cause health risks (Dada & Gyawali, 2021). Sewage overflows in flooding can transmit the virus into floodwater and spread it on streets and households (Han & He, 2021). Therefore, avoiding exposure to floodwater and keeping hygiene is necessary to protect residents from infectious diseases, especially during the COVID-19 pandemic.

The proposed framework and methods in this study can be applied to other similar case studies that have the potential to be affected by post-flooding health impacts. Although the study is reported over a typical case study, urban flooding and polluted floodwater issues increase in other cities in Vietnam (Bangalore et al., 2016; Nguyen et al., 2021) and other developing countries (Nkwunonwo et al., 2020). We propose the QMRA and disease burden approach which have both practical and theoretical advantages to assess the microbial health risk (Howard et al., 2006; Murray & Acharya, 1997). They may choose to add more microbial pathogens or create a new method to analyze the new exposure groups of the framework, if necessary.

Further studies can improve the findings: first, we referenced exposure behaviors such as intake rate from other similar studies, primarily taken in developed countries. Therefore, it may not accurately transfer the situation in this case study. Questionnaire surveys could be used to determine these data. Second, this study only takes into account exposed people on the streets. However, this is not the whole picture of exposure in a case study during flooding. People who live in flooded houses may contact floodwater by many other means, for example, by cleaning up their houses. The infection risk due to such exposure should also be considered. Third, infection risk and total DALYs could be updated to reduce the uncertainties when new knowledge about these input variables is available for people in developing countries such as the illness given infection ($P_{\text{inf|ill}}$) and the severity and duration of symptoms.

Additionally, increasing urban flooding and its impacts in the future due to urbanization processes and climate change is one of Can Tho's significant challenges (Borris et al., 2013; Huong & Pathirana, 2013; Leloup et al., 2013). In 2050, the Ninh Kieu district could be one of the most vulnerable areas to flooding (Balica et al., 2013). The socio-economic changes in the future can affect the estimate of microbial health risk. According to the UN (i.e., United Nations), two-thirds of the world's population is expected to live in urban areas by 2050, with the most rapid urbanization in LMICs (UN, 2018). Rapid population growth and poor urban planning reduce the perviousness areas which increases the frequency of flooding (Rahman et al., 2021). Besides, the sewer systems may receive more wastewater and increase the pollution in floodwater. Therefore, exposed people to floodwater and microbial health risks are expected to increase in future scenarios. Combining the hydrodynamic model and HRA may help assess the vulnerability of exposed groups in future scenarios of socio-economic change and climate change.

6 | CONCLUSION

For the first time, this study revealed the disease burden per flood event due to rotavirus A in floodwater through traffic activities. All exposure groups showed a high infection probability due to rotavirus A per person per exposure (0.96–0.98). We estimated the illness cases were 20–30 times higher than local epidemiological reports. Motorcyclists showed the highest exposure to contaminated floodwaters on flooded streets in Ninh Kieu District, which contributed to the highest disease burden expressed as total DALYs per flood event (12,835 DALYs per event, 95%). The disease burden of cyclists, adult pedestrians, and child pedestrians was 379, 270, and 16 DALYs, respectively. The infection risk was most sensitive to the rotavirus concentration. The disease burden showed high sensitivity to flooded areas and concentration. Besides, exposed people density and standard DALYs significantly reduced the disease burden. In contrast, the length of flooded streets and the speeds of exposed people had a much lower effect on health outcomes. These differences in sensitivity and associated uncertainties of input data should be acknowledged to assess the health risk results presented in this study.

This study used a combination of the estimated infection risks with population data to understand better the disease burden caused by enteric pathogens (i.e., rotavirus A) through contact with floodwater. The total DALYs were calculated to quantify how many healthy life years people may lose when exposed to contaminated floodwaters. These results emphasize the need to raise community awareness about the health risk associated with urban flooding. The Mekong Delta residents are familiar with the slogan “Living with a flood,” which is usually beneficial for rural areas during the “floating water season.” However, in urban areas, contact with floodwater may have a significant health risk that people are largely unaware of. Urban flooding, crowded people, and polluted floodwater can lead to disease burden caused by microbial pathogens. The infectious disease cases have been predicted to increase in future climate change (Nichols et al., 2018; Portier et al., 2010). Therefore, more understanding of the environmental drivers and spatial health risk mapping can help to estimate the future change of disease burden and apply appropriate mitigation measures to reduce adverse health impacts.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The authors declare that all data supporting the findings of this study are available within the article and its supplementary information files.

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REFERENCES

Ahern, M., Sari Kovats, R., Wilkinson, P., Few, R., & Matthies, F. (2005). Global Health impacts of floods: Epidemiologic evidence. *Epidemiologic Reviews*, *27*, 36–46. https://doi.org/10.1093/epirev/mxi004

Arnold, M., Patton, J. T., & Mcdonald, S. M. (2012). Culturing Rotaviruses. *Current Protocols in Microbiology*, 1–29. https://doi.org/10.1002/9780471729259.mc15c03s15.Culturing

Atmar, R. L., & Estes, M. K. (2006). The epidemiologic and clinical importance of norovirus infection. *Gastroenterology Clinics of North America*, *35*(2), 275–290. https://doi.org/10.1016/j.gtc.2006.03.001

Balica, S., Dinh, Q., Popescu, I., Vo, T. Q., & Pham, D. Q. (2013). Flood impact in the Mekong Delta, Vietnam. *Journal of Maps*, *10*(2), 257–268. https://doi.org/10.1080/17445647.2013.859636

Bangalore, M., Smith, A., & Veldkamp, T. (2016). Exposure to floods, climate change, and poverty in Vietnam. *Economics of Disasters and Climate Change*, 79–99. https://doi.org/10.1596/1813-9450-7765

Borris, M., Viklander, M., Gustafsson, A.-M., & Marsalek, J. (2013). Simulating future trends in urban Stormwater quality for changing climate, urban land use and environmental controls. *Water Science and Technology: A Journal of the International Association on Water Pollution Research*, *68*(9), 2082–2089. https://doi.org/10.2166/wst.2013.465

Bosina, E., & Weidmann, U. (2017). Estimating pedestrian speed using aggregated literature data. *Physica A: Statistical Mechanics and its Applications*, *468*, 1–29. https://doi.org/10.1016/j.physa.2016.09.044

Brata, C., Gudka, S., Schneider, C. R., Everett, A., Fisher, C., & Clifford, R. M. (2013). A review of the information-gathering process for the provision of medicines for self-medication via community pharmacies in developing countries. *Research in Social and Administrative Pharmacy*, *9*(4), 370–383. https://doi.org/10.1016/j.sapharm.2012.08.001

Can Tho Wassco. (2017). Flood event report in Ninh Kieu from Can Tho water supply–sewerage joint stock company.

Can Tho's People Committee. (2019). Annual report on environmental status in Can Tho City (In Vietnamese). Can Tho.

Cann, K. F., Thomas, D. R., Salmon, R. L., Wyn-Jones, A. P., & Kay, D. (2013). Extreme water-related weather events and waterborne disease. *Epidemiology and Infection*, *141*(4), 671–686. https://doi.org/10.1017/S0950268812001653

Cherry, C., & He, M. (2009). Alternative methods of measuring operating speed of electric and traditional bikes in China-implications for travel demand models. *Journal of the Eastern Asia Society for Transportation Studies*, *8*(1), 1424–1436. https://doi.org/10.11175/eastpro.2009.0.246.0

Cook, A., Watson, J., Buynder, P. V., Robertson, A., & Weinstein, P. (2008). Natural disasters and their Long-term impacts on the health of communities. *Journal of Environmental Monitoring*, *10*(2), 167–175. https://doi.org/10.1039/b713256p

Cullen, A. C., & Christopher Frey, H. (1999). Probabilistic techniques in exposure assessment. A handbook for dealing with variability and uncertainty in models and inputs, New York.

Dada, A. C., & Gyawali, P. (2021). Quantitative microbial risk assessment (QMRA) of occupational exposure to SARS-CoV-2 in wastewater treatment plants. *Science of the Total Environment*, *763*, 142989. https://doi.org/10.1016/j.scitotenv.2020.142989

Doan, L. T., Phuong, S. O., Nishio, O., Pham, D. T., Nguyen, D. H., & Ushijimal, H. (2003). Epidemiological features of rotavirus infection among hospitalized children with Gastroenteristis in Ho Chi Minh City, Vietnam. *Journal of Medical Virology*, *69*(4), 588–594. https://doi.org/10.1002/jmv.10347

Donovan, E., Unice, K., Roberts, J. D., Harris, M., & Finley, B. (2008). Risk of gastrointestinal disease associated with exposure to pathogens in the water of the lower Passaic River. *Applied and Environmental Microbiology*, *74*(4), 994–1003. https://doi.org/10.1128/AEM.00601-07

Dorevitch, S., Panthi, S., Huang, Y., Li, H., Michalek, A. M., Pratap, P., Wroblewski, M., Liu, L., Scheff, P. A., & Li, A. (2011). Water ingestion during water recreation. *Water Research*, *45*(5), 2020–2028. https://doi.org/10.1016/j.watres.2010.12.006

Elsamadony, M., Fujii, M., Miura, T., & Watanabe, T. (2021). Possible transmission of viruses from contaminated human feces and sewage: Implications for SARS-CoV-2. *Science of the Total Environment*, *755*, 142575. https://doi.org/10.1016/j.scitotenv.2020.142575

EPA. (2011a). Exposure factors handbook. www.epa.gov.

EPA. (2011b). Human health risk assessment bulletins.

Few, R., Lake, I., Hunter, P. R., & Tran, P. G. (2013). Seasonality, disease and behavior: Using multiple methods to explore socio-environmental health risks in the Mekong Delta. *Social Science and Medicine*, *80*, 1–9. https://doi.org/10.1016/j.socscimed.2012.12.027

Few, R., & Tran, P. G. (2010). Climatic hazards, health risk and response in Vietnam: Case studies on social dimensions of vulnerability. *Global Environmental Change*, *20*(3), 529–538. https://doi.org/10.1016/j.gloenvcha.2010.02.004

Fewtrell, L., & Bartram, J. (2001). *Water quality—Guidelines, standards and health: Assessment of risk and risk management for water-related infectious disease* (Vol. 12). IWA Publishing. https://doi.org/10.2166/9781780405889

Fewtrell, L., Kay, D., Matthews, I., Utzinger, J., Singer, B. H., & Bos, R. (2008). Health impact assessment for sustainable water management: The lay of the land. In L. Fewtrell & D. Kay (Eds.), *Health impact assessment for sustainable water management* (pp. 1–14). IWA Publishing.

Fewtrell, L., Smith, K., Watkins, J., Blanksby, J., & Saul, A. (2008). An exploration quantitative microbial risk assessment of urban flooding and gastrointestinal illness. In L. Fewtrell & D. Kay (Eds.), *Health impact assessment for sustainable water management* (pp. 156–173). IWA Publishing.

Fuhrimann, S., Nauta, M., Pham-duc, P., Tram, N. T., Nguyen-Viet, H., Utzinger, J., Cisséa, G., & Winkler, M. S. (2017). Disease burden due to gastrointestinal infections among people living along the major wastewater system in Hanoi, Vietnam. *Advances in Water Resources*, *108*, 439–449. https://doi.org/10.1016/j.advwatres.2016.12.010

Fuhrimann, S., Winkler, M. S., Stalder, M., Niwagaba, C. B., Babu, M., Kabatereine, N. B., Halage, A. A., Utzinger, J., Cissé, G., & Nauta, M. (2016). Disease burden due to gastrointestinal pathogens in a wastewater system in Kampala, Uganda. *Microbial Risk Analysis*, *4*, 16–28. https://doi.org/10.1016/j.mran.2016.11.003

Gao, T., Wang, X. C., Chen, R., Ngo, H. H., & Guo, W. (2015). Disability adjusted life year (DALY): A useful tool for quantitative assessment of environmental pollution. *Science of the Total Environment*, *511*, 268–287. https://doi.org/10.1016/j.scitotenv.2014.11.048

George, J., An, W., Joshi, D., Zhang, D., Yang, M., & Suriyanarayanan, S. (2015). Quantitative microbial risk assessment to estimate the health risk in urban drinking water Systems of Mysore, Karnataka, India. *Water Quality, Exposure and Health*, *7*, 331–338. https://doi.org/10.1007/s12403-014-0152-4

Gerba, C. P., Rose, J. B., Haas, C. N., & Crabtree, K. D. (1996). Waterborne rotavirus: A risk assessment. *Water Research*, *30*(12), 2929–2940. https://doi.org/10.1016/S0043-1354(96)00187-X

GOPFP. (2019). From the Trend of rapid population aging in Vietnam–opportunities and challenges, 2019. http://gopfp.gov.vn/tin-chi-tiet/-/chi-tiet/tu-xu-huong-gia-hoa-dan-so-nhanh-o-viet-nam-co-hoi-va-thach-thuc-10505-3601.html.

GSO. (2019). Area, population and population density in Vietnam, 2019. https://www.gso.gov.vn/en/px-web/?pxid=E0201&theme=population-and-employment.

Gurian, P. L. (2015). Uncertainty propagation in QMRA, 2015. http://qmrawiki.canr.msu.edu/index.php/Uncertainty_Propagation.

Haas, C. N., Rose, J. B., & Gerba, C. P. (1999). *Quantitative Microbial Risk Assessment*. John Wiley & Sons.

Haas, C. N., Rose, J. B., & Gerba, C. P. (2014). *Quantitative microbial risk assessment* (2nd ed.). John Wiley & Sons.

Hammond, M. J. J., Chen, A. S. S., Djordjević, S., Butler, D., & Mark, O. (2013). Urban flood impact assessment: A state-of-the-art review. *Urban Water Journal*, *1–16*, 14–29. https://doi.org/10.1080/1573062X.2013.857421

Han, J., & He, S. (2021). Urban flooding events pose risks of virus spread during the novel coronavirus (COVID-19) pandemic. *Science of the Total Environment*, *755*, 142491. https://doi.org/10.1016/j.scitotenv.2020.142491

Havelaar, A. H., & Melse, J. M. (2003). Trace elements in groundwater of Hindon-Yamuna interfluve region, Baghpat district, Western Uttar Pradesh. In *Quantifying public health risk in the WHO guidelines for drinking-water quality–a burden of disease approach*. RIVM Report. https://doi.org/10.1007/s12594-013-0053-3

Howard, G., Pedley, S., & Tibatemwa, S. (2006). Quantitative microbial risk assessment to estimate health risks attributable to water supply: Can the technique Be applied in developing countries with limited data? *Journal of Water and Health*, *4*(1), 49–65. https://doi.org/10.2166/wh.2005.058

Hung, N. T., Ketzel, M., Jensen, S. S., & Oanh, N. T. K. (2010). Air pollution modeling at road sides using the operational street pollution model–a case study in Hanoi, Vietnam. *Journal of the Air and Waste Management Association*, *60*(11), 1315–1326. https://doi.org/10.3155/1047-3289.60.11.1315

Huong, H. T. L., & Pathirana, A. (2013). Urbanization and climate change impacts on future urban flood risk in Can Tho City, Vietnam. *Hydrology and Earth System Sciences Discussions*, *8*(6), 10781–10824. https://doi.org/10.5194/hessd-8-10781-2011

Huyen, D. T. T., Hong, D. T., Trung, N. T., Hoa, T. T. N., Oanh, N. K., Thang, H. V., Thao, N. T. T., Hung, D. M., Iijima, M., Fox, K., Grabovac, V., Heffelfinger, J., Batmunkh, N. & Anh, D. D. (2018). Epidemiology of acute diarrhea caused by rotavirus in sentinel surveillance sites of Vietnam, 2012–2015. *Vaccine*, *36*(51), 7894–7900. https://doi.org/10.1016/j.vaccine.2018.05.008

Huynh, T. T., Nguyen, H. Q., Nguyen, P. V., Vinh, S. B., & Pathirana, A. (2020). Enteric pathogens in flood-related Waters in urban areas of the Vietnamese Mekong Delta: A case study of Ninh Kieu District, Can Tho City. *Urban Water Journal*, *16*(9), 634–641. https://doi.org/10.1080/1573062X.2020.1713381

Ihsanullah, I., Bilal, M., & Naushad, M. (2021). Coronavirus 2 (SARS-CoV-2) in water environments: Current status, challenges and research opportunities. *Journal of Water Process Engineering*, *39*(10), 101735. https://doi.org/10.1016/j.jwpe.2020.101735

Iowa State University. (2002). Traffic volume counts. Handbook of simplified practice for traffic studies.

Ishaq, S., Sadiq, R., Chhipi-Shrestha, G., Farooq, S., & Hewage, K. (2022). Developing an integrated 'regression-QMRA method' to predict public health risks of low impact developments (LIDs) for improved planning. *Environmental Management*, *70*, 633–649. https://doi.org/10.1007/s00267-022-01657-0

Jalilov, S. M., Kefi, M., Kumar, P., Masago, Y., & Mishra, B. K. (2018). Sustainable urban water management: Application for integrated assessment in Southeast Asia. *Sustainability (Switzerland)*, *10*(1), 1–22. https://doi.org/10.3390/su10010122

Jensen, P., Rouquier, J. B., Ovtracht, N., & Robardet, C. (2010). Characterizing the speed and paths of shared bicycle use in Lyon. *Transportation Research Part D: Transport and Environment*, *15*(8), 522–524. https://doi.org/10.1016/j.trd.2010.07.002

Katukiza, A. Y., Ronteltap, M., van der Steen, P., Foppen, J. W., & Lens, P. N. L. (2013). Quantification of microbial risks to human health caused by waterborne viruses and bacteria in an urban slum. *Journal of Applied Microbiology*, *116*(2), 447–463. https://doi.org/10.1111/jam.12368

Kingston, D. G., Thompson, J. R., & Kite, G. (2011). Uncertainty in climate change projections of discharge for the Mekong River basin. *Hydrology and Earth System Sciences*, *15*(5), 1459–1471. https://doi.org/10.5194/hess-15-1459-2011

Kouamé, P. K., Dongo, K., Biémi, J., Bonfoh, B., Nguyen-Viet, H., & Zurbrügg, C. (2017). Microbiological risk infection assessment using QMRA in agriculture systems in Côte D'ivoire, West Africa. *Environmental Monitoring and Assessment*, *189*(11), 587. https://doi.org/10.1007/s10661-017-6279-6

Labite, H., Lunani, I., Van Der Steen, P., Vairavamoorthy, K., Drechsel, P., & Lens, P. (2010). Quantitative microbial risk analysis to evaluate health effects of interventions in the urban water system of Accra, Ghana. *Journal of Water and Health*, *8*(3), 417–430. https://doi.org/10.2166/wh.2010.021

Langford, B. C., Chen, J., & Cherry, C. R. (2015). Risky riding: Naturalistic methods comparing safety behavior from conventional bicycle riders and electric bike riders. *Accident Analysis and Prevention*, *82*, 220–226. https://doi.org/10.1016/j.aap.2015.05.016

Lau, C. L., Smythe, L. D., Craig, S. B., & Weinstein, P. (2010). Climate change, flooding, urbanisation and leptospirosis: Fuelling the fire? *Transactions of the Royal Society of Tropical Medicine and Hygiene*, *104*(10), 631–638. https://doi.org/10.1016/j.trstmh.2010.07.002

Leloup, V., Ky, Q. V., Nguyen, H. D., & Razafindrazay, L. Z. (2013). *Can Tho (Viet Nam) comprehensive resilience planning for integrated flood risk management*. The World Bank.

Lim, K.-Y., Hamilton, A. J., & Jiang, S. C. (2015). Assessment of public health risk associated with viral contamination in harvested urban Stormwater for domestic applications. *Science of the Total Environment*, *523*, 95–108. https://doi.org/10.1016/j.scitotenv.2015.03.077

Limaheluw, J., Medema, G., & Hofstra, N. (2019). An exploration of the disease burden due to cryptosporidium in consumed surface water for sub-Saharan Africa. *International Journal of Hygiene and Environmental Health*, *222*(5), 856–863. https://doi.org/10.1016/j.ijheh.2019.04.004

Lodder, W. J., & de Roda Husman, A. M. (2005). Presence of noroviruses and other enteric viruses in sewage and surface Waters in The Netherlands. *Applied and Environmental Microbiology*, *71*(3), 1453–1461. https://doi.org/10.1128/AEM.71.3.1453-1461.2005

Luo, P., Kang, S., Apip, M. Z., Lyu, J., Aisyah, S., Binaya, M., Regmi, R. K., & Nover, D. (2019). Water quality trend assessment in Jakarta: A rapidly growing Asian megacity. *PLoS One*, *14*(7), 1–17. https://doi.org/10.1371/journal.pone.0219009

Machdar, E., van der Steen, N. P., Raschid-Sally, L., & Lens, P. N. L. (2013). Application of quantitative microbial risk assessment to analyze the public health risk from poor drinking water quality in a low income area in Accra, Ghana. *Science of the Total Environment*, *449*, 134–142. https://doi.org/10.1016/j.scitotenv.2013.01.048

Man, H., van den Berg, H. H. J. L., Leenen, E. J. T. M., Schijven, J. F., Schets, F. M., van der Vliet, J. C., van Knapen, F., & de Roda Husman, A. M. (2014). Quantitative assessment of infection risk from exposure to waterborne pathogens in urban floodwater. *Water Research*, *48*, 90–99. https://doi.org/10.1016/j.watres.2013.09.022

Man, N., Luan, L. T., Trach, D. D., Thanh, N. T. H., Phan Van, T., Long, N. T., Ann, D. D., Fischer, T. K., Ivanoff, B., Gentsch, J. R., & Glass, R. I. (2005). Epidemiological profile and burden of rotavirus diarrhea in Vietnam: 5 years of sentinel hospital surveillance, 1998-2003. *Journal of Infectious Diseases*, *192*, 1998–2003. https://doi.org/10.1086/431501

Mark, O., Jørgensen C., Hammond, M., Khan, D., Tjener, R., Erichsen, A., & Helwigh, B. (2015). A new methodology for modelling of health risk from urban flooding exemplified by cholera - case Dhaka, Bangladesh. *Journal of Flood Risk Management*, 1–15. https://doi.org/10.1111/jfr3.12182

Mcbride, G. B., Stott, R., Miller, W., Bambic, D., & Wuertz, S. (2013). Discharge-based QMRA for estimation of public health risks from exposure to stormwater-borne pathogens in recreational waters in the United States. *Water Research*, *47*(14), 5282–5297. https://doi.org/10.1016/j.watres.2013.06.001

Medema, G., & Ashbolt, N. (2006). *QMRA: Its value for risk management April 2006*. European Commission.

Mills, F., Willetts, J., Petterson, S., Mitchell, C., & Norman, G. (2018). Faecal pathogen flows and their public health risks in urban environments: A proposed approach to inform sanitation planning. *International Journal of Environmental Research and Public Health*, *15*(2), 1–26. https://doi.org/10.3390/ijerph15020181

MOH. 2018. "*Health statistics yearbook of Vietnam*." Ministry of Health.

Mukemo, A., Katumbo, T. T., Sonny, S. J., Sangwa, M. L., Kayinga, M. P., Mulunda, M. O., Numbi, L. O., & Kaj, M. F. (2020). The practice of self-medication in children by their mothers in Lubumbashi, Democratic Republic of Congo. *Journal of Advanced Pediatrics and Child Health*, *3*(1), 27–31. https://doi.org/10.29328/journal.japch.1001014

Murray, C. J. L., & Acharya, A. K. (1997). Understanding DALYs. *Journal of Health Economics*, *16*(6), 703–730. https://doi.org/10.1016/S0167-6296(97)00004-0

Ngaosuwankul, N., Thippornchai, N., Yamashita, A., Morales, R. E., Vargas, W. T., Mahakunkijchareon, Y., Ikuta, K., Singhasivanon, P., Okabayashi, T., & Leaungwutiwong, P. (2013). Detection and characterization of enteric viruses in flood water from the 2011 Thai flood. *Japanese Journal of Infectious Diseases*, *66*(5), 398–403. https://doi.org/10.7883/yoken.66.398

Nguyen, H. Q., Radhakrishnan, M., Huynh, T. T. N., Baino-Salingay, M. L., Ho, L. P., van der Steen, P., & Pathirana, A. (2017). Water quality dynamics of urban water bodies during flooding in Can Tho City, Vietnam. *Water*, *9*(4), 260. https://doi.org/10.3390/w9040260

Nguyen, H. D., Fox, D., Dang, D. K., Pham, L. T., Viet, Q. V., Du, T. H., Nguyen, T., Dang, T. N., Tran, V. T., Vu, P. L., Nguyen, Q.-H., Nguyen, G. T., Bui, Q.-T., & Petrisor, A.-L. (2021). Predicting future urban flood risk using land change and hydraulic modeling in a river watershed in the Central Province of Vietnam. *Remote Sensing*, *13*(2), 1–24. https://doi.org/10.3390/rs13020262

Nguyen, V. M., Nguyen, V. T., Huynh, P. L., Dang, D. T., Nguyen, T. H. T., Phan, V. T., Nguyen, T. L., Le, T. L., Ivanoff, B., Gentsch, J. R., & Glass, R. I; Vietnam Rotavirus Surveillance Network. (2001). The epidemiology and disease burden of rotavirus in Vietnam: Sentinel surveillance at 6 hospitals. *The Journal of Infectious Diseases*, *183*, 1707–1712.

Nichols, G., Lake, I., & Heaviside, C. (2018). Climate change and water-related infectious diseases. *Atmosphere*, *9*(10), 1–60. https://doi.org/10.3390/atmos9100385

Nkwunonwo, U. C., Whitworth, M., & Baily, B. (2020). A review of the current status of flood modelling for urban flood risk management in the developing countries. *Scientific African*, *7*, e00269. https://doi.org/10.1016/j.sciaf.2020.e00269

Kim, O., Thi, N., Phuong, M. T. T., & Permadi, D. A. (2012). Analysis of motorcycle Fleet in Hanoi for estimation of air pollution emission and climate mitigation Co-benefit of technology implementation. *Atmospheric Environment*, *59*, 438–448. https://doi.org/10.1016/j.atmosenv.2012.04.057

Oral, H. V., Carvalho, P., Gajewska, M., Ursino, N., Masi, F., van Hullebusch, E. D., Kazak, J. K., Exposito, A., Cipolletta, G., Andersen, T. R., Finger, D. C., Simperler, L., Regelsberger, M., Rous, V., Radinja, M., Buttiglieri, G., Krzeminski, P., Rizzo, A., Dehghanian, K., … Zimmermann, M. (2020). A review of nature-based solutions for urban water management in European circular cities: A critical assessment based on case studies and literature. *Blue-Green Systems*, *2*(1), 112–136. https://doi.org/10.2166/bgs.2020.932

Pande, A., & Wolshon, B. (2003). *Traffic engineering handbook. Institute of Transportation Engineers* (7th ed.). Wiley. https://doi.org/10.1002/ejoc.201200111

Payment, P., & Locas, A. (2011). Pathogens in water: Value and limits of correlation with microbial indicators. *Ground Water*, *49*(1), 4–11. https://doi.org/10.1111/j.1745-6584.2010.00710.x

Pham, T. M., Thy, V. R., & Pawar, N. J. (2010). Urban expansion of Can Tho City, Vietnam: A study based on multi-temporal satellite Imagies. *Geoinformatics*, *21*(3), 147–160. https://doi.org/10.6010/geoinformatics.21.147

Phung, D., Chu, C., Rutherford, S., Nguyen, H. L. T., Luong, M. A., Do, C. M., & Huang, C. (2017). Heavy rainfall and risk of infectious intestinal diseases in the most populous city in Vietnam. *Science of the Total Environment*, *580*(74), 805–812. https://doi.org/10.1016/j.scitotenv.2016.12.027

Phung, D., Huang, C., Rutherford, S., Chu, C., Wang, X., Nguyen, M., Nguyen, N. H., do Manh, C., & Nguyen, T. H. (2014). Association between climate factors and Diarrhoea in a Mekong Delta area. *International Journal of Biometeorology*, *59*(9), 1321–1331. https://doi.org/10.1007/s00484-014-0942-1

Portier, C. J., Thigpen Tart, K., Grambsch, A. E., Gohlke, J., Hess, J., Howard, S. N., Luber, G., Lutz, J. T., Maslak, T., Prudent, N., Radtke, M., Rosenthal, J. P., Rowles, T., Sandifer, P. A., Scheraga, J., Schramm, P. J., Strickman, D., Trtanj, J. M., & Whung, P.-Y. (2010). *A human health perspective on climate change: A report outlining the research needs on the human health effects of climate change*. Environmental Health Perspectives/National Institute of Environmental Health Sciences. https://doi.org/10.1289/ehp.1002272

Preventive Medical Center in Can Tho. (2016a). Annual report about preventive and health care in Can Tho City, 2013–2016 (in Vietnamese). Can Tho City, Vietnam.

Preventive Medical Center in Can Tho. (2016b). Report about disease cases every month in all districts in Cantho City, 2014–2016 (in Vietnamese) Cantho.

Rahman, M., Ningsheng, C., Mahmud, G. I., Islam, M. M., Pourghasemi, H. R., Ahmad, H., Habumugisha, J. M., Washakh, R. M. A., Alam, M., Liu, E., Han, Z., Ni, H., Shufeng, T., & Dewan, A. (2021). Flooding and its relationship with land cover change, population growth, and road density. *Geoscience Frontiers*, *12*(6), 101224. https://doi.org/10.1016/j.gsf.2021.101224

Sales-Ortells, H., & Medema, G. (2014). Screening-level microbial risk assessment of urban water locations: A tool for prioritization. *Environmental Science & Teachnology*, *48*(16), 9780–9789. https://doi.org/10.1021/es5020407

Sales-Ortells, H., & Medema, G. (2015). Microbial health risks associated with exposure to Stormwater in a water plaza. *Water Research*, *74*, 34–46. https://doi.org/10.1016/j.watres.2015.01.044

Salingay, M. L., van der Steen, P., Pathirana, A., Rijke, J., Quan, N. H., Zevenbergen, C., & Vinh, K. Q. (2014). *Flood-related water quality assessment using water quality sampling and household survey in Can-Tho City, Vietnam* (pp. 1–8). 13th International Conference on Urban Drainage.

Sattar, S. A., Susan Springthorpe, V., & Tetro, J. A. (2018). Rotavirus. In *Foodborne disease handbook: Volume II: Viruses, parasites, pathogens, and HACCP* (Vol. 4, pp. 99–125). CRC Press. https://doi.org/10.1201/9781351072106

Schets, F. M., van Wijnen, J. H., Schijven, J. F., Schoon, H., & Roda Husman, M. (2008). Monitoring of waterborne pathogens in surface Waters in Amsterdam, The Netherlands, and the potential health risk associated with exposure to cryptosporidium and giardia in these Waters. *Applied and Environmental Microbiology*, *74*(7), 2069–2078. https://doi.org/10.1128/AEM.01609-07

Sterk, G., Veldhuis, J., Clemens, F. L. H. R., & Berends, B. R. (2008). Microbial risk assessment for urban pluvial flooding. In *11th international conference on urban drainage* (pp. 1–10). Edinburgh.

Structured Data LLC. (2005). RiskAMP Software, 2005. https://www.riskamp.com/.

Sunger, N., & Haas, C. N. (2015). Quantitative microbial risk assessment for recreational exposure to water bodies in Philadelphia. *Water Environment Research*, *87*(3), 211–222. https://doi.org/10.2175/106143015X14212658613073

Tang, V. T., Oanh, N. T. K., Rene, E. R., & Binh, T. N. (2020). Analysis of roadside air pollutant concentrations and potential health risk of exposure in Hanoi, Vietnam. *Journal of Environmental Science and Health – Part A Toxic/Hazardous Substances and Environmental Engineering*, *55*(8), 975–988. https://doi.org/10.1080/10934529.2020.1763091

Teunis, P. F. M., & Havelaar, A. H. (2000). The beta poisson dose-response model is not a single-hit model. *Risk Analysis*, *20*(4), 513–520.

Teunis, P. F. M., Heijden, O. G., Giessen, J. W. B., & Havelaar, H. (1996). The dose-response relation in human volunteers for gastro-intestinal pathogens. RIVM (National Institute of Public Health and the Environment).

Teunis, Peter, and Jack F. Schijven. 2017. *Generic guidance to quantitative microbial risk assessment for food and water.* RIVM (National Institute of Public Health and the Environment).

Thompson, C. N., Phan, M. V. T., Hoang, N. V. M., Minh, P. V., Vinh, N. T., Thuy, C. T., Nga, T. T. T., Rabaa, M. A., Duy, P. T., Dung, T. T. N., Phat, V. V., Nga, T. V. T., Phuong Tu, L. T., Tuyen, H. T., Yoshihara, K., Jenkins, C., Duong, V. T., Le Phuc, H., Tuyet, P. T. N., … Baker, S. (2015). A prospective multi-center observational study of children hospitalized with diarrhea in Ho Chi Minh City, Vietnam. *American Journal of Tropical Medicine and Hygiene*, *92*(5), 1045–1052. https://doi.org/10.4269/ajtmh.14-0655

Timm, C., Luther, S., Jurzik, L., Hamza, I. A., & Kistemann, T. (2016). Applying QMRA and DALY to assess health risks from river bathing. *International Journal of Hygiene and Environmental Health*, *219*(7), 681–692. https://doi.org/10.1016/j.ijheh.2016.07.017

UN. (2018). 68% of the world population projected to live in urban areas by 2050, Says UN. United Nations. 2018. https://www.un.org/development/desa/en/news/population/2018-revision-of-world-urbanization-prospects.html.

van Aalst, M. K. (2006). The impacts of climate change on the risk of natural disasters. *Disasters*, *30*(1), 5–18. https://doi.org/10.1111/j.1467-9523.2006.00303.x

Veldhuis, J. A. E., Clemens, F. H. L. R., Sterk, G., & Berends, B. R. (2010). Microbial risks associated with exposure to pathogens in contaminated urban flood water. *Water Research*, *44*(9), 2910–2918. https://doi.org/10.1016/j.watres.2010.02.009

Ward, R. L., Bernstein, D. I., Young, E. C., Sherwood, J. R., Knowlton, D. R., & Schiff, G. M. (1986). Human rotavirus studies in volunteers: Determination of infectious dose and serological response to infection. *Journal of Infectious Diseases*, *154*(5), 871–880. https://doi.org/10.1093/infdis/154.5.871

Waters, R. L., Hislop, H. J., Thomas, L., & Campbell, J. (1983). Energy cost of walking in Normal children and teenagers. *Developmental Medicine & Child Neurology*, *25*(2), 184–188. https://doi.org/10.1111/j.1469-8749.1983.tb13742.x

WHO. (2003). WHO–Guidelines for safe recreational water environments. Volume 1. http://www.who.int/water_sanitation_health/bathing/srwe1/en/.

WHO. (2016). *Quantitative microbial risk assessment: Application for water safety management*. WHO Press.

WHO. (2017). *Flooding: Managing health risks*. WHO Press. http://www.euro.who.int/en/publications/abstracts/flooding-managing-health-risks-in-the-who-european-region-2017.

Yapo, R. I., Koné, B., Bonfoh, B., Cissé, G., Zinsstag, J., & Nguyen-Viet, H. (2013). Quantitative microbial risk assessment related to urban wastewater and lagoon water reuse in Abidjan, Côte D'ivoire. *Journal of Water and Health*, *12*(2), 301–309. https://doi.org/10.2166/wh.2013.051

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

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