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Huynh Thi Thao Nguyen

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DISSERTATION

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by

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Dedicated to the affected people in the flooding who inspired me to keep moving in this research

‘Connaître, découvrir, communiquer – telle est, au fond, notre honorable destinée.

To know, to discover, to publish—this is the destiny of a scientist.’

— François Arago, (1855) as quoted in ‘De L’Utiliteé des Pensions’, oeuvres complètes of François Arago (1855), Vol. 3, 621.

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SUMMARY

Urban areas are experiencing an increase in the frequency of flooding incidents, posing a significant threat to public health. This is primarily due to the potential presence and dissemination of microbial pollutants within the urban floodwater. Even minimal exposure or ingestion of floodwater can lead to an increased risk of infection for individuals. However, estimating the associated health risks related to microbial pathogens in floodwater is a complex undertaking, hindered by factors such as the intricate nature of the microorganisms involved and the susceptibility of those exposed to them. To address these challenges and contribute to the existing knowledge, this research aims to fill the following critical research gaps:

- One significant research gap in the field is the variability of pollutants found in floodwater, which is influenced by the source and location of the flood. In urban areas, flooding can occur due to fluvial or pluvial flooding or even a combination of them. However, there is a lack of studies on flood risk associated with health impacts (via floodwater when merged with sewer water and/or surface water). Microbial pathogens in floodwater are highly related to sources of contamination such as sewer water or household waste, but the evidence on the association between contamination sources and cause-specific microbial pathogens is limited. In addition, there is a lack of standardization in the methods used to identify microbial concentration in floodwater, making it challenging to compare results and accurately estimate health risks. For example, instead of using measured concentrations, the concentrations of pathogens are calculated on the referenced ratio between pathogens and indicator (i.e., *E. coli)*, which is easier to measure. However, the associations and the ratio may be different from case to case. These challenges underscore the need for further research and improvement in monitoring and testing methods to better understand the microbial health impact of urban waters. It is essential to have more observational evidence of enteric pathogens by analyzing pathogen concentrations in flood-related waters.
- To successfully incorporate health risk with flood risk, multi-hazard or integrated risk assessments must account for both the physical and health implications of floods. Due to variability in exposure patterns and differences in susceptibility among populations such as children, adults, and individuals with compromised immune systems, determining the natural relationship between microorganisms in urban waters and health risk (i.e., infection risk and illness risk) is difficult. Furthermore, health outcomes incorporate not just the influence on a single person but also the exposure of a community. This can make determining the best technique and measure to assess the health effects of those who have been exposed more complex. However, there is a paucity of methods for developing

scientifically valid estimations of the microbiological health effect of floodwater. During floods, regular transportation activities in urban areas, such as motorbikes, can increase the risk of direct contact with polluted water, particularly in low- to middle-income nations (LMICs). This emphasizes the need of combining traffic patterns and circumstances into flood risk assessments to predict possible microbial pathogen health concerns and inform appropriate response and mitigation methods. However, there is no obvious way to locate and adjust criteria to reflect vulnerability or information about people's exposure to floodwater.

- Estimating the microbiological health risk associated with floodwater may be a difficult undertaking. The intricacy stems from the transient nature of floodwater quality. Flood waters are distinguished by their complicated water dynamics, which are reflected in differences in water levels and pollutant content. Although certain data from water sampling can offer information on pathogens of relevance, the volume and geographical distribution of enteric pathogens in urban floodwater are difficult to estimate without computer models. Monitoring microbiological contaminants is very difficult since it necessitates specialized equipment, proper facilities, safety considerations, and trained workers. As a result, computer models of urban drainage, such as flood mathematical models that employ advection-diffusion equations to describe the propagation of estimated water quality, are an essential tool for addressing the issues of missing data in health risk assessment. As a result, conceptual formulations for pollutant movement and concentrations are developed. However, little research has looked into the prevalence of enteric pathogens in flooding in real-time.

- Health impact formulations that incorporate such methods are not generally accessible and are not designed to consider people's inherent socioeconomic vulnerability in underdeveloped nations. While urban and urban floodwater models are commonly utilized, linking floods, microbiological risks, health consequences, and susceptibility to predict health risk is seldom done. Overall, the complexities of calculating the likelihood and measuring the health effects caused by microbial pathogens in floodwater can have a major influence on flood risk estimates. Risk estimation necessitates the use of real-time monitoring data, expert knowledge, computer models, and a complete understanding of the complex and dynamic nature of water quality in floods.

- Furthermore, in flood risk management (FRM), the indirect intangible impact of health consequences related to microbial pathogens is understudied in concepts like vulnerability or exposure. Health is an indicator of social vulnerability in flood vulnerability assessments. However, the health consequences of adverse factors influenced by floods, such as microbial pathogens in floodwater have been less considered. A better understanding of the vulnerability of exposed communities such as how flooding impacts and creates loss of people’s well-being can bring about a socially fair approach to prioritising investment in FRM.

However, an approach to include the quantitative health impact during and after flooding in flood vulnerability assessment is still lacking.

Therefore, this study aims to develop a combined framework that helps assess both microbial hazards in floodwater and the vulnerability of exposed people using a combined approach to formulate a microbial health risk assessment. The methodology in this study consisted of three main components: (1) analyze microbial pathogens in flood-related waters, (2) formulate a framework of microbial health risks related to traffic activities with observed concentrations, (3) analyze a combined framework that helps to assess vulnerability and flood risk in one concept with supporting of the hydrodynamic model.

The study considered traffic activity, which is a common factor of exposure during floods, especially in developing countries. The case study was conducted in Ninh Kieu District in Can Tho City (Vietnam) located on the western side of the Hau River, a Mekong tributary. This urban area experiences annually flooding due to heavy rain, high sea level, and flows from upstream regions. Floodwater is polluted, especially with microbial pathogens such as *E. coli*. Motorcyclists, cyclists, adult pedestrians, and child pedestrians often find themselves in flooded streets. However, the consequences for microbial health have not yet been fully considered in this area. The following part summarises the methodology, the results, and the contributions of the findings corresponding to each gap mentioned above.

First, this study investigated floodwater contamination in Ninh Kieu to analyze the microbial concentration. Water samples from sewers, surface water bodies, and floodwater were taken before, during, and after specific flooding events. Total nucleic acid was extracted from the samples and subjected to a quantitative polymerase chain reaction (qPCR) to detect specific enteric pathogens. The difference between pathogen concentrations in floodwater and sewer water was compared using the Mann-Whitney U test. Correlations between the different pathogens were determined using the nonparametric Spearman test. The study found that the floodwater in Ninh Kieu was contaminated with fecal pollution comprising *E. coli* and rotavirus A, most probably originating from sewer water. The quality of floodwater did not show any difference from the quality of the sewer water in terms of *E. coli* and Rotavirus A concentrations ($p>0.05$, Mann Whitney U test). The *E. coli* concentration was 2 to 4 log10 higher than the Vietnamese surface water quality standard (QCVN 08:2015/BTNMT) and the European bathing standard (Directive 2006/7/EC of the European Parliament) (European Parliament, 2006). Furthermore, the study observed a weak association between *E. coli* and rotavirus A, also among other pathogens of interest in flood-related waters ($r<0.5$, non-parametric Spearman test). Our findings provide evidence of the presence of enteric pathogens in floodwater in the case study, which represents a hazard to human health during the flood period. These findings stressed the importance of using the relationship between *E. coli* and other microbial pathogens in calculating health risks related to pathogens in floodwater (Huynh *et al.*, 2020).

Second, the study applied a quantitative microbial risk assessment (QMRA) that proposes the inclusion of exposure to traffic due to rotavirus in floodwater. Furthermore, the burden of the disease was expressed in disability-adjusted life years (DALY). The exposed groups were pedestrians (children and adults), motorcyclists, and cyclists. The number of people exposed on the streets was estimated for one street using video footage to monitor traffic. Then it was extrapolated to other streets. The scale factor for the traffic density was assumed to represent the difference in the density of exposed people between the streets. A street with a larger width was supposed to have more crowded people than others. Furthermore, the nominal range sensitivity analysis (NRSA) method was used to assess the variability of the results due to changes in the input parameters and variables. To determine the uncertainty of which parameter is more important than the others, the study used the Spearman test to find the correlation coefficient (rho) between the input (that is, intake volume, concentration, flood length) and the output (that is, infection risk). The study found that the average probability of infection due to rotavirus was highest for children walking with 0.98 followed by adult walking and cyclists, then motorcyclists with 0.97 and 0.96, respectively. Motorcyclists are the largest contributor to the DALYs (95%), followed by cyclists (2.8%), adult pedestrians (2%), and child pedestrians (0.2%). Therefore, a large number of motorcyclists during flood time increase the disease burden due to microbial pathogens in floodwater. The total DALYs per flood event for all exposure groups were $1.35x10^4$ for 63,390 exposed people (that is, 2,129 DALYs per 10,000 cases) (Huynh *et al.*, 2019a, 2019b, 2023). Our result exceeded by 4 log10 – 5 log10 of the tolerable burden of disease related to drinking water according to WHO (0.1-0.01 DALY/10,000 people 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. The infection risk was most sensitive to the concentration of rotavirus. The burden of the disease showed high sensitivity to flooded areas and concentration (Huynh *et al.*, 2022a).

Third, flood modeling and floodwater quality modeling were developed to simulate the microbial concentrations and identify the spatial distribution in floodwater by one-dimensional hydrodynamic (SWMM) and two-dimensional hydrodynamic (PCSWMM) models. It showed that the calibrated water quality model was appropriate to simulate microbial pathogens in floodwater. The average values of the (maximum) simulated concentrations of *E. coli* and rotavirus A from the floodwater quality model were similar to the average measured concentration with magnitudes of 4 log10 and 8 log10, respectively. The range of simulated rotavirus concentrations ranged from 1.01E+01 - 7.18E+08 gc/L (genome of copies/liter) in flooded areas. The simulated concentration of *E. coli* in floodwater showed 1-2 log10 higher than the Vietnamese surface water quality standard and the European bathing water quality for inland water (Directive 2006/7/EC). The simulated concentration of rotavirus A in floodwater was 3 – 4 log10 higher than the river water or domestic wastewater referenced in the literature review. The largest spatial area (94.5% and 92% of the flood areas, respectively) was with *E. coli* and RVA concentrations ranging from 1E +04 – 1E+06 (CFU/liter) and 1E+06 – 1E+08 (gc/liter),

respectively. The high concentration of pathogens in floodwater was found in the inner areas with many activities of residents that coincide with flooding time. Meanwhile, the lower concentrations were in the surrounding areas near large rivers. The simulated results explained the transport and concentrations of microbial pathogens in urban floodwater in the case study, which are essential for identifying the priority areas with higher risk and helping plan the measurements to reduce risk. The finding contributes to the knowledge of simulating enteric pathogens in floodwater, which is essential to estimate health risks in flood risk management but is rarely considered (Huynh *et al.*, 2021).

Fourth, the study represented a new approach to quantifying waterborne-related health risks through traffic exposure. The study incorporates traffic conditions such as traffic density, vehicle speed, and duration of exposure through the flooded areas considered to assess microbial health risk assessment in flood analysis. The study quantified the probability of infection and disease burden at each flooded grid cell based on the simulated concentrations and the people exposed people in this grid cell. The number of DALYs per grid was calculated by multiplying the base DALYs per case by the number of illness cases per grid for each exposed group. The total DALYs per flood event were the sum of the DALYs for each exposed group in all flooded cells. The calculation was applied to flooded grid cells using QGIS 3.22.7. The results show that the average infection probability for motorcyclists, cyclists, adult pedestrians, and child pedestrians was 0.7, 0.69, 0.61, and 0.64, respectively. This infection probability was calculated using simulated concentrations and was 1.5 times lower than the measured concentrations. It indicated that the mean measured concentrations may lead to an overestimation of the infection risk compared to the average simulated concentrations. Motorcyclists contributed the highest disease burden to total DALYs (34,161, 95%), followed by cyclists (989, 2.8%), adult pedestrians (609, 1.7%), and child pedestrians (36, 0.5%). The burden of disease due to RVA in floodwater was 35,795 DALY for 230,538 exposed people in four groups exposed groups (i.e., 1,552 DALY per 10,000 cases). It means that the DALYs calculated by simulated concentrations were 3,5 times higher than the DALYs calculated by measured concentrations (Huynh *et al.*, 2022b). The areas with a higher risk of infection and DALYs were located at higher concentrations and people density, such as schools and markets in the case study. The results indicated that the advanced approach in using the hydrodynamic model provides quantitative data on the microbial pathogens and the exposed people required to calculate the microbial health consequences. Including the spatial distribution of health risks can help to establish a more comprehensive picture of high-priority areas of health risks in flood events. The population in Ninh Kieu District may suffer from waterborne diseases due to rotavirus A through traffic activities during the flood season, especially motorcyclists.

The results of this study can be used separately as quantitative health outcomes to identify the impact of microbial pathogens on floodwater for a specific flood event. Results can also be integrated into flood risk management to measure microbial health as an outcome

of the bearable objective of social sustainability. The potential metric for quantifying microbial health outcomes was considered for the first time. The research applied the disease burden (with DALY) as the variable of the health indicator to represent the social dimension in the assessment of flood vulnerability. The approach was used to identify the vulnerability related to the health perspective of ten wards in the Ninh Kieu district. This study is the first to examine the level of flood vulnerability, including microbial health consequences, by (1) quantifying the burden of disease caused by microbial pathogens in floodwater through traffic activities and (2) identifying flood vulnerability areas with health effects. The variables to determine the level of flood vulnerability were the density of people and disease burden with DALYs (social dimension), the number of low-income households (economic dimension), and the number of pharmacy stores, and hospitals (medical services) for ten wards of Ninh Kieu district (Can Tho, Vietnam). The highly vulnerable areas comprised the inner city which was mainly assigned to low-income households, lacking medical services, and some were caused by a high burden of disease and population density, while lower vulnerability areas were close to rivers. The findings can help to emphasize the importance of the management of the environment and public health. For the first time, the indirect intangible impact of the health perspective was quantified for people exposed to microbial pathogens in floodwater through traffic activities. The burden of the disease with DALY indicated the health consequences for affected people. The evaluation of health risks, the estimation of disease burden, and the hydrodynamic model were combined to estimate the adverse health consequences of microbial pathogens in floodwater. The study developed a framework and application to transform *pollution data (microbial concentration in floodwater)* into *related disease data useful for DALY* calculations for traffic exposure. The research involved an evaluation of traffic exposure to collect quantitative data on exposed people to quantify microbial health outcomes. Additionally, the study highlighted the support of the hydrodynamic model in simulating the microbial concentration and developing a new approach to assess microbial health risks through traffic exposure in urban flooding.

In general, the research highlights the health risk due to rotavirus A in the floodwater in Ninh Kieu district through traffic activities. The study contributes to the new methodology to combine health risk and flood risk, especially the indirect/intangible impacts caused by the adverse factor of flooding. The study included the parameters related to exposure and vulnerability of local Vietnamese people to calculate the health risk and quantify the burden of the disease. Furthermore, the study developed an approach to estimate the health risks of people exposed due to enteric pathogen concentrations from observed and simulated data which can improve the assessment of health risks (i.e., infection probability and DALY) in a flood event. The study emphasizes the importance of considering the input parameter concentrations, and the number of exposed people to reduce the health impact of flood risk. It resulted in the notion that mitigation measures should not only focus on reducing urban floods but also on raising awareness of the local people of the risk of microbial concentrations in floodwater. In future research, the health

risk and disease burden can be updated when further data about pollution sources, exposure pathways, and future scenarios with climate change and population growth. Some potential interventions related to sensitivity parameters, such as microbial concentrations and flooded areas, can be invested to reduce microbial health risks. Residents and the local government should be aware of the microbial risk during the flood season. Furthermore, the annual burden can be estimated by DALYs to provide quantitative data on health damage due to adverse consequences for flood risk management.

SAMENVATTING

Overstromingen komen de laatste tijd steeds vaker voor in stedelijke gebieden. Stedelijk overstromingswater kan een ernstig risico vormen voor de volksgezondheid, aangezien het microbiële verontreinigende stoffen kan bevatten en verspreiden. Mensen lopen een infectierisico door zelfs maar een kleine hoeveelheid overstromingswater in te nemen wanneer ze in direct/indirect contact komen met overstromingswater. Het inschatten van de gezondheidsrisico's van microbiële ziekteverwekkers in overstromingswater is complex vanwege verschillende factoren, zoals de detectie van potential aanwezige micro-organismen en de bepaling van de kwetsbaarheid van mensen die aan dergelijke micro-organismen kunnen worden blootgesteld.

Ten eerste is de variabiliteit van verontreinigende stoffen in overstromingswater afhankelijk van de bron en locatie van de overstroming. In stedelijke gebieden kunnen overstromingen optreden als gevolg van rivierwater dat buiten de oevers treedt- of door hevige regenval of zelfs een combinatie van beide. Er is een gebrek aan kennis over gezondheidsrisico's die samenhangen met overstromingen (bijvoorbeeld door overstromingswater, rioolwater, oppervlaktewater). Microbiële ziekteverwekkers in overstromingswater zijn sterk gerelateerd aan besmettingsbronnen zoals rioolwater of huishoudelijk afval, maar het bewijs voor het verband tussen besmettingsbronnen en oorzaak-specifieke microbiële ziekteverwekkers is beperkt en niet vooralsnog niet eenduidig. Bovendien is er een gebrek aan standaardisatie van de methoden die worden gebruikt voor het identificeren van microbiële concentraties in overstromingswater. Dit bemoeilijkt het vergelijken van de onderzoeksresultaten om de gezondheidsrisico's nauwkeurig in te schatten. In plaats van gemeten concentraties te gebruiken, worden de concentraties van ziekteverwekkers bijvoorbeeld berekend op basis van de verhouding tussen ziekteverwekkers en een indicator (bijvoorbeeld *E. coli*), die gemakkelijker te meten is. Dezeverhouding kan echter van geval tot geval verschillen. De genoemde uitdagingen onderstrepen de noodzaak van verder onderzoek en verbetering van monitoring- en testmethoden om de microbiële gezondheidseffecten van stedelijk water beter te begrijpen. Het is essentieel om meer onderzoek te doen naar de risico's van darmpathogenen door pathogeenconcentraties in overstromingsgerelateerde wateren te analyseren.

Ten tweede is hetbelangrijk om rekening te houden met zowel de fysieke als de gezondheidseffecten van overstromingen door middel van multi-hazard of geïntegreerde risicobeoordelingen. Het is moeilijk om de relatie tussen micro-organismen in stedelijke wateren en het gezondheidsrisico (d.w.z. infectierisico en ziekterisico) te bepalen vanwege de variabiliteit in blootstellingspatronen en verschillen in gevoeligheid tussen populaties zoals kinderen, volwassenen of personen met een gecompromitteerd immuunsysteem. Bovendien gaan de gezondheidsresultaten niet alleen over de risico's voor één individu, maar over de blootstellingsgemeenschap. Dit vormt een uitdaging om de juiste benadering en maatstaf te handteren om de gezondheidsresultaten van blootgestelde mensen te kwantificeren. Tot dusver ontbreekt het aan een methodologie om wetenschappelijk verdedigbare schattingen te kunnen maken van de microbiële gezondheidseffecten van overstromingswater. In stedelijke gebieden zijn het de verkeersactiviteiten tijdens overstromingen, zoals motorfietsen, die de kans op directe blootstelling aan verontreinigd water kunnen vergroten, vooral in lage- tot middeninkomenslanden (LMICs). Dit benadrukt het belang van het opnemen van verkeerspatronen en -omstandigheden in de beoordelingen van overstromingsrisico's, om de potentiële gezondheidsrisico's in verband met microbiële ziekteverwekkers in te schatten en effectieve respons- en beperkingsstrategieën te ontwikkelen. Eris echter geen eenduidige manier om parameters te identificeren die gebruikt kunnen worden om de blootstelling van mensen aan overstromingswater door het verkeer te bepalen

Ten derde is het inschatten van het microbiële gezondheidsrisico van overstromingswater een complexe taak. De complexiteit komt voort uit de dynamische aard van de waterkwaliteit bij overstromingen. Overstromingen worden gekenmerkt door hun dynamisch karakter, weerspiegeld in het verschil in waterstanden, diffusie van verontreinigende stoffen en concentraties. De omvang en ruimtelijke verspreiding van darmpathogenen in stedelijk overstromingswater is om deze reden niet eenvoudig te bepalen zonder computermodellen. Bovendien vraagt het monitoren van microbiële verontreinigende stoffen gespecialiseerde apparatuur, en dus geschikte laboratoria, en opgeleid personeel. Daarom zijn computermodellen van stedelijke afwatering een belangrijk hulpmiddel om de uitdagingen van ontbrekende gegevens bij de beoordeling van gezondheidsrisico's aan te pakken. Wiskundige modellen van overstromingen gebruiken advectie-diffusievergelijkingen om de voortplanting van geschatte waterkwaliteit weer te geven. Het is dus mogelijk om f transport en concentraties van verontreinigende stoffen in te schatten middels deze modellen Er zijn echter maar weinig studies die de real-time aanwezigheid van darmpathogenen in overstromingswater hebben onderzocht.

Ten vierde zijn de formules voor het bepalen van deze gezondheidseffecten niet ontworpen voor de specifieke context van ontwikkelingslanden. Hoewel modellering van stedelijk en stedelijk overstromingswater met succes en op grote schaal wordt toegepast, wordt het verband tussen overstromingen, microbiële bedreigingen, de gevolgen voor de gezondheid en de kwetsbaarheid om het gezondheidsrisico in te schatten zelden onderzocht. De inschatting van het risico vereist een combinatie van gegevens uit de real-time monitoring, deskundige kennis, rekenmodellen en een grondig begrip van de complexe en dynamische aard van de waterkwaliteit bij overstromingen.

Bovendien wordt bij het beheer van overstromingsrisico's de indirecte en immateriële impact van gezondheidsgevolgen door microbiële pathogenen onvoldoende bestudeerd. Gezondheid is een indicator van sociale kwetsbaarheid bij de beoordeling van de kwetsbaarheid voor overstromingen. Er wordt echter minder rekening gehouden met de gevolgen voor de gezondheid als gevolg van ongunstige factoren die worden beïnvloed door overstromingen, zoals microbiële ziekteverwekkers in overstromingswater. Een beter begrip van de kwetsbaarheid van blootgestelde gemeenschappen, zoals hoe overstromingen het welzijn van mensen beïnvloeden en veroorzaken, kan leiden tot een sociaal rechtvaardige benadering om prioriteit te geven aan investeringen in ORB. Het ontbreekt echter aan een aanpak om de kwantitatieve gezondheidseffecten tijdens en na overstromingen te betrekken bij de beoordeling van de kwetsbaarheid voor overstromingen.

Daarom heeft deze studie tot doel een gecombineerd raamwerk te ontwikkelen dat helpt bij het beoordelen van de microbiële risico's van zowel het overstromingswater en als de kwetsbaarheid van blootgestelde mensen. De methodologie in deze studie bestaat uit drie hoofdcomponenten: (1) analyse van de microbiële ziekteverwekkers in overstromingsgerelateerde wateren, (2) formulering van een microbieel gezondheidsrisicokader gerelateerd aan verkeersactiviteiten met waargenomen concentraties (3) analyse van een gecombineerd raamwerk dat helpt bij het beoordelen van de kwetsbaarheid en het overstromingsrisico in één concept met ondersteuning van een hydrodynamische model.

De studie richtte zich op verkeersactiviteiten, die ook tijdens overstromingen plaatsvinden vooral in ontwikkelingslanden. De casestudy was in het Ninh Kieu-district in de stad Can Tho (Vietnam), gelegen aan de westelijke kant van de rivier de Hau, een zijrivier van de Mekong. Dit stedelijke gebied krijgt jaarlijks te maken met overstromingen als gevolg van hevige regenval, hoge zeespiegel en rivierwater van stroomopwaarts gelegen gebieden. Dit overstromingswater is vervuild, vooral met microbiële ziekteverwekkers zoals E. coli. Motorrijders, fietsers, volwassen voetgangers en kindervoetgangers komen vaak overstroomde straten tegen. De gevolgen hiervan voor de microbiële gezondheid zijn nog weinig onderzocht. Het volgende deel geeft een samenvatting van de methodologie ende resultaten

Ten eerste is in dit onderzoek gekeken naar de microbiele verontreinigingen van het overstromingswater in Ninh Kieu. Watermonsters van riolen, oppervlaktewaterlichamen en overstromingswater werden genomen voor, tijdens en na specifieke overstromingen. Totaal nucleïnezuur werd uit de monsters geëxtraheerd en onderworpen aan een kwantitatieve polymerasekettingreactie (qPCR) om specifieke darmpathogenen te detecteren. Het verschil tussen de ziekteverwekkerconcentraties in het overstromingswater en rioolwater werd vergeleken met behulp van de Mann-Whitney U-test. Correlaties tussen de verschillende pathogenen werden bepaald met behulp van de niet-parametrische Spearman-test. Uit de studie bleek dat het overstromingswater in Ninh Kieu vervuild is met met E. coli en rotavirus A, die hoogstwaarschijnlijk afkomstig was van rioolwater. De kwaliteit van het overstromingswater vertoonde geen verschil met de kwaliteit van het rioolwater voor E. coli- en Rotavirus A-concentraties ($p>0,05$, Mann Whitney U-test). De concentratie E. coli was 2 tot 4 log10 hoger dan de Vietnamese kwaliteitsnorm voor oppervlaktewater (QCVN 08:2015/BTNMT) en de Europese zwemnorm (Richtlijn 2006/7/EG van het Europees Parlement). Bovendien werd een zwak verband waargenomen tussen E. coli en rotavirus A, en ook tussen andere pathogenen die van belang zijn in overstromingsgerelateerde wateren (r<0,5, niet-parametrische Spearman-test). Onze bevindingen toonden aan dat darmpathogenen in overstromingswater in de casestudy een risico vormen voor de menselijke gezondheid tijdens de overstromingsperiode. De resultaten ondersteunden de aanname dat het toepassen vande verhouding tussen E. coli en andere microbiële ziekteverwekkers bij de berekening van de gezondheidsrisico's van ziekteverwekkers in overstromingswater zinvol is (Huynh *et al.*, 2020).

Ten tweede paste de studie een kwantitatieve microbiële risicobeoordeling (QMRA) toe om de blootstelling aan verkeer als gevolg van rotavirus in overstromingswater te bepalen. Daarnaast werd de ziektelast uitgedrukt in voor een individu gecorrigeerde levensjaren (DALY). De blootgestelde groepen waren voetgangers (kinderen en volwassenen), motorrijders en fietsers. Het aantal blootgestelde mensen op straat werd geschat voor één straat door middel van videobeelden waarmee het verkeer werd gevolgd. Vervolgens werd het geëxtrapoleerd naar andere straten. Voor de schaalfactor voor de verkeersdichtheid is het verschil genomen in dichtheid van blootgestelde mensen tussen de straten. Een straat met een grotere breedte zou meer mensen kunnen accomoderen dan een met smallere straten. Bovendien werd de methode voor nominale bereikgevoeligheidsanalyse (NRSA) gebruikt om de variabiliteit van de resultaten te beoordelen als gevolg van veranderingen in de invoerparameters en variabelen. Om de associatie tussen de ziekteverwekkers van overstromingsgerelateerde wateren te bepalen, wordt de Spearman-test gebruikt om de correlatiecoëfficiënt (rho) tussen de *E. coli*-concentratie en andere ziekteverwekkerconcentraties te vinden. Uit de studie bleek dat de gemiddelde infectiekans door rotavirus het hoogst was voor kindervoetgangers met 0,98, gevolgd door volwassen voetgangers en fietsers, en vervolgens motorrijders met respectievelijk 0,97 en 0,96. Motorrijders leveren de grootste bijdrage aan de DALY (95%), gevolgd door fietsers (2,8%), volwassen voetgangers (2%) en kindervoetgangers (0,2%). Zo verhoogt een groot aantal motorrijders tijdens overstromingstijd de ziektelast door microbiële ziekteverwekkers in overstromingswater. Het totale aantal DALY's per overstroming voor alle blootstellingsgroepen was 1,35 x 104 voor 63.390 blootgestelde mensen (d.w.z. 2.129 DALY per 10.000 gevallen) (Huynh *et al.*, 2019a, 2019b, 2023). Ons resultaat overtrof met 4 log10 – 5 log10 de aanvaardbare ziektelast gerelateerd aan het drinkwater volgens de WHO (0,1-0,01 DALY/10.000 per jaar) (WHO 2003). Aangezien we de DALY per overstroming hebben berekend, kunnen de DALY voor mensen die meer dan eens per jaar worden blootgesteld aan overstromingswater hoger zijn dan deze norm. Het infectierisico was het meest gevoelig voor de concentratie rotavirus. De ziektelast vertoonde een hoge gevoeligheid voor overstroomde gebieden en concentratie (Huynh *et al.*, 2022a).

Ten derde werden overstromingsmodellering en overstromingswater kwaliteits modellering ontwikkeld om de microbiële concentraties te simuleren en de ruimtelijke verdeling in overstromingswater te identificeren door middel van eendimensionale

(SWMM) en tweedimensionale (PCSWMM) hydrodynamische modellen. Het toonde aan dat het gekalibreerde waterkwaliteitsmodel geschikt was om de microbiële ziekteverwekkers in overstromingswater te simuleren. De gemiddelde waarden van (maximale) gesimuleerde concentraties van *E. coli* en rotavirus A uit het overstroming waterkwaliteitsmodel waren vergelijkbaar met de gemiddeld gemeten concentratie met respectievelijk 4 log10 en 8 log10 magnitudes. Het bereik van gesimuleerde rotavirusconcentraties was van 1,01E+01 - 7,18E+08 gc/L (genoom van kopieën/liter) in overstroomde gebieden. De gesimuleerde concentratie van E. coli in overstromingswater bleek 1-2 log10 hoger te zijn dan de Vietnamese kwaliteitsnorm voor oppervlaktewater en de Europese zwemwaterkwaliteit voor binnenwater (Richtlijn 2006/7/EG). De gesimuleerde concentratie rotavirus A in overstromingswater was 3 – 4 log10 hoger dan het rivierwater of huishoudelijk afvalwater waarnaar wordt verwezen in het literatuuronderzoek. Het grootste ruimtelijke gebied (respectievelijk 94,5% en 92% van de overstroomde gebieden) was met E. coli en de RVA-concentratie varieerde van 1E + 04 – 1E+06 (CFU/liter) en 1E+06 – 1E+08 (gc/liter), respectievelijk. De hoge concentratie ziekteverwekkers in overstromingswater bevond zich in de binnengebieden met veel activiteiten van bewoners die samenvallen met de overstromingstijd. Ondertussen concentreerden de lagere concentraties zich op omliggende gebieden in de buurt van grote rivieren. De gesimuleerde resultaten verklaarden het transport en de concentraties van microbiële ziekteverwekkers in stedelijk overstromingswater in de casestudy, die essentieel zijn voor het identificeren van de prioritaire gebieden met een hoger risico en het helpen plannen van de metingen om het risico te verminderen. De bevinding draagt bij aan de kennis van het simuleren van darmpathogenen in overstromingswater, wat essentieel is voor het inschatten van de gezondheidsrisico's bij overstromingsrisicobeheer (Huynh et al., 2021).

Ten vierde vertegenwoordigde de studie een nieuwe benadering voor het kwantificeren van het door water veroorzaakte gezondheidsrisico door blootstelling aan het verkeer, dat niet volledig is weergegeven bij overstromingen met de ondersteuning van het hydrodynamische model. De studie omvat verkeersomstandigheden zoals verkeersdichtheid, de snelheid van voertuigen en de blootstellingsduur door de overstroomde gebieden die werden overwogen om de microbiële gezondheidsrisicobeoordeling bij overstromingsanalyse te beoordelen. De studie kwantificeerde de infectiekans en ziektelast bij elke overstroomde gridcel op basis van de gesimuleerde concentraties en blootgestelde mensen in deze gridcel. Het aantal DALY per grid werd berekend door de basis DALY per case te vermenigvuldigen met het aantal ziektegevallen per grid voor elke blootgestelde groep. De totale DALY per overstroming was de som van DALY voor elke blootgestelde groep in alle overstroomde cellen. De berekening werd toegepast op overstroomde rastercellen door QGIS 3.22.7. Uit de resultaten blijkt dat de gemiddelde infectiekans voor motorrijders, fietsers, volwassen voetgangers en kindervoetgangers respectievelijk 0,7, 0,69, 0,61 en 0,64 was. Deze infectiekans werd berekend door gesimuleerde concentraties en was 1,5 keer lager dan de gemeten concentraties. Het gaf aan dat de gemiddeld gemeten concentraties kunnen leiden tot een overschatting van het infectierisico ten opzichte van de gemiddelde gesimuleerde concentraties. De motorrijders droegen de hoogste ziektelast bij aan de totale DALY (34.161, 95%), gevolgd door fietsers (989, 2,8%), volwassen voetgangers (609, 1,7%) en kindervoetgangers (36, 0,5%). De ziektelast door RVA in overstromingswater was 35.795 DALY voor 230.538 blootgestelde mensen in vier blootgestelde groepen (d.w.z. 1.552 DALY per 10.000 gevallen). Dit betekent dat DALY berekend op basis van gesimuleerde concentraties 3,5 keer hoger waren dan de DALY berekend op basis van gemeten concentraties (Huynh et al., 2022b). De gebieden met een hoger infectierisico en DALY bevonden zich in hogere concentraties en bevolkingsdichtheid, zoals scholen en markten in de casus. De resultaten wezen op de geavanceerde aanpak bij het gebruik van het hydrodynamische model om kwantitatieve gegevens te verstrekken voor microbiële pathogenen en blootgestelde mensen voor het berekenen van de gevolgen voor de gezondheid van microben. Het opnemen van ruimtelijke spreiding van gezondheidsrisico's kan helpen om een vollediger beeld te krijgen van de gezondheidsrisico's met hoge prioriteit bij overstromingen. De bevolking in het Ninh Kieu-district kan tijdens het overstromingsseizoen last krijgen van door water overgedragen ziekten als gevolg van rotavirus A door verkeersactiviteiten, vooral motorrijders.

De resultaten in deze studie kunnen afzonderlijk worden gebruikt als de kwantitatieve gezondheidsuitkomsten om de impact van microbiële ziekteverwekkers in overstromingswater voor een specifieke overstroming te identificeren. De resultaten kunnen ook worden geïntegreerd in overstromingsrisicobeheer om de microbiële gezondheid te meten. Het onderzoek gebruikt de ziektelast (met DALY) als de variabele van de gezondheidsindicator van de sociale dimensie bij de beoordeling van de kwetsbaarheid voor overstromingen. De aanpak werd gebruikt om de overstromingskwetsbaarheid in verband met het gezondheidsperspectief van tien afdelingen in het Ninh Kieu-district te identificeren. Deze studie is een van de eerste die de mate van overstromingskwetsbaarheid, inclusief microbiële gezondheidsgevolgen, onderzoekt door (1) de ziektelast veroorzaakt door microbiële ziekteverwekkers in overstromingswater te kwantificeren door middel van verkeersactiviteiten, en (2) overstromingsgevoelige gebieden met gezondheidseffecten te identificeren. De variabelen voor het bepalen van de mate van kwetsbaarheid voor overstromingen waren bevolkingsdichtheid en ziektelast met DALY's (sociale dimensie), aantal huishoudens met een laag inkomen (economische dimensie) en aantal apotheken en ziekenhuizen (medische diensten) voor tien afdelingen van Ninh Kieu-district (Can Tho, Vietnam). De zeer kwetsbare gebieden bevonden zich in de binnenstad, die meestal werd toegewezen aan huishoudens met een laag inkomen, zonder medische diensten, en sommige werden veroorzaakt door een hoge ziektelast en bevolkingsdichtheid, terwijl minder kwetsbare gebieden dicht bij rivieren lagen. De bevindingen kunnen helpen bij het prioriteren van maatregelen en beleid inzake de volksgezondheid en het milieu. Voor het eerst zijn de indirecte gevolgen voorde gezondheid gekwantificeerd voor mensen als gevolg van microbiële ziekteverwekkers blootgesteld aan overstromingswater door verkeersactiviteiten. De ziektelast met DALY geeft de gezondheidsgevolgen voor de getroffenen aan. Beoordeling van gezondheidsrisico's, schatting van de ziektelast en een hydrodynamisch model werden gecombineerd om de nadelige gevolgen voor de gezondheid van microbiële pathogenen in overstromingswater in te schatten. De studie ontwikkelde een raamwerk en de toepassing daarvan om de vervuilingsgegevens (microbiële concentratie in overstromingswater) om te zetten in gerelateerde ziektegegevens die nuttig zijn voor DALY-berekeningen voor verkeersblootstelling. Het onderzoek omvatte een beoordeling van de verkeersblootstelling om kwantitatieve gegevens over blootgestelde mensen te verzamelen om de microbiële gezondheidsresultaten te kwantificeren. Bovendien benadrukt de studie het belang van het gebruik van het hydrodynamische model bij het simuleren van de microbiële concentratie en bij het ontwikkelen van een nieuwe benadering om microbiële gezondheidsrisico's te beoordelen door blootstelling van het verkeer in stedelijke overstromingen.

Over het algemeen wijst het onderzoek op het gezondheidsrisico als gevolg van rotavirus A in overstromingswater in het district Ninh Kieu door verkeersactiviteiten. De studie draagt bij aan een nieuwe methodologie om de gezondheidsrisico's en overstromingsrisico's te combineren waarnee met name de indirecte/immateriële effecten veroorzaakt door de ongunstige factor van overstromingen kunnen worden geschat. De studie omvat de parameters met betrekking tot blootstelling en kwetsbaarheid van lokale mensen in Vietnam om het gezondheidsrisico te berekenen en de ziektelast te kwantificeren. Daarnaast ontwikkelt de studie de aanpak voor het inschatten van gezondheidsrisico's voor blootgestelde mensen als gevolg van darmpathogenenconcentraties op basis van waargenomen gegevens en gesimuleerde gegevens die de beoordeling van gezondheidsrisico's (d.w.z. infectiekans en DALY) bij een overstroming kunnen verbeteren. De studie benadrukt om rekening te houden met de invoerparameters concentraties en het aantal blootgestelde mensen om de gezondheidseffecten van overstromingsrisico's te verminderen. Het resulteerde in het idee dat mitigerende maatregelen niet alleen gericht moesten zijn op het verminderen van stedelijke overstromingen, maar ook op het bewust maken van de lokale bevolking van het risico van microbiële concentraties in overstromingswater. In toekomstig onderzoek kunnen het gezondheidsrisico en de ziektelast worden bijgewerkt wanneer er meer gegevens zijn over bronnen van vervuiling, blootstellingsroutes en onder toekomstige scenario's met klimaatverandering en bevolkingsgroei. In sommige mogelijke interventies met betrekking tot gevoeligheidsparameters zoals microbiële concentraties en overstroomde gebieden kan worden geïnvesteerd om de microbiële gezondheidsrisico's te verminderen. De bewoners en de lokale overheid moeten zich bewust zijn van het microbiële risico tijdens overstromingen. Daarnaast kan de jaarlijkse ziektelast worden geschat door DALY's om kwantitatieve gegevens te verkrijgen over gezondheidsschade door nadelige gevolgen voor de waterveiligheid.

CONTENTS

1
INTRODUCTION

Microbial pathogens in urban floodwaters pose an infection risk. However, it challenges to express and collect quantitative data on microbial hazards, the path of exposure, and vulnerability of people. This study aims to quantify the adverse health consequences of microbial pathogens in floodwater through direct exposure, for example, traffic activity. This Introduction chapter will provide the background of urban flooding and floodwater quality and the current state of research into microbial health risk associated with flooding, followed by the research problem, the research aims, objectives and questions, the significance and finally, the limitations.

1.1 Background

In tropical monsoon countries, annual flooding brings both benefits and drawbacks to its inhabitants. On the one hand, annual flooding plays an important role in social-economic development in terms of agriculture, transportation, irrigation, etc. On the other hand, residents suffer from flooding in urban areas in their daily life (Atta-ur-Rahman et al., 2016). Pluvial flooding is one of the major problems in urban areas (Tingsanchali, 2012). The main causes are inadequate drainage systems, increased impervious areas, and lack of water storage areas. Additionally, climate change has further increased the unpredictability of intense precipitation. When the drainage system does not have enough capacity to drain high-intensity rainfall, cities are inundated. Fluvial flooding is influenced by high river water levels that exceed the river bank. In addition, river water flows back into the drainage system and causes flooded streets and houses. In flat floodplains, floodwaters move slowly and shallowly so they may not reach the level of risk to life. However, floodwater increases the spread of pollutants (Dahria et al., 2015), especially microbial pathogens such as *E. coli*, Salmonella, rotavirus, etc. which are the causes of waterborne diseases such as diarrhoea (Fewtrell and Kay, 2006; Miller and Hutchins, 2017).

Urban flood water originates from various sources, for example, sewage, surface runoff, or surface water like rivers/canals (McGrane, 2016; Rodak et al., 2020). When septic tanks are not properly maintained, pollutants, especially the microbial pathogens, are not treated efficiently (Withers et al., 2014; Richards et al., 2016). Furthermore, in some developing countries, wastewater is discharged directly into surface water. Therefore, during floods, these contaminants are diluted into and transported by floodwater.

Microbial pathogens in flooding cause significant public health issues, for example, the risk of infection by waterborne diseases (Ahern et al., 2005; Cann et al., 2013). An increase in infectious diseases such as malaria and diarrhea during floods was noticed (Gao et al., 2016a). In recent publications, the importance of health risk assessment (HRA) related to waterborne pathogens in urban flood risk management has been emphasised in England (Fewtrell et al., 2008b), the Netherlands (Sterk et al., 2008), Cambodia (Kazama et al., 2012), and Bangladesh (Mark et al., 2015). The infection risks caused by waterborne pathogens in floodwater help urban authorities understand the safety of floodwater and develop risk mitigation strategies (Sales-Ortells and Medema, 2014).

In general, the concept of risk includes three components: hazard, exposure, and vulnerability. A complete exposure pathway is a course a pathogen takes from a source to an exposed receptor (US EPA, 2012). In this study, microbial health risk refers to the probability of getting an infection risk due to microbial threats (hazards) in floodwater through direct contact with floodwater. Accidental exposure activities in urban flooding can be traffic activities and cleaning up of inundated houses. The vulnerability of people is the reaction of the body to the microbial concentration which may differ depending on age, gender, etc.

In addition, possible health outcomes also include diseases with different levels of symptoms or deaths. The disease burden expressed by Disability-Adjusted Life Years (DALYs) is the common way to determine healthy years lost due to certain adverse effects (Murray and Acharya, 1997). With the burden of disease, the health impacts can be considered for the exposed community rather than focussing only on the impact on the person. While the burden of environmental diseases focused on the purpose-activities like drinking/recreational/reuse water, the influence of polluted floodwater has rarely been considered for (frequent) accidental exposures.

According to a UN report, “Urban risk, city planning, and the role of local governments in dealing with risk reduction have been recognised as key factors to build resilient communities and nations” (UN, 2010). Urban environment hazards such as air/water pollution which cause health impacts to residents need to be considered (McMichael, 2000). As the first step in urban flood risk management (FRM), policy makers must understand the flood hazard that can affect the urban environment (Jha et al. 2012). The hazard is not only the flood itself, but also the secondary hazard, like the microbial pathogens in floodwater. Floods have become more impactful and more frequent in urban areas (Kundzewicz et al., 2014). They can pose a threat to the well-being and living of residents not only today, but also in the future due to climate change (Nichols et al., 2018). Therefore, the impact of microbial pathogens in floodwater, the pathways and adverse health consequences must be considered. A more comprehensive assessment can help quantify the adverse health consequences and also identify possible variables to reduce health risks, leading to a more resilient urban area.

1.2 PROBLEM STATEMENT

In FRM, while direct impacts are well recognized such as asset damage, indirect intangible impacts like human health are hardly considered (Cho and Chang, 2017). Socioecological resilience can guide the development of more resilient FRM systems, but its application into practice remains a challenge (Zevenbergen et al., 2020). There is a lack of guidance or an appropriate approach to include environmental, social and health aspects since floods and communities differ from case to case (Few, 2006). This challenge also holds for the assessment of microbial risk related to urban floodwater which requires an understanding of exposure from pollution sources to calculate the microbial health risk. In addition, the variability of quantitative data, the collection of data, and the choice of the right metric are also limitations, especially in developing countries (ten Veldhuis, 2011).

One of the frequent and unavoidable activities is traffic during flooding, especially in low-middle-income countries (LMICs) (Zhu et al., 2018; Vajjarapu et al., 2019). Mixed transportation such as riding motorcycles/ bicycles or walking is typically observed in developing countries (T. P. Hsu, 2003). In particular, the ownership of private vehicles on urban streets is dominated by motorcycles due to their affordability and flexibility for daily life rather than public transportation (Gwilliam, 2010; Almselati et al., 2011; Susilo et al., 2015). Although pedestrians have been shown to be at high risk of infection (ten Veldhuis et al., 2010; De Man et al., 2014), motorcyclists/cyclists – who are the main contributor to traffic - have no involving yet.

The health impacts related to microbial pathogens in floodwater for accidental activities have not been fully quantified in terms of:

- The exposure pathway (from contaminated sources to receptors) for the common direct exposure - traffic activity, especially in developing countries, has not been fully described.
- Different levels of illness (i.e., possible courses of health outcomes for individuals with the starting point of exposure, Figure 9 in Section 2.3.3), only the infection/illness risk has been considered.
- In addition, the consequences of health impact have not been fully quantified for exposed communities, only the health risk for individuals has been considered.

Furthermore, the number of studies on the assessment of microbial health risks in developing countries was found to be less than in developed countries (Rui et al., 2018). The health risk in developing countries can be higher as the frequency of urban flooding is usually higher, polluted flood-related waters are more widespread, and the number of exposed people is higher. For example, traffic activities on flooded streets are an unavoidable practise for motorcyclists, cyclists, and pedestrians. Therefore, understanding the link between microbial pathogens in floodwater and the potential health impacts for these exposed groups is crucial to assess the associated health risks, especially in LMICs.

1.3 RESEARCH OBJECTIVES

1.3.1 The purpose of the research

This research aims to quantify the risk and burden of microbial health due to microbial pathogens in urban floodwater through direct exposure to floodwater.

Scope of the research: The study considers direct exposure through traffic activity: as a common and unavoidable activity in urban areas, especially in developing countries. This research mainly focuses on waterborne pathogens related to gastrointestinal diseases which are usually addressed in epidemiological reports, especially in LMICs. The Ninh Kieu district, which is the main urban area of Can Tho city (Vietnam), is the case study of this research. Can Tho City is one of the social and economic centres in the Vietnamese Mekong Delta.

Objectives:

- Assessing and characterising variations of microbial concentrations in flood-related waters (that is, domestic wastewater, surface water, and floodwater) and identifying the microbial concentration in floodwater by sampling and analysing water samples (Paper 1).
- Developing a water quality model to simulate microbial concentrations in floodwater (Paper 3).
- Analyzing the path of exposure through traffic activities (part of Papers 2 and Paper 4).
- Calculating the health consequences including infection risk and disease burden for people exposed to microbial pathogens in floodwater for observed flood events (i.e., calculations were based on measured concentrations of microbial pathogens). Identify the sensitivity parameters of the microbial health risk assessment (part of Paper 2).
- Calculating the health consequences including infection risk and disease burden for people exposed to microbial pathogens in floodwater for simulated flood events (that is, the calculations were based on simulated concentrations of microbial pathogens). Apply hydrodynamic models and traffic exposure assessment to quantify microbial risk (i.e., infection probability and DALYs) (part of Paper 4).

1.3.2 Research Questions

- ✓ Main question: What is the natural relationship between the health consequences and waterborne pathogens in floodwater for exposed people through traffic activity?
- ✓ Sub-questions:

1. What hazard? What is the microbial hazard (concentration, location) in urban floodwater?
2. What exposure? – What is the traffic exposure pathway? How to estimate exposed people and related parameters through traffic activity?

   What health outcomes? – What are the health risks/impacts for individuals exposed to microbial pathogens in floodwater? How to include input data from traffic exposure and microbial pathogens from observed flood events and simulated flood events to quantify health risks/impacts?

1.3.3 The significance of research

The study will contribute to the body of knowledge on the approach to quantifying the microbial health risk related to floodwater for residents living in flooded areas. The results will help address the current shortage of research on the health impacts of communities exposed to flood risks. Additionally, the findings provide quantitative values for decision makers responsible for the management of health impacts for residents in flood areas.

1.4 OUTLINES OF THE THESIS

This research includes ten chapters comprising:

Chapter 1 introduces the context of the study and the problem related to the assessment of microbial health in flood areas. It also identified the research objectives, scopes, questions, and values of the research.

Chapter 2 reviews the relevant studies on urban flooding and flood-related water quality in terms of microbial pathogens to identify causes, major pollution sources, and approaches to determine microbial pathogen pollution in urban floodwater. In addition, it will review the existing literature to identify appropriate approaches and strategies in the context of microbial health risk assessment and quantifying health consequences for exposed people.

Chapter three presents the theoretical framework. This chapter will justify the research approach to analyze and simulate microbial pathogens in flood-related waters, assess health risk, and quantify the disease burden.

Chapter Four briefly introduces the case study, Ninh Kieu district, Can Tho City, Vietnam. The chapter will include the problems of urban flooding situations, flood-related water pollution, and especially microbial pathogens in the case study.

Chapter Five conducts flood-related water sampling during flooding time and analyzes the microbial concentrations to identify microbial threats in floodwater in Ninh Kieu district.

Chapter Six assesses the risk of microbial health, analyses traffic exposure, and quantifies the burden of disease for exposed people. This chapter assesses the influence of traffic on urban flood health risk using the aggregated concentration from Chapter Five. Additionally, the sensitivity and uncertainty of variables in the assessment of health risks will be analysed.

Chapter Seven simulates the concentration of microbial pathogens in floodwater to analyse the location and concentration of enteric pathogens in urban floodwater in Can Tho city.

Chapter Eight assesses the risk of microbial health, analyses traffic exposure, and quantifies the disease burden for exposed people using the simulated concentration in Chapter Seven.

Chapter Nine discusses the opportunity to apply DALYs (Disabibily Adjusted Life Years, one of the metrics of disease burden) as the variable of health indicator for social vulnerability in neighbourhood flood vulnerability assessment.

Chapter Ten concludes the study and highlights the main contribution, including the limitations thereof. In addition, it also recommends future research on an intervention to reduce the risk of microbial health. In addition, it will provide a reflexion on the pros and cons of the approach which can be necessary for future application for other relevant case studies.

Figure 1 shows the chapters corresponding to the objectives and questions of this research.

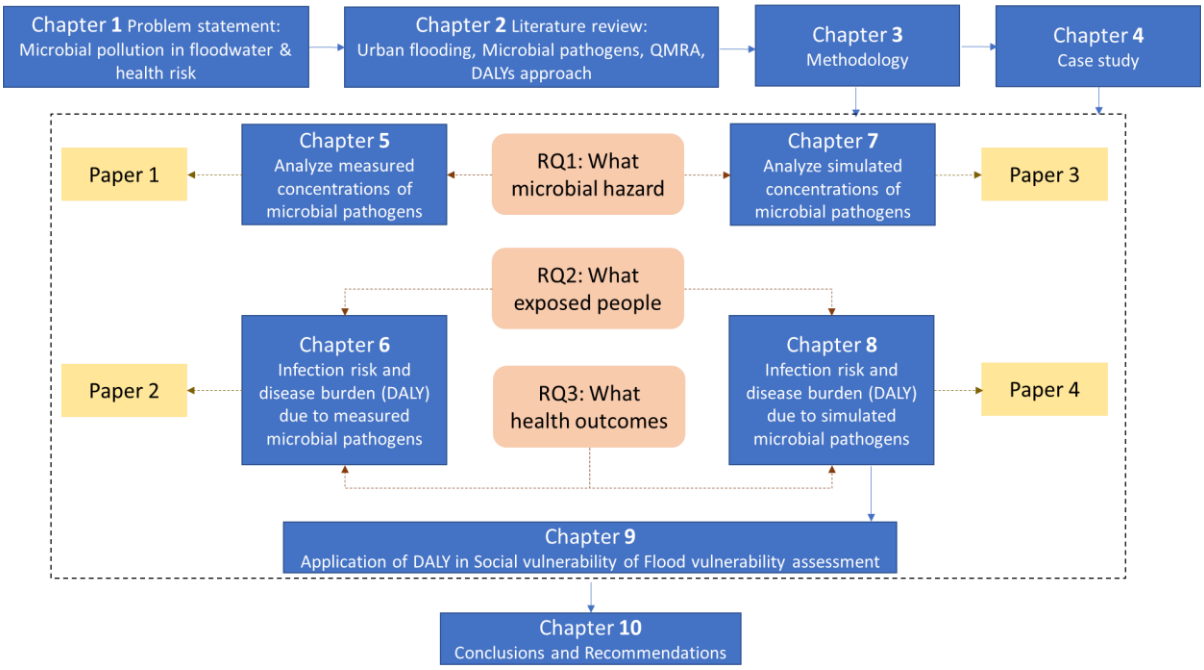

Figure 1. Diagram of the chapters corresponding to the objectives and questions of this research.

2

LITERATURE REVIEW

This chapter summarises the existing literature on the causes of urban flooding and the quality of urban floodwater, especially microbial pathogens. In addition, the chapter determines the perspective of health impact in FRM. It also shows the ability to analyse microbial threats in floodwater, assess the risk of microbial health, and estimate the disease burden for exposed people. From that, this chapter discovers the gaps and shows how this research links to quantifying microbial health risk through direct exposure to urban floodwater.

2.1 URBAN FLOODING

Urban flooding has a significant impact on the environment and human life. In the "2014 Year in Review" of Natural Disasters in Asia and the Pacific, floods were considered to have the highest occurrence, cause of death, and economic loss compared to all natural disasters. Urban areas are more affected than other areas due to their high-density population, infrastructure, etc. (K Jha *et al.*, 2012; ESCAP, 2015). Urban flooding is also a growing challenge. According to Gunerapl (2015), if we ignore the effect of climate change, floods and droughts in urban areas will increase by around two times by 2030, especially in coastal regions in Africa and Asia. These regions have a larger area exposed to flooding compared to coastal regions of developed countries on other continents. Deltas are the most vulnerable areas affected by water-related problems. Rapid urbanization is the main driver of increased flood risk in deltas cities such as China, India, and Vietnam (Güneralp et al. 2015).

Some factors have a particular influence on the increase in urban flooding. First of all, meteorological and hydrological extremes usually cause floods, and they are on the rise because of climate change (Schreider *et al.*, 2000; Lener, 2016). Urban areas can be flooded by fluvial, pluvial, coastal floods, etc. The other cause is urbanisation (Balk *et al.*, 2012; Chen *et al.*, 2015). In addition, increasing imperviousness and subsidence caused by groundwater withdrawal are features that further increase the flood risk in urban areas (McGranahan et al. 2007). There are other causes of urban flooding, such as an inadequate drainage system.

Urban drainage is an important infrastructure for maintaining human hygiene. Urban drainage systems play an important role in minimising the impacts caused by storm water. Rainfall flows into the urban drainage system and discharges to surface water. Urban drainage systems also receive domestic wastewater in a combined system (Butler and Davies, 2004). Figure 2 illustrates the interaction between the urban drainage system and the public and the environment.

Figure 2. Urban drainage interfaces with the public and the environment (Butler and Davies, 2004)

However, the capacity of the drainage system can be exceeded. The volume of flows from high intensity rainfall is greater in urban areas than in rural areas due to the higher imperviousness area. Furthermore, in some cases, when the river water level rises due to a flood or high tide, the surcharge also occurs in the drainage pipes (Borris *et al.*, 2013). Furthermore, drainage systems are usually blocked by tree or vegetation roots and by accumulation of solid waste accumulation (Leloup *et al.*, 2013). Many households/factories discharge illegal wastewater and garbage into rivers, lakes, or canals. There is an increase in the effect of human activity on water quality due to the growth of population and industry. Therefore, during flooding, urban areas face not only flooding but also dilution of pollutants from contamination sources. Floodwater is polluted with physical/chemical pollutants such as TSS, BOD, COD, etc. and microbial pathogens that cause adverse effects to human health.

2.2 MICROBIAL POLLUTION IN FLOODWATER

Urban floodwater quality is affected by several sources such as rainwater, surface runoff, roof runoff, sewer water, and river water (Ellis, 1986; Fewtrell et al., 2008c). Floodwater originating from overflowing combined sewers has the highest microbial concentration, followed by overflowing storm sewers and rainfall-generated surface runoff (Man et al. 2014). In particular, septic systems are a significant source of contamination. Floodwater originating from combined sewers is frequently contaminated with waterborne pathogens with evidence of fecal contamination, as demonstrated by the appearance of the fecal indicator bacteria *E. coli* and intestinal Enterococci in floodwater (ten Veldhuis et al., 2010). The indicator bacteria *E. coli* is the most found in floodwater and usually exceeds water quality standards. Furthermore, urban floodwater is polluted with other types of bacteria, viruses, and protozoa that can cause numerous diseases such as gastrointestinal diseases, cholera, hepatitis A, and typhoid. Table 1 provides an overview of the pathogens found in floodwater originating from different components of the pollution.

Culture-based methods are the most common conventional approach to analyzing microbial concentration, such as *E. coli*, and fecal coliform. However, for viruses and protozoa, molecular methods such as qPCR (Phanuwan *et al.*, 2006) and RT-qPCR; or metagenomic sequencing (Kim *et al.*, 2022) are used.

Table 1. Overview of microbial pathogens in urban floodwater originating from different sources

Microorganism	Countries	Methods to detect/analyze	Pollution components in floodwater	Concentrations in water quality standard	References
Bacteria					
E. coli	The Netherlands	Urban-runoff, Sewer water	$8.7x10^3$ – $1.08x10^7$ CFU/100 ml	900 CFU/100ml (EU Bathing Water Directive 2006/7/EC)	(ten Veldhuis *et al.*, 2010)
	Vietnam	River water, Sewer water	1,600 - 70,000 MPN/100ml	20 MPN/100ml (National technical regulation on surface water quality of Vietnam - QCVN 08:2015/BTNMT – column A1 for a drinking water source)	(Nguyen et al. 2014)
Salmonella	UK	River water, Sewer water, urban-runoff	2 – 13,900/L	-	(Fewtrell *et al.*, 2011)
	Vietnam	River water, Sewer water	430 - 5,000 MPN/100ml	-	(Nguyen et al. 2014)
Campylobacter		Sewer water	3.5 - 10^1 to 1.1 - 10^3 gc (genomic copies)/L	-	(Sales-Ortells and Medema, 2015)
V. Cholera			10^3 - 10^5 MPN/100ml		(Mark *et al.*, 2015)
Virus					
Rotavirus	Thailand	River water, sewer water	Not mention	-	(Ngaosuwankul *et al.*, 2013)
Norovirus	Indonesia	River water, sewer water	2.2 - $3x10^4$ PDU/L		(Phanuwan *et al.*, 2006)
	NL	Sewer water	530-40,000 PDU/L		(Man et al. 2014)
Adenovirus	Indonesia	River water, sewer water	55 PDU/mL		(Phanuwan *et al.*, 2006)

Protozoa					
Giardia	UK	Sewage	0.1-32/L		(Fewtrell *et al.*, 2011)
	NL	Sewage	0.1-142 cysts/L		(Man et al. 2014)
Cryptosporidium		Sewage, storm water	0.1 – 10 oocysts /L	-	(Man et al. 2014)

The previous findings highlight the microbial pollution of floodwater and the importance to consider fecal contamination of floodwater. In urban areas, one of the sources is untreated domestic wastewater. Given the various polluted water bodies through which floodwater passes, it can carry waterborne pathogens and thus may contribute to human health risks both in developed countries and in developing countries. There is evidence of an increased burden of gastrointestinal diseases caused by direct exposure to floodwater after flooding based on survey data (Wade *et al.*, 2004; Schnitzler *et al.*, 2007). The next section described the perspective of health impact of urban flooding, especially related to microbial pathogens.

2.3 HEALTH IMPACTS RELATED TO URBAN FLOODING

This section indicates the perspective on the health impact in the context of FRM. Furthermore, this section reviews the existing knowledge of approaches to assess microbial health risk and calculate health outcomes related to waterborne pathogens.

2.3.1 Health Impact Perspective on flood risk management

Flood risk management includes analysis, assessment, and mitigation. Risk analysis focuses on previous, current and future flood risks, risk assessment assesses flood risks due to ecological, social, and economic perspectives, and risk reduction provides measures to reduce flood risks (Schanze, 2006). An overview of the framework is indicated in Figure 3.

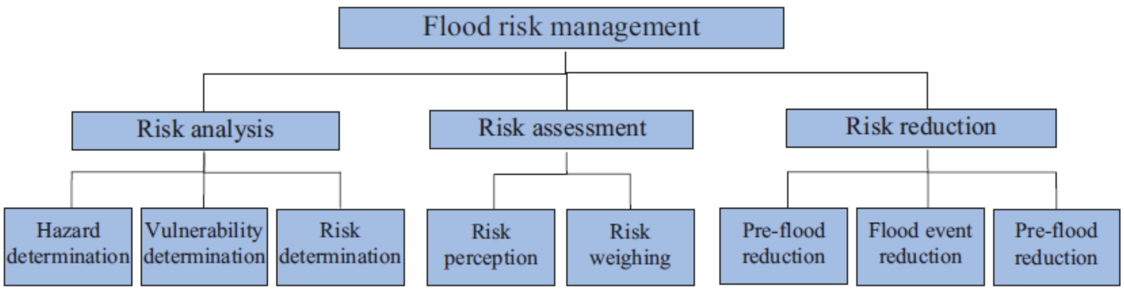

Figure 3. Flood risk management scheme (Schanze, 2006)

Analyzing the flood risk components is considered the first step of any FRM strategy that includes flood hazard mapping and flood vulnerability, assessment. Combining the information from flood risk/probability mapping with a vulnerability assessment provides the basic knowledge for understanding and reduce flood risk (Meyer *et al.*, 2009; Olsen *et al.*, 2015). In any risk analysis, the vulnerability component contains not only the economic vulnerability (direct and indirect cost), the ecological vulnerability (pollution of waters, soils, and ecological systems) but also the social and cultural vulnerability (loss of life, health impacts, loss of cultural heritage, etc.). (Messner and Meyer, 2006). According to Tapsell et al. (2002), flood impact reduction is flawed without including the social dimension (Tapsell *et al.*, 2002). Emerging FRM approaches involve sustainability for ecosystems, societies, and economies that are not taken into account in the traditional flood defence approach. Social sustainability refers to reducing the risk of risk from all flood sources ranging from exposed individuals to communities (Sayers *et al.*, 2014).

Flood damage can be classified in various ways using a direct/indirect and tangible/intangible classification based on the characteristics of damage (Figure 4). Some direct damages may be easier to identify and quantify than indirect impacts, such as human health. The potential health effects are divided into three time periods (Twigger-Ross, 2006):

- Immediate: death by drowning, injuries due to being knocked over by flood waters or struck by falling trees, overexertion during the event, hypothermia, electrocution, exposure to contaminants, the stress of the event itself;

- Medium-term: gastrointestinal illnesses, cardiovascular disease due to overexertion during recovery / cleaning processes, lacerations, sprains/strains, dermatitis, respiratory illnesses, carbon monoxide poisoning;

- Longer term: mostly psychological effects.

Health impacts also can be grouped into two kinds of effects: physical and mental health effects (Hajat *et al.*, 2005):

- Physical health effects sustained during the flood event include injuries and the loss of life, as well as diseases linked to the flooding, such as waterborne diseases (e.g., diarrhoea), vector-borne diseases (e.g., malaria and dengue fever) and rodent-borne diseases (e.g., leptospirosis);

- Mental health effects which occur as a direct consequence of the experience of being flooded (e.g., stress).

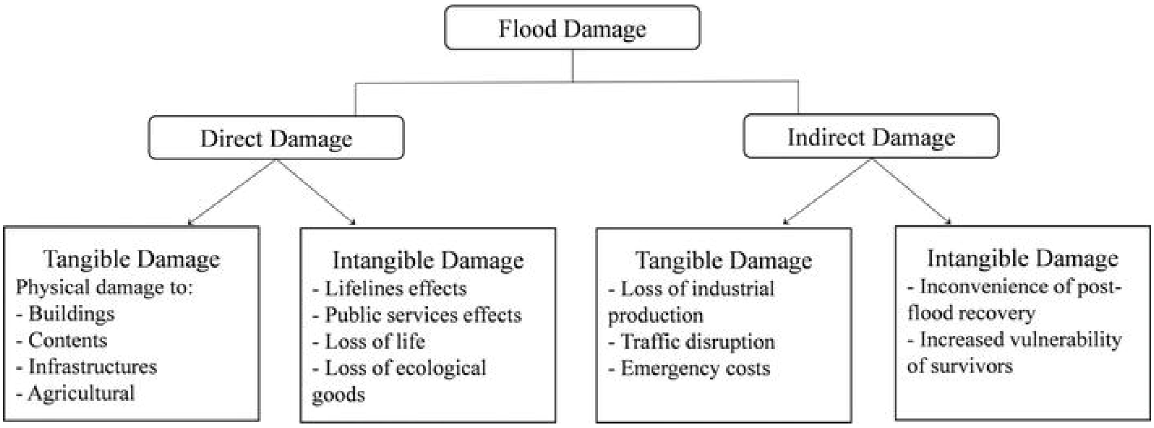

Figure 4. Categorisation of flood damage (Hammond et al. 2015) (Adapted from Shrestha et al. 2018)

The challenge of assessing and quantifying adverse health consequences is combining the approach of the environmental, social, health, and medical disciplines (Makri, 2005). While direct impacts like the number of people who lost their lives or got injured are relatively easy to assess because they are based on statistical numbers. The indirect and intangible impacts, such as the vulnerability of people through incident exposure (like traffic activity in flooded streets and cleaning inundated houses) due to potential threats (like microbial pathogens in floodwater) are difficult to estimate. One of the reasons is that quantitative data is not always available, especially in developing countries.

Few (2006) divides health risks due to climatic hazards into three components: external, personal, and internal (Few, 2006). The external component is the physical or social environment that drives the threats to receptors. The personal component is the actions and perceptions of receptors that lead to exposure to threats. The internal component is the reaction of the receptor body to threats, which may be different from person to person due to age, gender, health status, etc. (Figure 5).

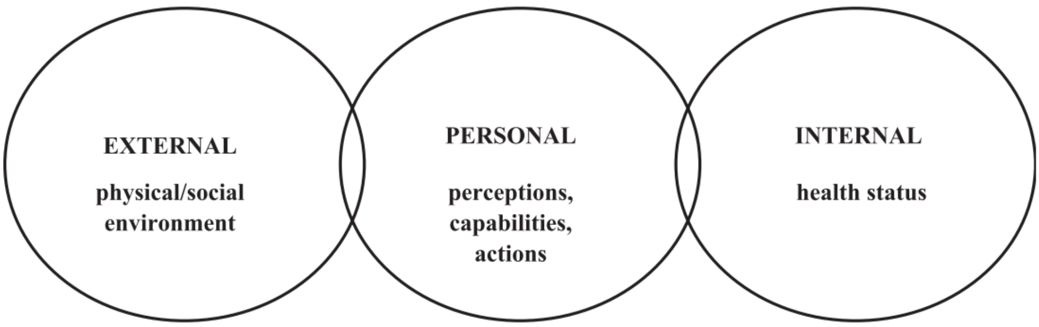

Figure 5. Components of vulnerability to health impacts of hazards (Few, 2006)

Recently, research on human health risks due to microbial pathogens through incident exposure to urban floodwater provided some new frameworks (Fewtrell *et al.*, 2008a; ten Veldhuis *et al.*, 2010). Fewtrell et al. (2008) assessed the impact of microbial pathogens in floodwater on human health through the model of the source-pathway-receptor concept (Figure 6).

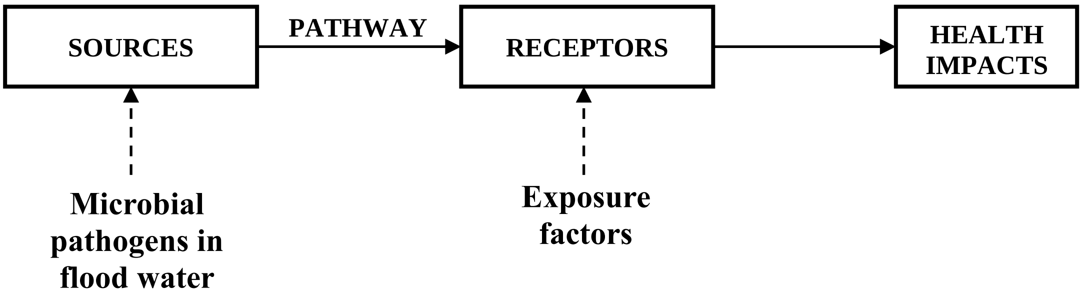

Figure 6. Source, pathway, receptor model, and health consequences (Fewtrell *et al.*, 2008c)

The source comprises flood-related waters that contain microbial pathogens. The pathway is the route of transmission. The receptor is people who are exposed to floodwater. The exposure routes can be cleaning up, escaping from inundated houses, or playing in flood water (Fewtrell et al. 2008). During these activities, people ingested amounts of floodwater that contains pathogens and may cause waterborne diseases. Health impacts, as explained by the quantitative microbial risk assessment (QMRA) approach, are infection or illness probability calculated by the dose-response relationship between pathogens and the exposed person (Haas, 2002).

Using the approaches of Fewtrell et al. (2008), Few et al. (2007), and Haas et al. (2014), the exposure pathways for microbial pathogens in floodwater to receptors with health outcomes are illustrated in Figure 7 below.

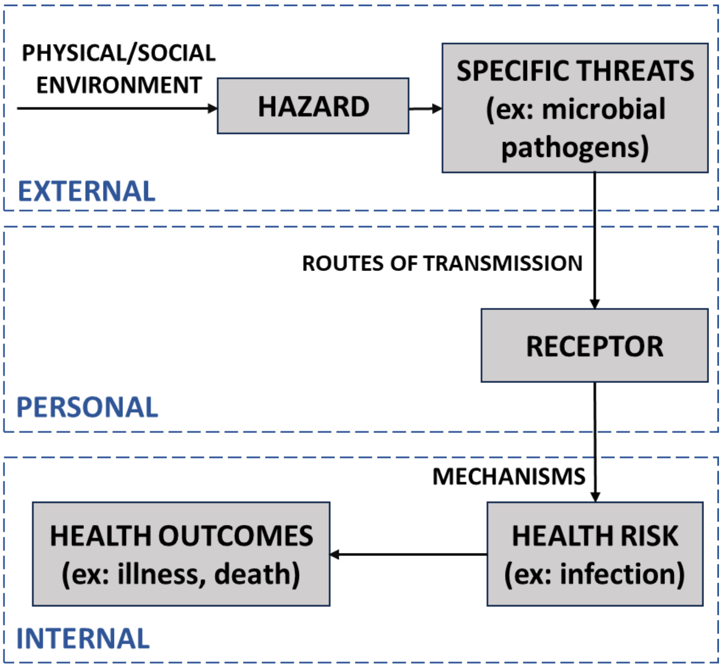

Figure 7. Source, pathway, receptor model, and health consequences for an exposed individual to microbial pathogens in floodwater (Adapted from (Few, 2006; Fewtrell and Kay, 2006; Haas et al., 2014))

The health impact assessment highly influences decision making, especially on sustainable water management (Fewtrell *et al.*, 2008b). According to Ahern et al. (2005), outbreaks of waterborne infectious diseases are associated with flood water. Flood water is found to be polluted with high concentrations of microorganisms. Exposures to incidence, such as traffic activities and cleaning up inundation houses, are common, especially in urban areas in developing countries. Therefore, the health risk during flooding time needs to be clearly considered in reducing its impact on local people. To identify to what extent, it poses a risk to public health, the next section summarises the existing literature on the approach, the steps considered and variables to conduct a microbial health risk assessment. The section closes by describing the remaining challenges in quantifying microbial health outcomes related to urban flooding.

2.3.2 State-of-the-art microbial health risk assessment in floods

The common approach to identifying microbial health risks is Quantitative Microbial Risk Assessment (QMRA). QMRA is a mathematical framework for evaluating infectious risks caused by microorganisms in food, air or water (WHO, 2003, 2016; Haas *et al.*, 2014). Many studies in various fields used QMRA to predict microbial health risks (Schets et al. 2008; Yapo et al. 2013; Sunger and Haas 2015) to improve environmental quality and ensure hygiene for human beings to meet the acceptable standard, especially waterborne pathogens in various water bodies, for example, water sources for drinking water (Katukiza *et al.*, 2013), recreation (Sales-Ortells and Medema, 2014).

➢ **Quantitative Microbial Risk Assessment (QMRA) approach**

QMRA includes four steps: hazard identification, exposure assessment, dose-response assessment, and risk characterisation.

- *Hazard Identification*

After addressing the problems in the case study, the pathogens of interest are indicated with information about the diseases that the pathogens caused to the host. The criteria for choosing the reference pathogens could be based on: permanent presence in the case study area, the diseases reported by the local authority, and the possibility of measurement.

- *Exposure assessment*

The exposure pathway includes the sources contaminated, the transmission routes, the number of exposed people and exposed groups. Microbial concentrations are usually identified by analysing the samples. In cases where it was difficult to take samples, such as floodwater quality, pathogens were referenced from previous studies, such as epidemiology studies, certain standards (e.g. WHO health standards) (WHO, 2008), or the ratio between *E. coli* and other pathogens (Howard et al. 2006; Suleiman, 2007; Labite, 2008; Machdar et al. 2013). The function below indicates the dose ingested for one exposure in an event in equation (2.1) (Haas, 2002).

$$\mu = \frac{c.v}{d} \qquad (2.1)$$

Where:

μ: the number of pathogens that a person ingested

c: number of pathogens/mL

v: Volume of water that a person intakes per event (ml).

d: Dilution factor. In case the “real event” floodwater can not be sampled, it is assumed with a certain dilution factor from the sewer water, for example. Thus, the dilution factor is involved. If the dilution factor is not involved, d = 1.

About the volume intake (v), it can be described as the volume of water that was ingested in certain exposure duration at a certain intake rate in an exposure event (EPA, 2011a). The equation can be rewriten as (with d=1):

$$\mu = c \times IR \times t_e \qquad (2.2)$$

Where:

c is the concentration of the microbial pathogens (number of pathogens/mL);

IR is the intake rate (mL/hour), 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

The challenges in identifying microbial pathogens in floodwater are related to sampling during flood events as it requires logistic preparation. Floodwater used in research is often synthetic water produced in the laboratory by mixing wastewater and rainwater rather than taking floodwater from a real flood event. However, there is uncertainty to apply the correlation and ratio between these pathogens and indicators like *E. coli* (Wu *et al.*, 2011). With these methods, specific interest pathogens can be detected by some floodwater samples, but may not represent the microbial concentrations in a flood event.

- *Dose-response assessment*

The dose-response assessment aims to represent the relationship between dose and infection/disease/death probability (Haas *et al.*, 2014). The dose-response relationship of infection probability has two types: exponential and Beta-Poisson model corresponding to which kind of pathogens, such as viruses, bacteria, and protozoa. The experimental values (r, α, β) and related functions were calculated based on the experiment in the healthy adult groups (Teunis *et al.*, 1996). The functions below are dose-response relationships representing exponential and beta-Poisson models, respectively.

$$P_{inf} = 1 - e^{-r\mu} \tag{2.3}$$

$$P_{inf} = 1 - (1 + \frac{\mu}{\beta})^{-\alpha} \tag{2.4}$$

Where:

P_{inf} is probaiblity of infection due to one pathogen for one person in a certain event.

μ is the dose of pathogen ingested by a person

r, α, β are the parameters characterising the relationship between dose-response functions

- *Risk Characterisation*

The risk characterisation is the integration of the three previous steps. Infection probability (P_{inf}) indicates the probability that people may get when they are exposed to the microbial hazard.

The probability of illness (P_{ill}) is calculated as

$$P_{ill} = P_{inf} * p_{ill\,|\,inf} \tag{2.5}$$

The $p_{ill|inf}$ is the probability of an infection giving rise to a disease. It is an experimental value and may vary by pathogen.

If the exposed people in step 2 are known, the number of people with infections and diseases can be estimated by multiplying by the infection or illness probability, for example, the number of ill people with illnesses due to drinking microbially contaminated water (Katukiza *et al.*, 2013). However, the approach to identifying the number of people to be exposed to the incident during flood times is rare. Common ways were to take the population through a case study (Fuhrimann *et al.*, 2017) or to survey with a large number of interviewees (De Man *et al.*, 2014). However, for some specific exposures, like traffic activities, there is no approach to identify the exposed people, which may need observation to determine the people's habits in the case study.

➢ **Application of the QMRA approach to microbial pathogens in urban floodwater**

QMRA was applied for microbial pathogens in urban floodwater to identify the infection risk of accidental exposures. The infection risk varied between the different receptors, the exposure pathways, and also the sources of microbial threats in floodwater (Table 2). Some activities during flood time like cleaning-up, playing/swimming in flood water for children and walking in flooded water were studied (Table 2). These activities reflected the actions and perceptions of the daily life of locals during flooding time. The different exposures lead to different assumptions in the ingestion volume and the ingested duration, and then lead to a difference in the ingested dose. Different risk levels depending on the receiving water which contains microorganisms from various contaminated sources. Thus, identifying common exposure and contamination sources in the case study is important for the microbial health risk.

Table 2. The infection risk to waterborne pathogens through direct exposure to floodwater or combined sewer overflows (CSO).

Microbial pathogens in floodwater	Sources of microbial pollution sources (Measurement of pathogens)	Exposures (Receptors, ingested volumes/rates)	Number of exposed people	Countries	References
Fecal Streptococcus/ Enterococcus, Giardia	CSOs (Cultured-based method)	Recreators, Homeless people (50mL/hour); Visitors (10m/hour)	Not mentioned	US	(Donovan *et al.*, 2008)
Campylobacter, Cryptosporidium, Giardia	sewer water, rainfall-runoff (Cultured-based method)	Adult and child pedestrians (10ml, 30ml per flood event)	Not mentioned	Netherlands	(Sterk *et al.*, 2008)

Salmonella, *Cryptosporidium*, *Giardia*, norovirus, adenovirus	CSOs treated wastewater, (Cultured-based method and molecular method PCR)	Recreators (19 ml per event)	Not mentioned	US	(Soller *et al.*, 2010)
Campylobacter, *Cryptosporidium*, rotavirus	River water, sewer water, Rainfall-runoff (Cultured-based method and literature review)	- Adults and children (withdrawing from inundated houses (30ml for adults, 20ml for children) - Adults (cleaning up flooded houses, 1 ml/h)	1080 exposed people (census data)	UK	(Fewtrell *et al.*, 2011)
Cryptosporidium, *Giardia*, *Salmonella*, norovirus, rotavirus, enterovirus, adenovirus	sewer water, rainfall-runoff (Cultured-based method and molecular method qPCR)	Swimmers: - (primary contact) Adults (10, 50, and 100 ml); children (increased by 50% than adults) - secondary contact or inhalation (reduced by 80% compared to primary contact)	Not mentioned	US	(Mcbride *et al.*, 2013)
C. Jejuni, *E. coli*, norovirus, *C. Parvum*, *G. Lamblia*	Wastewater in sewage, Rainfall-runoff	Swimming activities	1,312 – 1,365 people (census data)	Denmark	(Andersen *et al.*, 2013)
Escherichia coli, *Enterococci spp.*, *Campylobacter*	sewer water, rainfall-runoff	Accidental contact (10ml/event) Recreational activities	Not mentioned	Denmark	(Andersen *et al.*, 2014)

	(Cultured-based method)				
Campylobacter, Giardia, Cryptosporidium, norovirus, enterovirus	Sewer water, Rainfall-runoff (Cultured-based method and molecular method PCR)	Accidental contact and swimming - Children (1.7 ml) and adults (0.016 ml)	Not mentioned	Netherlands	(Man *et al.*, 2014)
Campylobacter spp., Salmonella spp., E. coli, Cryptosporidium spp. Ascaris lumbricoides	River water, rainfall-runoff, treated sewer water (Cultured-based method, and literature review)	Accidental contact with polluted river water (residents)	795 people (assumption from the population, census data)	Vietnam	(Fuhrimann *et al.*, 2017)
E. coli, Salmonella	River water, sewer water, rainfall-runoff (Cultured-based method)	Playing with flood water (children, 30 ml), accidental activities (adults, 10ml)	Not mentioned	Vietnam	(Nguyen *et al.*, 2017a)

QMRA is approved to assess the microbial health risk of small ingested volumes for the individual (Haas, 2002). If data on exposed people are available, the number of people with infections and diseases can be estimated. The studies highlighted the potential threat of microbial pathogens in polluted floodwater through occasional exposures. While recreational activities, cleaning up houses, and walking through flooded streets were considered, unavoidable common activities such as traffic activities for motorcycles or cycles have not been involved yet, especially for LMICs.

In addition, the average concentration can lead to an underestimation or an overestimation because flooding differs from case to case due to spatial and temporal factors. Therefore, the risk assessment includes many assumptions which may affect the risk result. To improve the reliability of the result, the uncertainty of these factors must be limited. In recent years, some researchers have found out how to decrease QMRA limitation by managing the microbial concentration (Andersen, 2015). The following section describes some new approaches to QMRA relating to water, especially for urban flooding cases.

- **The recent development of the QMRA on water-related issues**

Water sampling and analysis are essential and critical to the application of the QMRA approach. However, measured pathogen concentrations are difficult to quantify because flood events pertain to different seasons, times, and scenarios. Floods occur usually infrequently, which makes it difficult to collect water samples. The exposure or pathogens ingested may not be the same for each period of the flood event period. Therefore, some researchers studied simulating microbial concentration in floodwater using the hydrodynamic model to improve the result of QMRA (Andersen, 2015; Eregno *et al.*, 2016).

The water quality model plays an important role in environmental management by predicting the dynamic/concentration of pollutants. The application of the hydrodynamic model to simulate physical/chemical pollutants in water was used long time ago (Wang *et al.*, 2013). In urban flood modelling, the one-dimensional hydrodynamic model (1D) simulates the transport and dilution of wastewater and rainwater from the drainage system. The dilution of sewage water and stormwater on the surface is modelled in two-dimensional (2D). Incorporates advection-dispersion to describe the transport of pollutants in floodwater. With urban flood and floodwater quality modelling, the dilution and transport of microbial pathogens in floodwater were spatiotemporally simulated.

In general, the approach of a combination of the hydrodynamic model and QMRA using the simulated concentration of pathogens in floodwater to calculate the infection risk (Figure 8). For example, Andersen et al. (2013) used hydrodynamic models to simulate the extreme rain event that led to a combined sewer overflow to bathing water where a swimming competition later took place (Denmark). First, the drainage model (MIKE URBAN 1D) simulated wastewater in CSOs and then the 3D hydrodynamic model (MIKE 3 FM) estimated the attribution of wastewater from CSOs flowing into the bathing water. The decay of pathogens due to temperature and salinity was also considered using MIKE ECO Lab (Andersen *et al.*, 2013). Another example of using hydrodynamic models to simulate pathogen concentration is the use of the MIKE FLOOD model (combined 1D/2D model) in Dhaka flooding events. Dhaka is the capital of Bangladesh located near the rivers. This city often suffers from urban flooding caused by heavy rainfall. The flooding scenarios for this case study are developed based on data for the observed flood event in 2004. The MIKE FLOOD model was used to simulate the concentration of surface runoff water. On the basis of the estimated pathogen concentration, the health risk for exposed people was calculated.

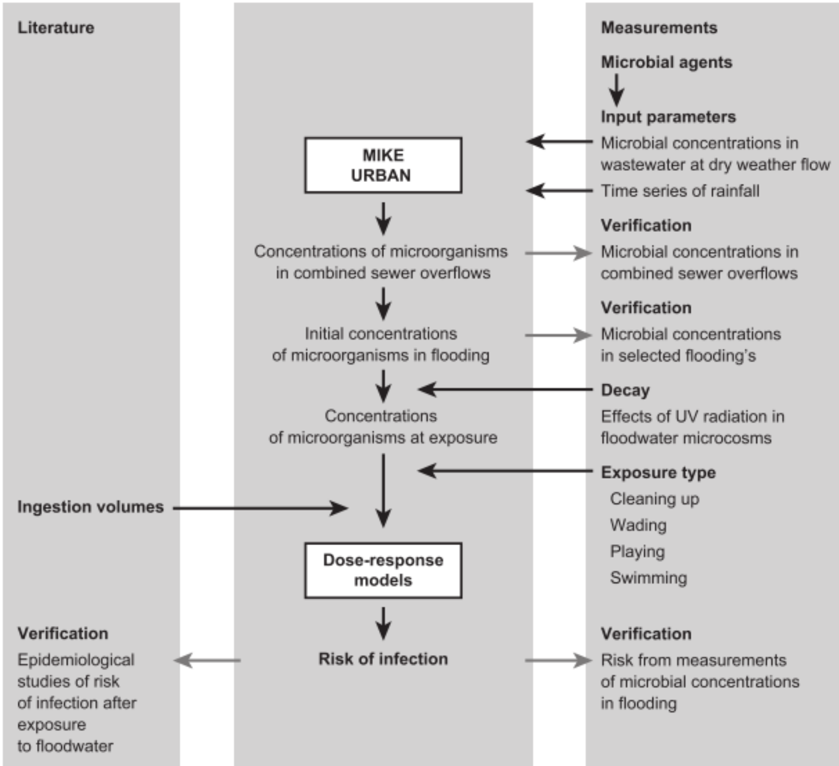

Figure 8. The approach of the hydrodynamic model to simulate pathogen concentration for QMRA (Andersen, 2015)

Hydrodynamic modelling can bridge the gap between the estimation of the concentration of microbial pathogens in floodwater and the related health risk. Models can also be used to estimate the potential spread of contaminants in urban waters and to identify areas that may be at high risk of contamination. These models can also be used to evaluate the effectiveness of different mitigation and management strategies to reduce exposure to contaminated urban waters and decrease the burden of disease in the community. For example, health risks that are caused by drinking and swimming exposure in the Danube River (Schijven et al., 2015) and the Göta älv in Sweden (Sokolova et al., 2015) can be reduced by controlling the contaminated sources, such as WWTP and human / animal deposition. In another study, LID-supported solutions for stormwater utility (low impact development) were identified to ensure microbial health risk at an acceptable level (Ishaq et al., 2022). In addition, by using the hydrodynamic model, the dynamic/transport of pathogens can be estimated including spatial and temporal factors. Therefore, the high-risk area can be estimated (Kazama et al., 2012).

However, while studies on microbial pollution in flood water were conducted in both developed countries and developing countries (Table 1) (Table 2), the risk of microbial health was dominant in developed countries and was less consideration in developing countries (Rui *et al.*, 2018). The reason is the lack of calibration and validation data for flood and microbial simulation. Using referenced data of concentrations or exposure pathways from the literature review can be an easy way, but can lead to underestimating or overestimating the risk of infection. The difference in geographic and habits/perceptions of residents from case to case can lead to an under or estimate of the infection risk. Therefore, the approach of using the hydrodynamic model and QMRA needs to have more implementation to limit the uncertainty of QMRA (Addison-Atkinson *et al.*, 2022).

Another limitation is that QMRA has not included the different symptoms of the disease in individuals. Although the number of people exposed was mentioned in some previous studies, it has not reflected the effects of disease on the individual and the exposed community. Therefore, the number of ill people, in general, may not reflect the suffering of people. We may not know the suffering and recovery of the exposed community. Thus, it is difficult to compare the vulnerability among communities. The next section indicated the approach to quantifying the loss of health which takes into account different potential outcomes of the disease.

2.3.3 Disease burden estimated by Disability-Adjusted Life Year (DALY).

- **Disease burden calculated by DALYs**

The burden of disease is the health consequences caused by adverse impacts measured by various measurements such as financial cost, morbidity, mortality, and quality of life (Murray and Acharya, 1997; WHO, 2004). DALY is one of the disease burden indicators to describe morbidity and mortality regarding years of lived with disability (YLD) and years of lost life (YLL) (Figure 10). The health consequences can be expressed as different levels of symptoms or death given by an infection (Figure 9). The severity of the disease is different based on age, sex, health status, etc. WHO (2002) used DALY to calculate the burden of disease caused by environmental hazards such as air and water pollution to public health (WHO, 2002). Until now, DALY has represented the health impacts of communities for various diseases in the regular WHO global disease burden reports.

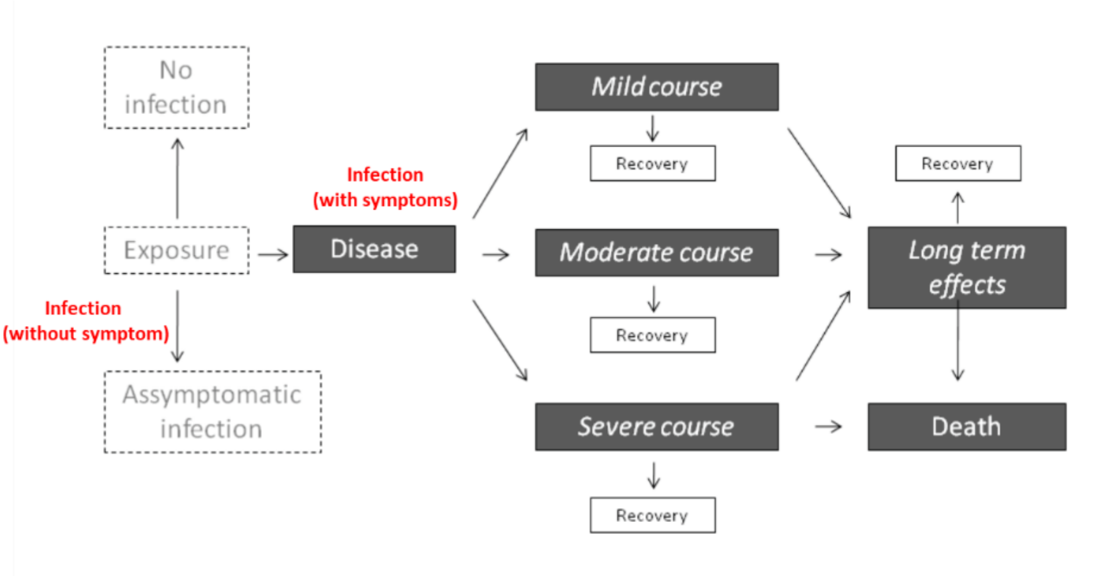

Figure 9. Diagram of possible courses of health outcomes for people with the starting point of exposure (adapted from Water Research Australia, 2013)

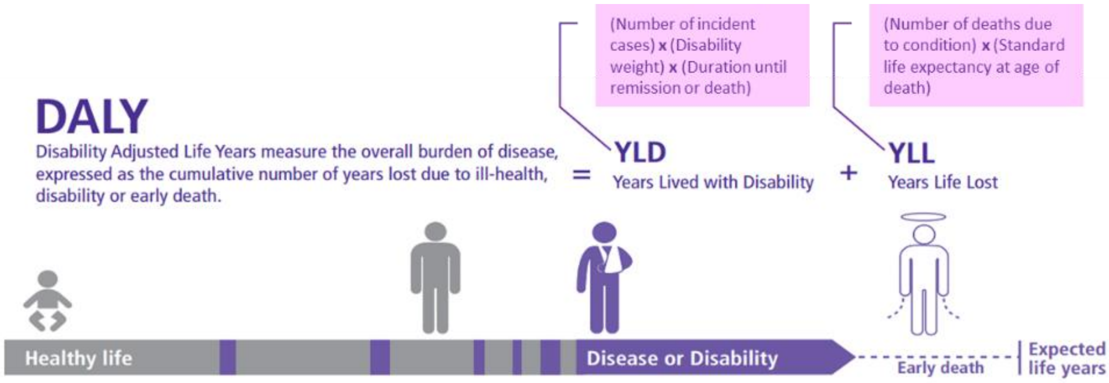

Figure 10. The concept of disability-adjusted life years (Anand and Hanson, 1997; Murray and Acharya, 1997; WHO, 2016) (Adapted the picture from the *National Collaborating Centre for Infectious Diseases, 2015*)

DALY (equation (2.6) combines years of life lost (YLL) (equation (2.7) and years lived with disability (YLD) standardised using severity weights (equation (2.8) for incident cases of the health condition (Murray and Lopez, 1994)

$$DALY = YLL + YLD \qquad (2.6)$$

The years of life lost (YLL) corresponds to the number of deaths multiplied by the standard life expectancy at the age at which death occurs. The basic formula for YLL is the following for a given cause, age, and gender.

$$YLL = N \times L \qquad (2.7)$$

where:

N = number of deaths;

L = standard life expectancy at age of death in years

Because YLL measures the incident stream of lost years of life due to deaths, an incidence perspective is also taken for the calculation of YLD. To estimate YLD for a particular cause in a particular period, the number of incident cases in that period is multiplied by the average duration of the disease and a weight factor is applied that reflects the severity of the disease on a scale from 0 (perfect health) to 1 (dead). The basic formula for YLD is as follows:

$$YLD = I \times DW \times d \qquad (2.8)$$

where:

I = number of incident cases

DW = disability weight

L = average duration of the case until remission or death (years)

Almost a quarter of the global burden is attributed to environmental risks such as pollution of air, water, soil, etc. (Prüss-Ustün *et al.*, 2016). Therefore, a greater understanding of the burden of environmental diseases and interventions can give the chance to reduce disease burden globally (Knol, 2005; Prüss-Üstün and Corvalán, 2007).

- **Application of DALYs in environmental pollution**

The of the disease of the burden calculation is considered the next step in the assessment of health risk (*Figure 11*). In the first step, health impacts are the probability of infection/illness calculated through the dose-response relationship of the pollutant and receptor. Then, the DALY estimates healthy years lost due to several symptoms of illness or death.

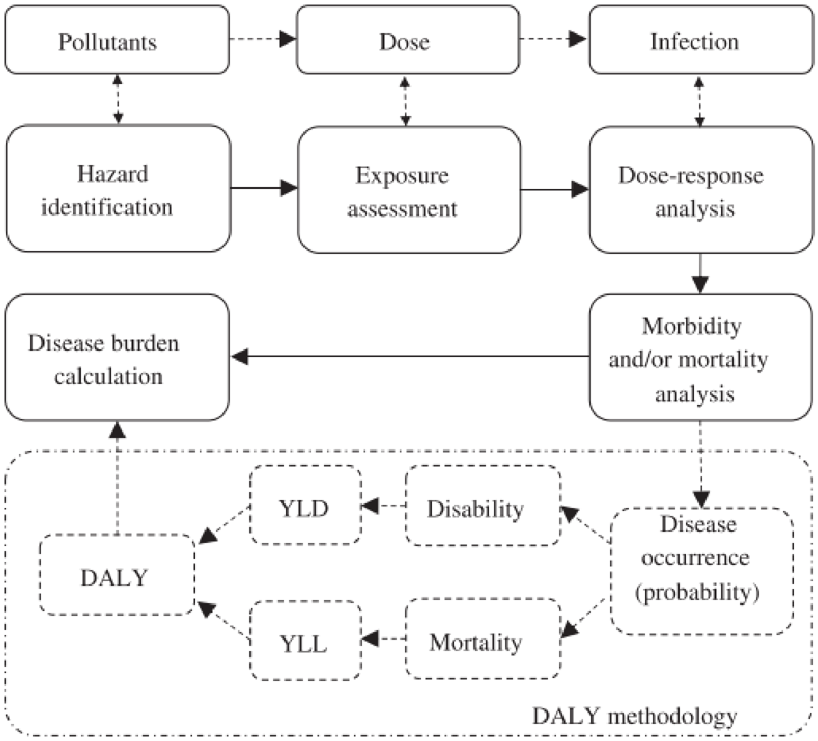

Figure 11. Methodological framework for assessing health risk and quantifying the burden of disease with DALYs due to environmental pollutants (Gao et al., 2015).

DALY has been commonly applied to identify public health risks associated with certain environmental hazards. Most studies focused on foodborne pathogens, while waterborne diseases have been considered recently. For example, the disease burden was quantified to evaluate the attribution of microbial pathogens in recreational water (Timm *et al.*, 2016), reused water (Gao *et al.*, 2016b), and drinking water (Machdar *et al.*, 2013; Uprety *et al.*, 2020).

In terms of water-related issues, interventions of reducing health risks were given to meet the WHO standard, for example, select interventions for drinking water treatment (Petterson, 2016). WHO guidelines for drinking water quality (10^{-6} – 10^{-5} DALYs per person per year) are the standard for a tolerable burden of disease (WHO, 2011). The WHO health-based targets for drinking water quality were also used to compare, for sanitation workers, farmers, and urban communities living near wastewater treatment plants, which are 10 - 100 times larger than the standard (Fuhrimann *et al.*, 2016). Ishaq et al. (2022) predicted a high disease burden caused by microbial pathogens in stormwater compared to the DALY standard of WHO. The results give some mitigation scenarios for the reuse of stormwater for landscape irrigation and recreational purposes for residents (Ishaq *et al.*, 2020, 2022).

The DALY method provides a potential tool for estimating the health consequences of environmental pollution, quantifying the vulnerability among the exposed communities, and providing the appropriate mitigations to ensure public health in flood-prone areas. However, the application of DALY to environmental disease burden still has some limitations. First, the lack of available data to quantify DALY is due to difficulty in quantitatively quantifying hazards, pathways of exposure, and exposed people. Second, data to validate DALY is usually referenced from epidemiological reports, which may not be available in some local areas, especially in LMICs (Gao *et al.*, 2015).

In addition, while DALY has been applied in various studies related to water, the disease burden caused by microbial pathogens in floodwater has not been fully indicated yet. In particular, issues need to be considered more often in the areas where flooding annually due to heavy rainfall and/or high tide and frequent accidental exposure to polluted floodwater.

2.4 CONCLUSIONS

The review study emphasises the need to quantify the health impacts as the social sustainability component of FRM. It also shows that there is a lack of knowledge about social vulnerability, especially regarding accepted and harmonized assessment methods of health impact. Urban flooding greatly spreads microbial pathogens from pollution sources to floodwater, especially sewer water. The QMRA approach complemented by a hydrodynamic model has been successful in analysing the microbial health risk for direct exposure of exposed individuals during floods. The burden of DALY disease is a useful tool to express the health consequences, including morbidity and mortality for exposed individuals and communities.

However, there are still some remaining gaps that need to be filled in assessing the health consequences of microbial pathogens in floodwater. Rarely are studies that analyze accidental exposures.

Firstly, an approach to involve the pollution sources, transmission routes and receptors to understand the pathways of exposure pathways and transform the concentration of the microbial pathogen into health consequences which include the burden of the probability of infection, but also the disease due to microbial pathogens in floodwater. Especially in LMICs, the evidence data on pathogenic microorganisms in flood-related water are very limited. As a result, it limits the research on microbial health risk assessment for these areas.

Second, the risk of microbial health was only studied for an individual exposed, while the health consequences have not fully involved the impact on the exposed community. In FRM, the impact is considered not only on the individual but also on the exposed groups to identify the vulnerability of the community. ‘Crucial research is also required at the microscale on the individual, household, and community vulnerability and response, both to identify increased risk to social groups and to support efforts to strengthen the grassroots coping capacity' (IFRC, 2004). Therefore, health impacts should include the assessment of the exposed community.

Third, in the QMRA and DALY approaches, it is important to collect quantitative data, especially related to microbial pathogens. Although data on microbial pathogens can be measured, simulated, or interpolated, it is not well understood how these data affect health outcomes (i.e., infection risk and disease burden). Additionally, analysing the parameters of sensitivity to health outcomes provide potential parameters to reduce microbial risk. This is important for the FRM in terms of social disadvantages to improve the adaptability of exposed communities in flooded areas.

The next chapter describes the development of the methodology for assessing microbial pathogens in flood-related waters and quantifying the health consequences due to microbial pathogens through traffic activities, which are common and unavoidable activities of residents during flood time.

3

METHODOLOGY FRAMEWORK FOR MICROBIAL HEALTH RISK ASSESSMENT THROUGH TRAFFIC EXPOSURE

This chapter describes and justifies the research design to assess the microbial health consequences of traffic exposure during urban flooding. First, it demonstrates the research design theory for quantifying the health consequences, including infection risk and disease burden due to microbial pathogens in floodwater. Second, the chapter describes the data collection, data analysis, and the steps of research to answer the corresponding research questions. Lastly, the chapter reflects on some shortcomings of the methodology and how their impacts can be mitigated in the scope of the study.

This chapter was presented in the conference presentation.

Oral presentation: Huynh, Thi Thao Nguyen, Gerald Corzo Perez, Assela Pathirana and Chris Zevenbergen. 2021. “A new concept to implement in a Spatiotemporal Health Impact Assessment related to waterborne pathogens in urban floodwater using QMRA, disease burden by DALY and 1D2D hydrodynamic model. Case Study: Ninh Kieu District, Can Tho City, A Lower Mekong Basin.” In the *17th International Conference on Urban Health*. Virtual conference.

3.1 INTRODUCTION

The previous chapters showed that direct exposure to floodwater causes health risks due to microbial pathogens. This research aims to assess the risk of microbial health and to quantify the disease burden for exposed people through traffic activities, which is a common and unavoidable activity during urban flooding, especially in low-income countries. Some existing knowledge and applications were also reviewed in terms of microbial health risks in floodwater, but the approach to quantify health loss has not fully considered direct exposure to floodwater. This chapter covers three main parts to identify and justify the research design.

Firstly, approaches to assess the health risk (that is, QMRA) and quantify the disease burden (that is, with DALY) are justified in this chapter. Furthermore, the 1D2D hydrodynamic model is described to support microbial pathogen simulation of the transportation in floodwater and the quantification of the health outcomes.

Secondly, in this chapter, the research strategy is developed to conduct the corresponding research questions indicated in the previous chapter. The main focus is on the natural relationship between health consequences and waterborne microbial pathogens through exposure to floodwater. The contents of the subquestions are: (1) identify the microbial threats; (2) develop the flood and floodwater quality model; (3) assess the microbial health risk and quantify the health outcomes: with aggregated microbial concentrations, and (4) with simulated microbial concentrations.

The third part of this chapter describes the method for collecting/analysing data on microbial pathogens, exposed people, and relevant variables to calculate the microbial health risk, quantify the burden of the disease with DALY, and develop the hydrodynamic model.

The methodology in this chapter is applied to a case study which is described in the next chapter (Chapter 4). Attention is paid to the collection of the required data in that same chapter. The research results are given in Chapter 5, chapter 6, chapter 7, and chapter 8.

3.2 RESEARCH PHILOSOPHY

The research philosophy was based on quantification of microbial health risk and disease burden with DALY (Figure 12).

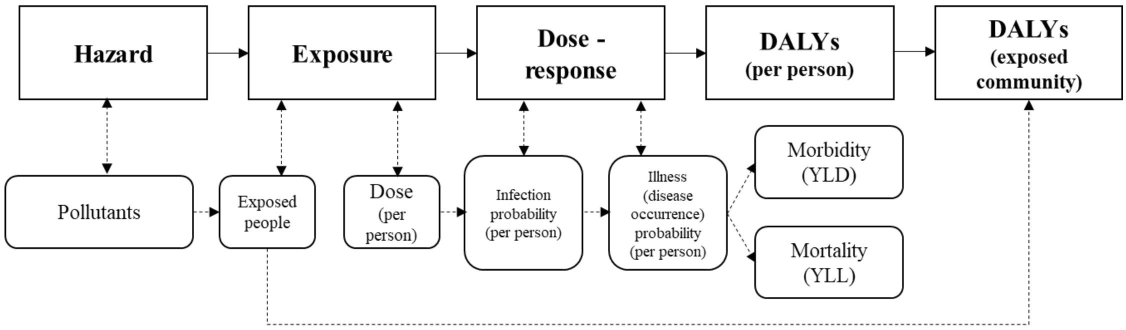

Figure 12. The methodological framework of environmental disease burden research (with the DALY metric for exposed individuals and community (adapted from (Havelaar and Melse, 2003; Haas *et al.*, 2014)

Given the aim of this research, the dose-response relationship in the QMRA approach was used to calculate the probability of infection and disease. The rationale for choosing QMRA is that the availability of the dose-response relationship between the microbial pathogen and the exposed individual allows the infection risk and illness risk with different exposure scenarios. Another rationale is that in case the illness cases (which are essential to DALY calculation) are not available by epidemiological study, the illness cases can be deduced from infection and illness probability for the people exposed (Crabtree et al., 1997; Soller et al., 2015).

In addition, the study used the DALY methodology to quantify the microbial health consequences. Although there are several methodologies to represent the disease burden such as monetary and nonmonetary metrics, this research chose DALY – a non-monetary metric with several rationales. Firstly, DALY involves morbidity and mortality that capture all possible health outcomes which occurred from exposure to infection and illness with different symptoms. Based on the qualitative health outcome tree (Figure 9 - Section 2.3.3 in Chapter 2), the DALY approach gives the quantitative calculation by weighting the multiform health loss with severity, duration of symptoms, life expectancy, and the number of affected people. The second rationale was that DALY represents the life reduction by time (i.e., year) for the affected individual, but also for the communities. Therefore, comparison and prioritizing can be done between areas, communities, and countries, for example, disease burden caused by microbial pathogens in the river for exposed communities (Fuhrimann et al., 2017).

In addition, apart from the conventional approach of sampling and analysing water samples to identify the concentration of microbial pathogens in floodwater, this research applied the advanced approach of simulating microbial pathogens from urban flood modelling. The 1D2D hydrodynamic model approach was applied to simulate the dilution and transportation of microbial pollutants. The one-dimensional hydrodynamic model (1D) simulates the transport and dilution of wastewater and rainwater from the drainage system. The dilution of sewage water and stormwater on the surface is modelled in two-dimensional (2D). Incorporates advection-dispersion to describe the transport of pollutants in floodwater. The study simulated the concentrations in urban floodwater originating from the pollutants in the dry weather flow, mixed and transported in the rainwater and surface runoff. In contrast to physical and chemical pollutants, microbial pollutants have growing and dying stages. However, in a short period of inundation, the microbial pollutants are considered inert. Since the short duration of floods (up to 1-2 hours) may not affect pathogen decay or growth of pathogens, these factors are not considered (ten Veldhuis et al., 2010).

The reason for choosing both approaches to identify microbial pathogens is that the conventional-based approach provides initial data on the microbial concentrations in floodwater, but in reality, they are difficult to take and may also may not represent the microbial pathogens in the flood area. These disadvantages can lead to overestimating / underestimating the microbial health risk. Therefore, with the simulated microbial pathogens from the model-based approach, the infection risk and disease burden are estimated for flooded areas with another quantitative data source of microbial concentration. Furthermore, given the purpose of the research, microbial concentration data from both approaches allow the study to analyze the changes to the final result of health consequences (ie, infection risk and disease burden).

3.3 RESEARCH DESIGN

3.3.1 Methodology framework to analyse microbial concentration in flood-related waters

In this section, the methodology is developed to answer research question 1 on analyzing the microbial pathogens in floodwater that are a microbial hazard for health risks and identifying the sources of microbial pathogens in floodwater (Figure 13). The results of applying this methodology to the case study are shown in Chapter 5.

First, the pathogens of interest for the case study were identified on the epidemiological data. For example, it can be extracted from the report on common gastrointestinal disease cases such as diarrhoea caused by *Vibrio cholera* in Dhaka (Bangladesh) (Mark *et al.*, 2015). The microbial detection in literature reviews can also be a reference source.

Second, the sampling strategy for flood-related waters (that is, surface water, sewer water, floodwater) was developed. This study applied a cross-sectional time horizon to take water samples in certain flood events. The molecular analysis was chosen to detect enteric pathogens.

Finally, in conjunction with the descriptive analysis, the study used the Mann–Whitney U test to identify the probability of microbial concentrations of sewer water in floodwater. Furthermore, the correlation coefficient among microbial pathogens was determined to test whether they have a relationship in flood-related waters.

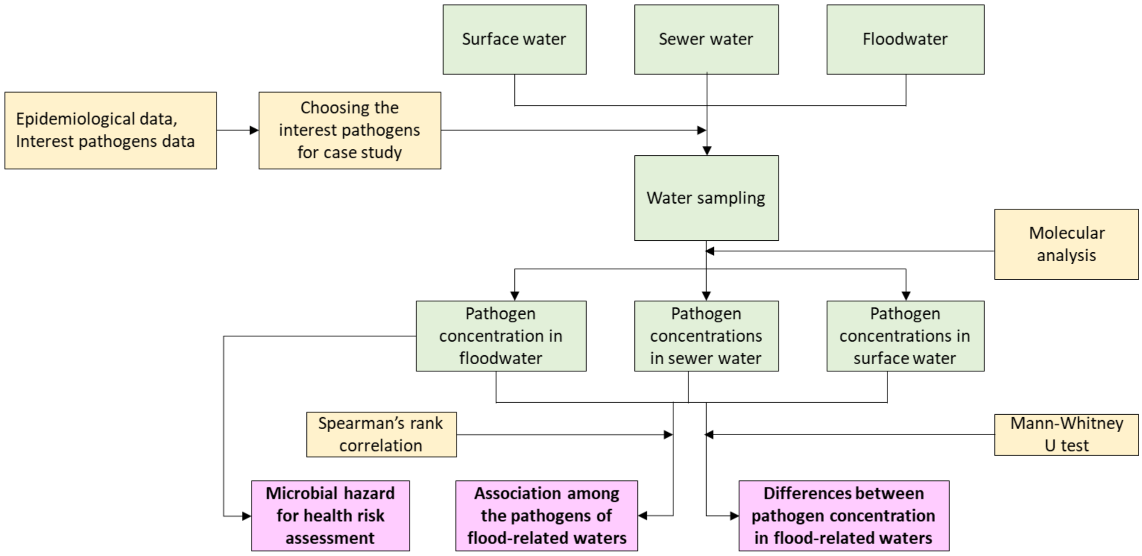

Figure 13. Methodological framework to collect and analyse microbial pathogens in flood-related waters

3.3.2 Methodology framework to assess microbial health risk and to estimate the disease burden with aggregated microbial concentrations for traffic exposure

This section describes the methodology to answer *research question 2* about exposure assessment and *research question 3* about health outcomes. Figure 14 illustrates the burden of approach to quantifying the disease due to microbial pathogens for exposure to traffic. The microbial hazards identified in *research question 1* were applied to calculate the health risks.

The approach to identify exposed people through traffic activities in a flood event included identifying the exposed person density (exposed people/m^2 flooded area) on 1 flooded street, then, extrapolating to other flooded streets. Manual traffic counting was used to identify people exposed on the street during a flood event. Since it can be difficult, if not impossible, to observe the change of the flooded area on the street that affects the density of exposed people, it was assumed that the flooded area (m^2) on the observed street has not changed much. The observation of the flooded areas was chosen as the largest flooded area. The traffic scale factor was used to correct for the difference in exposed person density among streets. This approach was applied when data on other flooded streets was available. It may be difficult to observe all flooded streets in a flood event. These data can be referenced in the local report of the corresponding authorities in flood management. Street cameras can also help collect data about the lengths and widths of flooded streets.

The probability of infection and illness per person was calculated based on the QMRA methodology. Then the DALY approach was applied to calculate the DALY per person and for exposed people per flood event. The results of applying this methodology to the case study are shown in Chapter 6.

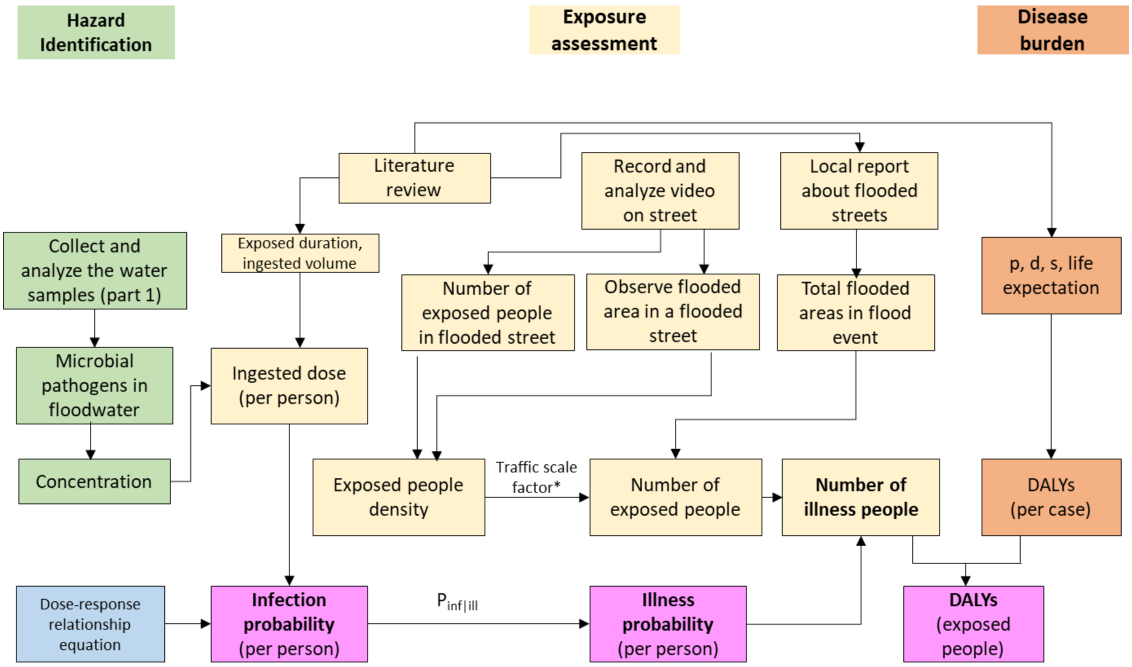

Figure 14. Methodological framework to assess the risk to microbial health and estimate the disease burden due to pathogens in floodwater for exposed people through traffic exposure in a flood event

3.3.3 Methodology framework to develop flood and water quality modelling to assess microbial pathogens in floodwater

This section describes the methodology to answer *research question 1* on microbial concentration in floodwater. This methodology applies the 1D2D hydrodynamic model to simulate microbial pathogens in floodwater. The input data and the steps to develop the urban flood and floodwater quality model are presented in Figure 15. The urban flood model was developed based on hydraulic data (drainage system), hydrometeorological data (rainfall, river water level) and spatial data (land use). The measured sewer water levels collected during the water sampling campaign were then used to calibrate the model. Pollutant concentrations in sewer water under dry weather were used as input for the water quality model. This model was calibrated using measured pollutant concentrations in sewer water collected from the water sampling campaign. Finally, the 1D model was coupled in 2D to simulate the microbial pathogens in floodwater. The results of applying this methodology to the case study are shown in Chapter 7.

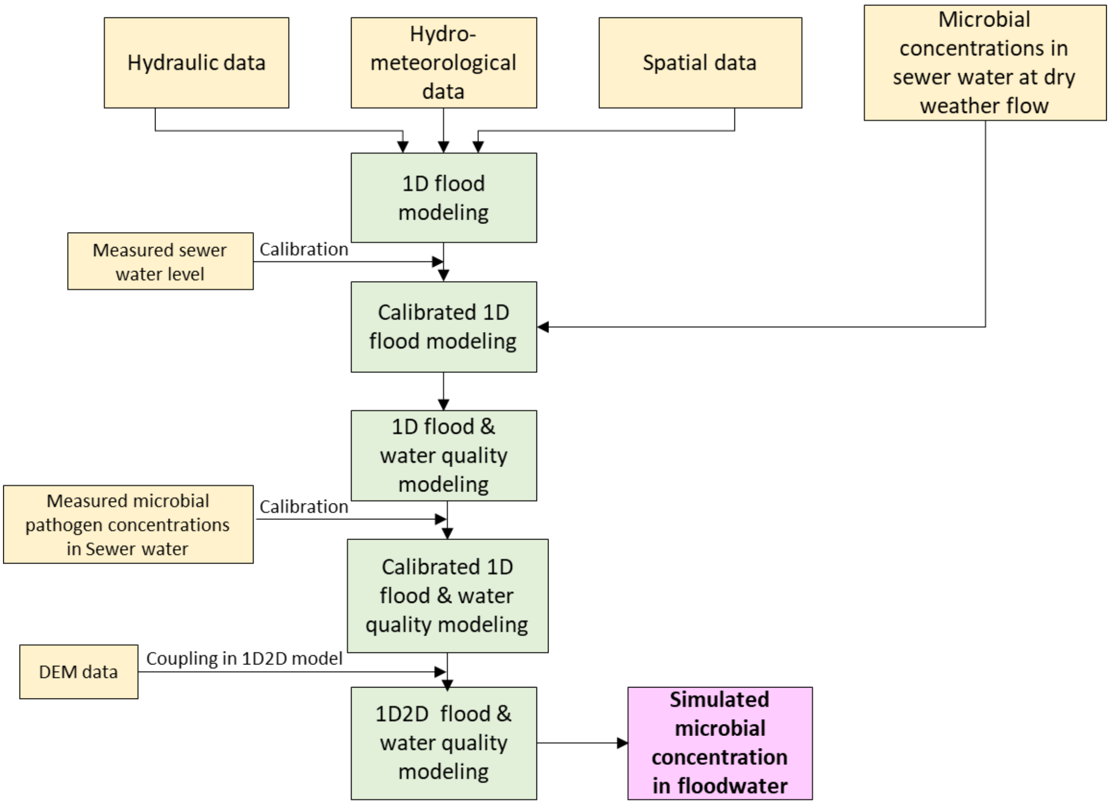

Figure 15. Methodological framework to develop flood and water quality modeling to assess microbial pathogens in floodwater

3.3.4 Methodology framework to assess the risk to microbial health and estimate the disease burden with simulated microbial concentrations for the traffic exposure

This section describes the methodology to answer *research question 2* and *research question 3*. Here a similar approach to the methodology of Section 3.3.2 is followed in *the use of* QMRA and DALYs is followed here, however, this methodology applied the advanced approach of using the 1D2D hydrodynamic model to improve the calculation of infection risk and disease burden (Figure 16).

The 1D2D flood model simulates the microbial pathogens in floodwater. Calculations were carried out in the flooded grid cell of the model. Therefore, the duration of exposure is the time that the exposed individual passes through the flooded cell. Instead of using the density of exposed people, the density of people on the street (people/m^2) was calculated. The rationale is that the density of exposed people changed over time due to the change of flooded areas on the street, which causes high uncertainty in health outcomes. Therefore, the density of people relied on the observed data of people on a certain street at a certain time (people) (in this case during the flood) and the area of this street (m^2). The total of exposed people or people ill were the sum values at all flooded grid cells (equation (3.1). The burden is the total DALY of ill people in all flooded grid cells. The results of applying this methodology to the case study are shown in Chapter 8.

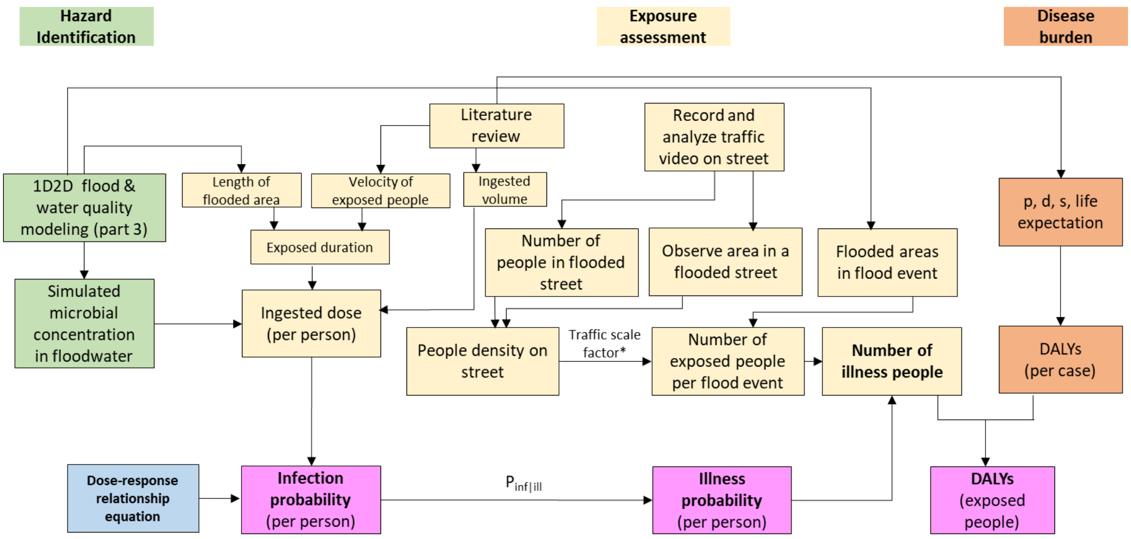

Figure 16. Methodological framework to assess the risk to microbial health and estimate the disease burden due to pathogens in floodwater for exposed people through traffic exposure in a flood event with the combination of 1D2D hydrodynamic model

* Traffic scale factor: used to correct the traffic density in each flooded street due to the difference in people density between streets.

$$\text{Total DALYs} = \sum_{j=1}^{m}(\text{DALYs})_i \qquad (3.1)$$

Where:
j: flooded grid cell;
m: number of grid cells from the urban flood model.

3.4 Conclusions

This chapter started by restating the research objective and questions to understand the natural relationship of health consequences (ie, infection risk and disease burden) related to microbial pathogens in floodwater through traffic activities. Thereafter, it presents a methodology framework in response to research questions about the use of quantitative data of traffic exposure and microbial hazard to quantify the risk of infection and estimate the disease burden with DALY. A quantitative methodological approach is used based on the dose-response relationship in QMRA and the potential course of illness to quantify the disease burden. Furthermore, this chapter provides two ways of access to data and contextual appropriateness by collecting and analysing quantitative data of microbial hazard in floodwater in two ways: (1) by measuring flood-related water samples and (2) by simulating flood and water quality modeling.

Furthermore, there are some limitations of the methodology, including a lack of data to validate the hydrodynamic model and the health-risk outcomes (illness people, DALYs). In the future, when these data are available, the methodology can be improved. In the scope of this research, with the highlight of value despite its limitations, the methodology indicated the novel approach to explore the linkage of microbial pathogens and the health consequences of traffic exposures in flooding. The next chapter (Chapter 4) will present the chosen case study and the methodology will be applied to analyse the data and test the hypotheses in the following chapters.

4

Brief background of the case study - Can Tho city, Vietnam

Following the methodology chapter that justifies the approach to explore the link between microbial pathogens in urban floodwater and human health risk through direct exposure, this chapter shows the case study in Ninh Kieu district, Can Tho city, Vietnam. This chapter describes urban flooding, flood-related water quality, and the social behavior related to exposure of residents during flood time. These data will be used as input data to conduct the methodology in the next chapters.

4.1 Introduction

The city of Can Tho, which has around 1,389.59 km^2, is one of the three main urban areas in the Mekong Delta. This area is located southwest of the Hau River – a branch of the Mekong River (Figure 17). The Hau River is a benefactor of this city and deposits large amounts of alluvia in rice fields through annual floods. Can Tho city is one of the vulnerable areas to climate change, because of its flat topographic position with 1m-2m above mean sea level.

The Ninh Kieu district is the central urban area in the city of Can Tho and is the case study of this research. Many commercial buildings, schools, hospitals, markets, tourist areas, and almost administrative offices of Can Tho city are located in the Ninh Kieu district (Figure 19). This district is the densest urban centre in Can Tho with 10,400 people/km^2, while the average population density for Can Tho is 859 people/km^2 (GSO, 2019). The total area of the district is about 2,900 ha. However, the available sewer system data only cover part of the district (660 ha), to which we applied the urban flood model (Figure 18).

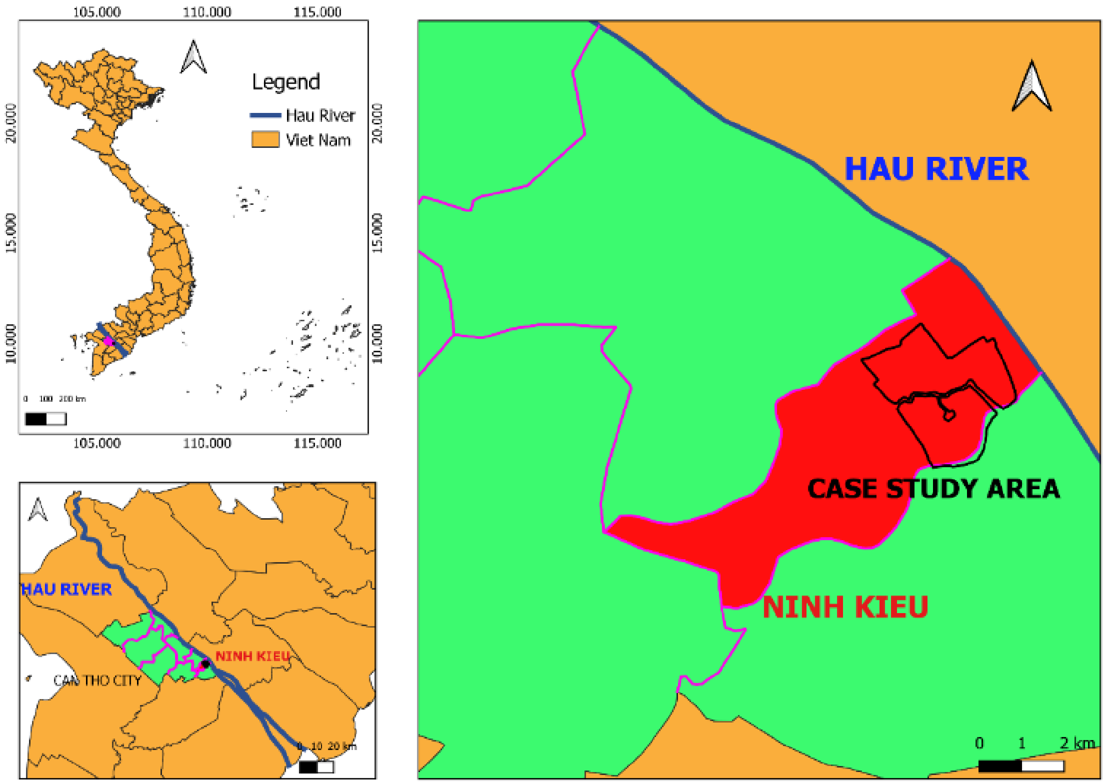

Figure 17. Maps of Vietnam, Can Tho city and case study area (bounded by the black line) within Ninh Kieu district

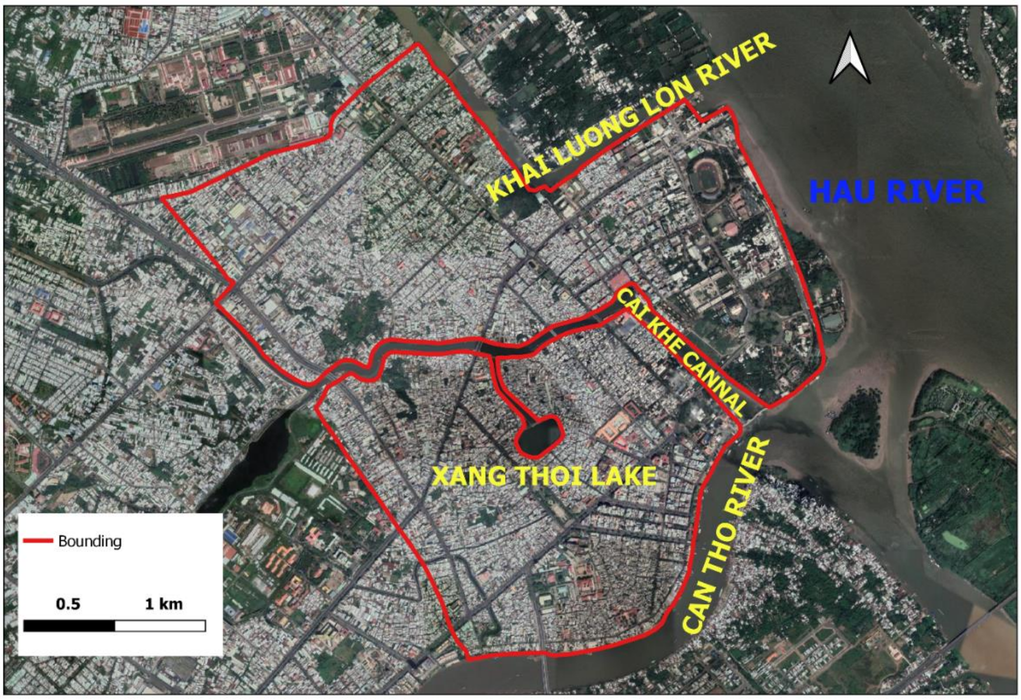

Figure 18. Study area bounded by the red line in the Ninh Kieu district
(Background Google ™ satellite data)

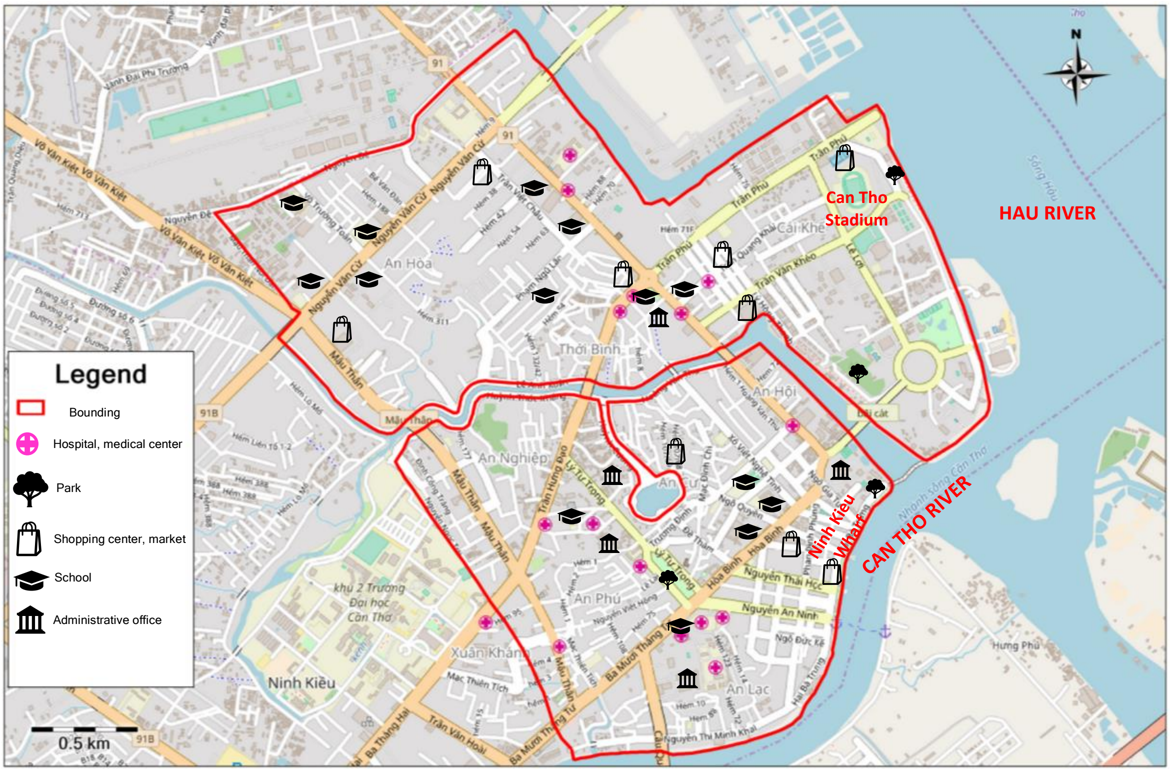

Figure 19. Some public locations in case study area in the Ninh Kieu district
(The base map is from OpenStreetMap)

Flooding in Can Tho is strongly affected not only by the Mekong upstream but also by high tides and heavy rain. Tho has two seasons: the monsoonal rainy season, and the dry season which occurs from June to November and December to May next year, respectively. During the rainy season, high-intensity rainfall accounts for nearly 90% of annual rainfall. At that time, flows from upstream areas (Myanmar, Thailand, Laos, etc.) increased the water level on the Mekong River. In addition, a high level of Northeast wind blows to the South and combines with Coriolis forces from the South that cause an increase in sea level at the mouth of the Mekong River. These three factors cause widespread flooding in Can Tho city, which is known as the annual ‘floating season’. Inhabitants, especially in rural areas, benefit from this ‘floating season’. This season brings aquatic products, large quantities of alluvia, and water resources that enrich the floodplain (Tuan *et al.*, 2007). In addition to the benefits that flooding annually brings to the area, some adverse effects cause disadvantages to residents, especially in urban areas, for example, urban flooding and polluted surface water. There are some other disadvantages that the case study must face due to flooding-related issues.

4.2 URBAN FLOOD AND ITS IMPACTS IN NINH KIEU, CAN THO CITY

4.2.1 Flooding in Ninh Kieu, Can Tho city

This urban area faces several issues during flood times, such as flooding and surface water pollution. In recent years, floods occurred more frequently due to not only the Mekong upstream, but also high tides and heavy rain. In 2000, a rare flood event that inundated around 11,000 houses had a maximum water level of 1.79 m in Can Tho city. In 2011, the maximum water level reached 2.15 m in Can Tho. Almost all parts of this city experienced flooding caused by annual upstream, high tide, and heavy rain (Leloup *et al.*, 2013). Pham et al. (2010) showed that around 230 thousand households representing 70-75% of households in Can Tho suffer from drainage problems, for example flooding and water pollution (Pham et al. 2010). The annual assets from the flood risk damage in Can Tho were estimated at around 3340 thousand dollars, which was approximately 2.5% of the total annual income of this city (Chinh *et al.*, 2017).

The flood affects central urban areas such as Ninh Kieu and Binh Thuy district, especially when there is high intensity of rainfall or high tide occurs. Flooding currently occurs annually at least 2 to 3 times or even 5-6 times, especially during the rainy season, inducing water accumulation in streets, with water depths often of a few centimetres up to 20 to 30 cm (even up to 50 cm in some places) for about a few minutes to a few hours. The highest water level in Can Tho occurs regularly in “floating season”. The highest water level time in a flood event usually coincides with the peak of the tide (CCCO and ISET, 2015).

In Ninh Kieu district, the inner city usually floods with heavy rainfall in a short time, while the area near the river floods by high river water levels due to upstream flow and/or high tide (Huong and Pathirana, 2013). Despite the higher terrain compared to a rural area, local flooding usually occurs due to the high imperviousness and insufficient drainage networks in the urban area. This is also characteristic of developing countries, where measures often do not help efficiently reduce the impact of the flood (Balica et al. 2014). Furthermore, this area faces a lack of pumping systems to evacuate water and current blockages in gullies by garbage along the streets (Leloup *et al.*, 2013).

4.2.2 Impact of flooding in the case study area

(i) Impact on water quality;

Untreated wastewater in the combined sewer system backed up and pollutes floodwater during the flooding period. Figure 20 summarises the urban water during flooding in the Ninh Kieu district.

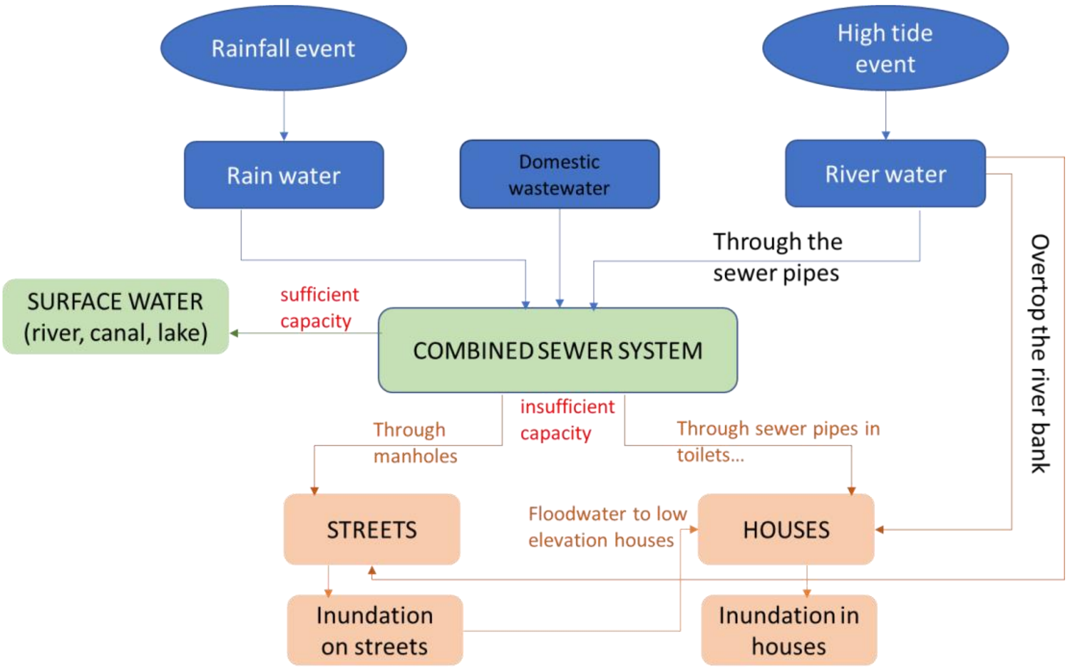

Figure 20. Diagram of urban water during floods in Ninh Kieu district

The drainage system in Ninh Kieu is a combined sewage system. Almost 98.8% of the households in the Ninh Kieu district have septic tanks with two chambers. The effluent of the septic tank is commonly discharged into the combined sewer system (82%), and the rest flows directly into surface water (17.1%) or absorbs into the soil without any treatment (0.9%) (Can Tho City People's Committee, 2015). According to the report of the Can Tho water supply and sewerage authority, only 2% of households in Ninh Kieu regularly maintained or pumped solid sludge waste from septic tanks. The first domestic WWTP for the urban area (Ninh Kieu district) has been built. At this time, this WWTP has not finished yet. Current untreated wastewater is still discharged into receiving water bodies (eg, river/canal, sewer systems) causing pollution. Furthermore, this polluted water can be mixed with flooded water in urban areas (Nguyen et al., 2014).

For surface water, during the October 2013 flood event, the coliform concentration in river water was higher than the national standard for irrigation or transportation (QCVN08:2008/BTNMT) from 5 to 50 times. All surface water during flooding contained high concentration pollutants, such as TN, TP, COD and BOD, especially *Escherichia coli*, and total colons range from 1,536MPN/100ml to 83,083 MPN/100ml (Salingay *et al.*, 2014). For floodwater, the concentration of Coliforms was not much different in the sewer and surface (river) water since a (large) part of the sewer and flooded water originated from the river water (Nguyen et al. 2014).

Wastewater is the main cause of water pollution in Can Tho city. Untreated industrial/domestic wastewater is usually discharged directly into a river/canal. Waste from agricultural activities, especially animal production, contains a high concentration of *E.coli* and *Salmonella*, which are also found in most river water samples (Birkmann *et al.*, 2012).

Domestic wastewater and garbage that are discharged illegally into surface water are the main sources of pathogen concentration. For example, in the Ninh Kieu district, the total garbage collection is 296 tons / day, which is 90%. 10% of the garbage is still discharged illegally. Of these, 50% of the garbage is discharged into sewer drainage, river/canal.

Although Can Tho city has many efforts to improve water quality, domestic wastewater treatment and drainage systems are still insufficient, especially during flood times (Leloup *et al.*, 2013). Water quality monitoring is reported annually for surface water. However, microbial pollution has received little attention, especially flood-related water quality. Furthermore, contaminated flooded water can affect local citizens, especially with health risks. Currently, there is very limited consideration of this aspect.

(ii) Impact on human health

Flooding in the city of Can Tho affects the daily life of people. For example, collapsed and damaged houses or drownings are serious to children, elderly people, disabled people, poor people, and women. Lost crops, aquaculture ponds, and business loss are the cost during flooding time (Clemens, 2014).

The other disasters that residents usually face during urban flooding are the effects on daily living activities, for example, cleaning up houses, maintaining houses to avoid inundation, direct exposure to flooding, and other relevant physical/mental health impacts influenced by flooding. While activities occur frequently in flood events, these intangible and indirect damages have been understudied. During floods, most residents in Ninh Kieu are exposed to floodwater through traffic activities, especially motorbikes. The flooding time coincides with crowded morning and afternoon/evening traffic activities to go to/back offices/schools in Ninh Kieu (5:00-7:00 and 17:00-19:00). The most common residents on the street are employees, students, and maybe housewives who pick up the students. The population of Ninh Kieu (2016) was around 300,000 people. The percentages of employees by types of economic activities and students were respectively 74% and 7% compared to the total population in Ninh Kieu (Can Tho City Statistical Office, 2016). In Vietnam, most people use motorcycles for traffic activities (Kim Oanh *et al.*, 2012; Tang *et al.*, 2020). The percentage of motorbikes, private cars, and buses compared to the total number of vehicles on the streets of Ninh Kieu was 88% – 99%, 0.01% - 0.4% and 0.01% - 0.1%, respectively (Bang *et al.*, 2018). Therefore, direct exposure to polluted floodwater on the streets is unavoidable for a large proportion of residents of the Ninh Kieu district. Exposure to polluted floodwater can pose a health risk due to microbial pathogens. Nguyen et al. (2017) predicted the risk of microbial infection due to *E. coli* and *Salmonella* in floodwater through direct exposure to polluted floodwater walking in the Ninh Kieu district (Nguyen *et al.*, 2017a).

Although the reasons and pathways are still unclear in the local area, some epidemiological reports showed an increase in gastrointestinal diseases in the flooding months in Can Tho city. According to the Department of Health and Social Care in Can Tho City from 2011- 2016, diarrhea was the main contributor to communicable disease cases in the flooding months. Common gastrointestinal diseases were diarrhoea (usually caused by pathogenic *E. coli*, rotavirus), typhoid fever (caused by *Salmonella* bacteria), bacterial dysentery (Caused by *Shigella* bacteria), and amine dysentery (caused by *Entamoeba histolytica* protozoa). In Ninh Kieu district, diarrhoea cases were recorded as high during the flood period, according to the annual health report of 2014 – 2016.

Furthermore, in the Mekong Delta, there is a relationship between climate change and the incidence of diarrhoea diseases (Phung *et al.*, 2014). After evaluating vulnerability including three criteria: exposure, sensitivity, and adaptive capacity, Phung et al. (2015) identified that areas located near main river channels and upstream of the Mekong delta in Viet Nam have a higher potential health risk of flooding (Phung et al. 2015). It has evidence of the relationship between the number of cases of disease and the maximum water level. The number of cases increases due to water pollution induced by rainfall and stagnant water rather than by floods themselves (Leloup *et al.*, 2013). However, the health risk associated with polluted flood water is not well considered in this flooding area, including Can Tho city. Therefore, attention must be paid to developing public health and intervention in local areas, especially during flooding.

Furthermore, increasing urban flooding and its impacts in the future due to urbanisation processes and climate change is one of the major challenges in Can Tho (Huong and Pathirana, 2011; Leloup et al. 2013; Borris et al. 2013). In 2050, Ninh Kieu district will be one of the most vulnerable areas to flooding (Balica *et al.*, 2013). Water quality and health risks, therefore, may change due to increased flooding in future scenarios.

Therefore, the vulnerability of social groups that are exposed to flood needs to be assessed in terms of water problems during floods, such as water service (e.g. water supply, wastewater treatment), health issues, and environmental management practises (Birkmann *et al.*, 2012).

4.3 CONCLUSIONS

The Ninh Kieu district is the socioeconomic area of the city of Can Tho. This urban area faces annual problems with flooding and water pollution. This chapter provides general information about the hydrometeorological situation in Ninh Kieu district, Can Tho city; the hydraulic data such as drainage systems and sewage systems in Ninh Kieu district. Besides, it highlights some severe issues, such as frequent flooding and polluted flood-related water quality (sewer water, surface water, floodwater) with microbial pollution originating from domestic wastewater. In addition, most residents are exposed to floodwater, as it coincides with the time go to work / home. Therefore, it clearly showed the elements of health risk in Ninh Kieu district with annual urban flooding, the potential microbial threats (hazards) in floodwater, and the exposure of many residents during flood time (exposure pathway). However, the health risk and burden related to microbial pathogens in floodwater through direct exposure to residents of Ninh Kieu have not been fully been considered.

The Can Tho City is a Rockefeller Foundation's 100 Resilient Cities Network (100R) member. Understanding public health vulnerability and, in particular, the relationship between health risks and waterborne pathogens in floodwater is essential to healthy and resilient cities (Singh et al. 2020). To deal with floods and their impacts, Can Tho City has many infrastructure projects and plans for short- and long-term periods. These plans require interdisciplinary efforts from the government and local people. Focusing on vulnerable groups is mentioned as one of the most important goals in these plans, for example, improving their awareness and improving adaptation capacity, especially in future scenarios. However, the relationship between polluted floodwater and health risk due to exposure to flood water is still unclear. Therefore, there is a need for more understanding of flood water and its impacts/risks to human health to support the local government in ensuring the living area of local people.

The input data from this chapter about urban flooding and the exposure behaviour of residents will be applied to the methodology in the previous chapter (**Chapter 3).** The results will be provided in the following chapters: microbial hazard **(Chapter 5),** microbial health risk with measured data of microbial pathogens, and quantitative data collected from traffic exposure assessment **(Chapter 6)**. Additionally, the urban flood and water quality model in **Chapter 7** simulates the microbial concentration in floodwater. The microbial risk assessment and disease burden calculation in **Chapter 8** is calculated based on (simulated) quantitative data on microbial hazards and traffic exposure.

5

ANALYSIS OF MICROBIAL PATHOGENS IN URBAN FLOOD-RELATED WATERS

The previous chapter addressed flood characteristics and flood-related water quality aspects, and potential health risks through direct exposure in the Ninh Kieu district. To investigate the health consequences, the occurrence and concentrations of microbial pathogens must be studied. This chapter focusses on an analysis of microbial pathogens in the flood waters of the case study area. Sewer water, surface water (river / canal / lake) and flood water were sampled before, during and after specific flooding events. Total nucleic acid was extracted from the samples and subjected to a quantitative polymerase chain reaction (qPCR) to detect certain enteric pathogens. The resulting pathogen data were compared between flood water and sewer water using the Mann-Whitney U test; correlations between different pathogens were determined using the nonparametric Spearman test. These data on enteric pathogens in flood waters will serve as a baseline for the next chapter, which deals with health consequences including infection risk and disease burden.

This chapter was published/ presented in:

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Poster presentation: **Huynh, Thi Thao Nguyen**, Hong Quan Nguyen, Phat Voong Vinh, Quang Hieu Ngo, Stephen Baker, Assela Pathirana, and Chris Zevenbergen. 2019. “Microbial Pollution in Flood-Related Waters in Urban Areas: A Case Study in Ninh Kieu District, Can Tho City of Vietnam”. In *IWA Water and Development Congress and Exhibition*. Colombo, Sri Lanka.

5.1 INTRODUCTION

The water pollution from extreme weather events is a major challenge for communities living in urban areas. However, few studies have investigated the real-time presence of enteric pathogens in flood waters due to difficulties in sampling flood water (i.e., anticipating and preparing materials for flood events), especially in low-to-middle-income countries (LMICs). Consequently, we lack data on microbial pollutants in urban flood waters, which are essential for assessing disease risk of disease and providing information for suitable public health interventions. When fecal indicators are combined with an understanding of the sources of fecal contamination, improved interpretations can be taken (Schoen & Ashbolt, 2010; Schoen, Soller, & Ashbolt, 2011).

A previous study conducted a primary assessment of flood-related waters in the Mekong delta; however, it was limited to physical/chemical parameters (Nguyen *et al.*, 2017b). Here, the study incorporates an assessment of flood water and the most likely source of contamination (sewer water and surface water) to describe the occurrence, magnitude, and correlations between key enteric pathogens during flood events in Can Tho city in the Mekong Delta region of Vietnam.

This chapter describes the flood-related water sampling campaign, the occurrence, magnitude, and potential correlation between key enteric pathogens by sampling surface water bodies, sewers, and inundated water before, during and after flood peaks in Can Tho city in the Mekong delta region of Vietnam.

5.2 MATERIALS AND METHODS

The study design included: (a) Anticipating flood events in the study area, (b) Collecting water samples before, during and after flood events from the surface, sewers and floodwaters, and (c) molecular analysis of samples to detect enteric pathogens.

5.2.1 Flood events in Ninh Kieu district

The months of September and October (2016) were selected as the potential sampling period, as this is the period with the highest probability of flooding (Birkmann et al., 2012). We were able to sample during two flood events. The first flooding event was caused by heavy rain on 11 September during a low tide period. The second flooding event lasted four days (from 16th to 19th October) during high-tide periods. In the latter case, the flood occurred in the morning and afternoon-evening which coincided with the peak river level (Figure S2, Appendix). A heavy rain event occurred in the early morning on 17 October. On this day, the water level in the Can Tho River was recorded as the highest value at 2.03 m (Figure S2, Appendix).

5.2.2 Water Sample in the flood event

Sampling strategy

Anticipating floods and logistical difficulties such as preparing materials and labor in usually a few hours' notices were the major challenges in sampling campaigns. Basic sampling logistics, including support personnel, was organized to anticipate floods. All flooded sites were associated with the combined sewer system. Some inundated roads are shown in Figure S3, Appendix. Details of the characteristics of floodwater on some flooded streets, for example, rising time, peak, and receding time are shown in Table S2 (Appendix).

Water Sample

We collected 94 water samples from 16 sampling sites for sewer water (31 samples), surface water (26 samples), and flood water (37 samples) around the occurrence of the two flood events (Figure 21). Details of this sampling are provided in Figure 1 and Table S1 (Appendix).

Sewer water was collected from selected manholes before, around the peak, and after flooding. Floodwater samples were also collected during these three phases of the flood.

All water samples were collected in 0.5L sterile glass bottles. These bottles were stored in iceboxes, unexposured to light, and transported to the laboratory within 24 hours for analysis (APHA, 2012).

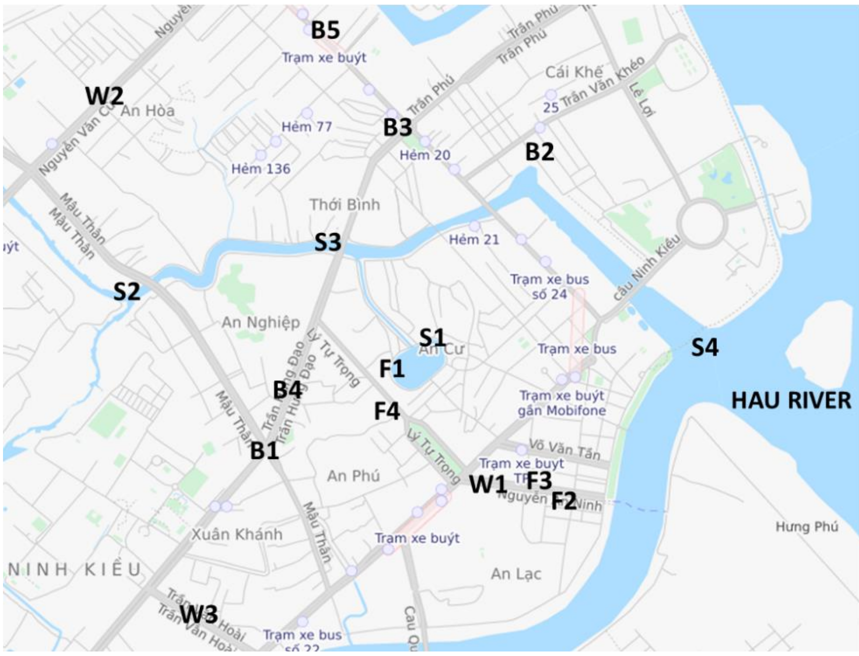

Figure 21. Water sampling sites in Ninh Kieu district, 2016.

(S1, S2, S3, and S4: Surface water sampling sites. W1, W2, and W3: Sewer water sampling sites. F1, F2, F3, and F4: Floodwater sampling sites. B1, B2, B3, B4 and B5: Both flood and sewer water were sampled at these places)

5.2.3 Molecular analysis for water samples

Quantitative real-time polymerase chain reaction (qPCR) was applied to detect and qualify the presence of various enteric pathogens(Pestana *et al.*, 2009). These pathogens were *E. coli*, *Salmonella*, *Campylobacter spp.*, *Shigella/EIEC,* Giardia spp., Cryptosporidium spp., Norovirus, and Rotavirus, specific primers in the qPCR were used instead of universal ones. PCR amplification was performed in the Laboratory of the Oxford University Clinical Research Unit (OUCRU) in Ho Chi Minh City, Vietnam. Details regarding the qPCR analysis are provided in the Appendix material (Section S1).

5.2.4 Statistical analysis for microbial pollutant parameters

We used the Mann-Whitney U test to identify differences between flood-related waters during flood times in terms of enteric pathogens. Spearman's rank correlation was applied to determine the association among the pathogens of flood-related waters. All analyses were performed in R software (Dalgaard, 2008).

5.3 RESULTS AND DISCUSSION

5.3.1 The prevalence of enteric pathogens in water bodies

E. coli and Rotavirus A were the most prevalent enteric pathogens found in water bodies (that is, sewer, surface, and floodwater) in flood events (Table 3).

Table 3. Microbial concentrations in flood water, surface water, and sewer water on flood days in Ninh Kieu district, 2016

Parameters	Range of concentrations Mean (Min-Max) (SD[1], positive samples)			References
	Flood water	**Surface water**	**Sewer water**	
Bacteria (10^6 CFU/100mL)[2]				
E. coli	0.7 (0.01 – 3.7) (1.2, 13/37)	0.4 (0.005 – 3.7) (1.1, 12/26)	7.8 (0.005 – 62) (15, 30/31)	2×10^2 – 2×10^3 (QCVN 08:2015/BTNMT) 5×10^3 (Directive 2006/7/EC)
Salmonella spp.	ND[3]	ND	0.3 (0.2 – 0.4) (0.14, 3/31)	
Campylobacter spp.	ND	ND	ND	
Shigella/EIEC	ND	ND	ND	
Viruses (10^6 gc[4]/100mL)				

[1] SD: standard deviation
[2] CFU: Colony forming-unit
[3] ND: not detected
[4] gc: genomic copies

Rotavirus A	59 (0.2 – 296) (84.6, 21/37)	32 (0.3 – 71) (24, 8/26)	61 (5.9 – 258) (65, 15/31)	2E-04 – 1E-03 (raw wastewater) (Henze et al., 2001) 9E-06 – 5E-04 (River water) (Sibanda & Okoh, 2013)
Norovirus GII	ND	0.004 (0.004 – 0.005) (1E-04, 2/26)	0.007 (0.003 – 0.01) (0.004, 4/31)	
Parasites				
Cryptosporidium spp.	ND	ND	ND	
Giardia spp.	ND	ND	ND	

E. coli was identified in more than one-third of the floodwater samples (13/37, 35%) and surface water samples (13/30, 41%). The mean concentration of *E. coli* in floodwater was of the same order of magnitude in surface water with $7x10^5$ CFU/100ml and $4x10^5$ CFU/100ml, respectively. Approximately 97% (30/31) of the sewer water samples were positive for *E. coli*, with a mean concentration of $7.8x10^6$ CFU / 100 ml, which was higher than flood water and surface water by an order of magnitude.

Rotavirus A was detected in approximately half of the floodwater samples (21/37, 57%), the sewer water samples (15/31, 48%) and almost one-third of the surface water samples (8/26, 30%). The mean concentration of Rotavirus A in floodwater was $5.9x10^7$ gc/100ml, which was similar to the mean concentration of sewer water ($6.1x10^7$ gc/100ml) and higher than the mean value in surface water ($3.2x10^7$ gc/100ml) (Table 1).

Approximately 10% of surface water and sewer water samples tested positive for Norovirus *Salmonella* and Norovirus was negative in floodwater samples. *Campylobacter spp., Shigella/EIEC,* Giardia spp. or Cryptosporidium spp., were not detected in any of the samples.

5.3.2 Floodwater Quality

The difference between floodwater and sewer water quality (in terms of *E. coli* and Rotavirus A concentration) was not significant ($p>0.05$, Mann-Whitney U test). The p-values for *E. coli* and Rotavirus were 0.09 and 0.2, respectively. The results showed an equivalent microbial concentration in flood and sewer water. The concentration of *E. coli* contamination was comparable between them on flood days 11/9/2016 and 17/10/2016 (Figure 2). During floods, at peak stages in the morning (6:00) and afternoon (17:00-18:00), the concentrations of *E. coli* and Rotavirus in the floodwater were close to those in the sewer water, which were sampled before flooding. The mean log10 concentration of *E. coli* and Rotavirus in floodwater was equivalent to sewer water with 6.0 and 7.5, respectively (Figure 22).

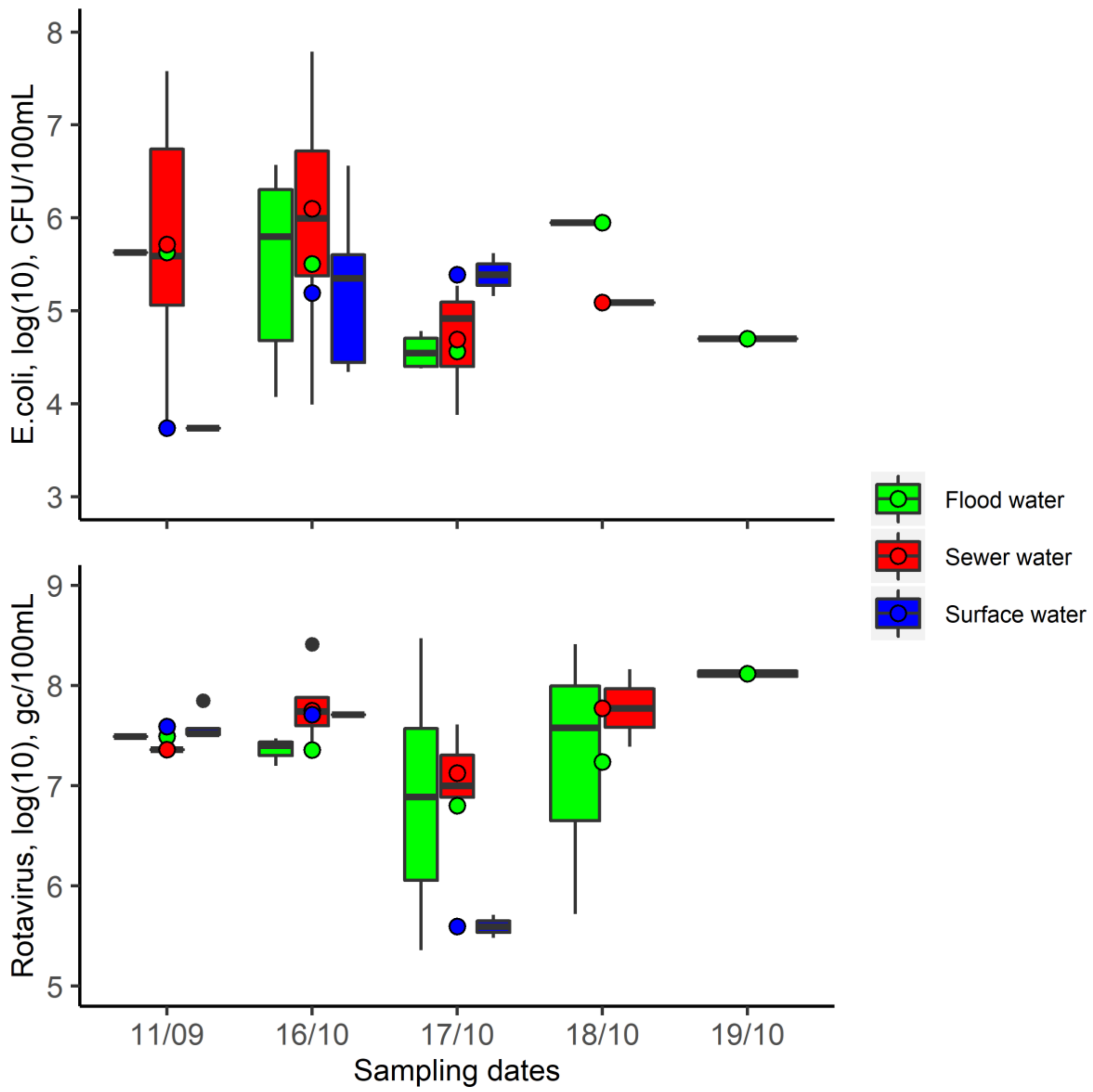

Figure 22. Box plots of *E. coli* and Rotavirus A in flood water, sewer water, and surface water samples during flooding days.

(On each day of sampling, from left to right, the green, red, and blue box plots indicate positive results of flood, sewer, and surface water samples. The green, red, and blue points represent the mean values and are arranged in the middle line to make it easier to compare their values. The black points are outliers.)

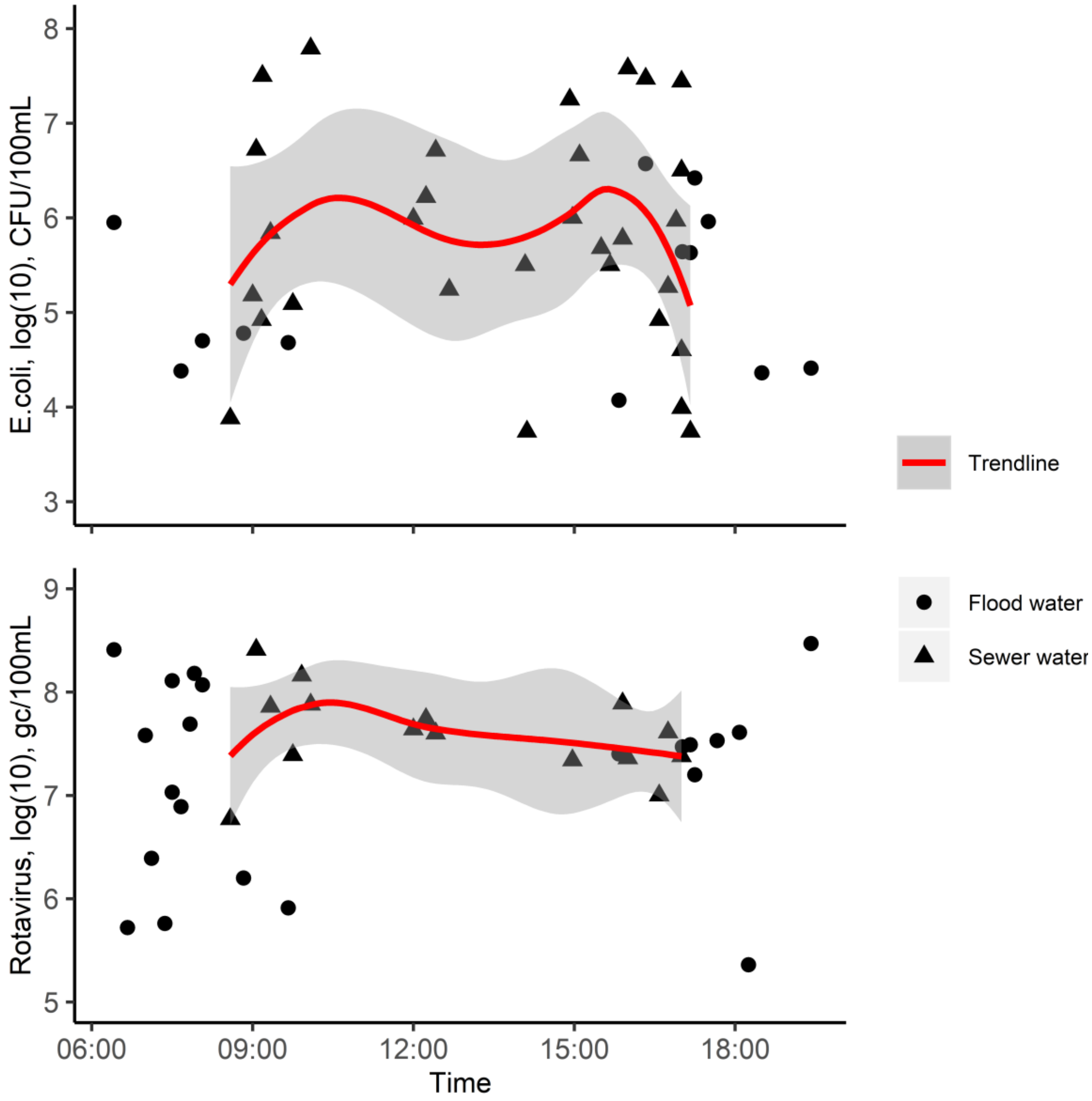

Figure 23. *Concentrations of E. coli* and Rotavirus A in flood water and sewer water. The red line is the moving average of *E. coli* and rotavirus in sewer water with standard deviation (grey area).

5.3.3 Surface water quality during floods

E. coli in surface water was at a high concentration on the day of heavy flooding (17/10/2016) (Figure 2). On this day, the mean concentration of *E. coli* in the surface water was 2.8x10^5 CFU/100mL, which was three times higher than the sewer water (9x10^4 CFU/100mL) and almost an order of magnitude (i.e., one log) greater than the floodwater (4x10^4 CFU/100mL) floodwater. Additionally, the *E. coli* concentrations in S1 (Xang Thoi Lake), S2 (Rach Ngong Canal) and S3 (Cai Khe canal) which are located near a residential area were an order of magnitude higher than at S4 (Hau River), which is located further from the residential area (Figure 3). Furthermore, Rotavirus was not detected in S4 but identified at S1, S2, and S3 with mean concentrations of 6 to 8 (Figure 24).

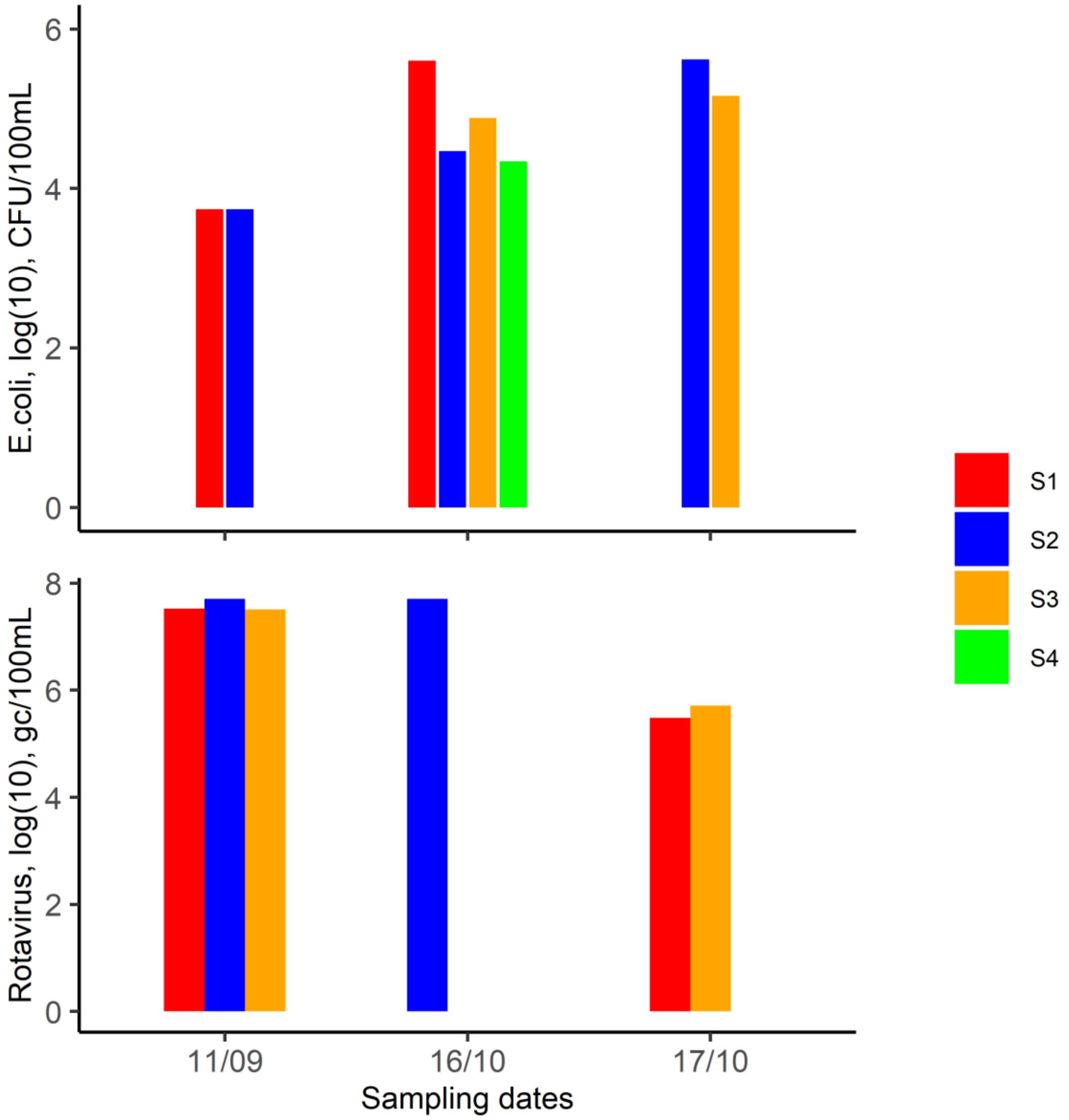

Figure 24. *Mean concentrations of E. coli* and Rotavirus for each sampling day at surface water sites: S1 (Xang Thoi lake), S2 (Rach Ngong canal) S3 (Cai Khe canal), and S4 (Hau River).

Highly polluted floodwaters

Surface water and floodwater were highly polluted with *E. coli* and Rotavirus A during flooding time in the Ninh Kieu district. According to previous studies, *Campylobacter* spp., *Shigella/EIEC, Giardia* spp., and *Cryptosporidium* spp. were found to pose a risk to human health (ten Veldhuis *et al.*, 2010; Fewtrell *et al.*, 2011; Sales-Ortells and Medema, 2015). However, we did not detect these pathogens in flood-related water samples. Alternatively, we commonly found *E. coli* and Rotavirus A in flood-related water in this environment. The concentration of *E. coli* in this study was up to three orders of magnitude (that is, three logs) higher than values recorded from other urban flood events in Can Tho city (Vietnam) after a flooding event in 2013 (Nguyen *et al.*, 2014a), Jakarta (Indonesia) (Phanuwan *et al.*, 2006), and The Hague (the Netherlands) (Sterk *et al.*, 2008). Furthermore, the *E. coli* concentration in floodwater was 1 –2 log10 higher than the Vietnamese surface water quality standard and the EU standard for bathing water (good level) (Table 3).

Since there is no standard available for rotavirus in water, the concentrations were compared to previous studies. Rotavirus concentration in surface water was two to three orders of magnitude higher than values reported from the Negro in Brazil (Vieira *et al.*, 2016). Additionally, the rotavirus concentration in floodwater in this study was 3 or 4 log10 higher than the rotavirus in domestic wastewater from other previous studies (Table 3). The occurrence of rotavirus in floodwater has been previously reported (Fewtrell *et al.*, 2010). For example, rotavirus A was detected in 9 out of 100 floodwater samples in Thailand (Ngaosuwankul *et al.*, 2013). However, the concentration was not mentioned in the study.

Flooding may connect additional sources of pollution.

Our data suggest that surface water may receive additional sources of contamination concerning fecal pollutants: For sewer water and floodwaters, the mean concentrations of *E. coli* on the high flooding day (17 October 2016) were lower than on other days (Figure 2). This is an expected result for flood and sewer water, as extreme rainfall and a high tide may dilute concentrations. On the contrary, for surface water, the mean concentration of *E. coli* was observed at high concentrations on this day. In addition, *Salmonella* spp. and norovirus GII in surface water were not detected, which may be attributed to dilution associated with rain and high tide. This result leads us to suspect that the concentration of *E. coli* in surface water on days of high flooding was likely impacted by other reasons beyond the dilution factor, which compensates for the expected dilution effect. Additionally, the concentrations of *E. coli* and Rotavirus near residential areas (S1, S2, and S3) were found to be higher than those of S4. This observation indicates that there are other potential pollutant sources in addition to sewer water. The probable sources of contamination that contain a high concentration of fecal pollutants could originate from septic tanks of local households located near rivers/canals. Due to the high floodwater level, these contaminated sources may connect directly to surface water.

5.3.4 The correlation of enteric pathogens in flood-related waters

Correlations of Enteric Pathogens Concentration in water samples

We identified a weak correlation (Spearman r) during flood periods between *E. coli*, *Salmonella spp.*, Rotavirus A, and Norovirus GII in flood-related waters ($r<0.5$, Spearman correlation), the same was not observed for *Salmonella* - Norovirus (Figure S1, Appendix). The correlation coefficient (r) between *Salmonella* and Norovirus was 0.7

($p<0.001$). The correlation of *E. coli* – *Salmonella*, *E. coli* - Rotavirus and *E. coli* – Norovirus in flood-related waters was 0.26 ($p<0.05$), 0.19, and 0.13, respectively.

In previous studies, due to the difficulty of detecting viruses, often an assumed correlation ratio between *E. coli* and Rotavirus A has been used to estimate Rotavirus concentration in drinking water (Howard *et al.*, 2007; Mara *et al.*, 2007; Lulani *et al.*, 2008; Machdar *et al.*, 2013). However, this approach has not been previously applied to floodwater. Our results indicate that care should be taken when using this ratio for future research on floodwater because no significant correlation was found between *E. coli* and Rotavirus A in flood-related waters.

Confirms previous results

The present study confirmed some results of a previous study by Nguyen et al. (Nguyen *et al.*, 2017c). First, Nguyen et al. originally observed that the quality of floodwater, wastewater, and surface water in fluvial flood events in Ninh Kieu district (2013) was not significantly different in their contamination because most of the sewer water and floodwater originated from surface water. The current study indicates a high probability of a large volume of sewer water entering floodwater, as there was no significant difference between the concentrations of *E. coli* and Rotavirus in flood and sewer water. Second, Nguyen et al. previously reported that floodwater quality deteriorated as the floodwater level increased. Similarly, in the current study, the concentration of pathogens was highest in the peak stage of flooding. The mean concentrations of *E. coli* and Rotavirus in the peak stage of floodwater were higher than those at the peak stage of sewer water before flooding (Figure 3).

5.4 CONCLUSIONS AND CONTRIBUTION

This study attempted to address the lack of observational evidence for microbial pathogen contamination (and their concentration) during flood events in LMICs. Our findings provide evidence regarding which waterborne pathogens can represent a hazard to human health during the flooding period. To our knowledge, this is the first study to detect the human enteric virus Rotavirus A in floodwater in Vietnam. The flooding in Can Tho showed the prevalence of *E. coli* and Rotavirus A. The concentrations exceeded the water quality standards and were much higher than in the relevant studies. Furthermore, the concentrations of these pathogens in floodwater were not statistically different from those in sewer water, indicating highly polluted floodwaters, which can pose a serious risk to health hazards.

Due to the difficulty in testing for viruses, some previous studies assumed a correlation of viruses with (an easily detectable) *E. coli*. Current findings may be used as input for health risk assessments of waterborne diseases during floods. Although more evidence is required regarding the health risk of flooding, it is important to advocate for more efficient approaches to reduce fecal pollution during flood events.

High concentrations of pathogens in floodwater can lead to potential health risks associated with waterborne diseases in the exposed population in LMICs (Nguyen *et al.*, 2001; Bich *et al.*, 2011; Fuhrimann *et al.*, 2017). Furthermore, diarrhoea cases have been reported to increase when *E. coli* and Rotavirus were found in flood events (Ahern *et al.*, 2005). In our study, variation in pathogen concentration, especially in the first stage of the flood event, may pose a specific risk when it coincides with a rush hour of traffic, for example, morning (5:30 – 7:00) and afternoon-evening (17:00 – 19:00) in Can Tho city (Figure S2 - Appendix). More people may be exposed to floodwater through transportation activity. Therefore, citizens of Ninh Kieu face not only ‘too much’ but also “too dirty” waters during flooding periods. In the next chapter, enteric pathogens will be taken into account to calculate the risk of infection and disease burden for the exposed population.

6

INFLUENCE OF TRAFFIC IN URBAN FLOOD HEALTH RISK USING AGGREGATED CONCENTRATION

The previous chapter analysed enteric pathogens in flood-related waters with a high concentration of enteric pathogens in floodwater. In this chapter, the linkage of these microbial pathogens will be explored to quantify the health consequences to exposed people by the QMRA and DALYs approach. Additionally, a sensitivity analysis was indicated to identify the sensitive parameters to health consequences. The results showed that traffic activities during floods caused disease burden to residents, especially motorcyclists, which are the majority in the case study.

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- The paper is accepted for publication: Thi Thao Nguyen Huynh, Nynke Hofstra, Hong Quan Nguyen, Stephen Baker, Chris Zevenbergen, Gerald A. Corzo Perez, Assela Pathirana (in press). "Estimating disease burden of rotavirus in floodwater through traffic in the urban areas – A case study of Can Tho city, Vietnam." *Journal of Flood Risk management*.
- Oral presentation: **Huynh, Thi Thao Nguyen**, Hong Quan Nguyen, Assela Pathirana, and Chris Zevenbergen. 2019. 'Health risk assessment related to Enteric Pathogens in Urban Flood Water. A case study in the Vietnamese Mekong area - Ninh Kieu District, Can Tho City. ' In the *20th International Symposium on Health-Related Water Microbiology*. 15 – 20 September. Vienna, Austria.
- Poster presentation: **Huynh, Thi Thao Nguyen**, Gerald Corzo, Nynke Hofstra, Hong Quan Nguyen, Stephen Baker, Assela Pathirana, and Chris Zevenbergen. 2022. 'Sensitivity analysis for Microbial Risk Assessment of microbial risk of exposed people through traffic during Urban Flooding." In the *7th BeNeLux Conference of Young Water Professionals.* Delft, The Netherlands.

6.1 INTRODUCTION

Infectious diseases are one of the most pressing health issues during flooding. Direct exposure to polluted urban floodwater, such as through traffic activities or cleaning up inundated houses, seems unavoidable, and these activities may cause public health issues related to waterborne diseases (Few and Tran, 2010; Few *et al.*, 2013). 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 so 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 behaviour of people during flooding is hardly ever reported. Veldhuis et al. (2010) and Mark et al. (2015) quantified the health risks of 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 burden of disease for traffic during floods has so far not been the focus of research. In particular, in LMICs, this disease burden can be significant. Therefore, this chapter aims to assess the health risks and burden for traffic associated with exposure to floodwater contaminated with enteric pathogens.

6.2 MATERIALS AND METHODS

6.2.1 Quantitative microbial risk assessment

The quantitative microbial risk assessment approach (QMRA) was used to assess the probability of infection of the probability and illness probability for a person per flood event. The disease burden is quantified by disability-adjusted life years (DALY). Floodwater data were based on the previous study (Huynh et al., 2020).

- **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 summarises the flood event and sampling campaign on 17 October 2016. On this day, high river water levels and rain were observed. However, the main cause of the flood was attributed to high river water levels (Figure S2, Appendix). The inundation was explained by the river water entering the combined sewer systems through the pipes at the outlets and later flowing 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, at 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. The study sampled floodwater at eight locations (Figure 25). The sampling sites, sampling time, and microbial concentration in the floodwater samples on the flooded streets are shown in Table S3 (Appendix).

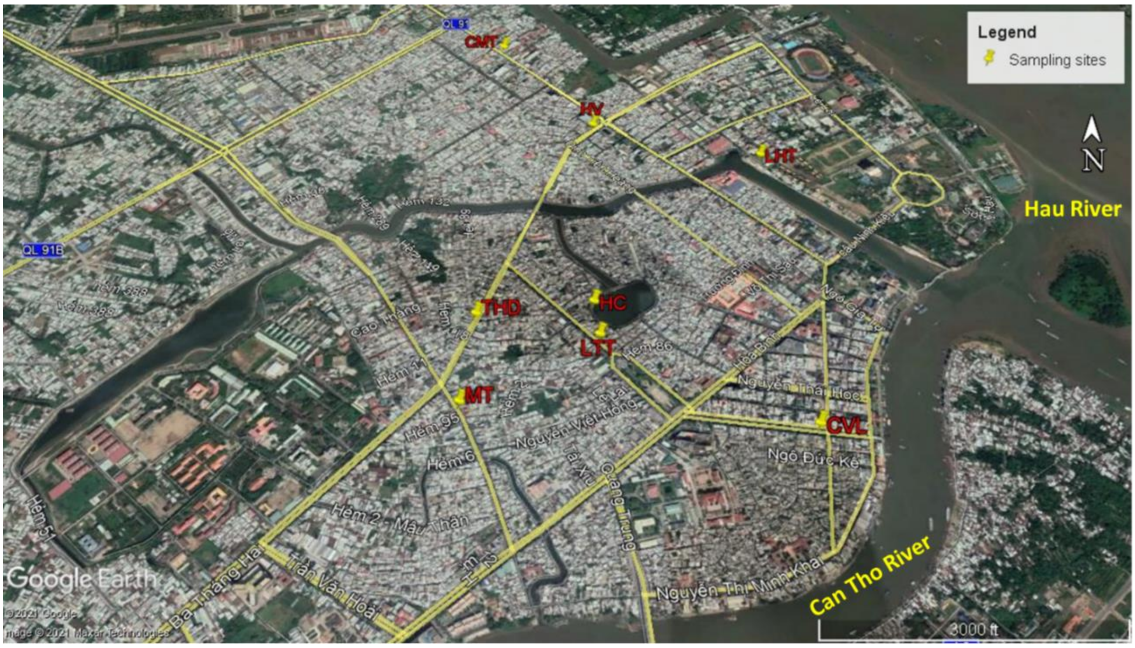

Figure 25. Eight floodwater sampling sites in Ninh Kieu District on 11 September and 16-19 October 2016. The initials correspond to the sampling sites in Table S3 (Appendix) (Google EarthTM satellite data).

- **QRMA**

Haas et al. (1999) were the first to introduce 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 and Haas 2015), and floodwater (Sales-Ortells and Medema 2015; Veldhuis et al. 2010, Nguyen et al., 2017b). QMRA involves four steps: (i) hazard identification, (ii) dose-response assessment, (iii) exposure assessment, and (iv)risk characterisation. This study applied the QMRA approach to calculate two results: the infection rate and the illness risk per person per flood event. The following parts explained these steps in detail.

✓ Hazard Identification

Flood-related water samples were analysed in our previous study. We considered several microbial pathogens, including *E. coli, Salmonella, Campylobacter spp., 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 analysed total *E. coli* and not 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 children and the elderly (Atmar and Estes 2006; Sattar 2018). Over two decades in Vietnam, rotavirus has been one of the predominant pathogens that cause diarrhoea in children (Nguyen *et al.*, 2001; Doan *et al.*, 2003; Van Man *et al.*, 2005; Thompson *et al.*, 2015; Huyen *et al.*, 2018). The measurement procedure for rotavirus A, the pathogen of interest, and other pathogens, is described by Huynh et al. (2020). From this, we use "rotavirus" to mean 'rotavirus A' in our study.

In some cases, the pathogen concentration is considered constant during the defined events. For example, in floodwater, pathogen concentrations do not change over the short time of flooding in an urban area (ten Veldhuis *et al.*, 2010; Ryan *et al.*, 2014). Therefore, ignoring the death and growth of pathogens during a flooding is acceptable for analyzing their concentration.

✓ Exposure assessment

The exposure analysis presented here is evaluated at the individual (person) level. These involve the pathway, duration, and ingested volume (Fewtrell et al., 2008b). In addition, 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 an exposure pathway in this study. Ingestion of water by hand-to-mouth contact and splashing from other vehicles were common exposure pathways of these groups. The study did not consider bathing in floodwater or washing/cooking/drinking contaminated water, since they are unusual activities in this local area. Children and adult pedestrians, motorcyclists, and cyclists are often observed on flooded streets and directly exposed to floodwater in the streets. Therefore, these four groups of exposed people were selected. Motorbike and bike groups included thousands of riders (i.e., the person seats behind the rider).

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

(a1) Intake rate

Child pedestrians and adult pedestrians: These can ingest water when wading through floodwater on their way to and from schools/offices. There were no estimates of ingestion during wading existed. The intake volumes of the literature included 30-50 ml and 01 mL - 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 include the duration of exposure per incident. Furthermore, bathing and playing in floodwater is rare in urban settings in Vietnam. Dorevitch et al. (2011) showed that the average intake volumes were 3.5 ml for walking/splashing in pool water for 60 minutes. Therefore, the study 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 one hour. Therefore, it was assumed that the volume ingested for these two groups was 3.7 ml / h.

(a2) Exposure duration

Since the study considered exposure through traffic activity, the duration of exposure (that is, the time spent in inundated areas) depends on the length of the flooded street and the speed of vehicles. Therefore, the study expressed the exposure duration ($\boldsymbol{t_e}$) on the flooded road as equation (6.1).

$$\boldsymbol{t_e = l/v} \qquad (6.1)$$

Where $\boldsymbol{l}$ (m) is the length of the flooded street and $\boldsymbol{v}$ (m/h) is the velocity of the individual. $\boldsymbol{l}$ in the flood event in the afternoon of 17 October 2016 ranged from 85-925 m. The study used the average length of all the flooded streets to calculate the average duration of exposure (Table 2). It was assumed that the individual kept the same speed when travelling through a flooded street. Tang et al. (2020) identified traffic flow speeds (i.e., motorcycles, cars, and buses) on 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, it was assumed that the velocity was 14 km/h since the study was carried out during rush hour. Several studies have determined that the average speeds of cyclists were 10 km/h in China (Cherry and He, 2009) and 13.5 km/h in France (Jensen *et al.*, 2010). It assumed a speed of 10 km/h for the case study, which seemed more suitable for Vietnamese. For pedestrians, the average speeds were 70 and 80 metres per minute for children and adults, respectively (Waters et al. 1983).

Furthermore, the difference in flood inundation depths of the streets in the study area was small (0.2-0.4 m, SD=0.06) (Table S4, Appendix). Furthermore, there is a lack of reliable information on the association between flood depth, intake rate, and duration of exposure. Thus, it was assumed that the variability of flood depth did not affect the intake rate or the duration of exposure.

(b) Number of people exposed during a flood event

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

Firstly, to estimate the density of the exposed population, the study recorded a video of an inundated street segment. The study 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 analyse traffic flow (Iowa State University, 2002; Pande and Wolshon, 2003). The study chose Chau Van Liem Street to record the video covering 30 minutes of inundation (Figure S4, Appendix). The description and the recording at Chau Van Liem Street are shown in the Appendix section. The exposed person density (d_e, people/m^2) was 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 x 100 m) at Chau Van Liem Street (equation (6.2).

$$d_e = \frac{n_{str}}{a_{str}} \tag{6.2}$$

Secondly, the total flooded areas in all the flooded streets were calculated (equation (6.3).

$$N_e = d_e \times A \times sf \tag{6.3}$$

$$A = \sum_i w_i \times l_i \tag{6.4}$$

Where:

A (m^2) is the sum of the inundated area of the flooded streets that were calculated based on the widths, w_i (m), and lengths l_i (m), of the inundated roads i (Table S4, Appendix).

sf is the scale factor to correct the traffic density on each flooded street. Since there was a lack of information on the flooded streets on the morning of 17 October 2016, the study referenced data on the flooded streets in the afternoon of this day reported by the Can Tho Drainage and Sewage Company. The flooded streets, duration of the flood, floodwater level, and lengths and widths of the inundated areas are shown in Table S4 (Appendix) (CanThoWassco, 2017). The study focused on flooded streets with inundated areas exceeding 200 m^2 and flood depth greater 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. The scale factors were 0.8 and 1.2 for those streets with smaller (<10 m) and larger (>10 m) widths, respectively (Table S4, Appendix).

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

✓ Risk Assessment

In the final step, the steps mentioned above are combined to estimate the probability of risk per person per exposure (i.e., exposure to floodwater). To show the health risk with the best available data, the study quantified the infection risk and disease burden for one street (that is, Chau Van Liem Street) based on the measured concentrations and exposed people of this street. Then the risk assessment of all the flooded roads was extrapolated. The equations for the intake dose, the probability of infection, the probability of illness, and the DALYs are described below. Table 4 shows the critical input for the QMRA approach.

- Intake dose

The intake dose (μ) is the dose of pathogens exposed people ingested when exposed to floodwater was calculated as equation (2.2). Where:

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

IR is the intake rate (mL/hour), 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 calculated as equation (6.1).

- 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 and Havelaar 2000; Ward et al. 1986). This study used a simplified version, the beta-poison model (equation (2.4). This model is regularly used in the literature to estimate the infection probability (P_{inf}) for rotavirus (Gerba *et al.*, 1996; Machdar *et al.*, 2013; Mcbride *et al.*, 2013).

Where α and β have been estimated as 0.253 and 0.422, respectively (Haas *et al.*, 2014); μ is the dose ingested of rotavirus in genome copies (gc), which was calculated by equation (2.4).

The probability of developing illness after infection (P_{ill}) was estimated by equation (2.5).

Where $P_{ill|inf}$ 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 of the distributions of intake rate, flood length, and rotavirus concentration distributions (Table 4). The study used RiskAMP software version 5.4.1, an add-in package in Microsoft Excel, to simulate the distribution (Structured Data L.L.C. 2005).

Table 4. Input data for the probability of QMRA model to calculate the infection of 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	
Rotavirus concentrations			
The average value (gc/mL)* for all floodwater samples		5.89×10^5 (95% CI 2.3 x 105 – 9.5 x 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/hour)	3.7 Lognormal (3.7,3.8)	(Dorevitch *et al.*, 2011)
Adult pedestrians	(mL/hour)	3.5 Lognormal (3.6,3.7)	
Motorcyclists	(mL/hour)		
Cyclists	(mL/hour)		
Speeds			
Child pedestrians	m/h	4,200a	a (Waters *et al.*, 1983)
Adult pedestrians		4,800a	
Motorcyclists		14,000b	

Cyclists		10,000c	b (Tang *et al.*, 2020) c (Cherry and He, 2009)
Flooded lengths (average)	m	300 (95% CI 0 - 1,488) Lognormal (5.4, 0.787, 0)	This article
Risk of illness given infection of rotavirus P(ill|inf)		0.5	(WHO, 2016)

* gc/mL: genome of copies per millilitre

6.2.2 Disease burden quantified by DALY

The study calculated the burden of the disease using the DALY metrics for the exposed people per flood event. The study assumed that each person was exposed one time during floods since the QMRA calculated for infection and illness per single exposure for an individual. DALY consists of years of life lost (YLL) and years lived with disability (YLD) (Fewtrell and Bartram, 2001; Machdar *et al.*, 2013). For rotavirus A, the standard DALY value of low-income countries is 482 DALYs per 1,000 cases (YLL = 480, YLD = 2.2). 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 the age at the time of death, we calculated a new value for YLL, using the average life expectancy at birth of Vietnamese people (73.6 years) (GOPFP, 2019). Normally, the average age at death of 1 due to rotavirus was assumed for the infants (Havelaar and Melse, 2003). However, the study considered four different groups including children, adults, motorcyclists, and cyclists at different ages. Therefore, the average age of death depended on the current age of the groups. The study assumed that the average age of child pedestrians was 11 years since the age range of pupils was 6 - 17. The people of labour age were the majority in the three remaining groups that ranged from 18 – 60 years of age. Therefore, the study assumed that the average age was 40 years. Therefore, the year loss for children and adults due to disease caused by rotavirus was 62.6 and 33.6, respectively, compared to the average life expectancy at birth of Vietnamese people (73.6 years). The study considered YLD due to rotavirus A with mild and severe diarrhoea symptoms (Table 5). The disease burden of each illness case (DALYs per case, $\mathrm{DALY_{pc}}$) for rotavirus (equation (6.5) involves YLL and YLD with the probability (%) of developing a negative health outcomes (disease symptom, j) given by an illness ($\mathrm{P_{outcome|ill}}$); the severity of symptoms (s); and the duration of symptoms (d, year).

$$DALY_{pc} = \sum(P_{outcome|ill} \times s \times d)_j \qquad (6.5)$$

Then, from equation (6.7), the disease burden per flood event was determined for each exposure group based on DALYs per illness case $(\mathrm{DALY_{pc}})$ and the number of illness cases in each group ($\mathrm{N_{ill}}$). $\mathrm{N_{ill}}$ (equation (6.6) was the product of exposed people in each group ($\mathrm{N_e}$, from equation (6.3) and $\mathrm{P_{ill}}$ (described in section and 3.2.3 calculated by equation (2.5). Lastly, the total DALYs provided the disease burden due to rotavirus for the four exposure groups through traffic activities (equation (6.8).

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

$$\mathrm{N_{ill}} = \mathrm{N_e} \times \mathrm{P_{ill}} \tag{6.6}$$

The disease burden for each exposure group per flood event is

$$\mathrm{DALYs}_{pe} = \mathrm{DALY_{pc}} \times \mathrm{N_{ill}} \tag{6.7}$$

The total DALYs of all exposure groups per flood event are

$$Total\ DALYs = \textstyle\sum_i (\mathrm{DALYs}_{pe})_i \tag{6.8}$$

Table 5. Probability of developing negative outcome $(\mathrm{P_{outcome|ill}})$, severity (s), and duration of symptoms (d) to calculate DALYs per case caused by rotavirus (Havelaar and 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	62.6 (child) and 33.6 (adult)

6.2.3 Sensitivity analysis and uncertainty analysis for parameters

- **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 variability in the input parameters and variables (Cullen and 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 in a range of plausible values with base, low and high values (Table 6).

The study assumed that the DALYs calculated with these values were the baseline, Scenario 1, and scenario 2, respectively. The influence of exposure duration, intake rate, and concentration on infection probability and disease burden is considered. The duration of exposure depends on the speed of the exposed people and the lengths of flooded streets (t_e, equation (6.1). 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). The study used these data as the low and high values of motorcycle speed. In contrast, during non-rush hours, pedestrians tended to walk 4% slower than during rush hours. Therefore, this percentage was used to calculate the low value of the speed of pedestrians (Bosina and Weidmann, 2017). The base value for the speed of pedestrians was 1.34 m/s and 1.16 m/s for adults and children, respectively (Waters *et al*., 1983). The study did not consider the high value of speed for pedestrians due to a lack of data. It was assumed that 9 km/h (Cherry and He, 2009) and 13.5 km/h (Langford et al., 2015) for the low and high value of cyclist speeds, respectively. For intake rates, the high values for child pedestrians and adult pedestrians / motorcyclists / cyclists wading through surface water were 50 ml / h and 10 mL/h, respectively (EPA, 2011b). The low value was 1.4 mL/h, applied to all exposed groups (Dorevitch *et al.*, 2011). The study fixed the low and high lengths of the inundated streets and measured the concentration at its 25^{th} and 95^{th} percentiles, respectively. Furthermore, the study evaluated the sensitivity of the rotavirus concentration 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.,al., 2016; Labite et al. 2010). Our previous study used the analysis of *E. coli* concentration in floodwater (average concentration 7.17×10^3 CFU / ml) (Huynh *et al.*, 2020) to estimate the rotavirus concentration. The rotavirus ratio concentration (3.9×10^{-2} CFU/mL) was 7 log10 lower than the mean measured concentration (5.9×10^5 gc / ml).

In addition, the study evaluated the number of exposed people considering the density of the exposed people. People's density during rush hours (base value) was 2.5 times higher than during nonrush hours (low value) (Tang *et al.*, 2020). Therefore, the density of low value of the exposed people was 2.5 times lower than the base value shown in Table 3. For the low value of DALYs per case, the study assumed that the standard DALYs due to rotavirus (0.014) were used for developed countries (Havelaar and 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 S5, Appendix). The flooded areas of these events ranged from 6,400-252,000 m^2 (SD= 55,288, 95%CI mean 29,647-73,000). In the sensitivity analysis, the study used the 25th and 95th percentiles of flood areas as low and high values. There were limited parameters available $P_{ill|inf}$, α, and β parameters in the beta-Poison model to study; therefore, the study did not include these in the sensitivity analysis.

Table 6. 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	$5.3x10^3$	-35%	$2.6x10^6$	11%	$5.9x10^5$
Rotavirus A concentration (ratio)		$7.17x10^2$	-120%	-		
Intake rate						
Child pedestrians	mL/h	1.4	-60%	50	1,329%	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
The flooded area on the streets	m^2	16,700		143,000		36,880
Speed						
Child pedestrians	m/h	4,000	-4%	4,800	14%	4,200
Adult pedestrians		4,600	-4%	5,200	8%	4,800
Motorcyclists		9,000	-36%	30,000	114%	14,000
Cyclists		9,000	-10%	13,500	35%	10,000

- **Uncertainty Analysis**

To determine the uncertainty of which parameter is more important than the others, the study used the Spearman test to find the correlation coefficient (rho) between the input and output (i.e., infection risk) (Gurian 2015; Haas et al. 2014). The study simulated the distributions of intake volume, concentration, flood length (Table 4), and infection risk by Monte Carlo with 10,000 iterations in the RiskAMP Monte Carlo Add-In Library version 5.4.1 software. Personal & Learning Edition.

6.3 RESULTS AND DISCUSSION

6.3.1 Exposed people and probability of infection for single exposure due to rotavirus A in floodwater

The number of people exposed on Chau Van Liem Street during a one-hour flood event was assumed to be twice as many as the exposed people counted in the video covering 30 minutes of inundation. Motorcycles were prevalent on the roads (95%). Of these, a quarter were shared motorcycles with two people. Cyclists, adult pedestrians, and child pedestrians were the minority with 2.8%, 2%, and 0.1%, respectively. The cases of gastroenteritis caused by rotavirus A in a flood event were 30,831 among the 63,390 people exposed people in the four groups (Table 7).

The average infection risk per person per exposure (pppe) (ie, exposure to floodwater) in Chau Van Liem Street and all the flooded streets was highest for child pedestrians at $9.6x10^{-1}$ and $9.7x10^{-1}$, respectively. The average probability of infection of adult pedestrians, motorcyclists, and cyclists was correspondingly $9.6x10^{-1}$-$9.7x10^{-1}$ (Table 7). Figure 26 indicates the probability that infection risk occurs for four groups. Of these, pedestrians show a slightly higher probability of being infected than cyclists and motorcyclists. Figure 27 shows that the infection risk for pedestrians is highest and that value had the highest probability of occurring than other groups. For all exposure groups, high values of infection risk had a higher probability of occurring. For example, at an infection risk of 0.96, the probability of occurring is 31%, 26%, 15%, and 18% for child pedestrians, adult pedestrians, cyclists, and motorcyclists. At an infection risk of 0.98, the probability of occurring is 53%, 37%, 36% and 30% for child pedestrians, adult pedestrians, cyclists and motorcyclists, respectively.

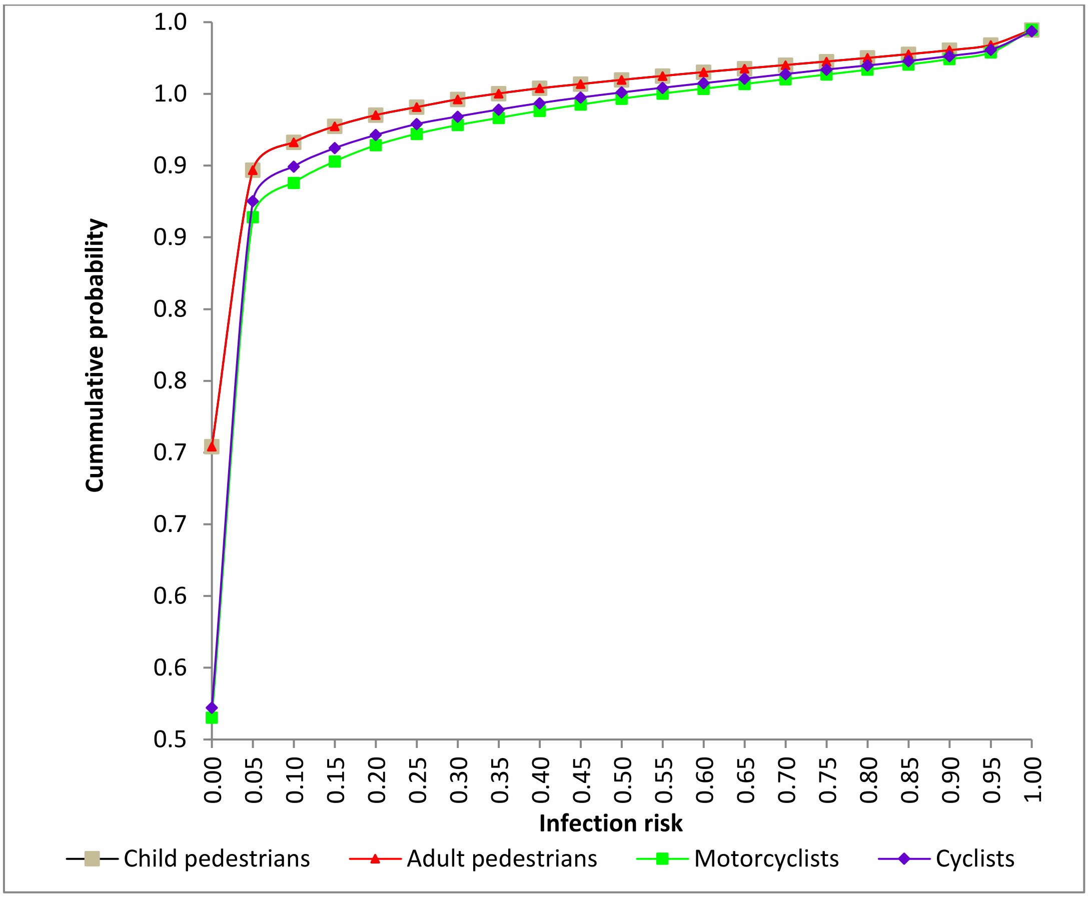

Figure 26. The cumulative probability distribution for the probability of infection from the Monte Carlo simulation with distributions for rotavirus concentration, intake rate, and flood length.

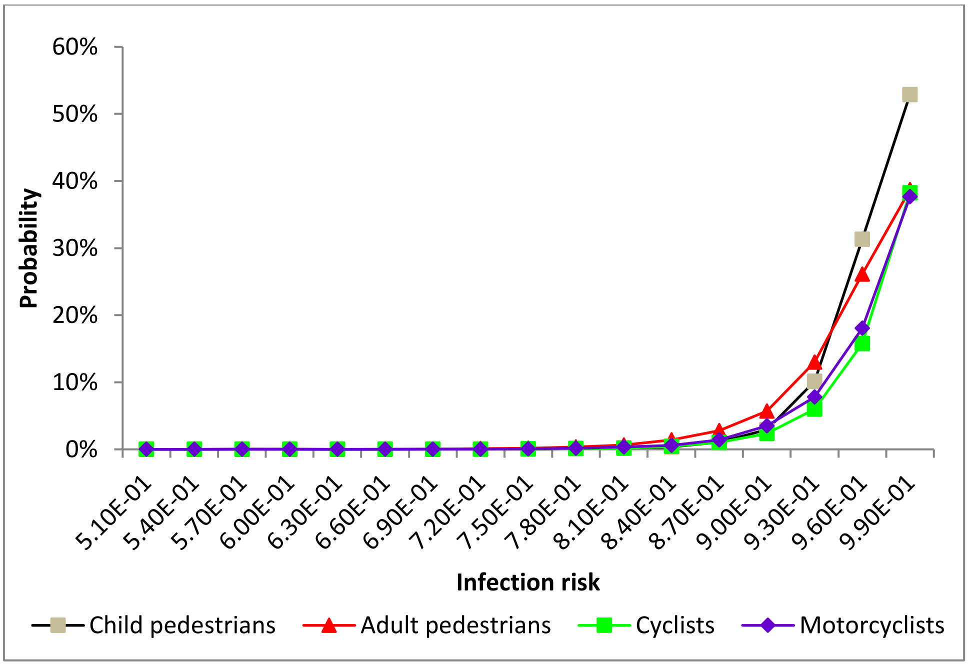

Figure 27. The probability distribution of the infection risk per person per exposure caused by rotavirus A in floodwater for the four exposure groups through traffic activities in Ninh Kieu District of Can Tho City.

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 infection risk, followed by adults (Man et al. 2014; Sterk et al. 2008; Veldhuis et al. 2010). The infection risk distribution showed that children walking on foot were more likely to be infected than motorcyclists and cyclists. The infection probability in our study was 1-4 orders of magnitude higher than those of previous studies. For example, according to Veldhuis et al. (2010), the infection probabilities for adult and child pedestrians were $5x10^{-5}$-0.2 and 10^{-4}-0.3, respectively. Man et al. (2014) identified infection risks for children as 0.33, 0.23, and 0.035, while the infection risks for adults were 0.039, $5.8x10^{-3}$, and $3.9x10^{-4}$ in the Netherlands. In the case study in Dhaka (Bangladesh), Mark et al. (2015) indicated that the infection risks caused by *Vibrio cholera* in floodwater for children and adults in low- and middle-class areas were $5.2x10^{-5}$-$5.6x10^{-3}$ and $1.5x10^{-6}$-$5.5x10^{-4}$, 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 relationship between *E. coli* and rotavirus ($1:10^{-5}$) to calculate the rotavirus concentration (Table 3), the estimated rotavirus concentration was 7 log10 smaller than the base value (that is, the measured concentration). It resulted in calculated infection risks for child pedestrians, adult pedestrians, motorcyclists, and cyclists in the same range as other previous studies with 0.1, 0.03, $8.9x10^{-3}$, and 0.013, respectively.

Some uncertainties may affect the probability of infection. 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). Therefore, it does not represent children. In addition, 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 analysed by qPCR, which only detected the genetic material, not the active state of the virus. To our knowledge, there is a lack of research mentioning rotavirus concentration in sampling of floodwater. Only one study detected rotavirus in floodwater (9%, 9/100 samples) in Thailand, but did not analyse the concentration (Ngaosuwankul *et al.*, 2013). Fuhrimann et al. (2017) estimated the rotavirus concentration based on the *E. coli* concentration and the ratio between *E. coli* and rotavirus. Rotavirus concentrations in river and sewer water in the Netherlands were 57-5,386 PDU/L (PCR-detectable units) and 339-55,000 PDU/L (Lodder and De Roda Husman, 2005). These results were much lower than those in this study, by between 3-6 orders of magnitude. Since the water quality in developed countries may be better than in developing countries, analysing enteric pathogens such as rotaviruses in floodwater in developing countries should 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).

6.3.2 Disease burden by DALYs for exposed people per flood event due to rotavirus A in floodwater

The DALYs of all the exposure groups in a flood event on Chau Van Liem Street were $3{,}62 \times 10^2$. The total DALYs for all roads were $1{,}35 \times 10^4$. Motorcyclists were the main contributor to total DALYs, followed by cyclists, adult pedestrians, and child pedestrians (Table 7).

Table 7. The density of exposed people, the dose ingested, the average probability of infection per person per exposure (pppe), the cases of illness, and disease burden for the four groups of exposure due to rotavirus infection on a flood event in Chau Van Liem Street and all the flooded streets.

	Units		Exposure groups				
			Child pedestrians	Adult pedestrians	Motorcyclists	Cyclists	Total
Exposed people density	People/1,000 m^2		2	34	1,632	48	
Number of exposed people	People per (1 hour) flood event	Chau Van Liem Street	2	34	1,632	48	1,716
		All the flooded streets	75	1,274	61,143	899	63,390
Ingested Doses	gc/pppe	Chau Van Liem Street	$3.65x10^6$	$6.39x10^5$	$2.19x10^5$	$3.07x10^5$	
		All the flooded streets	$2.1x10^6$	$3.68x10^5$	$1.26x10^5$	$1.76x10^5$	
(Average) Infection Probability	pppe	Chau Van Liem Street	$9.8x10^{-1}$	$9.7x10^{-1}$	$9.6x10^{-1}$	$9.7x10^{-1}$	
		All the flooded streets	$9.8x10^{-1}$	$9.7x10^{-1}$	$9.6x10^{-1}$	$9.6x10^{-1}$	
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	$3.62x10^2$
		All the flooded streets	16	270	12,835	379	$1.35x10^4$

This study conducted an experiment to identify the number of people exposed to floodwater through traffic during flooding. Motorcyclists were prevalent on the streets during this time. This result was similar to previous studies on 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% (that is, 13,600 ± 3170) on the 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. Furthermore, the number of cases of illness and estimated illness cases per flood event in our study (Table 7) was 20 times higher than the gastrointestinal cases reported by the local preventive medical centre. According to epidemiological data in Ninh Kieu, there were 1,550 cases of diarrhoea in 2014, 774 cases in 2015, and 757 cases in 2016 (Preventive Medical Centre in Can Tho, 2016a). One reason might be that sick people buy drugs in a pharmacy store without visiting doctors or hospitals, which is a common habit (Preventive Medical Centre in Can Tho, 2016b). Therefore, 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 probability of infection based on the high rotavirus concentration. 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 (Pinf|ill) may have been underestimated / overestimated (Teunis and Schijven 2017).

The DALY results in this study were compared with DALY in other daily life activities to assess the severity of health risks related to the waterborne pathogen. Motorcyclists contributed the highest disease burden 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 (that is, 2,129 DALYs/10,000 exposed people). This result was much higher 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, 6,775 DALYs/10,000 cases) (Katukiza et al., 2013). Since the standard of health risk is for low-exposure or occasional exposure, the study compared it with the DALY standard for drinking water. The result exceeded by four to five log10 of the tolerable burden of disease related to drinking water according to WHO (0.1-0.01 DALY/10,000 per year) (WHO, 2003). Since the study calculated the DALYs per flood event, the DALYs for people exposed to floodwater more than once per year could be higher than this standard.

6.3.3 Sensitivity and uncertainty analysis

According to the NRSA results (Figure S5 and Table S6, Appendix), the most influential variable for health outcomes was flooded areas (337%) followed by the (measured) concentration of rotavirus (11-15%). Increasing flood areas by 290% (i.e., four times higher than the base value) resulted in the most significant change in the disease burden (approximately 282% higher). For concentration, increasing the (measured) rotavirus concentrations by 1 log (that is, 11% higher than the base value) increased the infection risk and the DALY 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 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. In particular, using the relationship 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 burden of child pedestrians, cyclists, and motorcyclists/adult pedestrians by 88%, 97% and 99%, respectively.

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

Speed, flooded street lengths, and the intake rate only contributed to the result by less than 3%, except for pedestrian speed of pedestrians by 9%. Reducing the speed of child and adult pedestrians, motorcyclists, and adults by 4%, 36%, and 10%, respectively, caused an increase of 0.02%, 1.11%, 0.45%, and 0.1% in health outcomes. However, increasing speed by double and one-third for motorcyclists and cyclists reduced the risk of infection and disease burden by 1% and 0.3%, respectively. When the length of the flood area increased by two times longer than the base value, health outcomes increased by 0.4%, 0.6%, 0.8% and 0.7% for child pedestrians, adult pedestrians, motorcyclists and cyclists, respectively. By traveling on 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. Change in water intake (Table 3) had a limited effect on health outcome (1.1-1.4% lower or 1-2% higher).

The uncertainty of the input had a weak impact on the risk of 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 S7, Appendix).

Sensitivity analysis firstly highlights the influence of flooded areas on disease burden. Investing in reducing floods can reduce the disease burden and the risk of infection 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. Furthermore, in our study, when applying the ratio (that is, the ratio between *E. coli* and rotavirus) to calculate the concentration of rotavirus, the risk of infection and disease burden showed a noticeable difference compared to the base value (that is, the 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 and Locas, 2011). Therefore, in future studies, care should be taken 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 density of exposed people caused a significant reduction in health outcomes, the study indicated the importance of controlling the number of people on the streets during flooding. Furthermore, the study stated the importance of DALYs per case, since reducing DALYs per case resulted in a significant decrease in disease burden. In addition, 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} DALY per case) (Katukiza *et al.*, 2013). In contrast, for the same area, Fuhriman et al. (2016) 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 burden of the disease for the community. More research into standard DALYs may be needed to have a plausible range, especially LMICs. In contrast, intake rates, the length of flooded streets and the speed of exposed people had a minimal effect on health outcomes. Limaheluw et al. (2019) also indicated a less impact of the ingest volume on the burden for consuming polluted surface water in sub-Saharan Africa (Limaheluw *et al.*, 2019). Additionally, the uncertainty of concentration and the length of the flooded streets showed more importance to infection risk than intake rates, although the correlations were weak.

6.4 CONCLUSIONS AND CONTRIBUTION

In this chapter, the study used a combination of estimated infection risks with population data to better understand the disease burden caused by enteric pathogens (that is, rotavirus A) through contact with floodwater. Total DALYs were calculated to quantify how many healthy years of life people may lose when exposed to contaminated floodwaters.

This chapter revealed the burden of the disease per flood event due to rotavirus A in floodwater through traffic activities. All exposure groups showed a high average infection probability due to rotavirus A per person per exposure (0.96-0.98). The study estimated that the illness cases were 20-30 times higher than local epidemiological reports.

Motorcyclists showed the highest exposure to contaminated floodwater on flooded streets in Ninh Kieu district, contributing to the highest disease burden expressed as total DALYs per flood event (12,835 DALYs per event, 95%). The burden of cyclists, adult pedestrians, and child pedestrians was 379, 270, and 16 DALYs, respectively. The infection risk was most sensitive to the concentration of rotavirus. The burden of the disease showed high sensitivity to flooded areas and concentration. Furthermore, exposed population density and standard DALY significantly reduced the disease burden. In contrast, the length of the flooded streets and the speeds of the 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 health risk results.

To improve QMRA and disease burden, improving knowledge of ingestion volumes, dose-response models, and severity of illness involves ethical considerations and is less manageable than measuring microbial parameters. According to the sensitivity analysis in this study and other relevant studies, the microbial concentration was the most sensitive parameter. However, using average microbial pathogens based on measurements can lead to underestimating or overestimating, as some samples may not reflect the microbial concentration in the flood area. Also, it was difficult to take flood-related water samples during flood events. Therefore, to improve the essential factor of QMRA, another feasible evidence-based solution was that the hydrodynamic model can be used. The next chapter will present the urban flood model and simulation of microbial pathogens in floodwater.

7

ANALYSIS OF THE LOCATION AND CONCENTRATION OF ENTERIC PATHOGENS IN URBAN FLOODWATER IN CAN THO CITY - VIETNAMESE MEKONG DELTA

The previous chapter quantified the health consequences (ie, infection risk and disease burden) based on the measured concentration of pathogens. To improve QMRA for microbial pathogens, this chapter developed an urban flood model and simulated *E. coli* and rotavirus. The findings provide insight into the concentrations and location of simulated microbial pathogens in floodwater.

This chapter is published/presented in the following:

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7.1 INTRODUCTION

In the previous chapter, the contribution of measured microbial concentrations to health outcomes was highlighted in quantifying infection risk and disease burden. However, some floodwater samples may not fully describe the concentration and spatial distribution of pathogens in the flood area. The complexity arises from the dynamic nature of the water quality of floods. Floodwaters are characterised by the complex dynamics of water, which is reflected in the difference in water levels and pollutant concentration. Although some data observed from water sampling can give information about pathogens of interest, the concentration and spatial distribution of enteric pathogens in urban floodwater are not easily determined without computational models. In practise, taking floodwater samples is also challenging, as it is dependent on timely flood forecasting and logistic preparation for sampling. The concentrations of enteric pathogens in urban floodwater are not easily determined without computational models or building complex scenarios. Using a hydrodynamic model has the advantages of including dilution, spatial distribution, and changes over time. Determining the inputs of the water quality models is a challenge because the concentration of sewer water varies greatly depending on the location of sampling. Variations in wastewater quality (physiochemical and microbial pollutants), rainfall, and river water level affect floodwater quality.

This chapter aims to develop an urban floodwater quality model to simulate microbial pathogens in floodwater. It aims to identify the concentration in floodwater and the spatial distribution of the concentrations in the flood area. The environmental effects such as solar radiation and the die-off/growth of microbial pathogens were not considered in this study, as they were assumed to play no significant role. The rationale for this assumption was that the duration on streets in the case study is short (1-2 hours) and that these factors do not function on the microbial pathogens in floodwater. The results of the simulated microbial concentration provided essential input to assess the infection risk and calculate the disease burden due to exposure to traffic as described in this chapter.

7.2 MATERIALS AND METHODS

7.2.1 Urban Flood Modelling

The study simulated the concentrations of pollutant in urban floodwater originating from pollutants in the dry weather flow, mixed and transported in the rainwater and surface runoff.

The study used the detailed 1D urban model (Stormwater Management Model - SWMM) developed for the study area by Huong and Pathirana (2013) to simulate the effect of the flood drainage network on flooding in the Ninh Kieu district. The model was calibrated and showed good results with measured water depths in the manholes (Ngo *et al.*, 2020).

The total area of the district is about 2,900 ha. However, the sewer system covers only part of the district (660 ha), to which we applied urban inundation. This model includes 479 junctions, 612 conduits, 48 outfalls, and 303 subcatchments. The percentage of impervious surface area was 60%. The land-use classes (i.e., high intensity developed, medium intensity developed, and low intensity developed) were defined for each subcatchment. The drainage network consists of circular concrete sewer pipes with diameters ranging from 0.3 to 2 m. The maximum depth of the nodes was defined as 2 m. The maximum depth of the nodes was defined as 2 m. All outfalls are directly connected to the Hau River, Can Tho River, Cai Khe Canal, and Xang Thoi Lake. Figure 28 shows the model set up for the focus study area in the Ninh Kieu district.

The flood event on 17 October 2016 caused by high tide and rainfall was chosen to analyse the urban flood in the case study. The details of the flood event on 17 October 2016 are represented in Chapters 5 and 6. River water level time series with 1-hour intervals were used as boundary conditions at the outfalls (Figure S2, Appendix). Rainfall input of the same day with the same time interval was also used (Figure S6, Appendix). The model was simulated from 00:00 to 17:00. The routing model used was the dynamic wave and the Horton infiltration model was used as the infiltration model. The routing and reporting time steps are set to 0.5 seconds and 1 minute, respectively. The previous dry days were negligible since rain events occurred on the previous days (Table S8, Appendix).

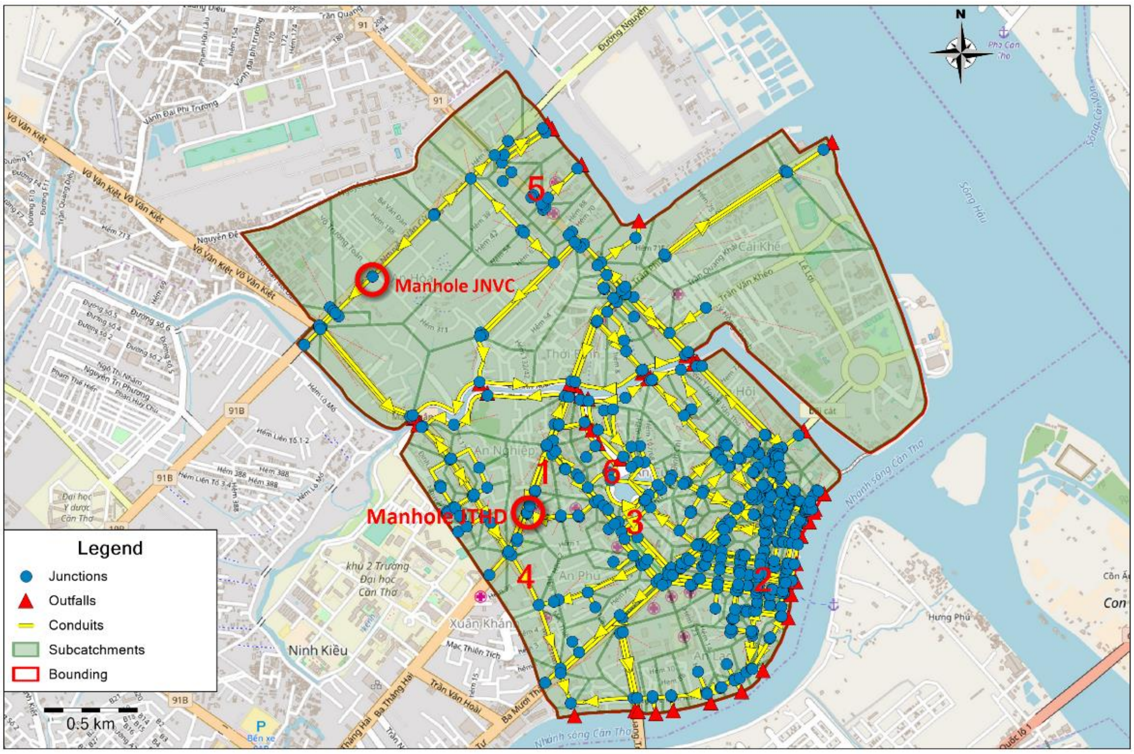


Figure 28. The detailed 1D urban flood drainage model for the study area (Huong and Pathirana, 2013)

(Two manholes (JNVC in Nguyen Van Cu Street and JTHD in Tran Hung Dao Street) were used for calibration by Ngo et al. (2020). The numbers indicated the floodwater sampling locations on the streets during the flood event on 17 October 2016.

7.2.2 Urban Floodwater Quality Modelling

Simulation of dilution and transport of pollutants in wastewater along the length of a conduit (that is, a pipe) was carried out using the 1D advection-dispersion model (SWMM) (Di Modugno *et al.*, 2015; Rossman and Huber, 2016). This study considered enteric pathogens, including *E. coli* and rotavirus A (RVA), which were assumed to be transported as conservative pollutants. Since the short duration of floods (up to 60 minutes) may not affect the decay or growth of pathogens, these factors are not considered (ten Veldhuis *et al.*, 2010). Furthermore, total suspended solids (TSS) and biological oxygen demand (BOD_5) are included to calibrate the water quality model. The following part describes the water quality setup and calibration for the 1D model.

- **Set up the urban floodwater quality model**

There are three primary sources of pollutants in the urban floodwater quality modelling of the case study:

1. *Rainfall Runoff:* Rainfall is presented by one hour time series data (Figure S6, Appendix). The concentrations of the pollutant in the rainwater for TSS and BOD were considered 8mg/l and 22mg/l, respectively (Göbel et al., 2007), while the concentration of *E. coli* and RVA in the rainwater was negligible.
2. *Surface water* includes the Hau River, theRiver, the Can Tho River, the Khai Luong Lon River, Cai Khe Canal and Xang Thoi Lake, which are bounded by the case study with time series data of the river water level (Figure S1, Appendix). During the high-tide period, surface water causes backwater in the pipes. The characteristic of pollutants in surface water is shown in Table 8.
3. *Wastewater from households*: Graywater and blackwater after septic tanks are described as the dry weather flow (DWF) in the model. Domestic wastewater flows are defined based on the discharge in the case study (9,024 people/km2,(Can Tho City Statistical Office, 2016)) and generated wastewater per person was considered as 120 litters/per day (Nguyen, 2010; CDIA, 2016). The model estimated wastewater concentration per subcatchment as a dry weather inflow. It was assumed that the population density is similar for all sub-catchments in the case study. The characteristics of pollutants in domestic wastewater were chosen from a plausible range for the inflow from dry weather (Table 9). Except for hourly patterns, the variations in daily, weekend and monthly wastewater discharge variations were neglected (Figure S7, Appendix).

Table 8. Pollutant Concentrations in surface water in Ninh Kieu District

Pollutants	Unit	Hau River	Can Tho River	Khai Luong Lon River	Cai Khe Canal	Xang Thoi Lake
TSS	mg/L	35-60* 23.5-54.5**	22-65* 24-49**	28-42*	12.5-66.5** 4-71*	13.5-68**
BOD	mg/L	5.8-10.5**	5-7.2**	5.5-8*	3-33** 4-7.3*	2-31**
E. coli	CFU/L	2.18E+05**	5.54E+04 - 2.23E+06**	-	5.54E+04 - 3.65E+07**	5.54E+04 - 4.83E+06**
RVA	gc/L	0	3.75E+08 - 8.35E+09**	-	3.75E+08 - 2.04E+09**	3.02E+06 - 1.12E+09**

(*) Source: Environmental report 2015-2020, Can Tho (Can Tho Department of Natural Resources and Environment, 2015).
(**) Source: (Huynh *et al.*, 2020)

Table 9. Characteristics of pollutants in the flow of sanitary dry weather in some references.

Pollutants	Unit	(Metcalf & Eddy, 2003)	(Henze and Comeau, 2008)	(Pham, 2014) (In Ha Noi, Vietnam)	(Huynh *et al.*, 2020) (In Can Tho, Vietnam)
TSS	mg/L	120 - 400	250-600	54-106	13.5-203
BOD	mg/L	110 - 350	230-560	104-346	8-567
E. coli	CFU/L	1E+07- 1E+11	1E+07 - 5E+09	7E+05 - 6.3E+06	5.54E+04 - 3.82E+08
RVA	gc/L	-	2E+02- 1E+05	-	1.59E+07 - 2.29E+09

In SWMM, the pollutants in surface runoff are also identified by the build-up and wash-off equations. The build-up equation indicated the accumulated concentration of pollutants during dry days, while the wash-off equation described the loss of pollutant during rainy days (Rossman and Huber, 2016). However, in this study, several rainfall events occurred before the day of 17 October 2016 (Table S8, Appendix), and the accumulation and washdown were considered negligible.

- **Calibrate the urban floodwater quality model**

For calibration of the water quality model, measured concentrations of total suspended solids (TSS), biological oxygen demand (BOD), *E. coli* and RVA in sewage water from two samples in the JTHD manhole and one sample at manhole JNVC on 17 October 2016

(Figure 28) were used (Table 10). The details of sampling and analysing the samples were described in our previous study (Huynh *et al.*, 2020).

Table 10. Pollutant concentrations were measured in two manholes (JTHD and JNVC) on 17 October 2016 in the Ninh Kieu district.

Manholes	Time	TSS (mg/L)	BOD_5 (mg/L)	*E. coli* (CFU/L)	RVA (gc/L)
JTHD	16:35:00	12.5	21	8.31E+05	9.93E+07
JNVC	8:35:00	7	7	7.51E+04	5.86E+07
	16:45:00	20	21	1.88E+06	4.05E+08

The calibrated 1D urban water quality model was then used to establish an integrated 1D/2D model using PCSWMM software to calculate floodwater quality (http://www.chiwater.com/Software/PCSWMM). A 15 m resolution DEM developed by the Vietnam Institute of Meteorology, Hydrology and Environment was used in all simulations (Ngo *et al.*, 2020).

7.3 Results and Discussions

7.3.1 Floodwater Quality Model Results

The simulated concentrations showed reasonable trends during flooding (Figures S4 – S7, Appendix). Pollutant concentrations steadily increased in the morning when floodwater was receding due to decreasing river water level (Figure S1). At that time, the pollutants in the sewage water had a lesser dilution from river water and surface runoff. The highest concentrations of pollutants were around 15:00, when the wastewater level got the lowest, coinciding with the lowest river water level. Then the simulated concentrations in the sewage water decreased due to the mixing of the river water during the high tide period after 15:00.

Compared to the observed data, the simulated concentrations for four pollutants were close to the measured concentrations (Table 11). Figures S8 – S11 (Appendix) showed the observation and simulation results for TSS, BOD, *E. coli*, and RVA at two manholes, JNVC and JTHD. The pathogen concentrations in the two results were nearly the same order of magnitude. It would be better to have more observed pollutant concentrations to assess the efficiency of the urban floodwater quality model. However, with the available input data, the study developed a suitable floodwater quality model that almost described the trend and the concentrations of pollutants in wastewater in some manholes for the flood event on 17 October 2016. Then the 2D advection-dispersion model was used to simulate the transport and dilution of pollutants into floodwater.

Table 11. Observed and simulated concentrations in wastewater at two manholes, JTHD and JNVC, during the flood event on 17 October 2016 in the Ninh Kieu district.

Manholes		JTHD	JNVC	
Time		16:35	8:35	16:45
TSS (mg/L)	observation	12.5	7	20
	simulation	13.1	4	17
BOD_5 (mg/L)	observation	21	7	21
	simulation	18.8	5	30
E. coli (CFU/L)	observation	8.31E+05	7.51E+04	1.88E+06
	simulation	1.28E+06	2.82E+05	1.39E+06
Rotavirus (gc/L)	observation	9.93E+07	5.86E+07	4.05E+08
	simulation	3.25E+08	7.24E+07	4.26E+08

The study compared the concentrations of simulated and measured pollutants in the floodwater at six locations (Figure 28) for BOD_5, TSS, *E. coli*, and RVA in a flood event on 17 October 2016. Details of the sampling and analyzing the floodwater samples were described in our previous study (Huynh *et al.*, 2020). It can be seen that the ranges of simulation concentrations of pollutants included the observation values (Table 12). Therefore, it can be considered that there is a good agreement between the measured concentrations and the simulated pollutant concentrations in floodwater from the modelling.

Table 12. Observed and simulated concentrations of pollutants in floodwater on 17 October 2016 in Ninh Kieu district.

Locations	TSS (mg/L)	BOD_5 (mg/L)	*E. coli* (CFU/L)	RVA (gc/L)
(Average) observed concentrations at sampling locations				
1	5	13.5	2.31E+06	1.46E+08
2	7.8	21.2	2.55E+05	7.17E+08
3	7.4	27	4.40E+05	1.09E+08
4	15	46.5	5.05E+04	4.03E+08
5	4	53.5	9.18E+05	1.84E+05
6	6	61	1.05E+04	2.27E+06
Simulated concentrations from modeling				

Maximum Concentrations (min-max values)	1 - 79	1 - 59	1 - 5.9E+06	3.7E+01 - 1.49E+09
Average concentrations (min-max values)	0.1 - 28	0.1 - 38	1 - 2.87E+06	1.01E+01 - 7.18E+08
QCVN 08:2015/BTNMT			2E+02–2E+03	-
Directive 2006/7/EC	-	-	5E+03	-
Domestic wastewater	-	-	-	2E+03- 1E+04 (Henze et al., 2001) 3E + 02- 8E + 05 PDU / L (raw wastewater); 5E + 02-2.4E + 04 PDU / L (treated wastewater) (Lodder & De Roda Husman, 2005)
River water	-	-	-	9E+01- 5E+03 (Sibanda & Okoh, 2013)

7.3.2 Simulated Enteric Pathogen Concentrations in floodwater

The spatial trends of the concentrations of simulated pathogens in floodwater reasonably described the dilution of the dry weather flow, surface runoff, river water, and floodwater transport. Floodwater had high concentrations in the middle areas, then it diluted with surface runoff and spread into the surrounding areas with lower concentrations. The areas near big rivers like the Hau River and the Can Tho River have a lower concentration of pollutants than the central areas.

The maximum concentration of *E. coli* in floodwater ranged from 3.5E+01 CFU/L to 5.9E+06 CFU/L. The spatial distribution of pollutants showed three main trends of simulated concentrations. First, the locations with the maximum concentration of *E. coli* ranging from 1E+04 CFU/L to 1E+05 CFU/L (the yellow area in Figure 29) showed the largest spatial variation (1.18 km^2). The concentrations ranged from 1E+05 CFU/L to 1E+06 CFU/L and were distributed about 0.46 km^2 of flood area (the orange area in Figure 29). These two areas (i.e., the yellow and orange areas) were around 94.5% of the total inundated areas. Second, the smaller spatial distribution (with 0.07 km^2, 4.5% of the total inundated areas) was in locations with lower concentrations (that is, less than 1E+04 CFU/L, the green area in Figure 29). Lastly, the higher concentrations (that is, higher than 1E+06 CFU/L, the red area in Figure 29) were located at 0.02 km^2 (1% of the total inundated areas), respectively.

A similar trend was found for simulated RVA concentrations in floodwater. Maximum simulated RVA concentrations ranged from 2.1E+02 gc/L to 1.49E+09 gc/L. The largest spatial variation was at locations with concentrations ranging from 1E+06 gc/L to 1E+07 gc/L (the yellow area in Figure 30) and 1E+07 gc/L to 1E+08 gc/L (the orange area in Figure 30) with 0.8 km^2 for each range (92% of the total inundated areas). The smaller spatial distribution (0.03 km^2, 1.5% of the total inundated areas) was in locations with lower concentrations (that is, less than 1E+06 gc/L, the green area in Figure 30). The highest concentration (that is, greater than 1E + 08 g / L, the red area in Figure 30) with and 0.1 km^2 (6.5% of the total inundated areas), respectively.

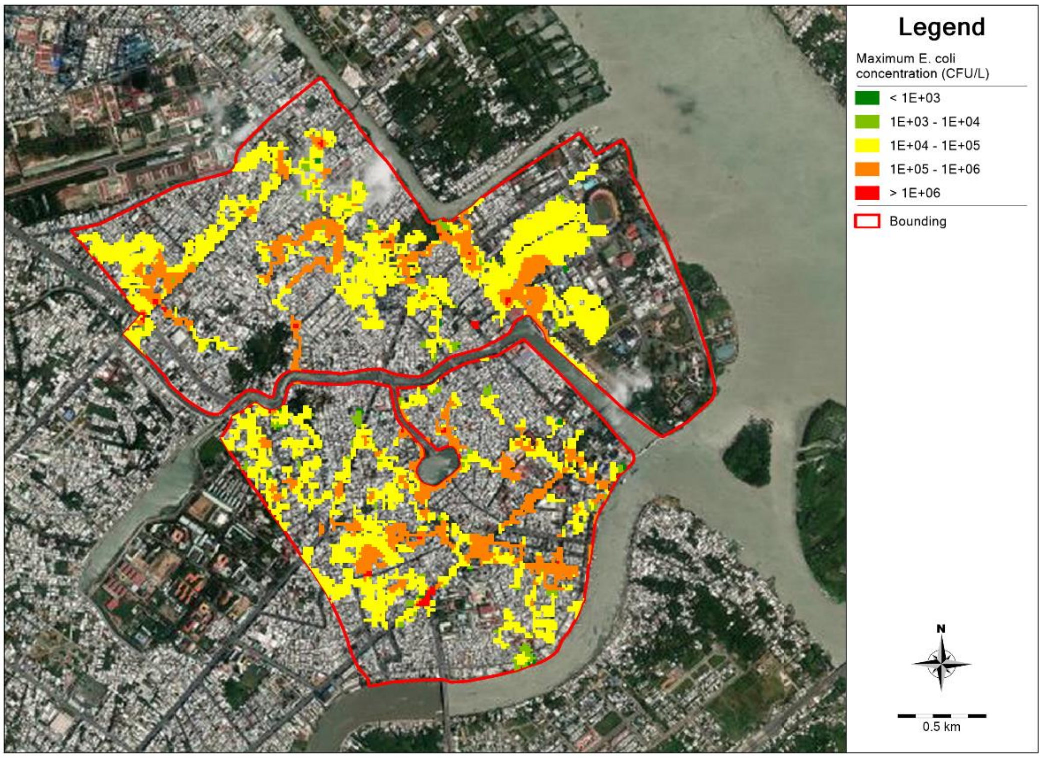


Figure 29. Maximum *E. coli* during flood event 17 October 2016 in the Ninh Kieu district

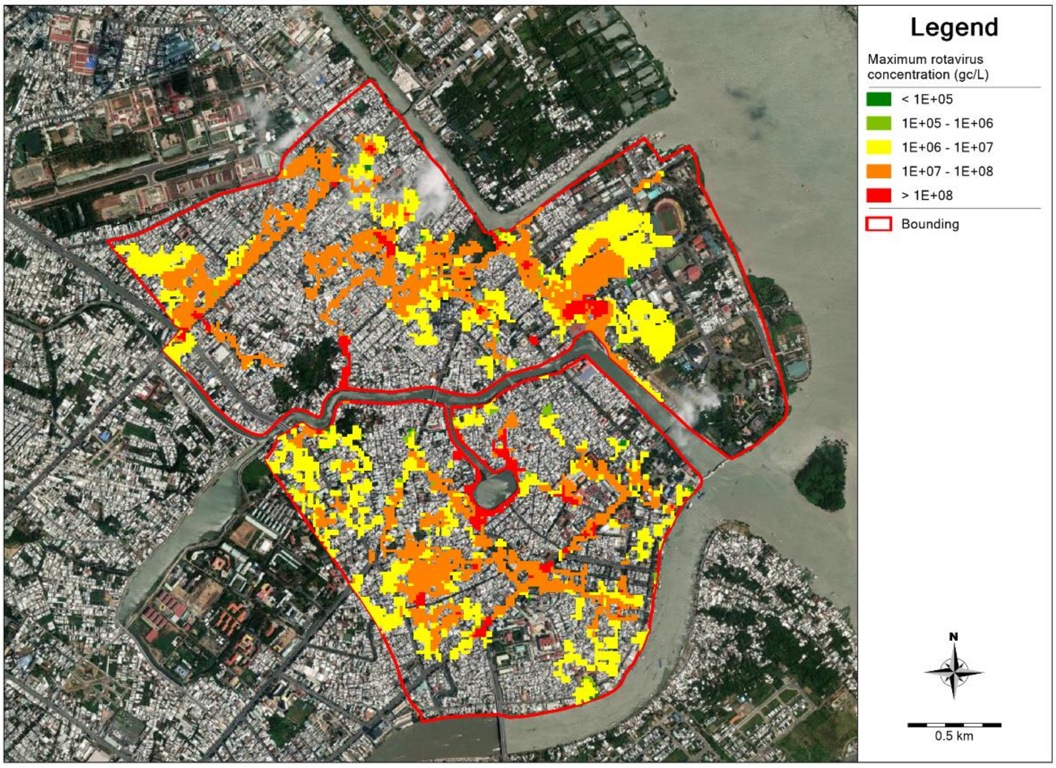


Figure 30. Maximal RVA concentrations of RVA during a flood event on 17 October 2016 in the Ninh Kieu district

Residents can be affected by the enteric pathogens in floodwater through some exposure pathways. Flooding time coincides with when people go to work/office and back home. Significantly, inner areas are the core urban areas of the city with high people density. Can Tho is the main city of the Vietnamese Mekong Delta, which focusses on many social-economic activities. The Ninh Kieu district is the core urban area of Can Tho city which has many hospitals, schools, parks, shopping centres, markets, and main streets with crowded people who may be affected by the inundation. In some locations near large rivers such as the Hau River, the areas concentrate on tourist activities, shops, restaurants, and ferries near Ninh Kieu Wharf. These locations usually have a high density of people who come into direct contact with floodwater through traffic activities and by cleaning up inundated houses. Therefore, with the simulated concentration of pathogens, the risk of microbial health was quantified for exposed people in the case study in the next chapter.

7.4 Conclusions and Contribution

In this chapter, the flood and floodwater quality model were described to simulate enteric pathogens *E. coli* and rotavirus A in the inundation areas of the Vietnamese Mekong Delta, Ninh Kieu District in Can Tho City. Pollutant parameters such as BOD, TSS, *E. coli*, and rotavirus A were calibrated using sampling data from the flood event on 17 October 2016 in Ninh Kieu. The model was in good agreement with the BOD, TSS, *E. coli*, and rotavirus A in wastewater and floodwater. Most of the highest concentrations of pathogens were found in inner areas, whereas the lower values were estimated in the surrounding regions and near large rivers. *The estimated E. coli* concentrations of 1E + 04 - 1E + 06 CFU / L covered the largest flooded areas (94.5% of the total inundated areas). Lower values (< 1E+04 CFU/L) and higher values (>1E+06 CFU/L) of *E. coli* were distributed in smaller areas (5.5% of the total areas inundated). A similar trend was found for RVA. RVA concentrations in most of the inundated sites were estimated at 1E + 06 g / L to 1E+08 gc/L. The smaller spatial areas were located in locations with lower concentrations (< 1E+06 gc/L) and higher concentrations (> 1E+08 gc/L). The concentrations of these fecal pathogens in floodwater were higher than the water quality standards (surface water quality of Vietnam and Directive 2006/7/EC - European Parliament concerning the management of bathing water quality for inland water). The average concentrations of simulated *E. coli* were 1 - 2 log10 higher than the water quality standards. The average simulated rotavirus A was 2 - 3 log10 higher than domestic wastewater in other references.

This study was the first to demonstrate the application of a hydrodynamic model to simulate the concentration in floodwater for the evaluation of health risks. The high concentration of pathogens was a potential hazard for residents who are usually exposed to floodwater in crowded areas in the case study during the flood season. In the next chapter, the simulated concentrations of rotavirus A were the input to calculate the infection risk and the burden of disease for traffic exposure.

8

INFLUENCE OF TRAFFIC IN URBAN FLOOD HEALTH RISK USING A 1D2D HYDRODYNAMIC MODEL

The previous study showed the concentration and location of rotavirus A in floodwater through streets using the 1D2D hydrodynamic model. This represented a new approach to quantifying waterborne-related health risk through traffic exposure, which has not been fully represented in flood events in terms of exposure duration on flooded streets, the number of people exposed, and spatial distribution of health risk. The findings indicated that motorcyclists contributed the most to total DALYs. The DALYs calculated by simulated concentration were 3.5 times higher than the DALYs calculated by measured concentration. The results indicated the advanced approach of using the hydrodynamic model to provide quantitative data for microbial pathogens and exposed people for calculating microbial health consequences.

This chapter is published/presented in the following:

Oral presentation: Huynh, Thi Thao Nguyen, Gerald Corzo Perez, Assela Pathirana, and Chris Zevenbergen. 2021. 'A New Concept to Implement in a Spatial-Temporal Health Impact Assessment Related to Waterborne Pathogens in Urban Floodwater Using QMRA, Disease Burden by DALYs and 1D2D Hydrodynamic Model. Case Study: Ninh Kieu District, Can Tho City, A Lower Mekong Basin." In the *17th International Conference on Urban Health. 06 – 08 July.* (online).

Oral presentation: Huynh, Thi Thao Nguyen, Gerald Corzo Perez, Chris Zevenbergen. 2022. "Exploring the link between microbial pathogens in urban floodwater and health consequences through traffic exposure on the streets. A case study in the Vietnamese Mekong Delta: Ninh Kieu district, Can Tho city". In *the Third IAHR Young Professionals Congress*. 29 November – 03 December. (online).

8.1 INTRODUCTION

Based on generic QMRA tools, the microbial health risk has been assessed based on three main elements: hazard, exposure, and vulnerability (Fewtrell *et al.*, 2011). This health risk assessment informed the average probability of microbial in floodwater (ten Veldhuis *et al.*, 2010; Man *et al.*, 2014). In the concentrations of case of QMRA, the microbial pathogens, which are the most sensitive parameters, are usually lacking. The sampling of pathogen concentrations in floodwater is often challenging to conduct. In addition, pathogen concentrations in floodwater are diluted by rainwater, river water, and sewer water and are variable during flood times. Therefore, monitoring floodwater quality is limited to identifying the range of microbial hazards. Some studies indicated that hydrodynamic modelling could improve the measured concentration (Eregno *et al.*, 2016; van Bijnen *et al.*, 2018). Hydrodynamics models describe the influence of sewer water and stormwater on floodwater quality (Andersen *et al.*, 2014). The transport and dilution of microbial pathogens can be simulated for inland floods (Collender *et al.*, 2016). Hydrodynamic modeling can support extracting the critical input parameter of QMRA, microbial concentrations in floodwater. However, regarding waterborne health risks through traffic exposure in urban areas, the integration of risk elements and spatial distribution has not been fully addressed in current research.

In addition, to assess the risk of microbial health, a detailed analysis of flood events on the streets has not involved some risk variables such as the number of exposed people and the effect of disease caused by pathogens. These two elements are essential to calculate the disease burden with DALY, indicating the healthy life years lost due to disease. The previous study usually assessed an individual's infection and illness probability rather than estimated other adverse health impacts (such as illness symptoms and death) on the population. Chapter 6 estimated the DALYs per flood event due to rotavirus A (RVA) in floodwater in the Ninh Kieu district. However, it used the average measured concentration of RVA to calculate the infection risk. The research activities described in the previous chapter used the density of exposed people (exposed people/m^2 of flooded area), which may be uncertain since the flooded area (m^2) changes over time. Chapter 7 simulated the microbial pathogens in floodwater which can be used to predict the infection risk and disease burden using the hydrodynamic model in this chapter 8.

This chapter aims to analyse traffic exposure during flood events by considering the hazard, exposure, and vulnerability to estimate the health risk related to waterborne pathogens in floodwater (i.e., infection probability and DALY). The study includes the simulation of the microbial pathogen using the hydrodynamic model. The density of people (people/m^2 of the street) on the observed street was estimated and extrapolated to other streets by the traffic scale. The study applied Quantitative Microbial Risk Assessment (QMRA) and Disability-Adjusted Life Years (DALY) to calculate the health risk. The study indicated the spatial distribution of the health risk results. Calculations were carried out in flooded grid cells with the support of QGIS 3.22.7. The study also compared DALY calculated by simulated concentrations with DALY calculated by measured concentration in Chapter 6. This research is the first to employ QMRA, disease burden, and hydrodynamic modeling in the exposure of traffic to urban floodwater.

8.2 MATERIALS AND METHODS

The study used QMRA to calculate the infection risk and DALY to estimate the disease burden. Figure 31 and Table 13 indicate the steps to take and the critical input data.

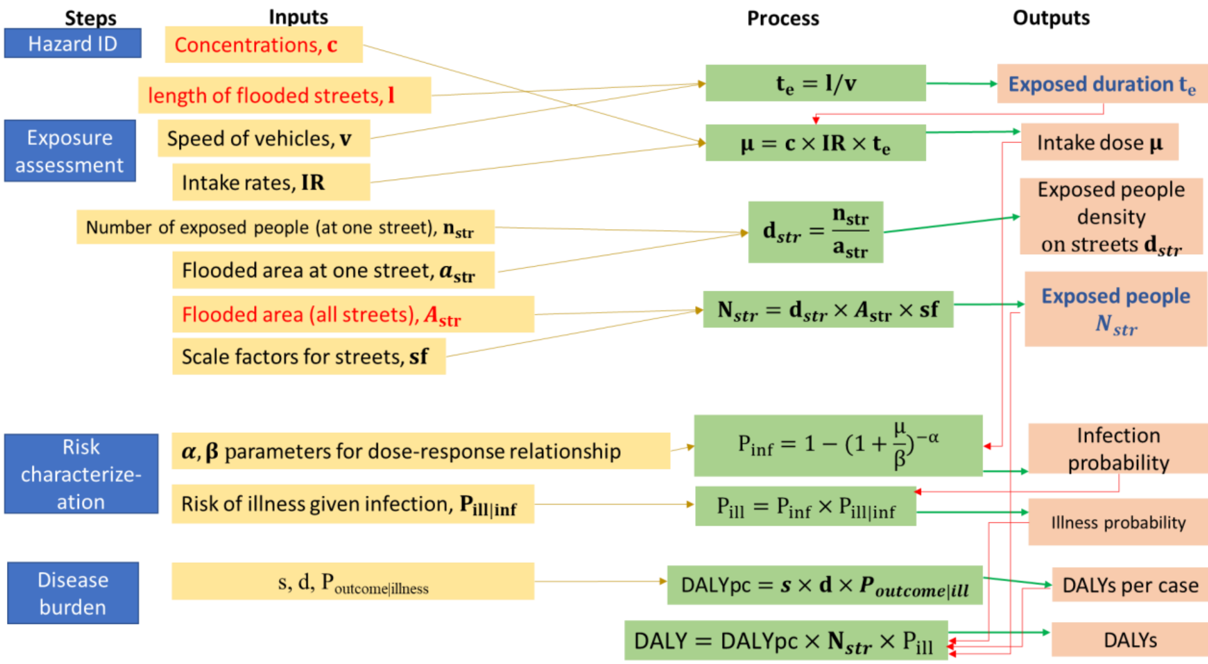


Figure 31. The diagram describes the steps to calculate the DALYs using the hydrodynamic model and the assessment of health risk related to waterborne pathogens in floodwater for a single flood event.

Table 13. Input data for the probability of QMRA model to calculate the infection and illness per person per event.

(* DALYs per case calculated for developing countries. The average expectation is 73.6 years for Vietnamese (GOPFP, 2019))

Inputs	Units	Values	References
α (rotavirus)		0.253	(Haas et al. 1999)
β (rotavirus)		0.4220	
Concentrations		(Maximum) simulated rotavirus concentration at grid cells (Figure 32)	(Chapter 7 in this thesis)
Intake rates			
Child pedestrians	(mL/hour)	3.7	(Dorevitch *et al.*, 2011)
Adult pedestrians	(mL/hour)	3.5	
Motorcyclists	(mL/hour)		
Cyclists	(mL/hour)		
Speeds			
Child pedestrians	m/h	4,200a	a (Waters *et al.*, 1983) b (Tang *et al.*, 2020) c (Cherry and He, 2009)
Adult pedestrians		4,800a	
Motorcyclists		14,000b	
Cyclists		10,000c	
Risk of illness given infection of rotavirus P(ill|inf)		0.5	(WHO, 2016)
Length of (flooded) grid cell	meter	5	This article
The scale factor for traffic density		Figure 33	(Bang *et al.*, 2018)
Population density on street			
Motorcyclist	(people/10,000 m^2)	3	(Huynh et al., unpublished article)
Cyclists		56	
Adult pedestrian		270	
Child pedestrian		80	
DALYs per case due to rotavirus A*	DALYs	0.4377	(Havelaar and Melse, 2003)

8.2.1 Interest Microbial Pathogen

The study used rotavirus A (RVA), which was simulated in Chapter 7 as the threat pathogens in floodwater. Rotavirus is one of the most common causes of diarrhea, especially in young children (Rutjes *et al.*, 2009; Lestari *et al.*, 2020). In the Ninh Kieu district, RVA was prevalent in sewer, river and floodwater samples during the flood event on 17 October 2016 (Huynh *et al.*, 2020). In this study, we used the maximum simulated

RVA concentration (Figure 32) to calculate the health risk. The simulated concentration ranged from 1.01E+01 - 7.18E+08 genome copies/L (gc/L).

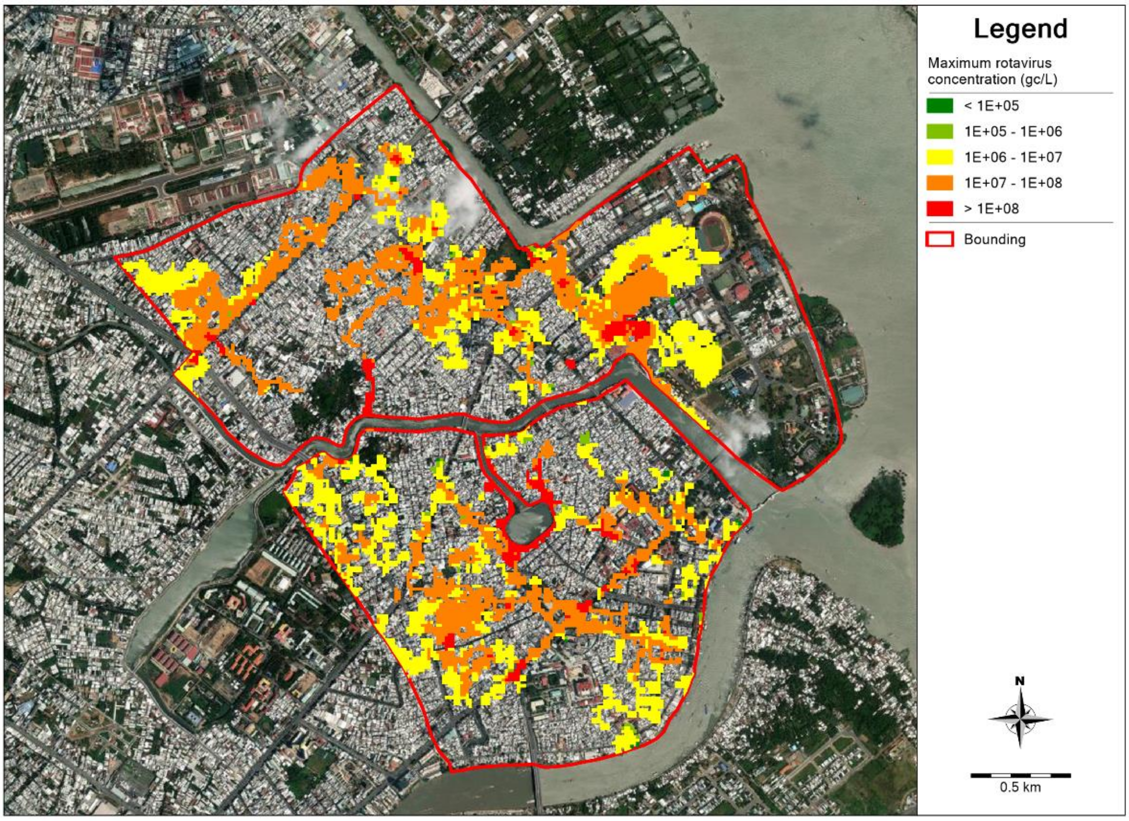


Figure 32. Maximal RVA concentrations of RVA during a flood event on 17 October 2016 in the Ninh Kieu district

The microbial concentration is an essential parameter in QMRA. Change in this input data can make a significant change in the assessment of health risk. Therefore, with two sources of concentration data, one from our measured data (the previous study, called 'scenario C1') and one from simulated data (this study, called 'scenario C2'), we also aim to compare the final health risk result calculated from these two scenarios (Table 14).

Table 14. RVA concentration (gc/L) in scenario C1 (measured concentration data) and scenario C2 (simulated concentration data)

	Scenario C1 (measured concentration)	***Scenario C2*** (simulated concentration)
RVA concentration (gc/L)	2.27E+06 – 2.96E+09 gc/L (min-max), 5.9E+08 gc/L (average)	1.01E+01 - 7.18E+08 gc/L (min-max), 1.16E+07 gc/L (average)

8.2.2 Exposure assessment

(a) Exposure pathways and exposure groups

The same four groups of exposed people were considered including child and adult pedestrians, motorcyclists, and cyclists as in Chapter 6. Motorbike and bike groups included thousands of riders.

(a1) Intake rate

Child and Adult Peers: The intake volumes from the literature were 30-50 ml (ten Veldhuis *et al.*, 2010) and 01 mL - 30 mL for children and adults per incident, such as playing and bathing (Donovan *et al.*, 2008). However, these studies did not incorporate the duration of exposure per incident. Furthermore, bathing and playing in floodwater is rare in urban settings in Vietnam. Dorevitch et al. (2011) showed that the average intake volumes were 3.5 ml for walking/splashing in pool water for 60 minutes. Therefore, the study used 3.5 mL/h as the intake rate for children and adult pedestrians.

Motorcyclists and cyclists: In the literature, no intake rates or volumes have been reported for motorcyclists or cyclists through floodwater. However, Dorevitch et al. (2011) identified that motorboat drivers ingested 3.7 ml in one hour. Therefore, the volume study assumed that the consumed for these two groups was 3.7 ml/h.

(a2) Exposure duration

Since the study considered exposure through traffic activity, the duration of exposure (that is, the time spent in inundated areas) depends on the length of the flooded street and the speed of vehicles. Therefore, we expressed the exposure duration ($\boldsymbol{t_e}$) on the flooded road as equation (6.1) in chapter 6.

Where $\boldsymbol{l}$ (m) is the length of the flooded area and velocity $\boldsymbol{v}$ (m/h) is the velocity of the individual crossing the flooded area. The length of flooded streets to which a person is exposed is variable and difficult to collect. Therefore, this study gave two options depending on the approach used to calculate the health risk. Firstly, for the observed flood event, the flooded streets ($\boldsymbol{l}$) to which a person was exposed in a flood event was calculated as the average length of a flooded street of all flooded streets reported on the flood event 17 October 2016 (Chapter 6). The second option was that the study calculated the health risk in flooded grid cells for a simulated flood event. Therefore, the health risk and the burden of the disease were calculated at grid cell (l = 5 m). The study named option 1 was **Scenario L1**, and option 2 was **Scenario L2**.

A similar assumption for speed vehicles has been made as described in Chapter 6. It was assumed that the individual kept the same speed when travelling through a flooded street. Tang et al. (2020) identified traffic flow speeds (i.e., motorcycles, cars, and buses) on an arterial road in Hanoi (Vietnam) to be 9-14 km/h during 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, since the study occurred during rush hour, we assumed that the velocity was 14 km/h. Several studies have determined that the average speed of cyclists was 10 km/h in China (Cherry and 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 speed was 70 and 80 metres per minute for children and adults, respectively (Waters et al. 1983).

In addition, there is a lack of reliable information on the correlation between flood depth, intake rate, and duration of exposure. Therefore, it was assumed that the variability of flood depth did not affect the intake rate or the duration of exposure.

(b) Number of people exposed during a flood event

The same equations (6.3) to calculate the total number of exposed people (N_e) at all flooded areas on streets was applied. Of these, number of people exposed during flood events was calculated based on the density of people ($\mathbf{d_e}$, equation (6.2), the scale factor for traffic ($\mathbf{sf}$), and the areas on the flooded street (**A**, equation (6.4). Since not all people on flooded roads could be counted, the density of study identified the people density on one street ($\mathbf{d_e}$) (equation (6.2) in chapter 6), then extrapolated to others. The scale factor ($\mathbf{sf}$) is included due to the difference in people density between streets. The scale factor is used to correct for traffic density in each flooded street. The people density ($\mathbf{d_e}$) was calculated by manually counting the people on one road (n_{str}, people) and the areas (a_{str}, m^2) on that street.

However, the values of people density, scale factor in a flood event, and total flooded areas were assumed different compared to chapter 6. For example, tor the areas on the flooded street (**A**), the previous study used the data from the local report, while in this chapter, the hydrodynamic model was applied to simulate the flooding. The details of assumptions for these values are described as two scenarios as ***Scenario E1*** (Chapter 6) and ***Scenario E2*** (this chapter) (Table 15). The table presents the input data and descriptions to calculate the exposed people for the two scenarios.

Scenario E1**:** Data on the lengths and widths of the flooded areas in flooded streets from the local report in Ninh Kieu were used to calculate the total flood areas **(A)** of the flood events on 17 October 2016. The density of exposed people density ($\mathbf{d_e}$) was determined based on the number of people ($\mathbf{n_{str}}$) who went through the street segment (Table A1, Appendix) and the flooded areas of that street from our observation ($\mathbf{a_{str}}$, 100 m (length) * 10 m (width) = 1,000 m^2). Chau Van Liem Street was chosen to record the video in 1 hour of the flood event on 17 October 2016. This manual counting method is used in transportation studies to analyse traffic flow (Iowa State University, 2002; Pande and Wolshon, 2003). The description and the recording on Chau Van Liem Street are shown in detail in our previous study (Huynh et al., unpublished paper). The scale factor **(sf)** was determined 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. The scale factors were 0.8 and 1.2 for those streets with smaller (<10 m) and larger (>10 m) widths, respectively. The total exposure of people on the streets during a flood event **(**$\mathbf{N_e}$) was then calculated.

Scenario E2**:** The scale factor was estimated to express the difference in traffic density between the streets based on the number of vehicles. Figure 33 shows the scale factor for traffic density by using traffic counting data to assume the scale factor (sf) for traffic density. Bang et al. (2018) manually counted traffic vehicles (motorbikes, buses, cars) for 75 roads in Ninh Kieu and found that some streets are more crowded than others (Bang *et al.*, 2018). Here, data from 6 am to 7 AM and 7 AM to 8 AM were taken to get a similar period of traffic activity as the flood event on 17 October 2016 (Figure 34). When calculating the scale factor, the average number of motorbikes from 6 AM was used to 7 AM and 7 AM to 8 AM for each street per hour. The baseline was on Chau Van Liem Street.

The density of people on street was calculated by the number of people who passed through the street and the area of the street (m^2). Manual counting method to count the number of people who crossed Chau Van Liem Street in one hour on October 2016. Here, the number of people on Chau Van Liem Street in 1 hour (Table S9, Appendix) was used to calculate the density of people per square meter of the street. The people density ($\mathbf{d_e}$, people/m^2) was calculated based on the number of people that we recorded (n_{str}, people) and the area of Chau Van Liem Street ($\mathbf{a_{str}}$, 600 m (length) * 10 m (width) = 6,000 m^2).

The reason for using two approaches to calculate exposed people in two scenarios was related to the uncertainty of the flooded area. In scenario 1, the study assumed that the flooded area did not change over 1 hour of flooding and calculated the exposed people in the flooded area (exposed-people density). This assumption was reasonable for scenario 1, since the flooded areas on all streets were available to calculate the total exposed people per flood event. However, in reality, the flood area in a street change over time, which causes a change in the density of exposed people and exposure duration. Therefore, instead of using the exposed person density from *Scenario E1*, in *Scenario E2*, the people density (i.e., people were available on the street) was used, which considers the number of people who went through the street area at a certain time (in this case is during flooding time, around 1 hour). Exposure people were calculated for each cell of the flooded grid on the street which was simulated by the flood model.

Since this chapter calculated the exposed people in the size of the grid cell and showed the spatial distribution of the health risk, the exposed people **($\mathbf{N_e}$)** at each flooded grid cell were calculated as ($N_e = d_e \times A \times sf$). **A** ($m^2$) was calculated based on the widths and lengths (5mx5m) of flooded grid cells. The total number of people exposed was the sum of exposed people in all flooded grid cells.

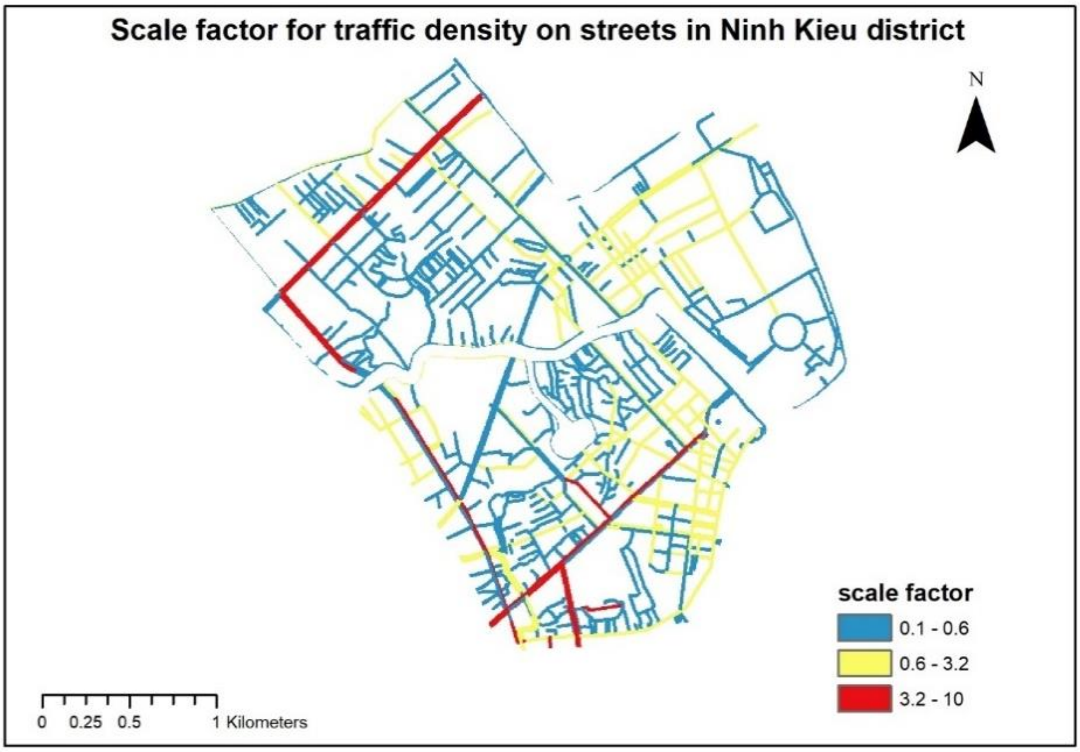
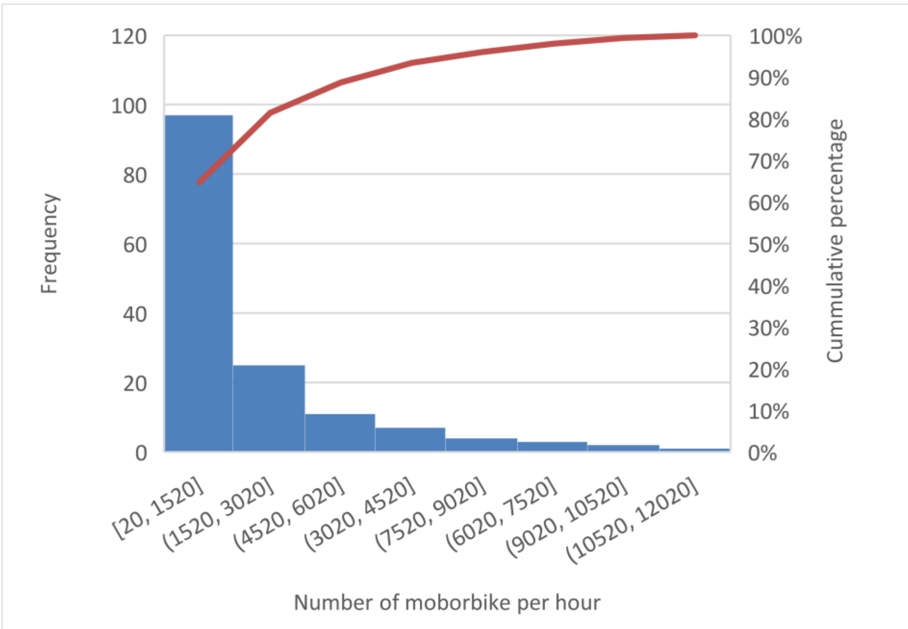
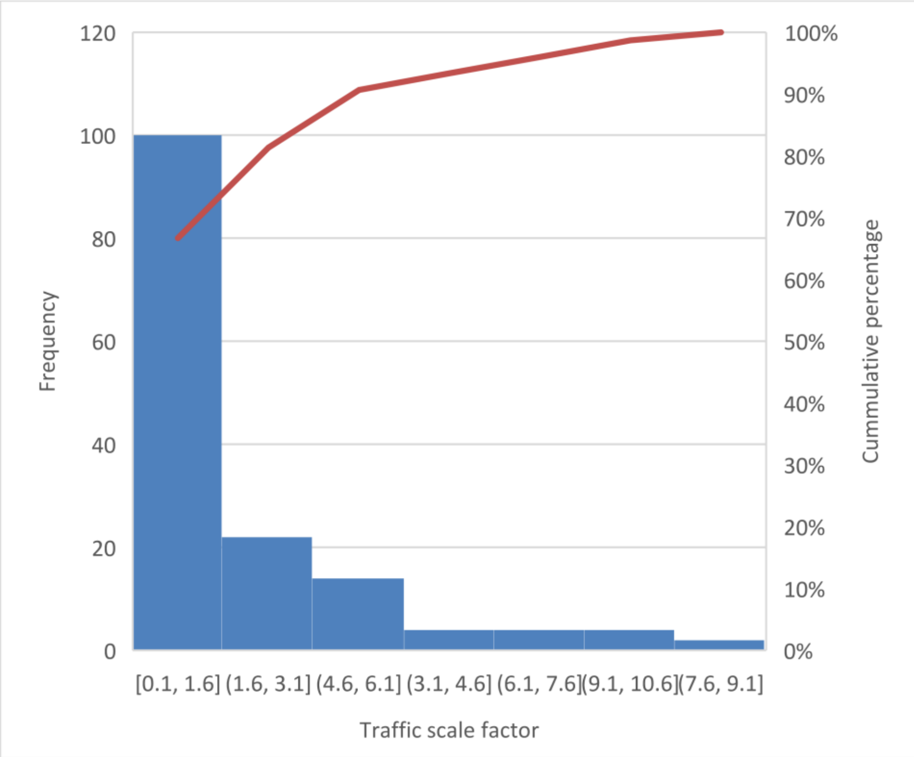


Figure 33. The scale factor for the density of traffic in Ninh Kieu district (2016).



(a)



(b)

Figure 34. The frequency of (a) the number of motorbikes per hour on each street and (b) the scale factor of traffic density in the Ninh Kieu district. The data included 75 streets from 6 amam to 7 AM and 7 AM – 8 AM, which were adapted from Bang et al. (2018).

Table 15. Scenarios to estimate the total number of people exposed to a flood event in Ninh Kieu district

	Units	***Scenario E1*** (Chapter 6)	***Scenario E2*** (Chapter 8)
1. People density (d_e)	(people/m^2)	Exposed People Density Per Square Metre of the flooded area on the street	People's density per square meter of street
1.1. People on one street	(people)	Number of people in 1 hour in a flooded area in Chau Van Liem Street	Number of people on 1 hour in Chau Van Liem Street (in flooding time)
1.2. Areas on one street	(m^2)	Flooded areas on Chau Van Liem Street (1,000 m^2)	Areas of Chau Van Liem Street (6,000 m^2)
2. Scale factor	-	Based on the widths of the streets compared to the ‘baseline’ width of Chau Van Liem Street	Based on the number of motorbikes on the streets compared to the ‘baseline’ number of motorbikes on Chau Van Liem Street
3. Total Flood Areas in flood event	(m^2)	The sum of flooded areas on all flooded streets in Ninh	The sum of all flooded grid cells (data from urban flood modeling)

17 October 2016		Kieu (data from the report of the local authority)	
4. Total exposed people in flood event on 17 October 2016	(people)	$N_e = \sum_{i=0}^{n} (d_e \times A \times sf)_i$ Of these, i is the flooded street, n is the number of flooded streets from the local report	$N_e = \sum_{j=0}^{m} (d_e \times A \times sf)_j$ Of these, j is the cell on the flooded grid and m is the number of flooded grid cells in the urban flood model.

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

8.2.3 Health Risk Assessment

In the final step, the above-mentioned steps are combined to estimate the probability of risk per person per exposure (to floodwater). The equations of infection, probability due to RVA, and critical input data for the QMRA approach are shown in Figure 31 and Table 13. The input data to calculate the burden of the disease with DALYs were similar to *Section 6.2.2* in Chapter 6, except for the exposed people that were described in *section 8.2.2* (this chapter).

The total DALYs of all exposure groups per flood event are: $Total\ DALYs = \sum_i (\mathrm{DALYs}_{pe})_i$

In this chapter, the spatial distribution of disease burden, infection probability, and disease burden at each flooded grid cell was quantified based on the simulated concentrations and exposed people at the grid cell. The number of DALYs per cell in the grid was calculated by multiplying the base DALYs per case by the number of illness cases per grid for each exposed group. The total DALYs per flood event is the sum of DALYs for each exposed group in all flooded cells. The calculation was applied to flooded grid cells using QGIS 3.22.7 https://www.qgis.org/en/site/. In this study, the cell size is 5mx5m.

In this study, we calculated the health risks and spatially distributed the probability of infection and DALYs. This chapter applied an approach to calculate quantitative data for health risk asssessment. Thus, the results from two data assumption may be different compared to chapter 6. Therefore, we compared the difference in health risk results (that is, infection risk and disease burden), which were calculated based on the different of RVA concentration and total exposed people per flood event Table 16). The other parameters were the same for both scenarios.

Table 16. Scenarios 1 and 2 to calculate infection risk and disease burden based on RVA concentration and total exposed people.

Input values	**Scenario 1**	**Scenario 2**
RVA concentration	Scenario C1	Scenario C2
Total exposed people	Scenario E1	Scenario E2

8.3 RESULTS AND DISCUSSION

8.3.1 People exposed per flood event in Ninh Kieu district

The number of people exposed to scenario E2 was 3.5 times higher than those exposed to scenario E1. During the flooding period, the total number of exposed people in the Ninh Kieu district was estimated at 230,538 (Table 17).

Table 17. People exposed to floodwater including child pedestrians, adult pedestrians, cyclists, and motorcyclists in a flood event in the Ninh Kieu district

Exposed groups	Scenario E1	Scenario E2
Child - pedestrians	75	258
Adult - pedestrians	1,274	4,514
Cyclists	1,798	6,450
Motorcyclists	61,143	219,316
Total	63,390	230,538

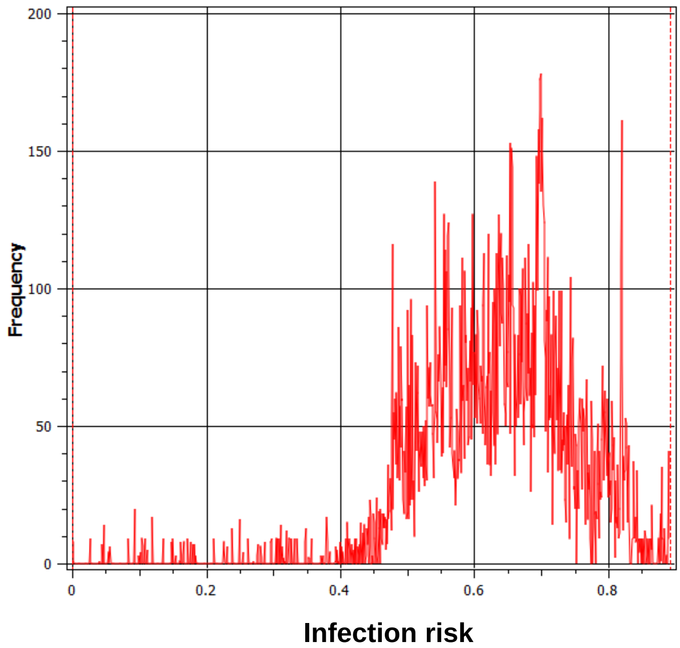
This study considered the essential input parameters: concentrations and exposed people, which are the most impact factors on health risk results. The research approached how to have more quantitative data about QMRA and DALYs through exposure to traffic activities. The exposed motorcyclists were estimated to have 219,316 people during the flooding time in Ninh Kieu. Bang et al. (2018) manually counted the number of motorbikes at 173,000 on 75 streets in Ninh Kieu from 6 AM -7 AM, which was 1.3 times less than our result. However, it is reasonable since we included riders and pillions directly exposed to floodwater, while Bang et al. (2018) only counted the number of motorbikes to calculate air pollution.

8.3.2 Infection risk due to rotavirus in floodwater in Ninh Kieu

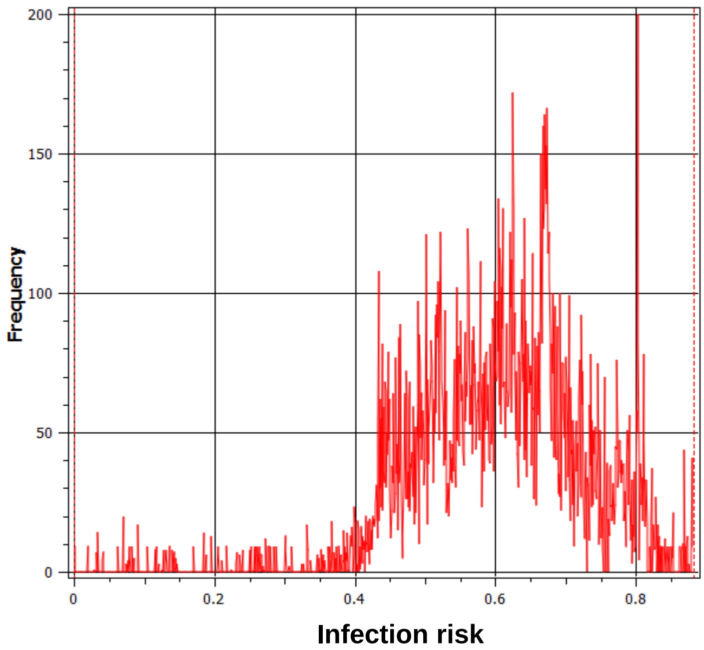
The average infection probability calculated by the simulated concentration (scenario 2) is less than the average infection probability calculated by the measured concentration (scenario 1) 1.5 times (Table 18). The frequency histogram of the infection risk showed that the majority values ranged from 0.5 to 0.8 (Figure 35). The highest infection risk is found in the areas with higher RVA concentrations in Figure 36 (ie, in the red and orange areas). These areas are primarily in the inner part of the case study, which was also near markets, while areas near open water like big canals/rivers were less susceptible to infection. The reason may be the dilution of river water into floodwater in those areas.

Table 18. The infection risk results due to RVA were calculated using measured concentrations (Scenario 1) and simulated concentrations (Scenario 2) for single exposure of pedestrians, cyclists, and motorcyclists of children and adults in a flood event on 17 October 2016 in the Ninh Kieu district.

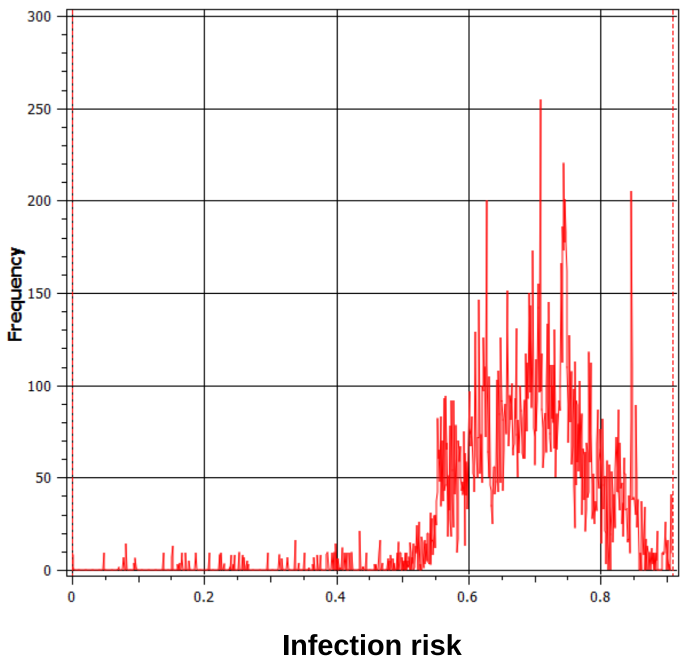
Exposed groups	Infection probability			
	Scenario 1		Scenario 2	
	Min – Max	Average	Min – Max	Average
Child pedestrians	0.91 – 0.99	0.98	0.0002 – 0.89	0.64
Adult pedestrians	0.87 – 0.98	0.97	0.0001 – 0.88	0.61
Cyclists	0.85 – 0.97	0.96	0.0004 – 0.91	0.69
Motorcyclists	0.83 – 0.97	0.96	0.0005 – 0.91	0.7


200
150
100
50
0
Frequency
0
0.2
0.4
0.6
0.8
Infection risk

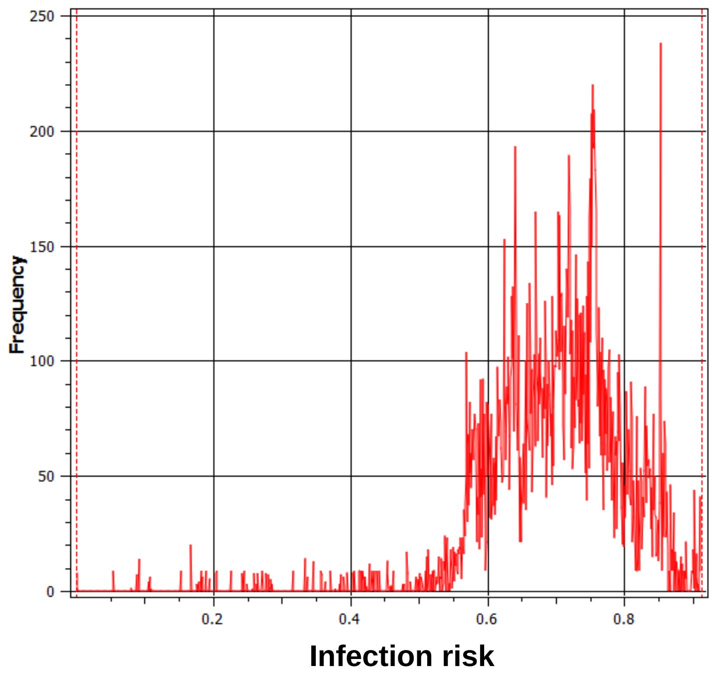
(a)


200
150
100
50
0
Frequency
0
0.2
0.4
0.6
0.8
Infection risk

(b)



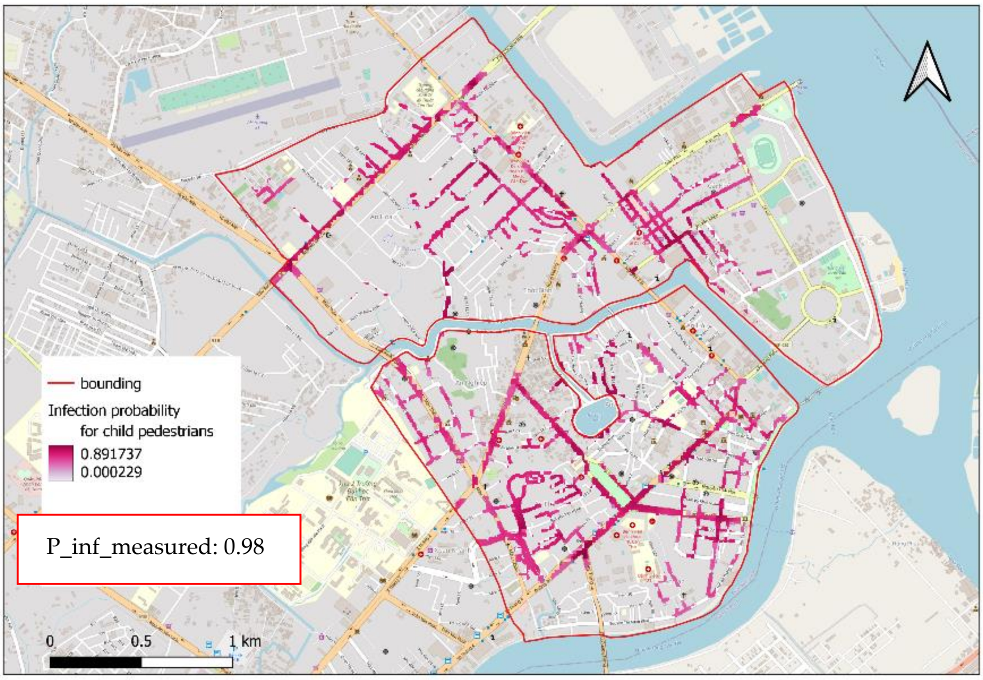
(c)

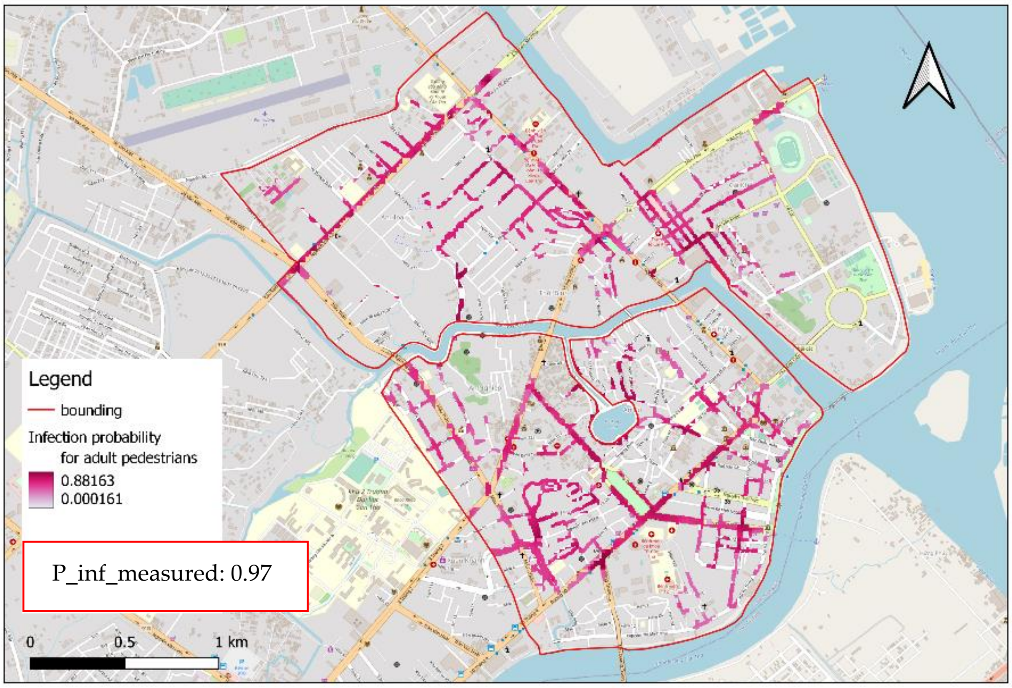


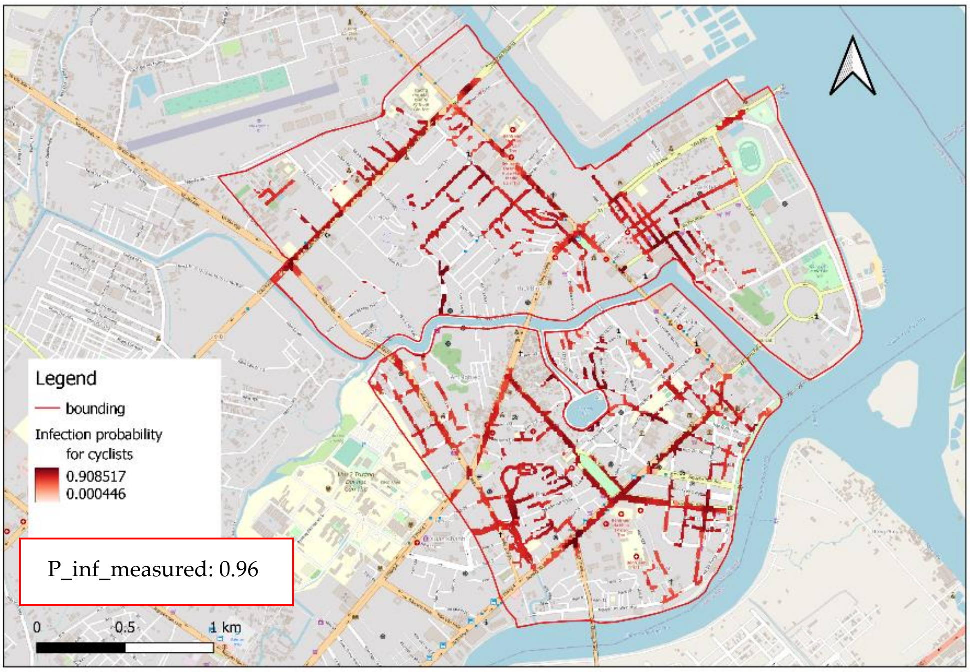
(d)

Min and max values of infection probability

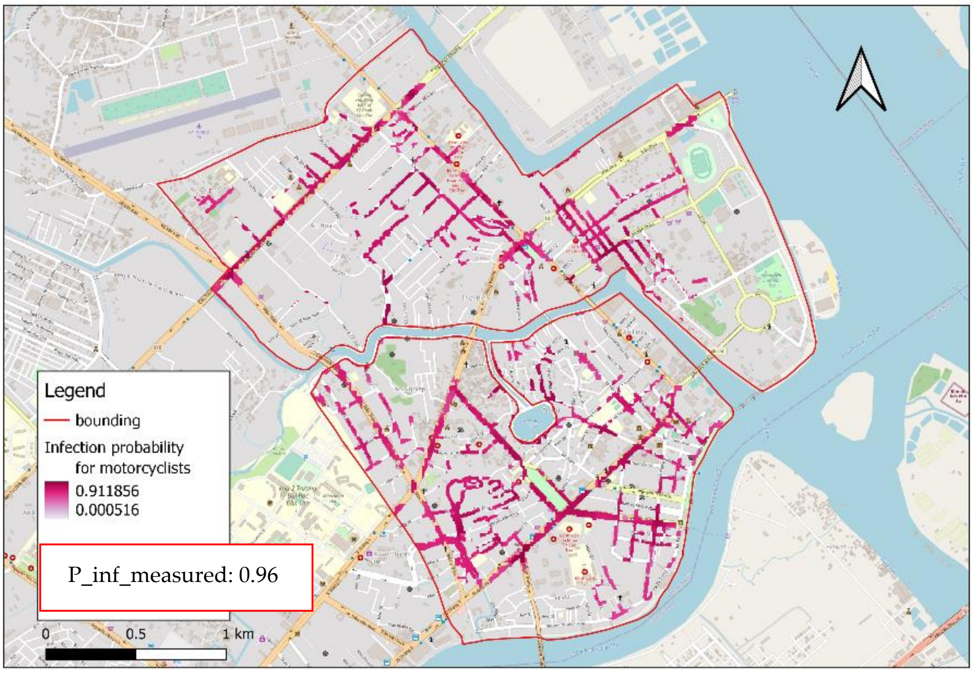
Figure 35. Histograms of the risk of infection for (a) child pedestrians, (b) adult pedestrians, (c) cyclists, and (d) motorcyclists due to (simulated) rotavirus A in floodwater in Ninh Kieu district for the 17 October 2016.


bounding
Infection probability
for child pedestrians
0.891737
0.000229
P_inf_measured: 0.98
0
0.5
1 km
(a)


Legend
bounding
Infection probability
for adult pedestrians
0.88163
0.000161
P_inf_measured: 0.97
0
0.5
1 km
(b)



(c)



(d)

Figure 36. Spatial distribution of the probability of infection (P_inf_simulated) for (a) children pedestrians, (b) adult pedestrians, (c) cyclists, and (d) motorcyclists by simulated rotavirus A during flood event 17 October 2016 in Ninh Kieu district. (P_inf_measured: Probability of infection by mean measured rotavirus A concentration in floodwater with respect to the exposure groups).

The ranges of infection probability were comparable to the infection risks of other relevant studies. The probability for child pedestrians, adult pedestrians, cyclists and motorcyclists due to RVA was 0.0002 – 0.89, 0.0001 – 0.88, 0.0004 - 0.91 and 0.0005 – 0.91, respectively. The infection risks caused by *C. jejuni*, noroviruses, and enteroviruses in floodwater in the Netherlands were 0.00039 – 0.33 for children and adults (De Man *et al.*, 2014). However, the average infection risk in this study was one log10 higher than the average infection risk caused by *V. cholera* in floodwater in Dhaka, Bangladesh. (Mark *et al.*, 2015). The average risk of infection due to RVA in this study was similar to the infection risk due to *E. coli* in surface water for drinking in Cambodia (0.7). The spatial distribution of the infection risk showed that higher infection risk values were located at higher concentrations in RVA areas. The different infection risk mainly caused by the difference of pathogen concentrations. The magnitude and pollution sources caused the difference in the dilution of wastewater stormwater where the high/low risk area is determined (Kazama *et al.*, 2012). High-risk areas in this study were located near the market, hospitals and some surface water areas such as the Xang Thoi lake and Cai Khe canal. These high-risk areas are also close to schools and administrative offices, which usually have a large number of people in the early morning and afternoon. Therefore, many people may have a high risk of infection from the RVA in floodwater during the flooding period in the Ninh Kieu district since the crowded time on the streets coincides with the flooding.

8.3.3 DALYs due to rotavirus in floodwater in Ninh Kieu

The burden of disease due to RVA in floodwater was 35,795 DALYs for 230,538 people exposed people in four exposed groups. Motorcyclists contributed the highest disease burden to total DALYs (34,161, 95%), followed by cyclists (989, 2.8%) adult pedestrians (609, 1.7%) and child pedestrians (36, 0.5%).

The number of children with illness pedestrians, adult pedestrians, cyclists, and motorcyclists calculated in scenario 2 was 2.2, 2.3, 2.6, and 2.7 times higher than the people with illness in scenario 1, respectively. The total DALY calculated for all exposed groups (that is, for all flood grid cells) in scenario 2 were 2.7 times higher than the DALY calculated in scenario 1 (Table 19). The location of the DALYs is represented in Figure 37. The DALYs on the flooded streets mainly generated at similar values (i.e., orange areas) except for some small areas (i.e., the purple and green areas) that represented the highest DALYs. The areas with the highest DALY were at some locations on Hoa Binh Boulevard, Nguyen Van Cu Street, and some pink areas on Mau Than Street, Ba Muoi Thang Tu Street, and Quang Trung Street. These areas are more vulnerable than others in terms of the health risk related to RVA in floodwater. The difference between the highest and lowest DALY values is around five log10 values. The higher DALY values can be explained by the higher density of exposed people on the streets in these areas, which can be observed in the scale factor of traffic density in Figure 33.

Table 19. People with the disease and DALY were calculated by the simulated concentrations and measured RVA concentrations of RVA in the flood event on 17 October 2016 in the Ninh Kieu district.

Exposed groups	Illness people		DALYs	
	Scenario 1	Scenario 2	Scenario 1	Scenario 2
Child pedestrians	37	83	16	36
Adult pedestrians	617	1,392	269	609
Cyclists	865	2,260	377	989
Motorcyclists	29,312	78,041	12,779	34,161
Total	30,831	81,776	13,441	35,795

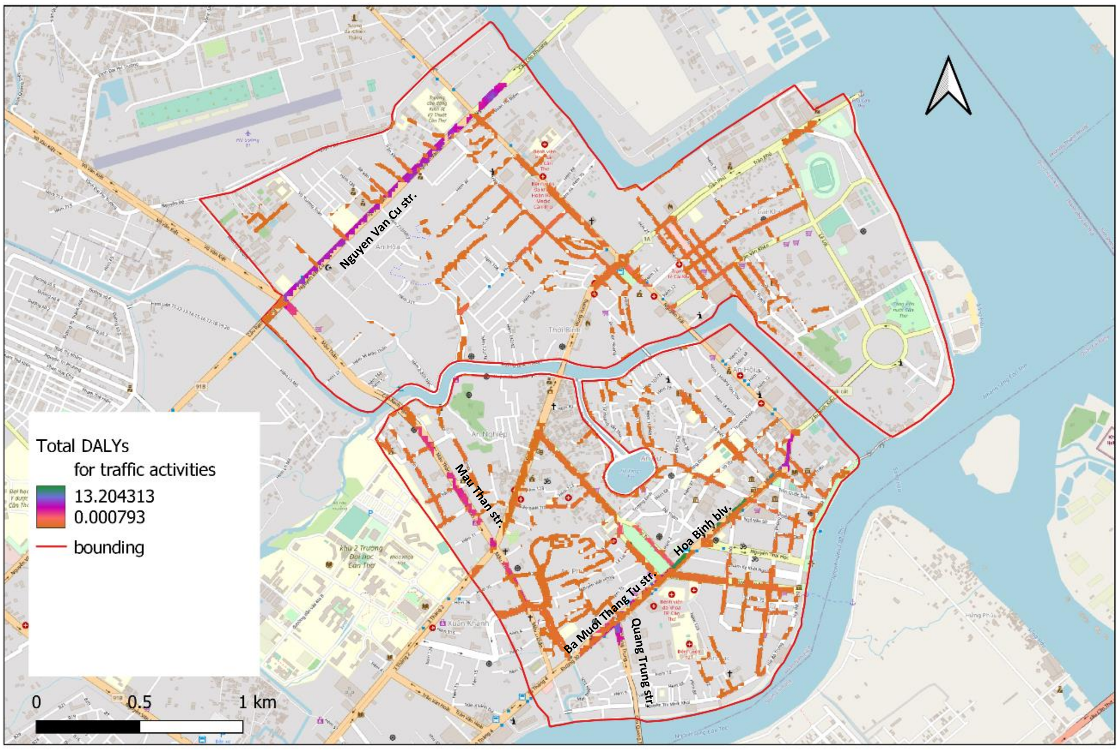


Figure 37. DALYs for cyclists, motorcyclists, and pedestrians due to simulated (maximum) Rotavirus concentration during a flood event on 17 October 2016 in Ninh Kieu district

It should be noted that the disease symptoms after infection depend on immunity which is affected by variety-specific factors such as age and sex. The rate of illness developed from RVA infection was applied from the experiment data for children. Adults are healthier than children. Therefore, the DALYs can be overestimated. The study did not consider the difference between age ranges. For example, disability weights were used the same for all ages of people with illnesses. The year of life lost in various age ranges and the mortality rates have not been considered. The study only the same mortality rate for all people. Therefore, the infection risk and disease burden can be updated in the future when these experimental data are available.

To our knowledge, it is the first time the combination of health risk assessment, disease burden, and hydrodynamic model has been applied to estimate microbial health risk. In this study, we calculated the probability of infection and DALYs due to enteric pathogens in floodwater through traffic exposure. Additionally, the spatial distribution showed the areas with higher risk and the most vulnerable people due to RVA in floodwater. The problem for urban residents is not only 'living with a flood" as a familiar slogan, but "living with certain risks of waterborne diseases' during flooding time. Therefore, some measures can be invested in the risk of future to reduce the microbial health during flooding time. In this study, we highlight the importance of exposed people and concentrations in the result of the health risk assessment. The number of exposed people can be reduced by avoiding traffic activities during flooding. An early alarm for health risks can be integrated into the early flood warning programme to make people aware of potential diseases related to microbial pathogens in floods. The locals should encourage hygiene, such as washing hands and changing wet clothes after exposure to water. For example, during hygiene Covid-19 pandemic, the propagation plays an essential role in reducing disease cases (Roy et al., 2020; Kaushik et al., 2021). On the other hand, to reduce the risk (that is, the concentration in floodwater), some technical solutions can be conducted, such as natural-based solutions and low-impact development to reduce flooding and improve floodwater quality.

8.4 CONCLUSIONS AND CONTRIBUTION

This chapter presented a simple approach to model the complex urban sewer system and assess the health risk related to the microbial pathogen in floodwater. The results help to better understand the risks to microbial health during flooding time through direct exposure to traffic activities, which is the most common 'unavoidable' activity during flooding time, especially in developing countries. Additionally, the study gave a comparison of the results of two scenarios when using measured data from observed flood events and simulated data from flood modelling. The infection probability calculated by simulated concentration (scenario 2) gives values lower than the results calculated by measured concentrations (scenario 1) about 1.5 times. The exposed people were 3.5 times higher in scenario 2 than in scenario 1. The total DALYs in Scenario 2 were 2.7 times higher than the DALYs in scenario 1. Motorcyclists contributed the most to DALYs compared to other exposed groups (95%). The findings indicated the alternative approach of using hydrodynamic modeling to have more solutions to get the quantitative data on the concentration of microbial pathogens, duration of exposure and people exposed to quantify the health consequences.

The spatial distribution shows that high-risk areas are located near sources of pollution areas, such as markets and other inner areas of the city, while areas near open water, such as large canals and rivers, had lower microbial risk. Areas with higher disease-burden are near crowded places such as schools, markets, and hospitals. The health risk assessment in this study highlights the years of potential risk and the healthy life lost due to rotavirus A in floodwater for residents in Ninh Kieu. This approach can be used to estimate microbial health risks following specific flood events. Risk assessments help to inform local authorities and people to raise awareness or early warning during heavy rainfall and high tide periods. In future research, an acceptable risk of infection and a reduction intervention can be involved. The burden of disease with the DALY metric can represent the vulnerability in terms of health for affected people in flood areas.

9

INCLUDING MICROBIAL HEALTH RISK IN FLOOD RISK ASSESSMENT

The previous chapters explored the link between microbial pathogens in floodwater and health consequences through direct exposure to floodwater by traffic activities. The hydrodynamic model simulated microbial pathogens, and estimated exposed people and exposure duration to calculate infection probability and disease burden. The DALY indicated the health consequences of affected people in the flooded area due to microbial pathogens. Health is an indicator of social vulnerability in flood vulnerability assessments. However, the health consequences due to adverse factors influenced by flooding, such as microbial pathogens in floodwater, have been less considered. This chapter examines the level of flood vulnerability including microbial health consequences by (1) quantifying the disease burden caused by microbial pathogens in floodwater through traffic activities, and (2) identifying flood vulnerability areas with health effects. The variables to determine the level of flood vulnerability are the density of people and disease burden with DALYs (social dimension), the number of low-income households (economic dimension) and number of pharmacy stores, and hospitals (medical services) for ten wards of Ninh Kieu district (Can Tho, Vietnam). The highly vulnerable areas are located in the inner city, which is mostly assigned to low-income households, lacking medical services, and some are caused by high disease burden and population density; while lower vulnerability areas are close to rivers.

This chapter is accepted in:

Oral presentation: Huynh Thi Thao Nguyen, Gerald Corzo Perez, Chris Zevenbergen. 2023. “Including microbial health risk in flood risk assessment. Case study: Ninh Kieu district, Can Tho City in the Vietnamese Mekong Delta. In the *21st Symposium on Health-related Water Microbiology*. 4 to 6 June 2023. Darwin, Australia.

9.1 INTRODUCTION

The prerequisites for building a water-sensitive city go beyond the management of water pollution. A water-sensitive city provides multifunctional benefits of water resources for the environment and the community at the same time (Radhakrishnan *et al.*, 2018; Rogers *et al.*, 2020). Effective implementation of the water-sensitive approach requires management to reduce public health risks when exposed to water sources (Bichai and Ashbolt, 2017). A better understanding of the vulnerability of exposed communities, such as how flooding impacts and creates losses in people's well-being, can bring a socially fair approach to prioritising investments in FRM (Hino and Nance, 2021). However, in FRM, the indirect intangible impact of health consequences related to microbial pathogens is understudied in concepts such as vulnerability or exposure.

Flood vulnerability assessment is the integration of various dimensions such as social/economic/ institutional/infrastructural/service available constituents. Health is part of the social dimension in FRM (Scheuer *et al.*, 2011; Zhong *et al.*, 2021). The 'health' perspective was included to assess social vulnerability in some indices such as SFVI (Social Flood Vulnerability Index) (Tapsell *et al.*, 2002), Social Vulnerability Index (SoVI) (Cutter *et al.*, 2003), NFVI (Neighbourhood Flood Vulnerability Index) (Sayers *et al.*, 2018). In previous studies, the variables were understood as the health status before flooding. Health problems before flooding are the disadvantage, since "post-flood morbidity (and health mortality) is significantly higher when flood victims suffer from pre-existing health problems" (Green *et al.*, 1994). Therefore, by considering the health status based on such as gender/age/ diseases before flooding, the vulnerability groups to flooding in terms of health can be identified.

However, while the "health" problem was commonly the pre-flooding health status, the health impacts regarding adverse factors of flooding have not been fully understood, such as physical / mental health during flooding, for example, the groups of people that are usually exposed to floodwater. The adverse factor (microbial pathogens in floodwater) during flooding has not been involved as the variable for 'health' indicators to identify the vulnerable groups in the assessment of flood vulnerability. There is a gap in knowledge about the (physical/mental) health impact caused by adverse factors and the involvement of this issue in the flood vulnerability assessment and FRM, in general. The challenges of quantifying microbial health risk are a lack of available data and the absence of the right metric to express health consequences (i.e., mortality and morbidity) for example, by disease burden with DALYs. The data shortage may come from the difficulty in identifying the microbial hazard and exposure pathway. Furthermore, the health risks of the different communities may have different characteristics due to demographic / behaviour / institutions / infrastructure, etc. which affects responding, recovering, and adapting to adverse factors such as disease due to microbial pathogens in floodwater.

In addition to the pre-health status, other factors influence the vulnerability of health effects for exposed communities. These 'pre/during/post flood' factors increase or decrease vulnerability to health effects (that is, the characteristics that increase the vulnerability of health effects when flooding) (Table 20) (Lowe *et al.*, 2013).

Table 20. Factors (before / during / after flood) that effect the vulnerability of health impacts of exposed people (Tapsell *et al.*, 2002; Cutter *et al.*, 2003; Scheuer *et al.*, 2011; Lowe *et al.*, 2013; Sayers *et al.*, 2018; Zhong *et al.*, 2021)

Dimensions	Factors	Pre	During	Post
Social	**Age (children, elders)**	+	+	+
	Health status (existing illness)	+	+	+
	Private pond water supply		+	
	Direct/indirect contact with floodwater		+	+
Economical	**Low income**	+	+	+
Institutional	Not determined			
Infrastructural	**Transportation system** (no/low evacuation related vehicles)		+	
	Renting houses			+
	Vulnerable houses (low elevation/flat/single level)			+
	Lack of access to health care (Medication interruption, number of hospitals)			+
Social services	No/having problem with **insurance**			+

While numerous research explored the impact of adverse factors related to floodwater on public health, challenges remain in developing the health factors or standard metrics that can be used to evaluate the vulnerability of communities. This chapter describes the first step in this process by identifying the flood-vulnerable communities from a health perspective to consider the DALYs in social vulnerability and other variables that affect the vulnerability of health.

There are several indicators/variables relevant to the "health" perspective in FVI (Table 21). These indicators can increase/decrease the vulnerability of health effects during/after flooding. However, due to the limited data available in this study, only some indicators were chosen. This study involves DALYs due to microbial pollution/pathogens in floodwater through traffic activities. The philosophy of involving DALY in social vulnerability is that it includes three dominant aspects of public health with quantitative variables including years lived with disability standardized by severity weights and duration of disease; years of life lost combined mortality and age of death data (i.e., expectancy); and these two values aggregate for people in a different age, gender.

Table 21. Some examples of indicators/variables relevant to the "health" perspective flood vulnerability index (FVI) from the literature review

Concepts/ Indicators	Type	Variables	Effect on FV	Descriptions (Rationale)
1. Social				**Socioeconomic status**: "ability to **absorb looses and enhances the resilience** of a community to hazards impact" (Cutter et al 2003)
Health				
Health status	Susceptibility	*Number of disability people (Sayer et al., 2012) * Percent population without a sensory, physical, or mental disability (Heinz Center 2002)	High value → Increase (+) FV	"**post-flood morbidity** (and health mortality) is significantly higher when the flood victims suffer from problems preexisting health problems (Green et al. 1994)".
Health coverage	Prepare/ Response/ Recover	*Percent population with health insurance coverage (Heinz Center 2002)	High value → Decrease (-) FV	**Medical services**: "Health care providers, including higher density physicians, nursing homes, and of medical hospitals, health insurance coverage, are important sources of relief. The **lack of proximate medical services will lengthen immediate relief and longer-term recovery from disasters**." (Source: Heinz Center for Science, Economics, and the Environment (2000), Morrow (1999), and Hewitt (1997)
Urban/ rural (demographic)	Prepare/ Response/ Recover	Population density	High value → increase (+) FV	- **High people density → higher pressure on mitigation** (Tasnuva et al. 2021)
2. Economic				

Income/wealth	Prepare/ Response/ Recover	* Income or wealth data as available (ex: GDP…) (Simonovic and Peck, 2013) * % unemployed * % low-income occupations… (Sayer et al., 2018)	High value → Decrease (-) FV	**Wealth** enables society to recover more quickly. **Low-income** status increases social vulnerability." (Cutter, Mitchell, and Scott (2000), Burton, Kates, and White (1993), Blaikie et al. (1994), Peacock, Morrow, and Gladwin (1997, 2000), Hewitt (1997), Puente (1999), and Piatt (1999)
3. Medical services				
***Health Access* (Medical capacity)**	Prepare/ Response/ Recover	* Number of physicians per 10,000 population (Norris et al. 2008) * Number of hospital's beds per 10,000 people (Auf de Heide and Scanlon 2007, American Hospital Directory www.ahd.com)	High value → Decrease (-) FV	"The **lack of proximate medical services will lengthen immediate relief and longer-term recovery from disasters**." (Source: Heinz Center for Science, Economics, and the Environment (2000), Morrow (1999), and Hewitt (1997)

In this chapter, the approach was applied to 10 wards in the Ninh Kieu district (Figure 38). Firstly, the approach to quantify disease burden with DALY as presented in Chapter 6 and chapter 8 was used to calculate DALY due to microbial pollution pathogens / in floodwater through traffic activities for the wards. Then, the study analyzed the vulnerability of flooding. The variables used to determine the level of flood vulnerability were people density and disease burden with DALYs (social dimension), number of low-income households per 1,000 people (economical dimension), and number of pharmacy stores, and hospitals per 10,000 people (medical services).

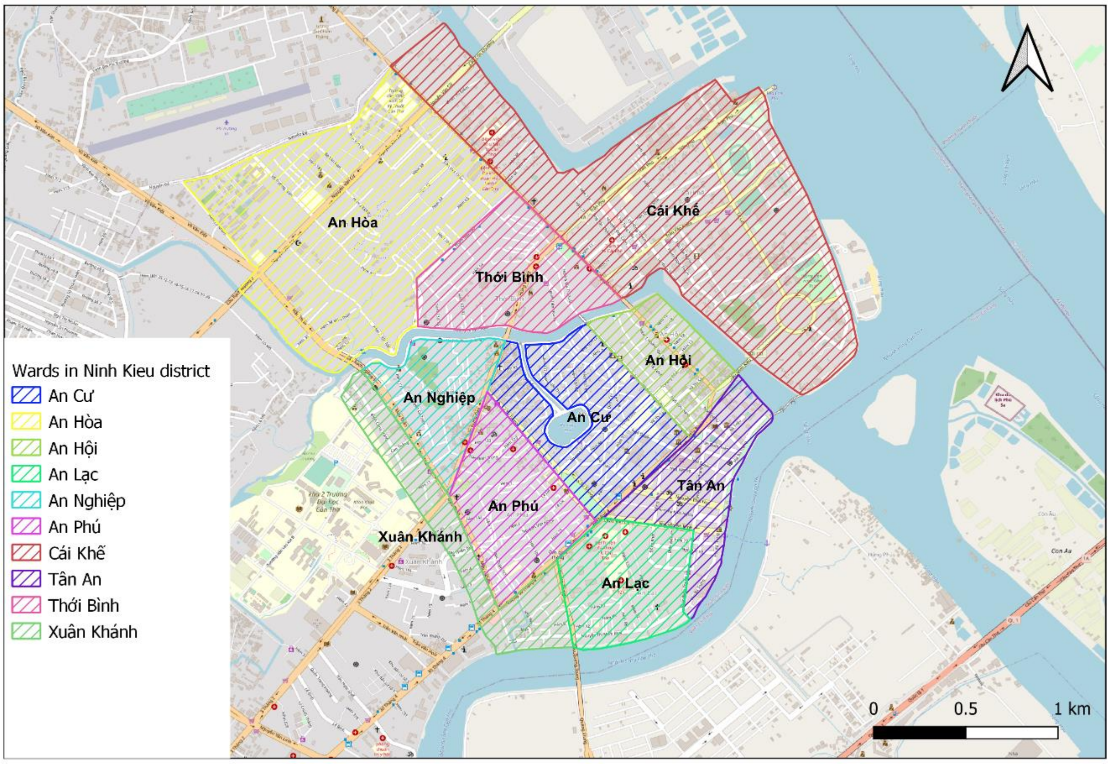


Figure 38. Wards of Ninh Kieu district in the case study area
(Base map: Open Street Map. Data of wards:
https://gadm.org/download_country.html)

9.2 FLOOD VULNERABILITY INDEX WITH CONSIDERING HEALTH EFFECT

9.2.1 Choosing indicators and supporting variables

The flood vulnerability index (FVI) was a function of social, economical, and medical service parameters (Table 24).

FVI_health = *f*(social, economical, medical service)

- Social = (health (s1), demographic(s2)) (with s1: disease burden, s2: population density)
- Economic = (low-income households)

- Medical service = (number of medical services like pharmacy stores/hospitals)

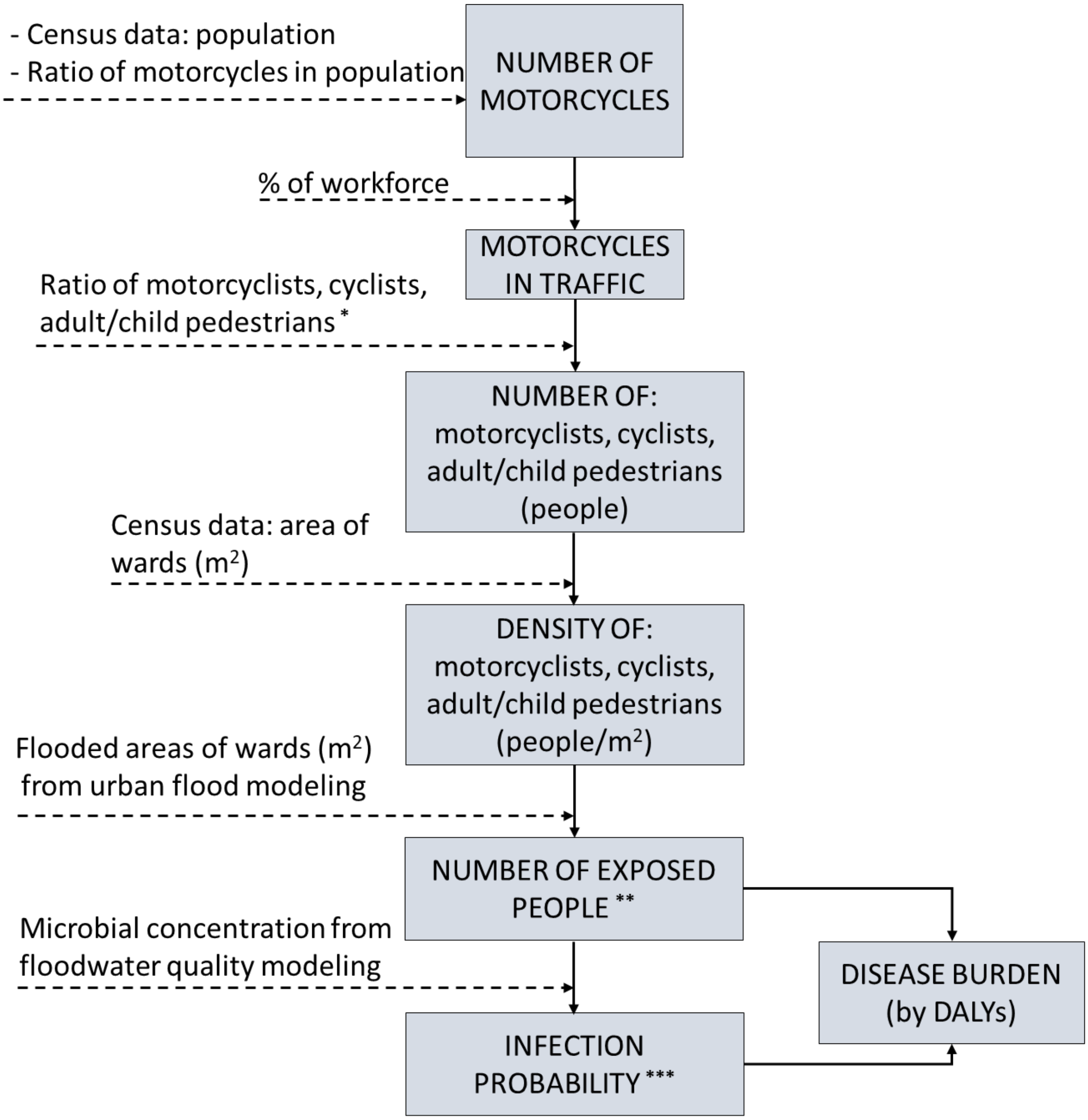
The flood vulnerability related to health effect were categorized into 5 vulnerable levels: very high, high, medium, low, and very low based on the range of final scores (FVI_health) for each ward.

The data of indicators and variables to calculate FVI was represented in Table 25, except for the DALY. The DALY calculation for each ward was described in the below section.

9.2.2 Calculating DALYs due to rotavirus in floodwater for traffic exposure in each ward

The approach to quantify DALYs due to microbial pathogens with the support of the hydrodynamic model in Chapter 8 was applied to calculate for each ward. However, the number of motorcyclists, cyclists, and adult/child pedestrians for each ward had a difference with some assumptions (Figure 39). The rationale was that each ward may have a different number of vehicles because of different populations. Data to calculate DALY in each ward were shown in Table 24 and Table 25.

- Assume that all wards have the same ratio of motorcycles in people; the ratio of traffic vehicles (motorcycles, cycles) and pedestrians on streets.
- Assume that most people in the workforce used motorbikes during flooding time since it coincides with time to work/back home. The percentage of workforce in the population among wards was different, which influenced the traffic flow in each ward. Assume that a higher percentage of workforce in the population means higher people in traffic activities.



* Ratios of one-person and two-person motorcycles on streets, ratios among motorcycles, cycles, adult/child pedestrians on street in 1-hour flood event

** Number of exposed people for each group of motorcyclists, cyclists, aduld pedestrians, and child pedestrians.

*** Infection probability for motorcyclist, cyclist, aduld pedestrian, and child pedestrian. The approach and equations to calculate infection probability were described in Chapter 8.

Figure 39. Framework to calculate disease burden for traffic in each ward in Ninh Kieu district

Table 22. Input data to calculate DALYs due to microbial pathogens in floodwater through traffic activities (for motorcyclists, cyclists, adult and child pedestrians) to each ward

Data	Value	Data sources
The ratio of motorcycles in people in Vietnam	2 motorcycles/3 people	(Chu et al.,2019)
The ratio of one-person and two-person motorcycles on street (in 1-hour flood event)	645:162	Traffic manual counting (this study)
The ratio of motorcycle:cycle:adult:child pedestrian on street (in 1-hour flood event)	816:24:17:1	Traffic manual counting (this study)

Table 23. Demographic input data to calculate DALYs for each ward in Ninh Kieu (Source: socioeconomic statistic data in Ninh Kieu)

Wards	An Lạc	An Cư	An Hoà	An Nghiệp	An Phú	Cái Khế	An Hội	Tân An	Thới Bình	Xuân Khánh
Area (km²)	0.47	0.6	1.77	0.35	0.49	6.57	0.34	0.56	0.54	2.05
Population (people)	9,578	15,003	30,702	7,319	9,842	22,369	6,284	5,353	11,169	29,564
% Workforce in population	**82.6%**	**81.7%**	**86.0%**	**78.6%**	**86.5%**	**83.2%**	**82.6%**	**82.6%**	**84.5%**	**88.9%**

Table 24. The indicators and variables to assess FVI in terms of health consequences

Concepts/ Indicators	**Variables**	**Unit**	**Rationale & Functional relationship to the Flood vulnerability**	**Data sources**
Socio				
Demographic	s1. Population density	People/m^2	- High people density → higher pressure on mitigation (Tasnuva et al. 2021) - High value → increase (+) Social vulnerability	Census data
Health	s2. Disease burden caused by adverse factors influenced by flooding for exposed people. (In this case, the microbial pathogens cause health risks to motorcyclists, cyclists, and pedestrians)	DALYs	- Potential healthy life year loss (DALYs) due to disease caused by microbial pathogens through direct exposure to floodwater in traffic activities (for motorcyclists, cyclists, and pedestrians) - High value → increase (+) Social vulnerability	This study
Economic				
Income	Low-income households per 1,000 people	Number	- Low-income status increases social vulnerability. (Cutter, Mitchell, and Scott (2000), Burton, Kates, and White (1993), Blaikie et al. (1994), Peacock, Morrow, and Gladwin (1997, 2000), Hewitt (1997), Puente (1999), and Piatt (1999) - High value → increase (+) Social vulnerability	Census data

Medical services				
Medical capacity	Number of pharmacy stores/hospitals per 10,000 people	Number	- The lack of proximate medical services will lengthen immediate relief and longer-term recovery from disasters." (Source: Heinz Center for Science, Economics, and the Environment (2000), Morrow (1999), and Hewitt (1997) - High value → decrease (-) Social vulnerability	Counting from OpenStreetMap

Table 25. Data of variables needed for calculating the flood vulnerability in terms of health consequences

	Unit	**Wards**									
		An Lạc	**An Cư**	**An Hoà**	**An Nghiệp**	**An Phú**	**Cái Khế**	**An Hội**	**Tân An**	**Thới Bình**	**Xuân Khánh**
Population density	People/km^2	20,379	25,005	17,346	20,911	20,086	3,405	18,482	9,559	20,683	14,421
Number of low-income households	Number	34	91	27	26	14	80	156	94	38	69
Number of pharmacy stores, hospitals	Number	20	6	9	9	26	28	7	16	16	9

9.2.3 Data weighting and aggregation

After having the raw data of variables, the data were normalized with the following equation:

- For the positive impacts (increase vulnerability):

$\mathbf{x_{(normalized)} = x_{(i)}/x_{(max)}}$

For the negative impacts (decrease vulnerability):

$\mathbf{x_{(normalized)} = 1 - x_{(i)}/x_{(max)}}$

Where: $x_{(normalized)}$ is the normalized value of $x_{(i)}$ (variable x number i); $x_{(max)}$ is the maximum value of variable x.

- **Weighting and aggregations**:

According to previous studies, no clear evidence for the assigned variables, the equal weight is used for all variables and indicators as they contribute the same importance. Each indicator is the sum of normalized variables. The final score of social vulnerability is the average of all indicators (Cutter *et al.*, 2008; Sayers *et al.*, 2018).

- **Flood vulnerability mapping**

The general steps were that the data of plausible variables were normalized and scored with equal weight. New categories were created based on intersecting features that were presented in two (or more) geo-registered indicators to create new categories (Li *et al.*, 1999). The final FVI was created by combining the layers of each indicator with equal scores. The scoring analysis and spatial overlay analysis are created by using Geographic Information System (GIS) technology in QGIS 3.22.7.

9.3 Results and discussions

9.3.1 The normalized data of variables in FVI_health

The results of DALYs due to microbial pathogens through traffic activities for each ward were shown in Table 26. The disease burden for each ward indicated the DALY of all exposed groups (motorcyclists, cyclists, adult/child pedestrians) due to rotavirus A in floodwater.

Table 26. DALYs due to microbial pathogens through traffic activities (motorcyclists, cyclists, adult/child pedestrians) in the wards in Ninh Kieu

Wards	**An Lạc**	**An Cư**	**An Hoà**	**An Nghiệp**	**An Phú**	**Cái Khế**	**An Hội**	**Tân An**	**Thới Bình**	**Xuân Khánh**
Disease burden (DALY)	81	258	458	185	183	48	66	59	97	68
Disease burden (DALY)/1,000 population	8.5	17.2	14.9	25.3	18.6	2.1	10.5	11.0	8.7	2.3

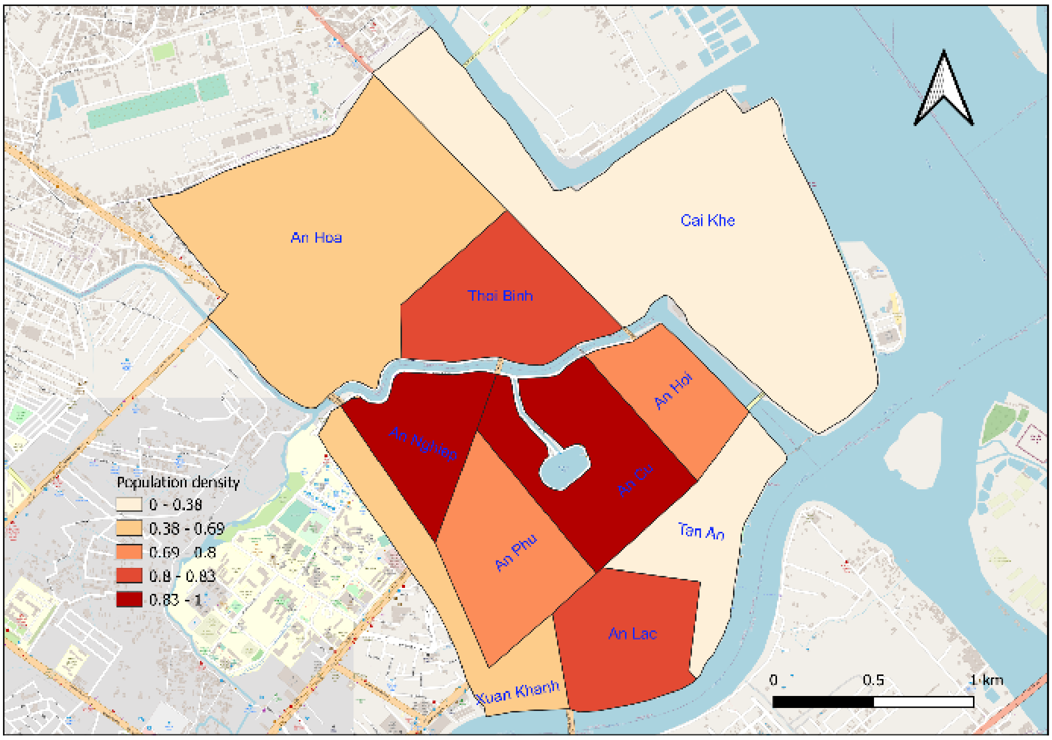
Then, the raw data from Table 25 and Table 26 were normalized in Table 27. The normalized data were then represented in each category as in Figure 40 – 42.

Table 27. Normalized data of variables needed for calculating the flood vulnerability (FV) in terms of health consequences

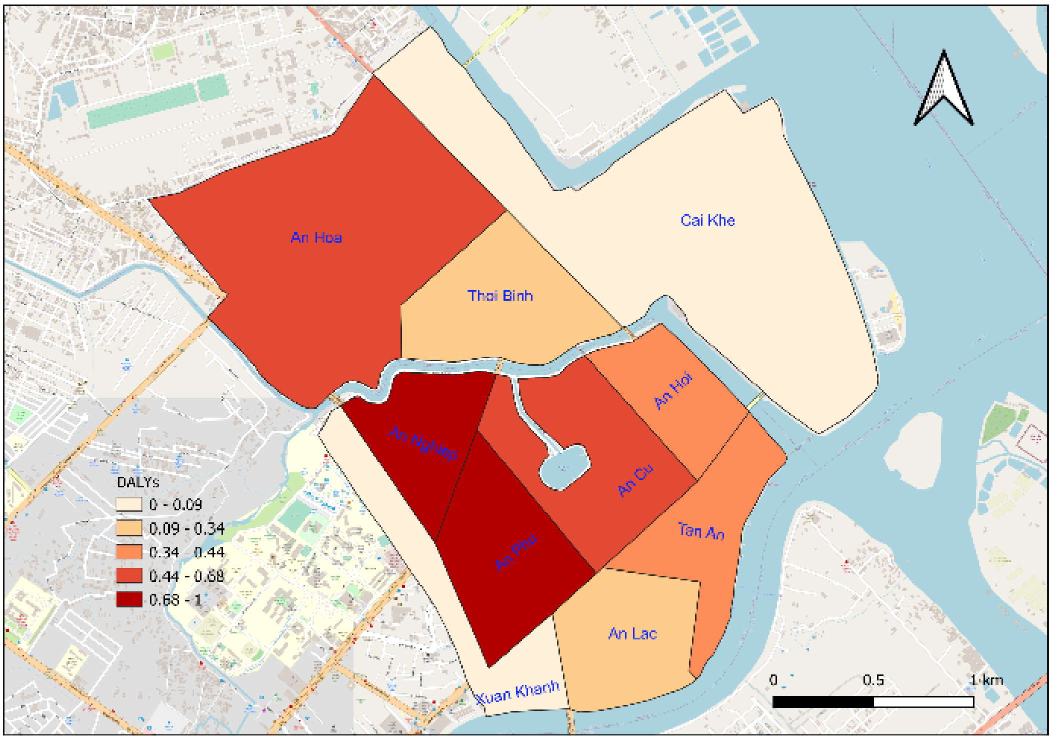
Variables	**Effect to FVI**	**Wards**									
		An Lạc	**An Cư**	**An Hoà**	**An Nghiệp**	**An Phú**	**Cái Khế**	**An Hội**	**Tân An**	**Thới Bình**	**Xuân Khánh**
Normalized population density	increase	0.81	1.00	0.69	0.84	0.80	0.14	0.74	0.38	0.83	0.58
Normalized disease burden (DALY)/ 1,000 population	increase	0.33	0.68	0.59	1.00	0.74	0.08	0.42	0.44	0.34	0.09
Normalized low-income households/1,000 population	increase	0.24	0.41	0.06	0.13	0.54	0.47	1.00	0.47	0.41	0.20
Normalize the number of pharmacy stores, hospitals/10,000 population	decrease	0.28	0.80	0.68	0.70	0.07	0.00	0.74	0.43	0.42	0.68

For population density, An Nghiep & An Cu have the highest population density, followed by Thoi Binh & An Lac, then An Phu & An Hoi, An Hoa & Xuan Khanh. Tan An &Cai Khe have the lowest population density (Figure 40a).

For disease burden, An Nghiep & An Phu have the highest population density, followed by An Hoa & An Cu, then Tan An& An Hoi, Thoi Binh & An Lac. Xuan Khanh & Cai Khe have the lowest disease burden (Figure 40b).



(a)



(b)

Figure 40. The (a) normalized population and (b) normalized DALYs due to microbial pathogens in floodwater through traffic activities for motorcyclists, cyclists, and adult/child pedestrians in a flood event for the wards in Ninh Kieu district

For social vulnerability, An Nghiep and An Cu have the highest social vulnerability, followed by An Hoa & An Phu, then Thoi Binh & An Hoi, Tan An & An Lac. Xuan Khanh & Cai Khe have the lowest social vulnerability (Figure 41).

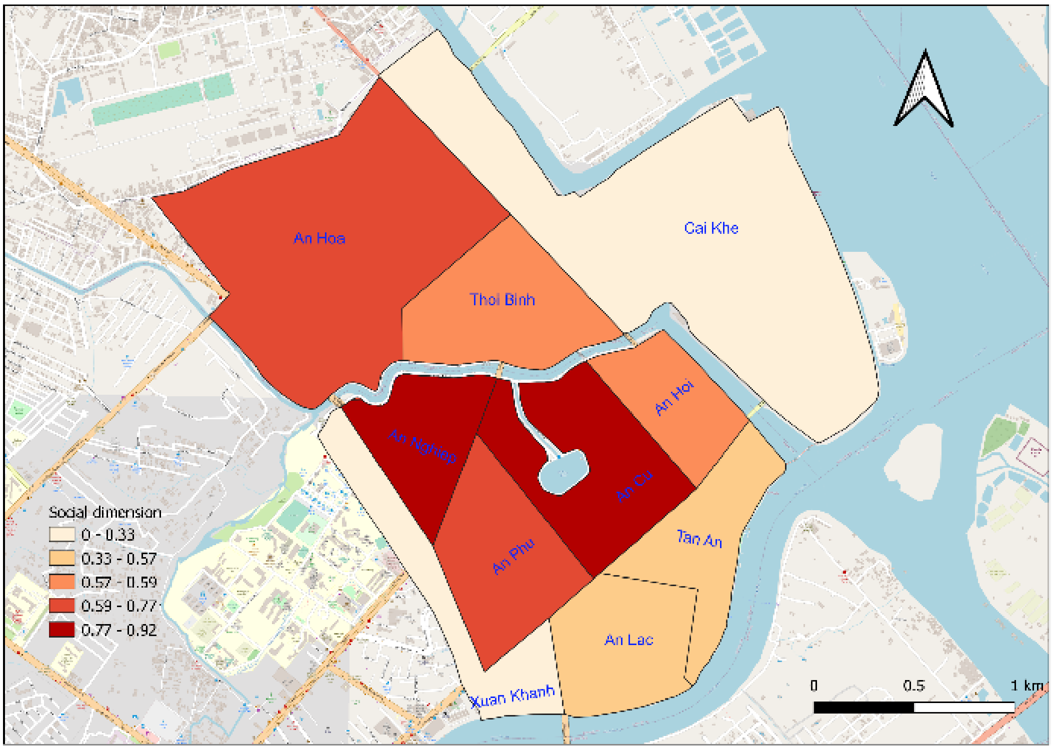
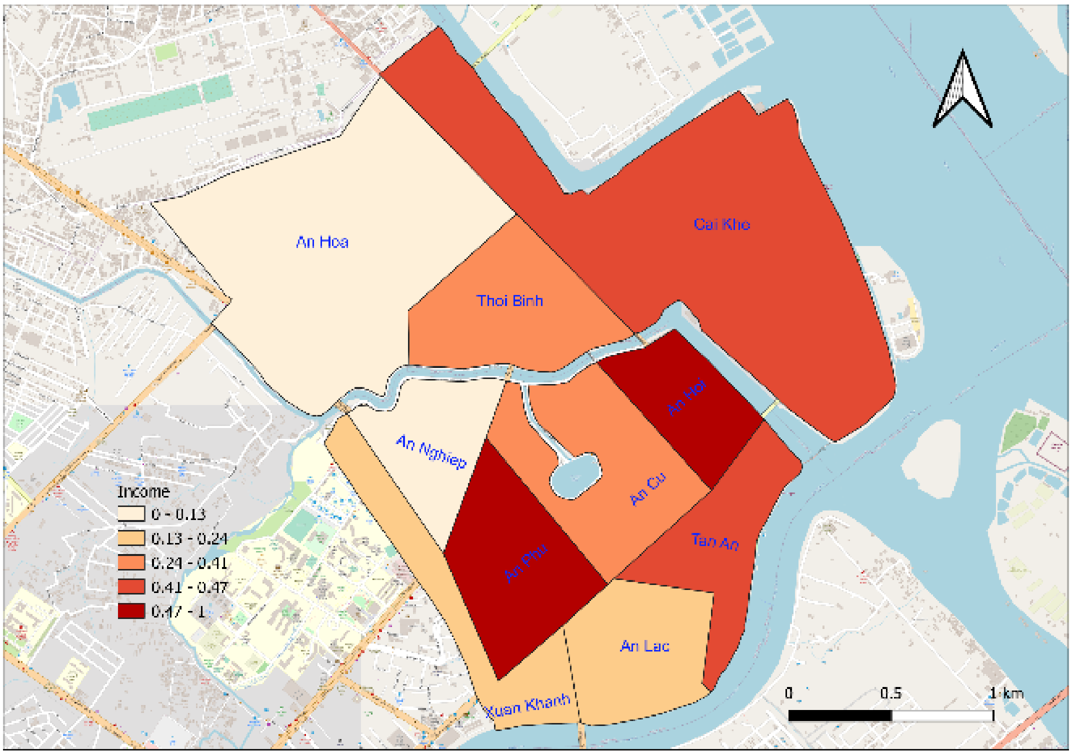


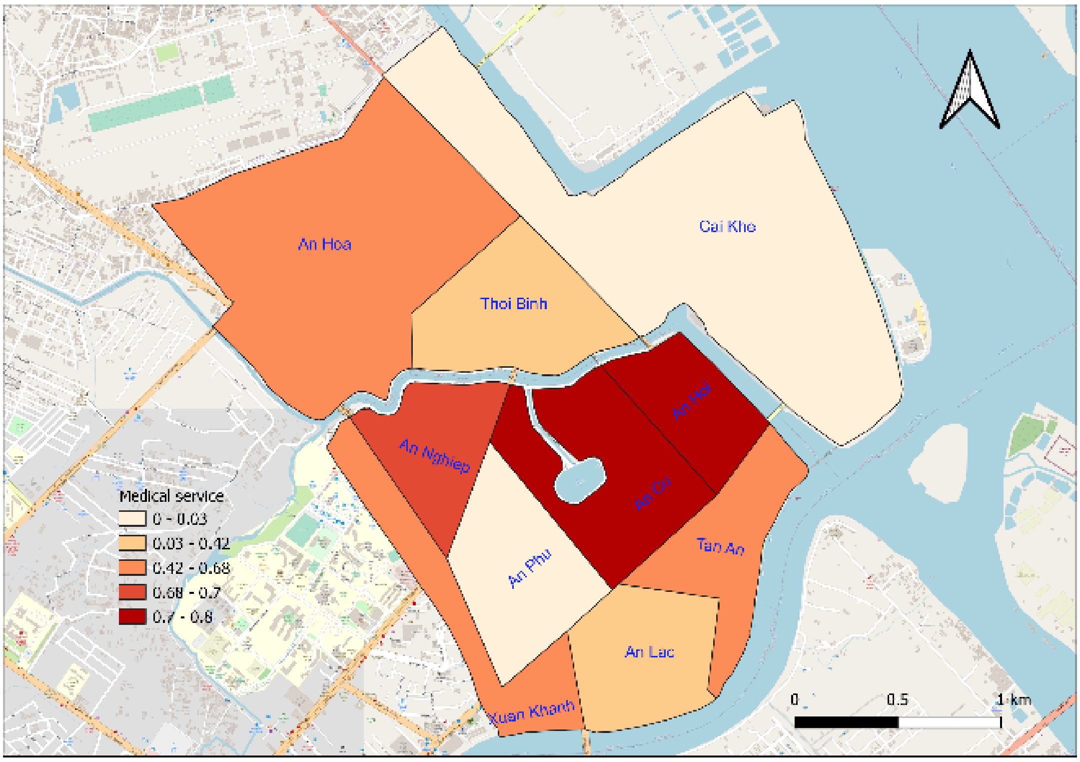
Figure 41. The normalized values of social vulnerability include two indicators: health (with DALY) and population density for the wards in Ninh Kieu district

For economic vulnerability, An Hoi & An Phu have the highest vulnerability due to the highest values of low-income households per 1,000 people, followed by Cai Khe & Tan An, then Thoi Binh & An Cu, An Lac & Xuan Khanh. An Hoa & An Nghiep have the lowest economic vulnerability due to fewer low-income households in the population (Figure 42a).

For medical services, An Hoi & An Cu have the highest vulnerability since they have the lowest number of pharmacy stores and hospitals per 10,000 people, followed by An Nghiep, then An Hoa & Xuan Khanh & Tan An, Thoi Binh & An Lac. An Phu &Cai Khe has the lowest vulnerability in terms of medical services preparing for recovery from illness since they have the highest values of pharmacy stores and hospitals (Figure 42b).



(a)



(b)

Figure 42. The normalized values of (a) low-income households/1,000 population which in “economic vulnerability” and (b) the number of pharmacy stores, and hospitals/10,000 people included in “medical services vulnerability” for the wards in Ninh Kieu district

9.3.2 Flood health vulnerability areas in Ninh Kieu district

Each ward had its vulnerability profile which indicated the different contributions of factors to the health vulnerability. **The flood vulnerability map** in terms of "health consequences" shows that An Hoi and An Cu have the highest flood vulnerability, followed by An Nghiep & Thoi Binh (high level), then An Hoa & An Phu (medium level), Tan An & Xuan Khanh (low level). An Lac & Cai Khe has the lowest flood vulnerability Figure 43.

The highest vulnerability areas were An Cu and An Hoi close to Cai Khe canal and Xang Thoi lake (Figure 43). An Cu and An Hoi were both highly influenced by fewer medical services. While An Cu was also vulnerable to a crowded population, An Hoi was affected by low-income households. Then the vulnerability reduces entering the canal at Thoi Binh and An Nghiep with less pressure from economic and medical services, but still highly affected by population density and high disease burden. The low vulnerability was found in the areas near the Hau River and Can Tho River.

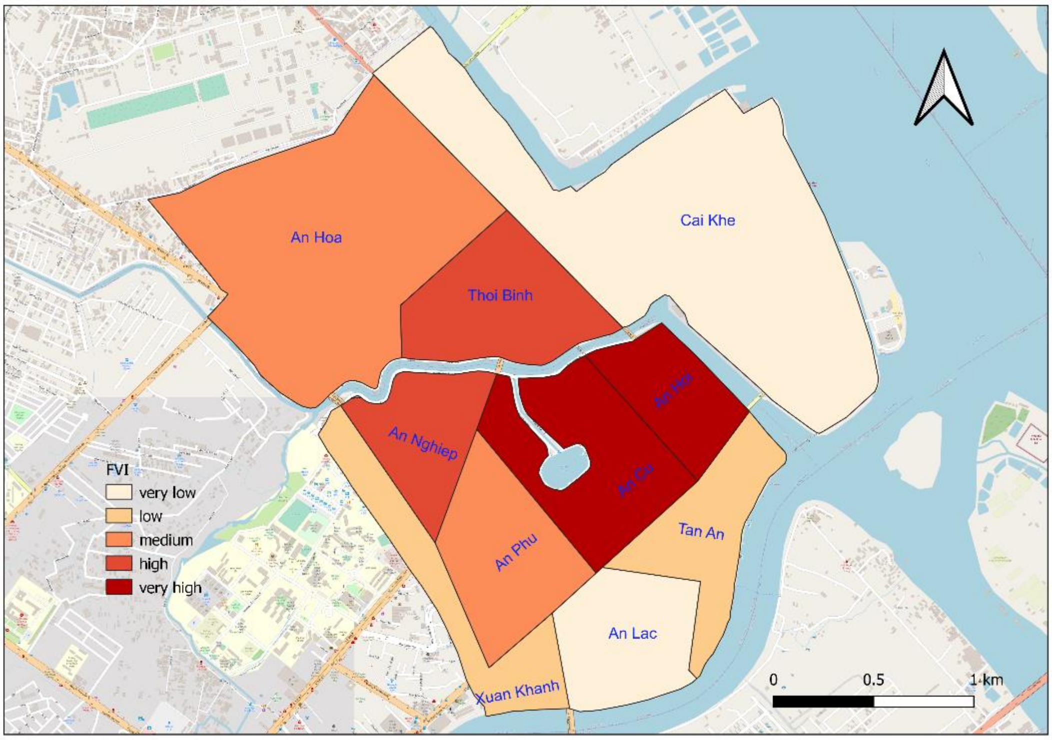


Figure 43. Flood vulnerability mapping for "health consequences" due to microbial pathogens in floodwater for the wards in Ninh Kieu district

With the same level of highest flood vulnerability ("very high" level), An Cu and An Hoi have different reasons:

- The highest flood vulnerability in An Cu is the combination of:

+ highest social vulnerability (with the highest density population and high disease burden)

+ highest vulnerability for medical services.

Therefore, a mitigation solution can be suggested by increasing the medical services with more pharmacy stores.

While the highest flood vulnerability in An Hoi is the combination of the:

+ highest economic vulnerability

+ highest vulnerability for medical services.

Therefore, a mitigation solution can be suggested alongside increasing the medical services, and the incomes of people in An Hoi also need to be improved.

Similarly for other ward cases, the assigned variables can be identified to determine the factors which increase the vulnerability under the impact of adverse factors from flooding to human health (Figure 44). Therefore, some suggestions for the appropriate priority solution can be given to improve the resilience of the exposed community.

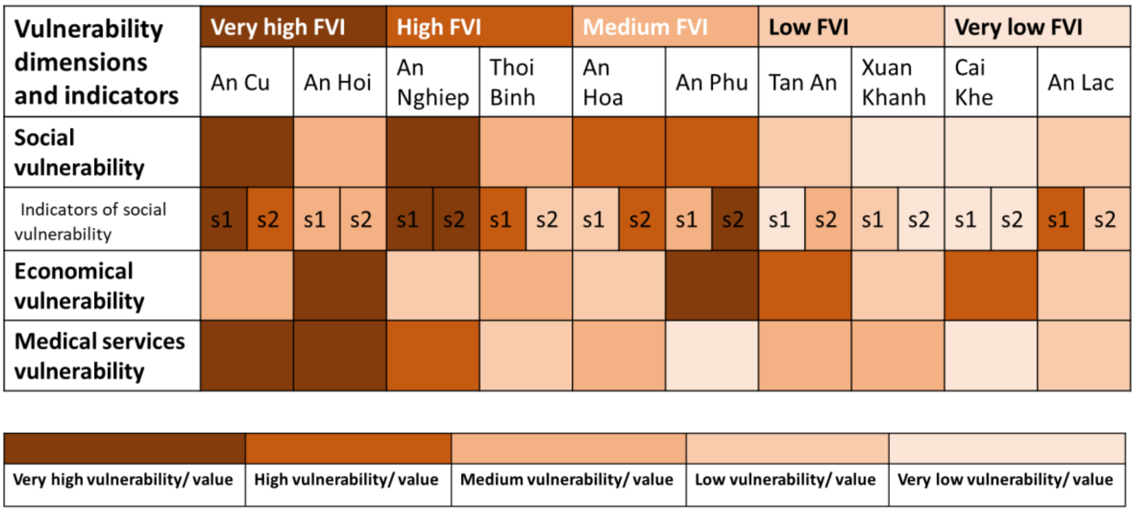


Figure 44. Flood vulnerability index including the social/economical/ medical services vulnerability and the supporting indicators (s1: demographic with "people density" variable, and s2: health with "disease burden" variable)

9.4 Conclusions and Contribution

This chapter considered **social vulnerability** with the *"health consequences"* indicator which is represented by disease burden (DALYs) caused by adverse factors from flooding (i.e., the microbial pathogen in floodwater through traffic activities). Therefore, it can provide more knowledge by including a quantitative variable (DALY) to indicate the indirect intangible impact of adverse factors from flooding which effected *during/after flooding* **social vulnerability** among neighborhoods.

Flood vulnerability is assessed for neighborhoods with socioeconomic/medical service vulnerability. Therefore, it indicated the utility of disease burden (DALYs) in social vulnerability together with other dimensions of vulnerability to identify the **priority areas** and **appropriate variables** to invest in. As the result, it helps to improve the resilience of the exposed community in terms of health issues.

The findings of the study can help to have more understanding of the health consequences caused by adverse factors influenced by urban flooding in neighborhood areas, in this case, the microbial pathogens. The results can help to prioritize the vulnerability areas, and potential variables to invest in to reduce the vulnerability and increase the adaptation/resilience capacity of communities in terms of microbial health consequences.

Further research in the future can be conducted to improve the understanding of flood vulnerability in terms of public health. More research on disease burden (with DALYs) from other adverse factors in flooding which may cause physical/mental effects, and more supporting indicators (depending on the community and the available data). In addition, not limited to flooding, the vulnerability of neighborhood areas to other (environmental) adverse factors (like air pollution...) can be also considered to assess the quality of life for residents in the urban area. The finding can give a better understanding of the disease burden to adverse factors of residents among communities which in turn can help to prioritize public health management in the urban area, FRM tools, or other advanced approaches like water-sensitive cities.

10

CONCLUSIONS AND RECOMMENDATIONS

10.1 CONCLUSIONS

This research provides insights into the health consequences of waterborne pathogens in floodwater for individuals exposed to floodwater through traffic activity. This study was conducted in the Ninh Kieu district of Can Tho city, in the Vietnamese Mekong Delta, where urban residents are at risk of exposure to enteric pathogens in floodwater, especially in low- and middle-income countries (LMICs). While living with floods is a way of life for rural residents during the "floating water season," in urban areas, exposure to floodwater can pose significant health risks, which are often overlooked.

The study makes several important conclusions based on its findings. Firstly, flood-related waters including sewer water, river water, and floodwater in the Ninh Kieu district were polluted with microbial pathogens. By using the molecular method (qPCR) to analyze the water samples, the study found the enteric pathogens (i.e., *E. coli* and rotavirus A) in real-time flood events in the case study. The concentrations of these fecal pathogens in floodwater were higher than water quality standards (surface water quality of Vietnam and Directive 2006/7/EC - European Parliament concerning the management of bathing water quality for inland water) and other relevant studies. The pathogens were likely to have originated from sewer water. Therefore, there is a need for more effective management of stormwater and domestic wastewater during high tide periods and high-intensity rainfall events. Additionally, the study was the first to apply computational models of urban drainage to simulate the transport and concentrations of enteric pathogens (i.e., *E. coli* and rotavirus A) in urban floodwater. The study propagated the concentration and spatial distribution of enteric pathogens in urban floodwater which may not easily be collected by observing real flood events. The largest spatial area (94.5% and 92% of inundated areas, respectively) were polluted with *E. coli* and RVA ranged from 1E+04 – 1E+06 (CFU/l) and 1E+06 – 1E+08 (gc/l), respectively. These simulated concentrations of *E. coli* in floodwater showed 1-2 log10 higher than the Vietnamese surface water quality standard and European bathing water quality for inland water (Directive 2006/7/EC). The simulated concentration of RVA in floodwater was 3 – 4 log10 higher than the river water or domestic wastewater referenced from the literature review. The high concentrations of pathogens in floodwater were located in the inner areas with many activities of residents that coincide with flooding time, while lower concentrations of pathogens in floodwater were near big rivers. Therefore, the results can help to identify the priority areas with higher risk and help plan the measurements to reduce risk. Moreover, the findings of microbial pathogens in floodwater were essential data to assess the health risk of residents who are usually exposed to floodwater in the case study during flooding time.

Secondly, the study developed a new approach to quantify disease burden through traffic exposure by the QMRA and DALY methodology. The study used traffic manual counting on one street and extrapolated people exposed to floodwater on other flooded streets by the traffic scale factors. The study found that direct exposure to floodwater through traffic activity causes a high infection probability due to rotavirus (0.96-0.98) for child/adult pedestrians, cyclists, and motorcyclists. The estimation of disease burden per flood event for all exposure groups exceeded by 4 log10 – 5 log10 of the tolerable burden of disease related to the drinking water according to WHO (WHO, 2003). Motorcyclists were the greatest contributors to the DALYs (95%) which were assigned for the high density of motorcyclists during flooding time. 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. The infection risk was most sensitive to the concentration of rotavirus, while the disease burden showed high sensitivity to both concentrations and flooded areas on streets. Therefore, alongside reducing flood areas in urban streets, managing the microbial pollution of floodwater also play an important role to reduce the microbial health risk for residents. Besides, controlling the number of motorcyclists exposed to floodwater can mitigate the health consequences due to microbial pathogens in the case study.

Thirdly, the study highlighted the use of hydrodynamic models to complement the QMRA and DALY methodology in estimating the exposed population and microbial concentrations on streets at flooded grid cells. This study assessed the evidence-based data in QMRA and DALYs approaches which provide more opportunities to better understand the risk, to reduce the uncertainty, and to have a better validation. The application of the hydrodynamic model gave more options that limited the reliance on large data sets which are difficult to collect. Identifying microbial pathogens in flood events by sampling and measuring was difficult as it required logistic preparedness and flood forecasting. Therefore, the study used the simulated microbial concentrations as the input data of QMRA. The average infection probability calculated by simulated concentration was 0.7, 0.69, 0.61, and 0.64 for motorcyclists, cyclists, adult pedestrians, and child pedestrians, respectively. These results were 1.5 times lower than the infection probability calculated by measured concentrations. The DALYs/10,000 people calculated by simulated data was 1.3 times lower than the result calculated by observed data. However, the total disease burden calculated by simulated concentration and exposed people at flooded grid cells were 3.5 times higher than the disease burden calculated by measured concentrations which were assigned for the 4 times greater of exposed people calculated at flooded grid cells of flood model than observed data. The illness cases estimated by this study showed much higher than the epidemiological report of the case study. One reason is that most mild-symptom cases were not recorded since local people usually have medicine by themselves instead of visiting hospitals. Another reason may come from using the same infection rate, illness rate, and mortality rate for all people without considering various ages and genders in this study. Besides, these rates were usually conducted for volunteers in developed countries while the people in developing countries may have different immunity to specific pathogens. Therefore, the infection risk and disease burden can be updated in the future when these experimental data are available.

In addition, the results showed that areas with higher infection risk and DALYs were located at higher concentrations and people density, such as schools and markets in the case study. The results indicated that the advanced approach in using the hydrodynamic model provides the quantitative data of microbial pathogens and exposed people required to calculate the microbial health consequences. Including the spatial distribution of health risks can help to establish a more comprehensive picture of the high-priority areas of health risks in flood events. The population in Ninh Kieu District may suffer from waterborne diseases due to rotavirus A through traffic activities during flood season, especially motorcyclists.

Lastly, the study applied the disease burden with DALYs using health indicators in FVI. The findings determined the vulnerable areas related to the health perspective of flooding due to rotavirus A through traffic exposure for ten wards in Ninh Kieu district. Moreover, the study provided the first step towards an understanding and involving of the intangible damage of affected people in flood vulnerability assessments.

In conclusion, with the presented methodology and achieved results, the research answered the question about the relationship between microbial pathogens in floodwater and health risk through direct exposure to traffic activities. It included the parameters related to exposure and vulnerability of local people in Vietnam to calculate the health risk and quantify the disease burden by the DALY metric. The study emphasizes that mitigation measures should not only focus on reducing urban floods but also on managing microbial concentrations in flood-related waters and raising awareness of the local people during flooding time. Moreover, the study presented the indirect/intangible impacts of health consequences which have been rarely considered in FRM.

10.2 RECOMMENDATIONS

The literature review in this study identified several gaps in knowledge about microbial health risk assessment related to urban floodwater. While the study in this thesis addressed some of these, others remain. In this section, the recommendations are given based on three aspirations. Firstly, suggestions were given to improve the methodology in this thesis, but also the out-of-scope aspects that can be invested in future research. Secondly, the feasible of interventions for sensitive variables to reduce health risks was introduced. Lastly, the study suggested the application of the DALYs metric to annually quantify the disease burden due to microbial pathogens in floodwater.

10.2.1 Recommendation about the methodology and scope of research

Firstly, about the pollution sources, to determine which source causes high *E. coli* concentration in surface water and floodwater during high flood events, other potential contamination sources, such as runoff from businesses like markets, landfills, or

neighborhoods with pit latrines have to be investigated. Besides, solid contamination sources that may affect the floodwater quality can be taken into account.
Secondly, regarding the exposure assessment, the study referenced exposure behaviors such as intake rates from other similar studies, primarily taken in developed countries. As a result, it may not accurately transfer the situation in this case study. Moreover, 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. Therefore, questionnaire surveys could be used to determine these data. Infection risk and total DALYs could be updated for new exposure pathways and to reduce the uncertainties when new knowledge about these input variables is available. Besides, the epidemiological data for illness cases and disease burden with DALY should be taken into account to validate the health consequences predicted by the methodology.
Thirdly, including climate change and population growth to assess human health risks due to microbial pathogens in urban flood water for future scenarios. Some evidence shows that the health risks due to flooding might become higher in future scenarios. Contaminated sources that affect the quality of receiving water may change due to population or climate change, for example, point sources from WWTPs and diffuse sources from direct manure discharging of humans/animals. Hofstra et al. (2011) mentioned that waterborne pathogen concentrations will increase under climate change with temperature and precipitation (Hofstra, 2011). Moors et al (2013) also showed that waterborne diarrhea may increase due to climate change including temperature, precipitation, and humidity in the river Ganges basin, India. This research indicated that nearly 13% of diarrhea incidences will be increased between the present and the year 2040 (Moors *et al.*, 2013). Most emission originates from urban area (Hofstra *et al.*, 2013) (Vermeulen *et al.*, 2015). Vermeulen et al. (2015) also determined that oocyte emissions will double in India and nearly triple in Bangladesh from 2010 to 2050 with the “business as usual” scenario. This scenario is assuming that the population growth rate, sanitation condition, and sewage service are the same as the current (Vermeulen *et al.*, 2015).
For the case study, 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 and Pathirana 2011; 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 hydrodynamic model, therefore, can help to estimate the microbial pathogens in floodwater for future scenarios.

10.2.2 Suggestions on mitigation measures to reduce microbial health risk related to urban floodwater

The interventions to reduce the microbial health risk were given based on the two most sensitive variables that were analyzed in Chapter 6: microbial pathogen and the number of exposed people (Figure 45). A health risk assessment should be a vital part of any FRM strategy. The findings of this research provided new insights into FRM tools that address public health. The goal is not only to reduce flooding but also to reduce the microbial pollutants in floodwater. If the focus would be only on reducing the flood water level, the dilution of pollutants will be less which in turn may lead to a higher microbial risk. Some interventions have been suggested in Figure 46. The interventions to reduce flood and improve water quality are very similar to those suggested and applied in the water-sensitive city concept aiming at utilizing using water as a resource. To ensure good public health, the appropriate guideline or standards need to be available to assure that the proposed, interventions are aligned with the principles mentioned above (Bichai and Ashbolt, 2017). Lastly, risk management including cost-benefit analysis for interventions to reduce risk needs to be considered.

For example, to reduce the flooding, some measures can be applied such as storing rain water by retention, increase the perviousness areas, and maintaining the flap gates. To reduce microbial pathogens in floodwater, the pathogens at the main original sources should be reduced such as maintaining the septic tank properly, maintaining and enhancing the sewer system. While improving the floodwater quality and reducing the chance of inundation are important to reduce the risk, actions could be taken from the side of exposed people such as reducing direct contact with floodwater and improving the health status. 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 of the risks they are exposed to during flooding. Riders were found to be the most exposed population to traffic activities. At high floodwater levels, people will obtain from traffic activity, but at lower floodwater levels, they tend to be not afraid to get exposed to floodwater through traffic activity. As a result, more people join the traffic and exposure to polluted floodwater which causes microbial risk. If they would have been aware of the likelihood to get infected and of 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 the benefits of washing their hands and clothes. Recently, some studies have shown the positive impacts of coronavirus 2 (SARS-CoV-2 virus) in untreated wastewater (Elsamadony *et al.*, 2021; Ihsanullah *et al.*, 2021) and cause health risks (Dada and Gyawali, 2021). Sewage overflows can transmit the virus into floodwater and spread it on streets and households (Han and He, 2021). Therefore, avoiding exposure to floodwater and keeping hygiene are necessary to protect residents from infectious diseases, especially during the COVID-19 pandemic. These results emphasize the need to raise community awareness about the health risk associated with urban flooding.

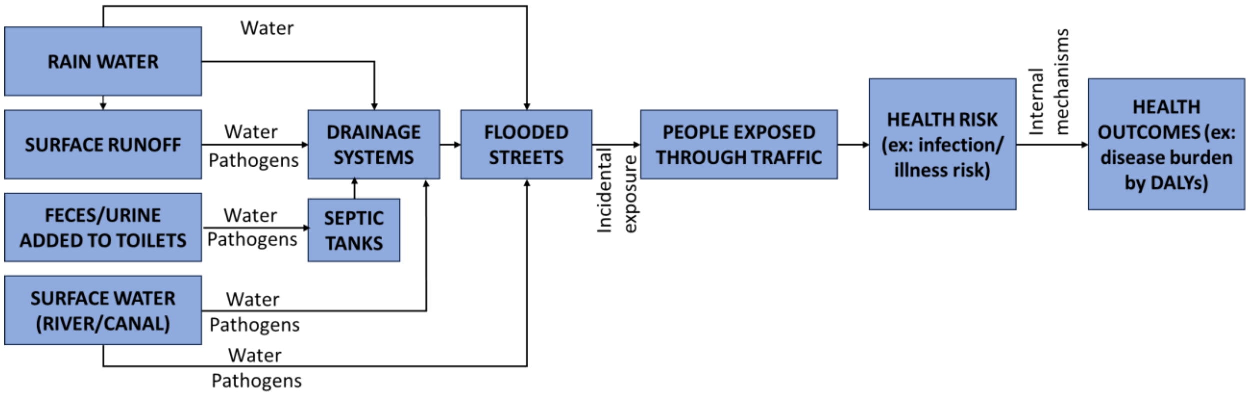


Figure 45. The conceptual model for pathogen exposure and health consequences for receptors through traffic activity on streets during flooding time with response mechanisms.

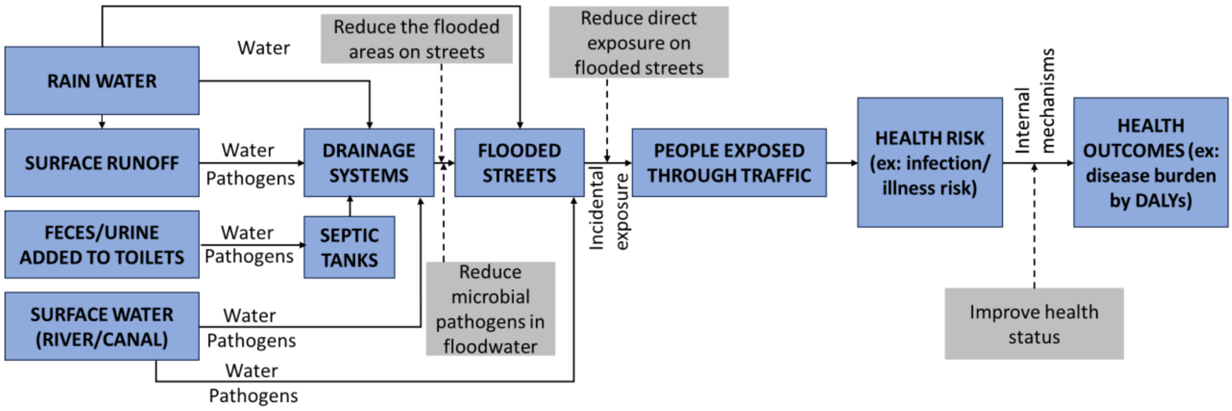


Figure 46. The conceptual model for pathogen exposure and health consequences for receptors through traffic activity on streets during flooding time with solutions to reduce the health consequences.

10.2.3 Expected Annual DALY (EADA)

The proposed concept aims to enhance FRM by calculating the annual expected "health effect" using the Disability-Adjusted Life Year (DALY) metric. While the Expected Annual Damage (EAD) is commonly used in FRM to predict asset damages in monetary terms, the proposed method focuses on the health consequences of flooding on exposed populations. To achieve this, the research considers four groups of exposed individuals with different behaviors related to traffic activities. The analysis takes into account the relationship between the exceedance probability and the return period of the flood event as well as the relationship between the flooded area and the flood return period, to represent the hazard and exposure respectively. The vulnerability is expressed as the damage to the flooded area. By incorporating the DALY metric, the research expands on previous work by Leandro et al. (2022), which only considered infection risk. The DALY metric takes into account both morbidity and mortality probabilities and represents them on a time scale. This allows for a more comprehensive evaluation of the health consequences of flooding for the exposed populations.

Overall, this proposed method provides a more holistic approach to FRM that considers both asset damages and health consequences. Therefore, taking the same concept of EAD, the Expected Annual DALY (EADA) can be developed as given by the Equation below. The area under the red line represented the DALYs ("health damage") for the certain exceedance probability of a flood event (Figure 47).

EADA = $\int_0^1 DALY(p_r)dp_r$

p_r is the exceedance probability formulated simply as the inverse of the return period of a flood event.

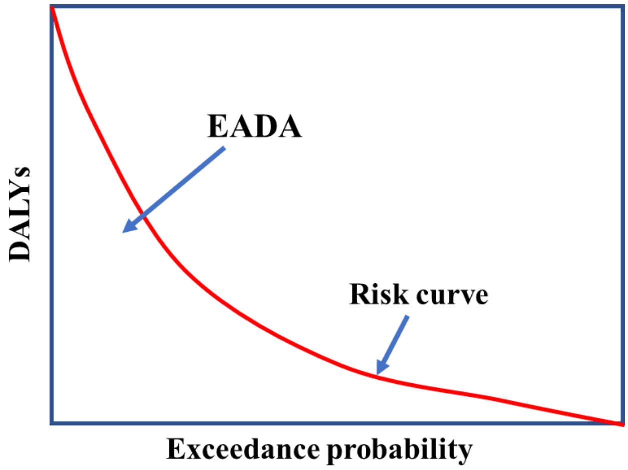


Figure 47. Expected annual DALY represented as the function of exceedance probability of flood event and DALYs caused by adverse factors influenced by flooding such as the microbial pathogens in floodwater) for exposed people. (Adapted from (Leandro *et al.*, 2022))

The various EADA from different adverse factors can be combined. The findings can provide knowledge about the health consequences predicted for the exposed community to identify the potential health damage, prioritizing the vulnerability related to health effects in FRM. Thus, alongside the traditional approach based on monetary values to evaluate the asset damage, the DALY metric can be used to assess the health lost due to flooding and related adverse factors. This also allows for the better inclusion of non-structural measures in the FRM strategies. These measures may not reduce asset-based damages but can have significant benefits of reducing welfare losses(de Bruijn *et al.*, 2022).

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APPENDIX

S1. Molecular analysis

In preparation for qPCR, 250ml of sewage water was filtered by 0.22µm membrane vacuum filter cup (Nalgene). The filter membrane was shredded and placed into 50ml tube with 5ml of ASL buffer (Qiagen). This solution vortexed at maximum speed for 1 minute and incubated at 70^{o}C for 15 minutes; 1ml solution this solution was stored at -80^{o}C freezer for bacterial and parasitic DNA extraction. Each sample was inoculated with an internal control (phHV or EAV) and placed into a processing cartridge (Roche) prior to extraction using a Magna Pure 96 machine (Roche) with Total Nucleic Acid Large Volume kit and elution in 50µl of buffer. qPCR was performed on all extracted DNA/RNA to detect sequences specific for *E. coli, Salmonella* spp. (Karkey *et al.*, 2016), *Shigella/*EIEC, *Campylobacter* spp. (Efstratiou *et al.*, 2017)(Anders *et al.*, 2015), *Cryptosporidium* spp., *Giardia* spp. (Guy *et al.*, 2003), Norovirus GI & GII, and Rotavirus A (Dung *et al.*, 2013).

The detection limits of Rotavirus, Norovirus 1, Norovirus 2 were 500, 5 and 50 copies of cloned target sequences. In the case of bacteria, detection limits were 5 copies for each pathogen. The detection limits are also 5-50 copies for parasites.

Moreover, about the concentration of *E. coli*. Technically, as one amplification is associated with one genome, if the bacteria were alive then one copy would equal 1 CFU. Thus, *E. coli* concentration is transformed from gc/mL to CFU/mL with assumption that they are still living.

FIGURE

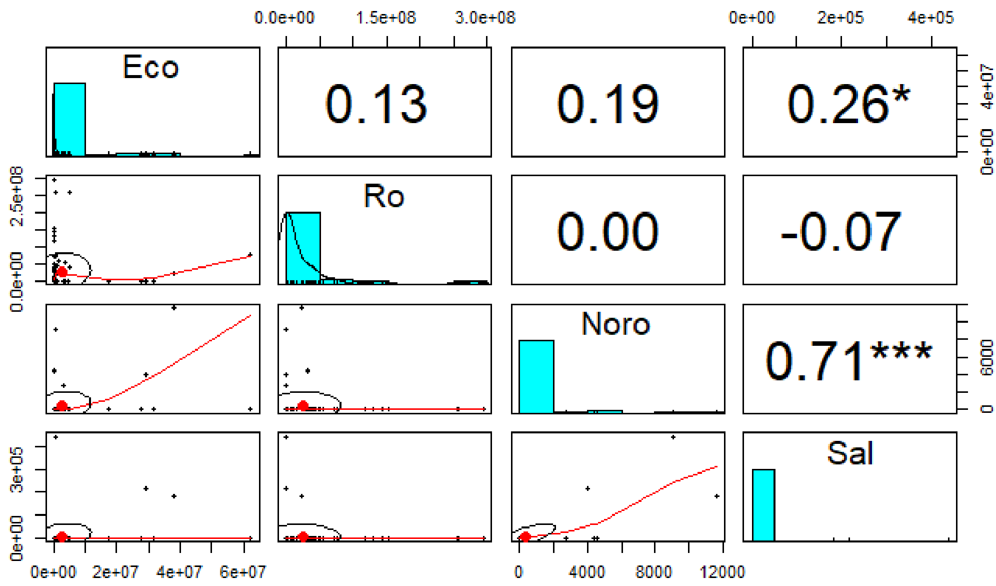


Figure S1. Association among microbial parameters (n = 94) in flood-related waters (Ninh Kieu, 2016). The numbers show correlation of *E. coli* (Eco), *Salmonella* (Sal), Rotavirus (Ro), and Norovirus (Noro) in all flood water, surface water and sewer water samples.

p < .0001 '****'; p < .001 '***', p < .01 '**', p < .05 '*'

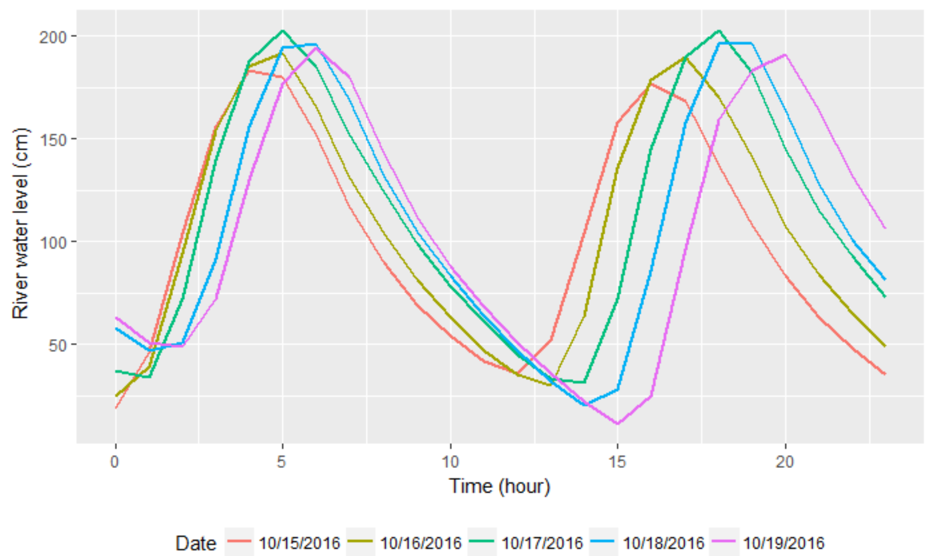


Figure S2: Water level at Can Tho River from 15/10/2016 to 19/10/2016 Time is local (ICT).(Data source: Southern Station of Hydro-Meteorological Forecasting, Vietnam National Administration of Hydrology and Meteorology)


(a)


(b)


(c)

(d)

Figure S3. Flood in some streets on 2016 in Ninh Kieu district. (a) After flooding event on Cach Mang Thang 8 Street (11th September), the flood water was receding. (b) Huynh Cuong Street was inundated on morning (11th September). The flood water was receding. (c) Flood on Huynh Cuong Street on evening (18:15) which was caused by very high tide (17th October). Surface water exceeded the bank of Xang Thoi lake (on the left hand in picture) and the pavement which had some motorbikes parked on. Flood water on street was the combination of surface water and Sewer water on sewage system. (d) Flood on Chau Van Liem Street on morning (7:00) which was caused by high tide and heavy rainfall from early morning (17th October)

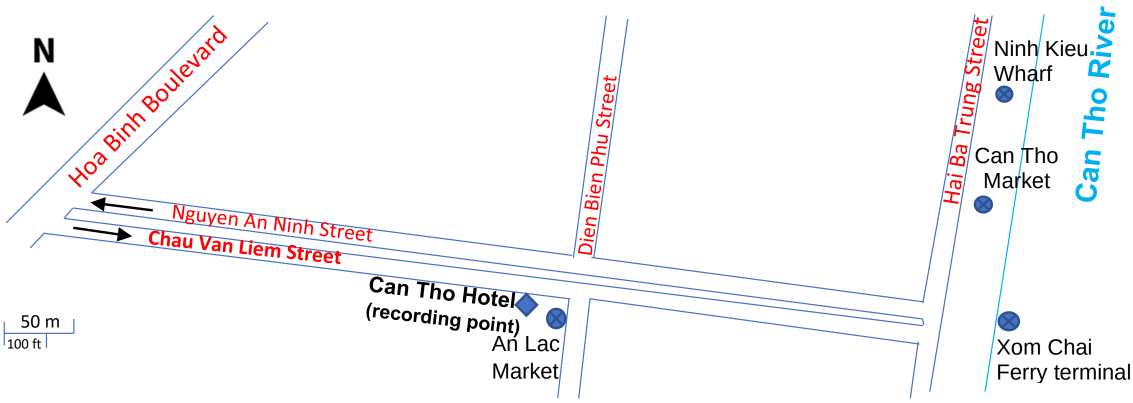
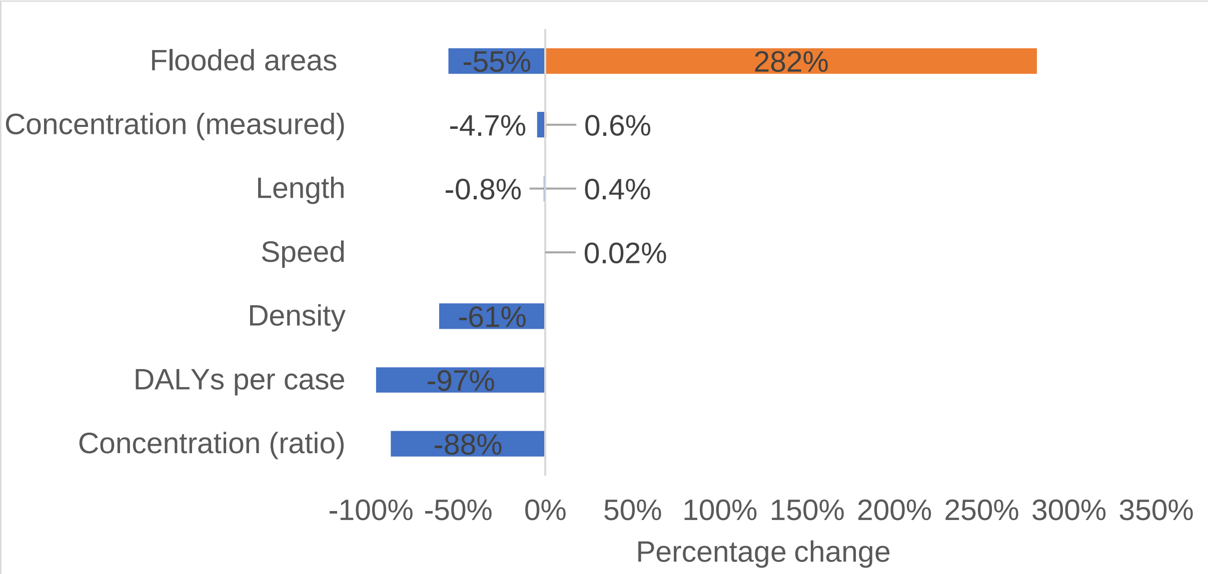
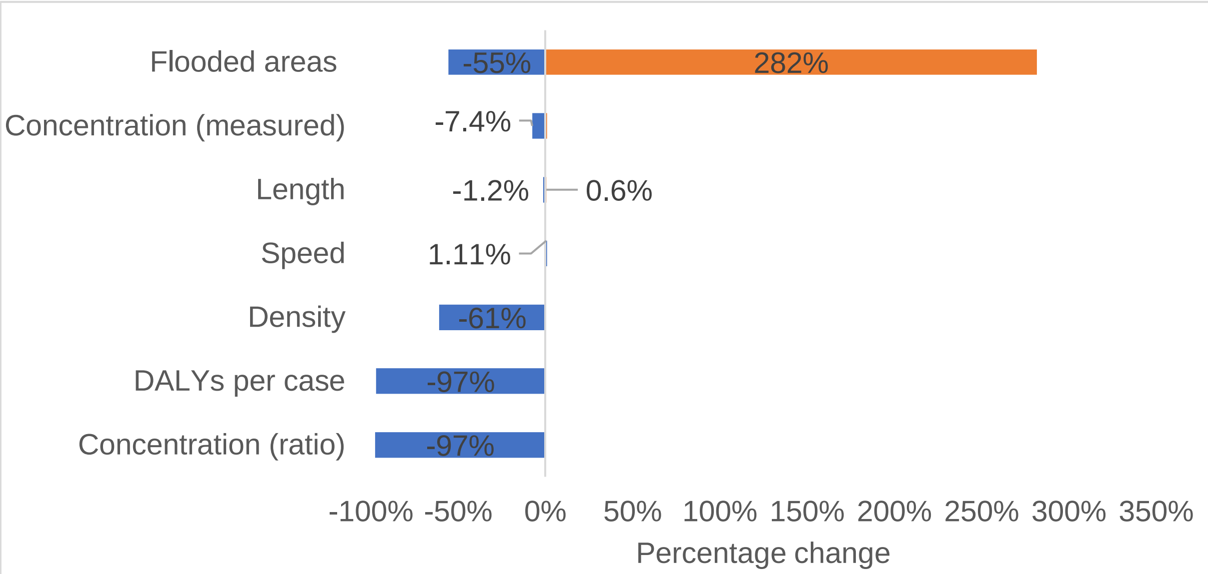


Figure S4. Chau Van Liem Street, video recording point and surroundings for the morning flood event on 17 October 2016;



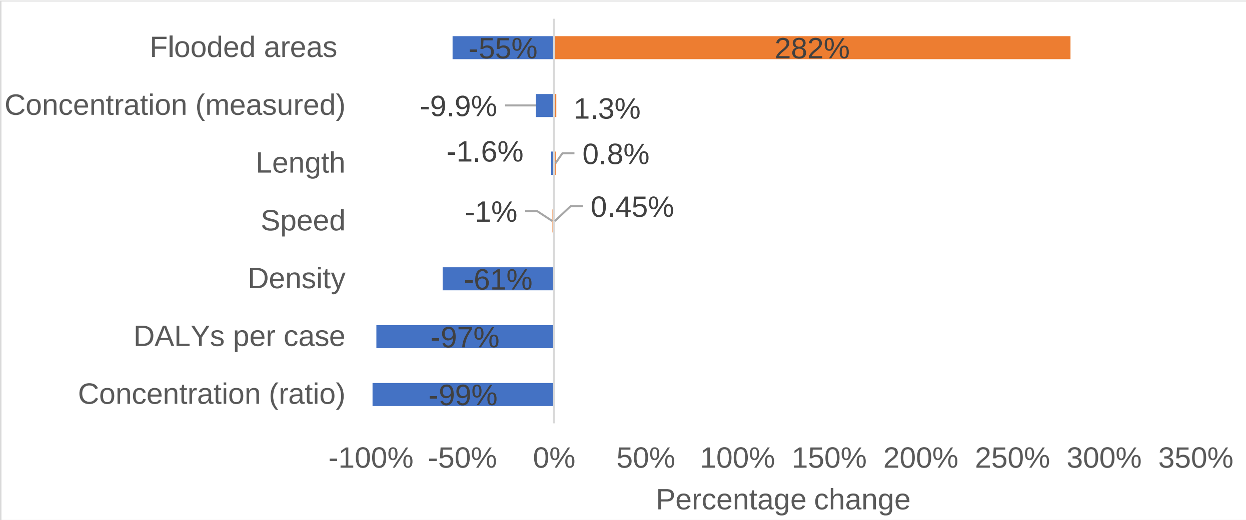
Flooded areas
-55%
282%
Concentration (measured)
-4.7%
0.6%
Length
-0.8%
0.4%
Speed
0.02%
Density
-61%
DALYs per case
-97%
Concentration (ratio)
-88%
-100% -50% 0% 50% 100% 150% 200% 250% 300% 350%
Percentage change

(A)

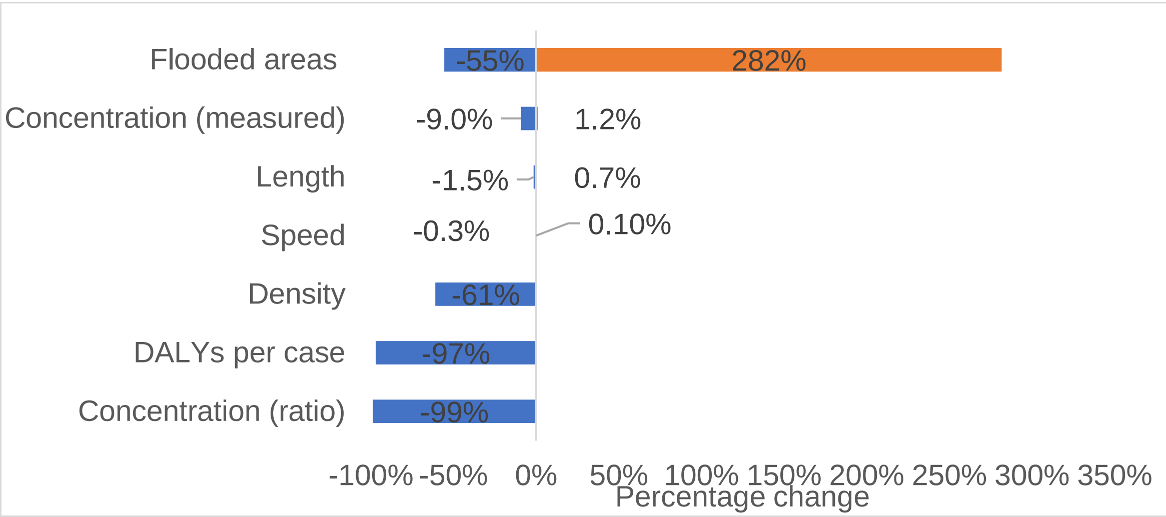


Flooded areas
-55%
282%
Concentration (measured)
-7.4%
Length
-1.2%
0.6%
Speed
1.11%
Density
-61%
DALYs per case
-97%
Concentration (ratio)
-97%
-100% -50% 0% 50% 100% 150% 200% 250% 300% 350%
Percentage change

(B)



(C)



(D)

Figure S5. The percentage changes in the DALYs between the baseline and scenario 1 (blue column) and scenario 2 (orange column) for four exposed groups: (A) child pedestrians; (B) adult pedestrians; (C) motorcyclists; and (D) cyclists. The input parameters include exposed people density (Density), DALYs per case, speeds of exposed people (Speed), length of flooded streets (Length), the rotavirus concentration with the 25th and 95th percentiles (Concentration (measured)), and rotavirus concentration calculated by ratio with *E. coli* (Concentration (ratio)).

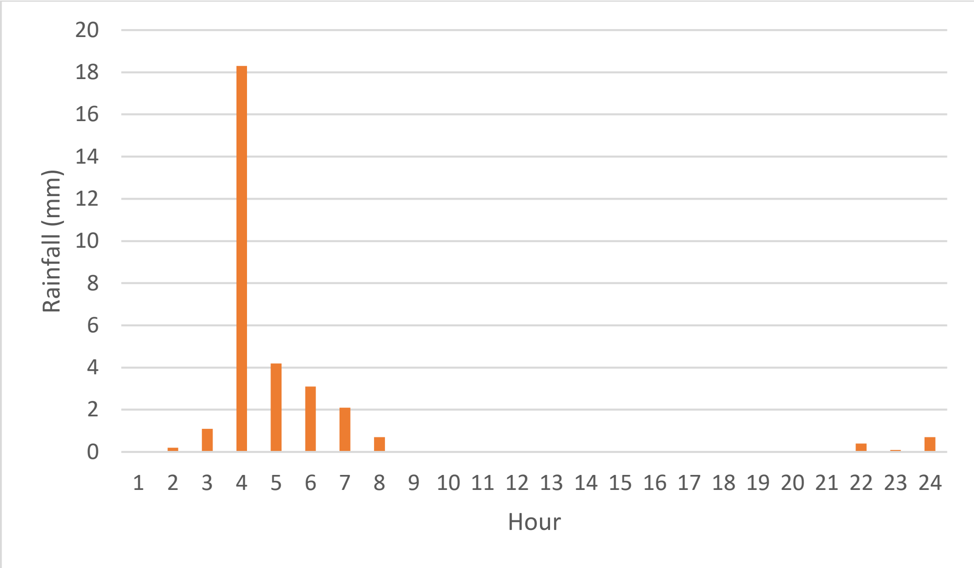


Figure S6. Rainfall time series in Ninh Kieu District on 17 October 2016. (Time is local ICT). Data source: Southern Station of Hydro-Meteorological Forecasting, Vietnam National Administration of Hydrology and Meteorology.

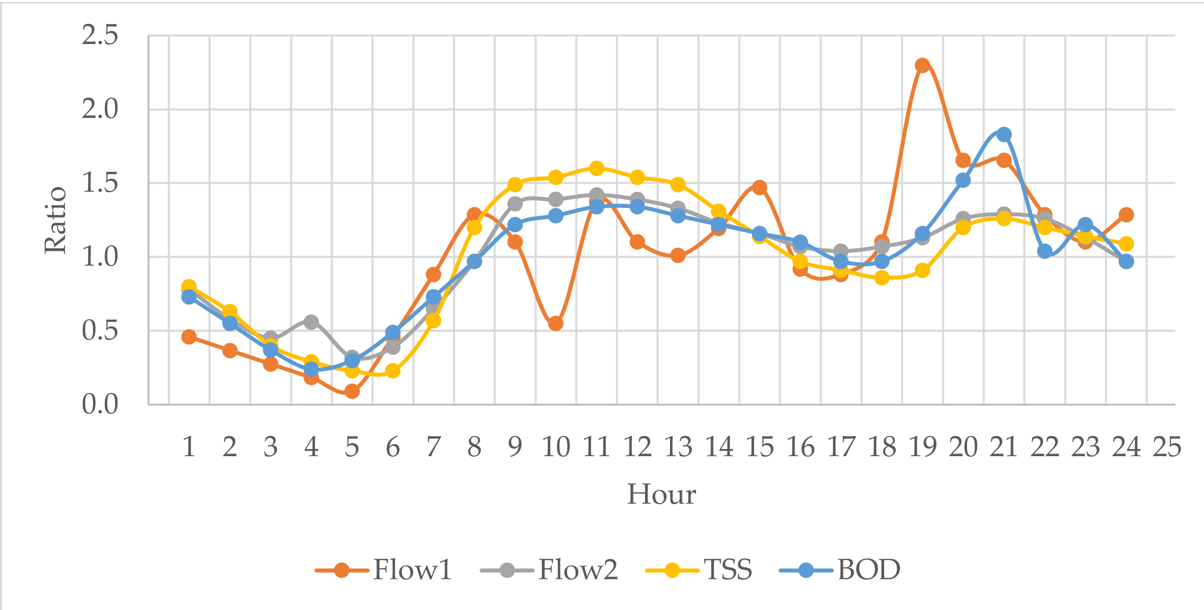


Figure S7. Hourly time pattern of domestic wastewater flow and pollutants (TSS, BOD) in sanitary dry weather flow. Source: Flow2, TSS, BOD (Metcalf & Eddy, 2003); Flow1 (Pham, 2014)

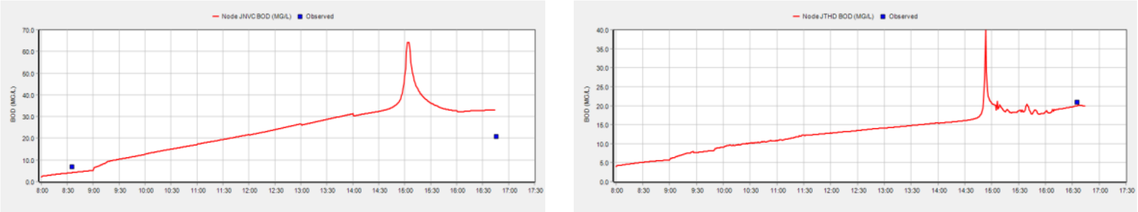


Figure S8. The simulated and observed BOD concentration (mg/L) in sewage water in two manholes JNVC (left) and JTHD (right)

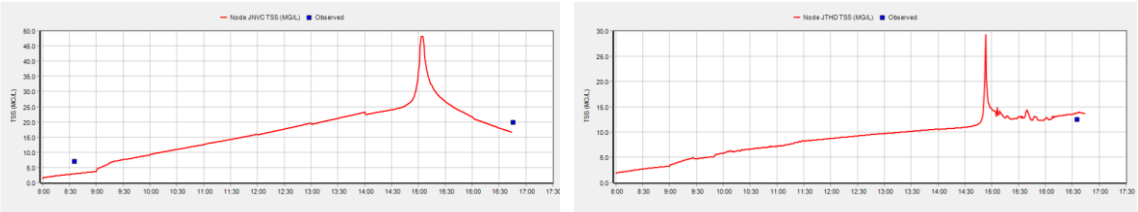


Figure S9. The simulated and observed TSS concentration (mg/L) in sewage water in two manholes JNVC (left) and JTHD (right)

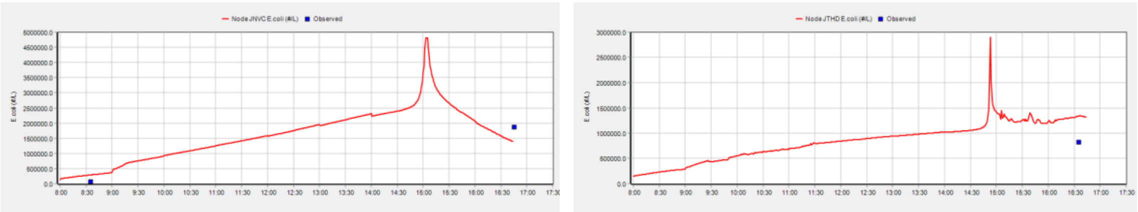


Figure S10. The simulated and observed *E. coli* concentration (CFU/L) in sewage water in two manholes JNVC (left) and JTHD (right)

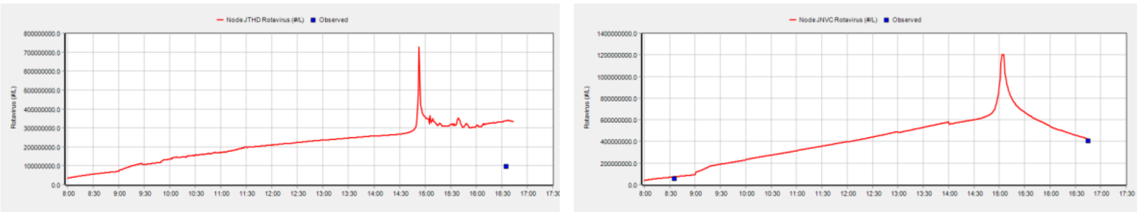


Figure S11. The simulated and observed *E. coli* concentration (gc/L) in sewage water in two manholes JNVC (left) and JTHD (right)

TABLE

Table S1. Sampling sites and dates of sewer water, flood water and surface

		Date				
Sites	Name	11/9	16/10	17/10	18/10	19/10
S1	Xang Thoi lake	S	S	S	S	
S2	Rach Ngong canal (at Rach Ngong 1 bridge)	S	S	S	S	
S3	Cai Khe canal (at Nhi Kieu Bridge)	S	S	S	S	
S4	Hau River (Near Ninh Kieu bridge)		S	S	S	
W1	Hoa Binh	W				
W2	Nguyen Van Cu	W	W, WL	W, WL	W, WL	
W3	Tran Van Hoai	W, WL				
F1	Huynh Cuong	F		F	F	
F2	Chau Van Liem			F	F, FL	
F3	Nguyen An Ninh			F		
F4	Ly Tu Trong			F		
B1	Mau Than	W		F	F	F, FL
B2	Ly Hong Thanh	W	W, F	F	F	
B3	Hung Vuong	W, WL, F	W			
B4	Tran Hung Dao		W, WL, F	W, WL, F, FL	W, WL	
B5	Cach Mang Thang Tam	F	W, F, FL	F	F	

W: Sewer water samples were taken
WL: Sewer water level was conducted
F: Flood water samples were taken
FL: Flood water level was conducted
S: Surface water samples were taken

Table S2. Flooding characteristics at flooded streets on 11th September, and from 16th to 19th October in Ninh Kieu district, 2016

No.	**Sites**	**Rising time**	**Time to peak**	**Receding time**	**Maximum levels (cm)**
11/9					
1.	F1	14:00	15:00	16:00	10
2.	B3	13:30	14:15	14:45	15

3.	B5	13:00	13:30	14:00	10
16/10					
4.	B4	16:30	17:00	18:30	10
5.	B2	15:50	17:15	18:50	30
6.	B5	16:00	17:40	17:50	10
17/10					
7.	B4	5:30	6:30	7:00	27
8.	F2*	5:45	6:30	7:00	20
		18:00	18:45	19:25	18
9.	F4*	5:30	6:30	7:40	30
		17:00	17:40	19:00	15
10.	B1	17:30	18:00	18:35	23
11.	B5	17:00	17:50	18:25	12
12.	F1	17:00	18:15	19:00	35
18/10					
13.	F2	6:00	6:25	6:45	15
14.	B2	5:30	6:00	6:40	25
15.	B1	5:45	6:15	7:00	30
16.	F1	5:30	6:00	6:20	30
17.	B5	5:40	6:15	6:50	15
19/10					
18.	B1	5:45	6:30	7:15	30

***** Flooding sites were observed on both morning and afternoon flooding.
Rising time: When water started to increase on roads.
Time to peak: When flood water stopped rising and reached maximum water level.
Receding time: When flood water started to decrease after lag time.

Table S3. The sampling sites, sampling time, *E. coli* and rotavirus A concentrations in the floodwater samples taken from the flooded streets on 17 October 2016 in Ninh Kieu District, Can Tho City ("neg." means no pathogens were detected in the floodwater sample).

Sampling site	Initials	Sampling dates	Sampling time	*E. coli* (CFU/mL)*	Rotavirus A (gc/mL)**
Huynh Cuong	HC	9/11/2016	15:10	neg.	neg.
		9/11/2016	17:10	4.30E+03	3.08E+05
		10/17/2016	18:15	neg.	2.27E+03
		10/18/2016	6:20	neg.	neg.
Hung Vuong	HV	9/11/2016	14:15	neg.	neg.
		9/11/2016	14:30	neg.	neg.
		9/11/2016	14:45	neg.	neg.

CMT8	CMT	9/12/2016	13:00	neg.	neg.
		10/16/2016	17:30	9.18E+03	neg.
		10/16/2016	18:35	neg.	neg.
		10/17/2016	17:50	neg.	neg.
		10/18/2016	6:50	neg.	neg.
Tran Hung Dao	THD	10/16/2016	17:10	4.39E+03	2.93E+05
		10/16/2016	18:30	2.30E+02	neg.
		10/17/2016	7:47	neg.	neg.
Ly Hong Thanh	LHT	10/16/2016	15:50	1.18E+02	2.49E+05
		10/16/2016	16:20	3.73E+04	neg.
		10/16/2016	17:15	2.66E+04	1.58E+05
		10/16/2016	18:50	neg.	neg.
		10/18/2016	6:40	neg.	5.30E+03
Chau Van Liem	CVL	10/17/2016	7:07	neg.	2.45E+04
		10/17/2016	7:22	neg.	5.69E+03
		10/17/2016	7:30	neg.	1.06E+05
		10/17/2016	7:50	neg.	4.93E+05
		10/17/2016	19:25	2.55E+02	2.96E+06
		10/18/2016	6:25	8.99E+03	2.56E+06
Ly Tu Trong	LTT	10/17/2016	7:40	2.38E+02	7.70E+04
		10/17/2016	8:50	6.05E+02	1.60E+04
		10/17/2016	8:54	neg.	neg.
		10/17/2016	9:40	4.78E+02	8.04E+03
		10/17/2016	17:40	neg.	3.36E+05
Mau Than	MT	10/17/2016	18:05	neg.	4.03E+05
		10/17/2016	18:35	neg.	neg.
		10/18/2016	7:00	neg.	3.82E+05
		10/19/2016	7:28	neg.	1.29E+06
		10/19/2016	7:55	neg.	1.52E+06
		10/19/2016	8:04	5.05E+02	1.18E+06

* CFU/mL: Colony-forming unit per milliliter

** gc/mL: genome of copies per milliliter

Table S4. Flooded streets in the afternoon-evening on 17 October 2016 in Ninh Kieu District.

No.	**Streets**	**Street width (m)**	**Scale factor for traffic flow**	**Begin of flood event**	**End of flood event**	**Length of flood time (hrs)**	**Average depth of flood (m)**	**W= average width of flood (m)**	**L = average length of flood (m)**	**Flooded area =W*L(m^2)**
1	Nguyen Van Cu	15	1.2	17:00	19:00	2:00	0.30	8	120	960
2	Pham Ngoc Thach	12	1	16:20	20:30	4:10	0.25	10	925	9,250
3	Mau Than 1	15	1.2	17:00	20:00	3:00	0.20	6	500	3,000
4	Mau Than 2	15	1.2	17:00	20:30	3:30	0.25	5	90	450
5	Mau Than 3	15	1.2	17:00	19:30	2:30	0.25	7	430	3,010
6	Huynh Cuong	s8	0.8	18:00	20:00	2:00	0.20	7	83	581
7	Ly Hong Thanh	8	0.8	16:30	20:30	4:00	0.20	5	290	1,450
8	Pham Ngu Lao 1	10	1	17:00	19:00	2:00	0.20	4	145	580
9	Pham Ngu Lao 2	10	1	17:00	19:00	2:00	0.30	8	195	1,560
10	Nguyen Thi Minh Khai	12	1	17:40	19:30	1:50	0.40	8	610	4,880
11	Quang Trung	12	1	17:45	19:30	1:45	0.35	8	85	680
12	Hai Ba Trung 1	8	0.8	17:45	19:00	1:15	0.20	3	230	690
13	Hai Ba Trung 2	8	0.8	18:00	19:00	1:00	0.20	8	95	760
14	Nguyen An Ninh	10	1	17:00	19:30	2:30	0.20	3	97	291
15	Phan Dinh Phung	10	1	17:45	19:30	1:45	0.25	9	415	3,735
16	Tran Van Hoai	10	1	17:00	20:20	3:20	0.25	10	480	4,800

Table S5. Flooded areas in inundated streets from 24 flood events in Ninh Kieu District from 2013-2017.

No.	Dates	Total flooded area (m^2)
1	6-Sep-2013	252,352
2	20-Sep-2013	22,783
3	7-Oct-2013	88,505
4	20-Oct-2013	149,497
5	15-Apr-2014	13,162
6	1-May-2014	15,251
7	29-Sep-2014	27,062
8	10-Oct-2014	58,805
9	4-Nov-2014	92,853
10	5-May-2015	51,194
11	10-May-2015	6,419
12	6-Jun-2015	17,182
13	19-Jul-2015	19,701
14	30-Jul-2015	7,261
15	8-Sep-2015	11,216
16	12-Oct-2015	70,354
17	30-Oct-2015	21,695
18	19-Jul-2016	20,120
19	11-Oct-2016	19,195
20	17-Oct-2016	43,819
21	7-May-2017	10,926
22	16-May-2017	48,583
23	11-Aug-2017	106,468
24	5-Sep-2017	67,980

Table S6. NRSA (%) for each variable.

	NRSA (%)
(Measured) CONCENTRATION	
Child pedestrians	11%
Adult pedestrians	11%
Motorcyclists	15%
Cyclists	13%
INTAKE RATE	

Child pedestrians	3%
Adult pedestrians	2%
Motorcyclists	3%
Cyclists	3%
FLOOD LENGTH (m)	
Child pedestrians	2%
Adult pedestrians	2%
Motorcyclists	3%
Cyclists	3%
SPEED (m/h)	
Child pedestrians	-9%
Adult pedestrians	-9%
Motorcyclists	-2%
Cyclists	-1%
FLOODED AREA (m^2)	
Child pedestrians	337%
Adult pedestrians	337%
Motorcyclists	337%
Cyclists	337%

Table S7. The coefficient correlation (rho, Spearman test) of input parameters with output (i.e., infection risk).

	Input parameters		
Exposure groups	Intake rate	Concentration	Flood length (m)
Child pedestrians	0.14	0.14	0.25
Adult pedestrians	0.1	0.18	0.26
Motorcyclists	0.08	0.21	0.24
Cyclists	0.09	0.22	0.27

Table S8. Daily precipitation (mm) in some days on October 2016. In this study, we modelled the flood event on day 17. Data source: Southern Station of Hydro-Meteorological Forecasting, Vietnam National Administration of Hydrology and Meteorology.

Day	Precipitation (mm)
4	18.4
6	9
7	4
8	22.5
9	8.5
10	2
11	26.4
13	16.7
15	20.3
16	8
17	30.9
19	29.7

Table S9. Number of people went through Chau Van Liem Street in 1 hour from 6:30 AM – 7:30 AM on 17 October 2016

Exposed groups	Number of people in 1 hour
Child pedestrians	2
Adult pedestrians	34
Motorcyclists	1,632
Cyclists	48

LIST OF ACRONYMS

1D	One Dimensional
2D	Two Dimensional
CFU/L	colony-forming unit per liter
DALYs	Disability-Adjusted Life Years
FRM	Flood risk management
FVI	Flood vulnerability index
gc/L	genome copies per liter
LMICs	Low- and middle-income countries
PCSWMM	Personal computer stormwater management model
QMRA	Quantitative microbial risk assessment
qPCR	quantitative polymerase chain reaction
RT-PCR	Real-time quantitative polymerase chain reaction
RVA	Rotavirus A
SWMM	Stormwater management model
WHO	World health organization
YLD	Years lived with disability
YLL	Years of life lost

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ABOUT THE AUTHOR

Huynh Thi Thao Nguyen was born in Binh Dinh, Vietnam, in 1989. She is now a researcher at the Institute of environment and resource (IER) of Vietnam national university Ho Chi Minh City (VNU). Her bachelor's was in environmental management at the Industrial University of Ho Chi Minh City, Vietnam (IUH) from 2007 – 2011. She studied for her master's degree in environmental and resource management at Ho Chi Minh City University of Technology (Vietnam) from 2012 - 2014. Her master's thesis was on assessing the health risk due to microbial pathogens in floodwater for pedestrians. The results were then published in a proceeding (in 2014) and an article (in 2017) as co-author with her supervisor and colleagues. Beginning the case study in Ninh Kieu (Can Tho, Vietnam) for her master thesis, a typical urban area in LMICs with water problems (urban flooding and water pollution) and direct exposure of residents to the microbial hazard, she was also interested in deep studying about the dynamic of microbial pathogens in floodwater and natural relationship to human health risks. In 2015, she got a scholarship from Nuffic and moved to The Netherlands to start her PhD at the IHE Institute for water education and Delft University of Technology (TUD) in Delft. The research was about urban floodwater quality, microbial pathogens in floodwater, direct exposure through traffic activities, and health consequences. Working in the Flood resilience group in IHE, she also learned about flood risk management and the lacking of understanding about indirect intangible impacts like health consequences of flooding. It is her motivation for her to keep working on adverse health consequences due to environmental adverse factors such as pathogens in floodwater. In 2019, she was one of five winners of scholarships for authors of best abstracts from developing countries at the 20th International Symposium on Health-Related Water Microbiology (Vienna, Austria). Her presentation was about “Health risk assessment (QMRA and DALYs) related to enteric pathogens in urban flood water A case study from an urban flood event in the Vietnamese Mekong area - Ninh Kieu district, Can Tho city”. In 2021, she got a scholarship for her abstract at the 17th International Conference on Urban Health (virtual conference). The presentation was about “A new concept to implement in a spatiotemporal health impact assessment related to waterborne pathogens in urban floodwater using QMRA, disease burden by DALYs, and 1D2D hydrodynamic model. Case study: Ninh Kieu district, Can Tho city - A lower Mekong basin”. In her free time, she loves cooking and sharing meals with friends and family, doing yoga and meditation. She enjoys traveling with her son and husband during their holidays.

Journals publications

1- Huynh, Thi Thao Nguyen, Nguyen, Hong Quan, Voong, Vinh Phat, Stephen Baker, and Pathirana, Assela. 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): 634–41. https://doi.org/10.1080/1573062X.2020.1713381

2- Thi Thao Nguyen Huynh, Nynke Hofstra, Hong Quan Nguyen, Stephen Baker, Chris Zevenbergen, Gerald A. Corzo Perez, Assela Pathirana (in press). "Estimating disease burden of rotavirus in floodwater through traffic in the urban areas – A case study of Can Tho city, Vietnam." *Journal of Flood Risk management*.

3- Thi Thao Nguyen Huynh, Nynke Hofstra, Hong Quan Nguyen, Stephen Baker, Assela Pathirana, Gerald A. Corzo Perez, Chris Zevenbergen. *"Analysis of the location and concentration of enteric pathogens in urban floodwater in Can Tho city - Vietnamese Mekong Delta area"*. (manuscript in preparation)

4- Thi Thao Nguyen Huynh, Nynke Hofstra, Hong Quan Nguyen, Stephen Baker, Assela Pathirana, Gerald A. Corzo Perez, Chris Zevenbergen. *"Incorporation of traffic conditions into microbial health risk assessment in flood analysis - Applying Quantitative Microbial Risk Assessment (QMRA), Disability Adjusted Life Years (DALYs) and hydrodynamic model in urban area – Can Tho city, Vietnam"*. (manuscript in preparation)

Conference presentations

Oral presentation:

1. ***Huynh, Thi Thao Nguyen***, Gerald Corzo Perez, and Chris Zevenbergen. 2022. "Exploring the Link between Microbial Pathogens in Urban Floodwater and Health Consequences through Traffic Exposure on Streets." In *3rd International Association for Hydro-Environment Engineering and Research (IAHR) Young Professionals Congress*. Virtual conference.

2. ***Huynh, Thi Thao Nguyen***, Gerald Corzo Perez, Assela Pathirana, and Chris Zevenbergen. 2021. "A spatiotemporal Health Impact Assessment Related to Waterborne Pathogens in Urban Floodwater Using QMRA, Disease Burden by DALYs, and 1D2D Hydrodynamic Model. Case Study: Ninh Kieu District, Can Tho City - A Lower Mekong Basin." In *17th International Conference on Urban Health*. Virtual conference.

3. ***Huynh, Thi Thao Nguyen***, Hong Quan Nguyen, Assela Pathirana, and Chris Zevenbergen. 2019. "Health Risk Assessment Related to Enteric Pathogens in Urban Flood Water. A Case Study in Vietnamese Mekong Area – Ninh Kieu District, Can

Tho City." In *20th International Symposium on Health-Related Water Microbiology*. Vienna, Austria.

Poster presentation*:*

1. ***Huynh, Thi Thao Nguyen***, Gerald Corzo, Nynke Hofstra, Hong Quan Nguyen, Stephen Baker, Assela Pathirana, and Chris Zevenbergen. 2022. "Sensitivity Analysis for Microbial Risk Assessment of Exposed People through Traffic during Urban Flooding." In *7th Young Water Professionals BeNeLux Conference*. Delft.
2. ***Huynh, Thi Thao Nguyen***, Hong Quan Nguyen, Phat Voong Vinh, Quang Hieu Ngo, Stephen Baker, Assela Pathirana, and Chris Zevebergen. 2019. "Microbial Pollution in Flood-Related Waters in Urban Areas: A Case Study in Ninh Kieu District, Can Tho City of Vietnam." In *IWA Water and Development Congress and Exhibition*. Colombo, Sri Lanka.

In addition, the following publications, not included in this thesis, were also published during the PhD study:

1. Van Sang Nguyen, Hoang Ngoc Khue Vu, Thoai Tam Nguyen, ***Thi Thao Nguyen Huynh***, Quoc Bang Ho. 2023. "Identify primary air pollution sources of BTEX by using positive matrix factorization (PMF). A case study of Ho Chi Minh City, Vietnam". Archives of Environmental Contamination and Toxicology Journal (Accepted).
2. Ho, Q.B.; Vu, H.N.K.; Nguyen, T.T.; ***Huynh, T.T.N***. An Innovative Method for BTEX Emission Inventory and Development of Mitigation Measures in Developing Countries—A Case Study: Ho Chi Minh City, Vietnam. Int. J. Environ. Res. Public Health 2022, 19, 16156. https://doi.org/10.3390/ijerph192316156
3. Ho, B. Q., Nguyen, K. D., Vu, K. H. N., Nguyen, T. T., Nguyen, H. T. T., Ngo, D. D. N., Tran, H. T. H., Le, P. H., Nguyen, Q. H., Ngo, Q. X., ***Huynh, N. T. T.*** & Nguyen, H. D. (2022). Apply MIKE 11 model to study impacts of climate change on water resources and develop adaptation plan in the Mekong Delta, Vietnam: a case of Can Tho city. Environmental Monitoring and Assessment, 194. https://doi.org/10.1007/s10661-022-10185-7
4. Kreibich, Heidi, Anne F. Van Loon, Kai Schröter, Philip J. Ward, Maurizio Mazzoleni, Nivedita Sairam, Guta Wakbulcho Abeshu, Svetlana Agafonova, Amir AghaKouchak, Hafzullah Aksoy, Camila Alvarez-Garreton, Blanca Aznar, Laila Balkhi, Marlies H. Barendrecht, Biancamaria Sylvain, Liduin Bos-Burgering, Chris Bradley, Yus Budiyono, Wouter Buytaert, Lucinda Capewell, Hayley Carlson, Yonca Cavus, Couasnon Anaïs, Gemma Coxon, Ioannis Daliakopoulos, Marleen C. de Ruiter, Claire Delus, Mathilde Erfurt, Giuseppe Esposito, Didier François, Frédéric Frappart, Jim Freer, Natalia Frolova, Animesh K. Gain, Manolis Grillakis, Jordi Oriol Grima,

Diego A. Guzmán, Laurie S. Huning, Monica Ionita, Maxim Kharlamov, Dao Nguyen Khoi, Natalie Kieboom, Maria Kireeva, Aristeidis Koutroulis, Waldo Lavado-Casimiro, Hong-Yi Li, María Carmen LLasat, David Macdonald, Johanna Mård, Hannah Mathew-Richards, Andrew McKenzie, Alfonso Mejia, Eduardo Mario Mendiondo, Marjolein Mens, Shifteh Mobini, Guilherme Samprogna Mohor, Viorica Nagavciuc, Thanh Ngo-Duc, ***Thi Thao Nguyen Huynh***, Pham Thi Thao Nhi, Olga Petrucci, Hong Quan Nguyen, Pere Quintana-Seguí, Saman Razavi, Elena Ridolfi, Jannik Riegel, Md Shibly Sadik, Elisa Savelli, Alexey Sazonov, Sanjib Sharma, Johanna Sörensen, Felipe Augusto Arguello Souza, Kerstin Stahl, Max Steinhausen, Michael Stoelzle, Wiwiana Szalińska, Qiuhong Tang, Fuqiang Tian, Tamara Tokarczyk, Carolina Tovar, Thi Van Thu Tran, Marjolein H. J. van Huijgevoort, Michelle T. H. van Vliet, Sergiy Vorogushyn, Thorsten Wagener, Yueling Wang, Doris E. Wendt, Elliot Wickham, Long Yang, Mauricio Zambrano-Bigiarini, Günter Blöschl, and Giuliano Di Baldassarre. 2022. "***The Challenge of Unprecedented Floods and Droughts in Risk Management***." **Nature**. https://doi:10.1038/s41586-022-04917-5

5. Nguyen HQ, Radhakrishnan M, ***Huynh TTN***, Baino-Salingay ML, Ho LP, Van der Steen P, Pathirana A. 2017a. Water quality dynamics of urban water bodies during flooding in Can Tho City, Vietnam. *Water* **9** (4). https://10.3390/w9040260
6. Nguyen HQ, ***Huynh TTN***, Pathirana A, Van der Steen P. 2017b. Microbial risk assessment of tidal—induced urban flooding in Can Tho City (Mekong Delta, Vietnam). *International Journal of Environmental Research and Public Health* **14** (12): 1–10. https://10.3390/ijerph14121485

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D I P L O M A

for specialised PhD training

The Netherlands research school for the
Socio-Economic and Natural Sciences of the Environment
(SENSE) declares that

Huynh Thi Thao Nguyen

born on 8 June 1989 Binh Dinh province, Vietnam

has successfully fulfilled all requirements of the
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The SENSE Director

Prof. Philipp Pattberg

The SENSE Research School has been accredited by the Royal Netherlands Academy of Arts and Sciences (KNAW)

K O N I N K L I J K E N E D E R L A N D S E
A K A D E M I E V A N W E T E N S C H A P P E N

The SENSE Research School declares that **Huynh Thi Thao Nguyen** has successfully fulfilled all requirements of the educational PhD programme of SENSE with a work load of 41.9 EC, including the following activities:

SENSE PhD Courses

- Environmental research in context (2015)
- Research in context activity: 'Co-organizing UNESCO-IHE PhD symposium and proceedings booklet (Delft, 28-29 September 2015)'
- SENSE writing week (2017)

Selection of Other PhD and Advanced MSc Courses

- "Asset management of water system" & "Green cities: a pathway to sustainable urban water systems", TU Delft (2015)
- Computer Programming for Water Modelers – a course using Python Programming Language, TU Delft (2016)
- Cross cultural communication skills in academia, TU Delft (2016)
- Numerical Modeling for Environmental and Water Resource Engineering, TU Delft (2017)
- PCSWMM and EPA SWMM5 course, TU Delft (2018)
- Flood risk management, TU Delft (2019)
- Data Science and Machine Learning Basic and Advanced levels, TU Delft (2017)
- Using Creativity to Maximize Productivity and Innovation in Your PhD, TU Delft (2017)
- Critical thinking, TU Delft (2017)
- Analytical storytelling, TU Delft (2017)

Management and Didactic Skills Training

- Member of PhD fellow Association Board at IHE (2016-2018)
- Supervising MSc student with thesis entitled 'Water Quality Modelling for Flood – Related Water in Urban Areas' (2018)

Oral Presentations

- *Health risk assessment (QMRA and DALYs) related to enteric pathogens in urban flood water – A case study from an urban flood event in Vietnamese Mekong area – Ninh Kieu district, Can Tho city*. 20th International Symposium on Health-Related Water Microbiology, 15 – 20 September 2019, Vienna, Austria
- *Health risk assessment - Challenges of urban hydrodynamic model to simulate waterborne pathogens in floodwater. A case study in Vietnamese Mekong area – Ninh Kieu district, Can Tho city, Vietnam*. The 14th IHE PhD Symposium on Collaboration for sustainability, 7-8th October 2020, Delft, The Netherlands

SENSE coordinator PhD education

Dr. ir. Peter Vermeulen

IHE DELFT

Institute for Water Education
under the auspices of UNESCO

TU Delft Delft University of Technology

Assessing microbial health risks related to floodwater is a complex undertaking, hindered by factors like the intricate nature of the microorganisms involved and the susceptibility of those exposed to them. This research contributes a framework and application that combines health risk assessment, disease burden calculation, and hydrodynamic modeling to estimate adverse health consequences of microbial pathogens in floodwater through traffic activities which is a common factor of exposure during floods. The case study is Ninh Kieu District (Can Tho City, Vietnam) located on the western side of Hau River, a Mekong tributary. The study focuses on the health risk and disease burden due to rotavirus A in floodwater in Ninh Kieu through traffic activities, especially for motorcyclist. This research is one of the first to consider the input parameter concentrations and the number of exposed people to reduce the health impact of flood risk. It reveals that mitigation measures should not only focus on reducing urban floods but also on raising awareness of the local people of microbial health risks in floodwater. The disease burden is considered the prime variable of the health indicator to represent the social dimension in the assessment of flood vulnerability.

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