Environment International 127 (2019) 801–809

Contents lists available at ScienceDirect

Environment International

journal homepage: www.elsevier.com/locate/envint

The impact of the 2016 flood event in Anhui Province, China on infectious diarrhea disease: An interrupted time-series study

Na Zhang[a,1], Dandan Song[b,1], Jin Zhang[b,1], Wenmin Liao[a], Kaichao Miao[c], Shuang Zhong[d], Shao Lin[e], Shakoor Hajat[f], Lianping Yang[a,*], Cunrui Huang[a,*]

[a] *School of Public Health, Sun Yat-sen University, Guangzhou, China*
[b] *Anhui Provincial Center for Disease Control and Prevention, Hefei, China*
[c] *Public Meteorological Service Center of Anhui Province, Hefei, China*
[d] *School of Government, Sun Yat-sen University, Guangzhou, China*
[e] *School of Public Health, University at Albany, State University of New York, Albany, USA*
[f] *Department of Public Health, Environments and Society, London School of Hygiene & Tropical Medicine, London, UK*

ARTICLE INFO

Handling Editor: Frederic Coulon

Keywords:
Floods
Climate change
Infectious diarrhea
Interrupted time series
China

ABSTRACT

Climate change may bring more frequent and severe floods which will heighten public health problems, including an increased risk of infectious diarrhea in susceptible populations. Affected by heavy rainfall and an El Niño event, a destructive flood occurred in Anhui province, China on 18th June 2016. This study investigates the impact of this severe flood on infectious diarrhea at both city-level and provincial level, and further to identify modifying factor. We obtained information on infectious diarrheal cases during 2013–2017 from the National Disease Surveillance System. An interrupted time-series design was used to estimate effects of the flood event on diarrhea in 16 cities. Then we applied a meta-analysis to estimate the area-level pooled effects of the flood in both flooded areas and non-flooded areas. Finally, a meta-regression was applied to determine whether proximity to flood was a predictor of city-level risks. Stratified analyses by gender and age group were also conducted for flooded areas. A significant increase in infectious diarrhea risk (RR = 1.11, 95% CI: 1.01, 1.23) after the flood event was found in flooded area with variation in risks across cities, while there was no increase in non-flooded areas. Diarrheal risks post-flood was progressively higher in cities with greater proximity to the Yangtze River. Children aged 5–14 were at highest risk of diarrhea post-flood in the flooded areas. Our study provides strong evidence that the 2016 severe flood significantly increased infectious diarrheal risk in exposed populations. Local public health agencies are advised to develop intervention programs to prevent and control infectious diarrhea risk when a major flood occurs, especially in areas close to water bodies and among vulnerable populations.

1. Introduction

Flood events are the most frequent and destructive natural disasters globally, and accounts for almost half of all natural disasters in the past ten years (Guha-Sapir et al., 2016). The frequency and intensity of floods are projected to increase under climate change scenarios due to extreme precipitation events and rising sea levels (Hirabayashi et al., 2013; IPCC, 2014). China is currently one of the most flood-prone countries in the world (Guha-Sapir et al., 2016) and expected to experience larger changes than the global average in its climate this century (Lim et al., 2012). Affected by El Niño, continuous heavy rainfall brought about a severe flood in June 2016 in the Yangtze River Basin. It was the largest flood since 1998 in this region, and it affected many provinces in the central and southern parts of China. In the worst-hit Anhui province, this flood affected 12.82 million people causing a direct economic loss of 8.25 billion US dollars (Anhui Meteorology Administration, 2017).

Floods have the potential to cause substantial health losses, including mortality, injuries, mental health problems, non-communicable diseases, vector-borne diseases and water-borne diseases (Alderman et al., 2012). The IPCC (2014) stated that the health risks associated with flood events are important issues and more evidences are required on the non-fatal health impacts attributable to flooding. Diarrhea is a health outcome sensitive to floods, and it remains a major public health

---

[*] Corresponding authors at: School of Public Health, Sun Yat-sen University, No. 74, Zhongshan 2nd Road, Guangzhou 510080, China.
E-mail addresses: yanglp7@mail.sysu.edu.cn (L. Yang), huangcr@mail.sysu.edu.cn (C. Huang).

[1] These authors contributed equally to this work.

https://doi.org/10.1016/j.envint.2019.03.063
Received 8 January 2019; Received in revised form 26 March 2019; Accepted 26 March 2019

concerns around the world, especially in low- and middle-income countries. The World Health Organization (WHO) estimated that four hundred million diarrheal cases occur annually and led to 1.31 million deaths globally in 2015 (Troeger et al., 2017). In China, there were about 393 million diarrhea cases and this led to a disease burden of 979 thousand Disability-Adjusted Life Years (DALYs) in 2017, and diseases burden of diarrhea in China is much heavier than most developed countries due to the large population according to the recent Global Burden of Disease study (Global Burden of Disease, 2018). Thus, better understanding of the relationship between floods and infectious diarrhea is critical to reduce the disease burden associated with these extreme weather events.

Evidences on the relationship between floods and diarrhea are not always consistent, although a predominant trend for positive relationship can be observed. Some previous studies suggested higher diarrheal risks during flood period compared to non-flooded period (Harris et al., 2008; Schwartz et al., 2006), and higher risks in flood-affected groups versus unaffected groups (Ding et al., 2013; Kondo et al., 2002; Wade et al., 2004). However, there are also studies that detected no increase in diarrheal risk in the aftermath of floods (Joshi et al., 2011; Milojevic et al., 2012; Zhang et al., 2016b). In China, Ding et al. (2013), X. Liu et al. (2016) and Zhang et al. (2016a) reported that floods increase the risks of diarrhea in some specific cities, while another study (Zhang et al., 2016b) found that the risk of other infectious diarrhea was not significantly associated with a flood in Qingdao, China. This indicates that the health risks of floods are context-specific and vary across regions due to various environmental, socioeconomic factors and also the magnitude of floods in question (Brown and Murray, 2014), but most of the evidences to date from China were based on just one or two cities with small sample size, and lacked of baseline health data (Ding et al., 2013; X. Liu et al. 2016; Zhang et al., 2016a). Although there was a recent provincial-level study conducted in Hunan province in China (Liu et al., 2018), it only considered a temporal comparison of floods periods and non-flood periods, but lacked a control group in non-flooded areas. Additionally, the 2016 flood assessed in the current study is the severest flood in the past few decades in China, and the impacts of this major event on diarrhea disease still remains unclear.

The aim of this study, therefore, is to quantitatively examine the impact of the 2016 severe flood event on infectious diarrhea risk at both city- and provincial level applying an interrupted time series design with a control series in Anhui province, China. The results will improve the evidence-base of the relationships between floods and infectious diarrhea, and can inform the development of strategies to reduce the risk of flood-related infectious diarrhea during future events.

2. Methods

2.1. Study area

Anhui province is located in the eastern part of mainland China (Fig. 1), and has a total area of 140,100 km^2, including 16 prefecture-level cities and a total population of 62.5 million in 2017. Situated in the lower reaches of the Yangtze River, Anhui province has a warm temperate and subtropical climate. It experiences abundant heavy rainfall in the summer, which is named the plum rain season, accounting for 40–60% of the annual rainfall.

Anhui province had suffered from a catastrophic flood disaster in 2016. During the plum rain season (starting from 18 June), the cumulative precipitation of Yangtze River basin was 700 mm, with at least 20 continuous rainy days (Anhui Meteorology Administration, 2017). As a consequence of the abundant precipitation during the plum rain season, the Yangtze River basin suffered from China's severest flood since 1998 (Ministry of Water Resources of China, 2016). This flood affected 11 cities in Anhui province, 12.8 million people were exposed, 34 people were killed, 1120 thousand hectare crop area was destroyed, and the direct economic loss was estimated to be 8.25 billion US dollars (Anhui Meteorology Administration, 2017).

For this study, "the 2016 severe flood" refers to the flood occurring on 18th June 2016. The flooded areas consist of 11 affected cities (Huainan, Chuzhou, Hefei, Maanshan, Wuhu, Tongling, Luan, Anqing, Chizhou, Huangshan and Xuancheng) while the non-flooded area is represented as by 5 other cities in Anhui province (Suzhou, Huaibei, Bozhou, Fuyang, Bengbu). In this study, the 3 years before the flood onset date (18th June 2013 to 17th June 2016) were selected as the "before flood period" to allow robust characterization of intra-annual seasonal patterns and pre-existing trends in diarrheal incidence. There was no severe flood event during the 3 years before the 2016 flood (Anhui Meteorology Administration, 2017). The "during flood period" is signified as 18th June 2016 to 31st August 2016 and the "after flood period" refers to the 1 year period after the flood (1st September 2016 to 31st August 2017) (Anhui Meteorology Administration, 2017).

2.2. Data

Anonymised information on individual infectious diarrhea cases was obtained from the National Disease Surveillance System (NDSS) for the period 18th June 2013 to 31st August 2017 with the approval of the Anhui Provincial Center for Disease Control and Prevention. We aggregated the individual infectious diarrhea data into weekly counts for statistical analyses. Weekly counts were created to provide a sufficient number of cases at each unit of time and to remove strong day-of-week effects. According to China's NDSS, infectious diarrhea is a group of human intestinal infectious diseases that are mainly caused by microbes (including bacteria, parasites and viruses) and have diarrhea as the typical symptom, including dysentery, cholera, typhoid, paratyphoid and other infectious diarrhea. In our study, all infectious diarrhea cases were diagnosed by clinical symptoms as well as by serological test confirmation. According to the National Communicable Diseases Control Act, doctors in hospitals or clinics must report each infectious diarrheal case to local health departments, and then local health departments must report these cases to the higher levels of the system within 24 h. Thus, the degree of compliance of disease notification over our study period should be consistent. Demographic information of individuals cases was also captured from NDSS, including age, gender, type of diarrheal disease, date of disease onset and the administrative division codes of residential address. The administrative division codes were used to assign each individual's home address to the specific city in the city-stratified analysis.

We also retrieved the annual population data from the *Statistical Yearbook of Anhui Province* (http://www.ahtjj.gov.cn/) to allow for standardization and comparability.

2.3. Statistical analysis

We considered two references groups in this study: one reference group was before-flood period and the other was non-flooded areas. Data analysis consisted of two stages. Firstly, we applied an interrupted time-series (ITS) method to examine the influence of the flood event on weekly infectious diarrheal risk (compared to that in before flood period) in 16 cities in Anhui province. Secondly, a random-effect meta-analysis was used to estimate the pooled effect of the flood on infectious diarrhea across cities separately for flooded areas and non-flooded areas. A meta-regression was then applied to explore the degree to which distance to Yangtze River predicted the magnitude of the post-flood diarrheal risks across the 16 flooded cities.

In the first stage, an interrupted time-series regression analysis with quasi-Poisson family was applied to examine the impact of flood on diarrheal risk in each city. Gender and age-group stratified analyses for flooded areas were also conducted to identify vulnerable subgroups. The interrupted time-series design is considered as the strongest quasi-experimental method for evaluating longitudinal effects of unplanned events at the population-level (Bernal et al., 2017; Phung et al., 2017;

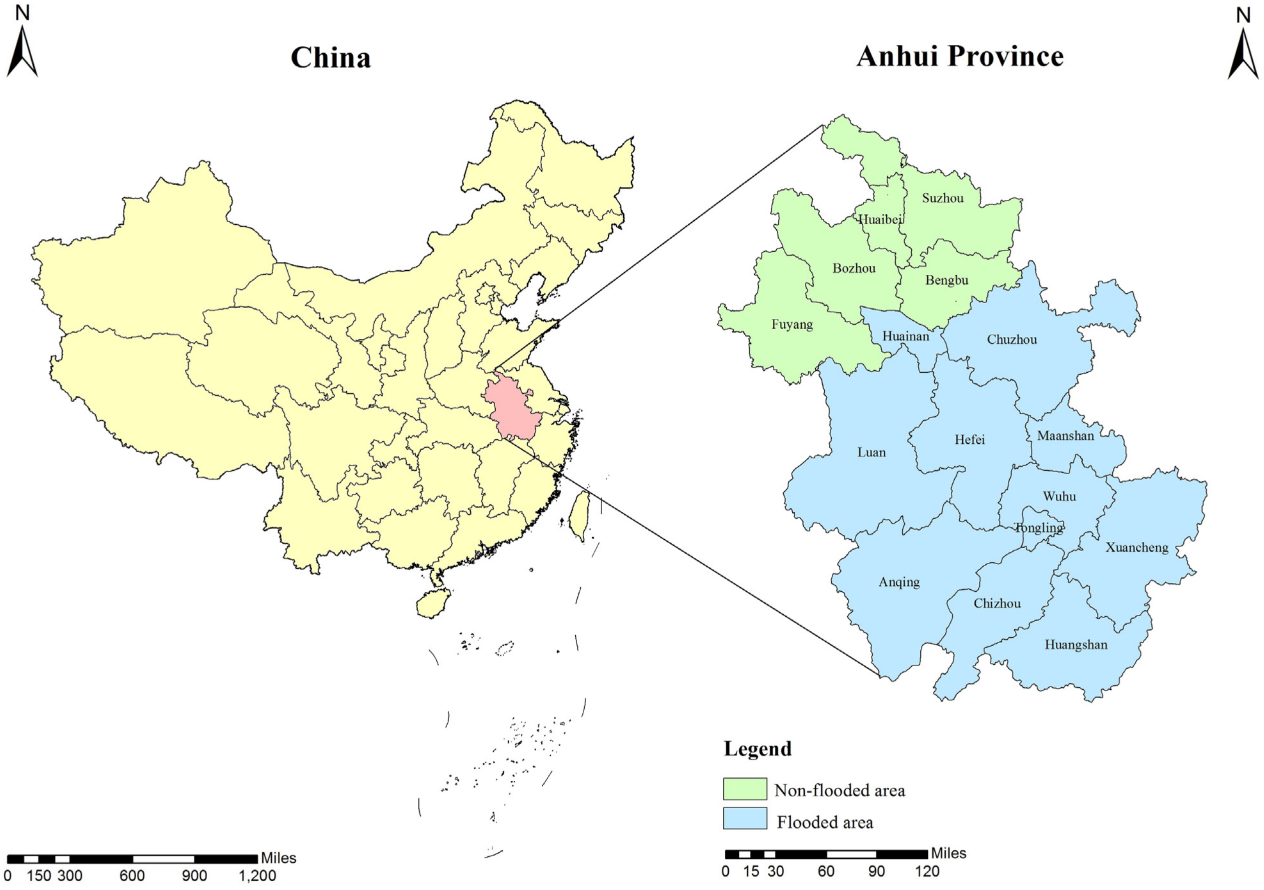

Fig. 1. Location of the study area in China.

Wagner et al., 2002). The interrupted time point was defined as the onset date of the flood (18th June 2016). We used a generalized liner model with a quasi-Poisson distribution to account for over-dispersion. Weekly counts of infectious diarrhea were selected as dependent variable and an indicator term for flood is independent variable. Population was included as an offset variable to convert the weekly infectious diarrhea counts into a rate and allow to adjust for potential changes in the population over time (Bernal et al., 2017). A Fourier terms were introduced in this model to adjust for seasonality of infectious diarrhea incidence, and we applied a linear term for long term trend (Bernal et al., 2017; Wagner et al., 2002). To control for autocorrelation, the first-order weekly lagged term of residuals was included in the model.

Eq. (1) summarises the model fitted:

$$Y_t \sim \text{quasi-Poisson}$$
$$\log E(Y_t) = \beta_0 + \beta_1 * \text{time}_t + \beta_2 * \text{flood}_t + \text{seasonality} + \text{Lag}(\text{residual}, 1 \text{ week}) \quad (1)$$

where, $E(Y_t)$ is the expected weekly infectious diarrheal counts at time_t; time_t is a continuous variable indicating time in weeks of year at time t from the start of the observation period; flood_t is a dummy variable indicating the before-flood period (coded 0) and the after-flood period (coded 1). In this model, β_0 is the intercept; β_1 can be interpreted as the change in infectious diarrheal risk associated with one week increase representing the underlying before-flood trend; β_2 estimates the change in the weekly infectious diarrheal risk immediately after t weeks following the flood onset date, which can therefore be described as the before-after change. The before-after change represents the differences between the weekly diarrheal risk in the before flood period and after the flood period and so represents the effects of the flood on infectious diarrhea. In this study, lag effects were not characterized because we aimed to explore the total effects of the 2016 severe flood across the full one year after the flood event.

Meta-analysis methods have been used to evaluate the pooled effects of the results from multiple events and multiple areas in the previous studies (Milojevic et al., 2012; Phung et al., 2016). Thus, in the second stage, we used meta-analysis to generate the pooled estimates of the before-after change on infectious diarrhea of this 2016 severe flood in flooded areas and non-flooded areas based on the city-specific results considering the cities' heterogeneity. The impact of the flood may vary across cities due to the variation in demographic, socio-economic and other factors, resulting in heterogeneity of findings. So a random-effect meta-analysis was used based on the coefficient of inconsistency (I^2) which describe the percentage of heterogeneity across cities and tested by using Cochran's Q χ^2 test.

A risk map of infectious diarrhea in Anhui province was also visualized according to the results of the ITS analysis of each city using ArcMap 10.2. Based on the pattern of the RRs distribution on the risk map, we applied meta-regression to explore if the distance to the Yangtze River affected the risk estimates across cities in Anhui province post-flood. For this, we extracted the centroid points of each city and calculated the nearest distance from the centroid points of each city to the Yangtze River in ArcMap 10.2 (see Supplementary Table 1a), and then we used meta-regression to explore whether the distance to Yangtze River of each city associated with the estimated diarrheal risks of these cities.

We chose 0.05 (two-sided) as our statistical significance level. Analyses were conducted using “tsModel”, “lmtest”, “Epi” “spline” and “meta” package in R v3.4.4.

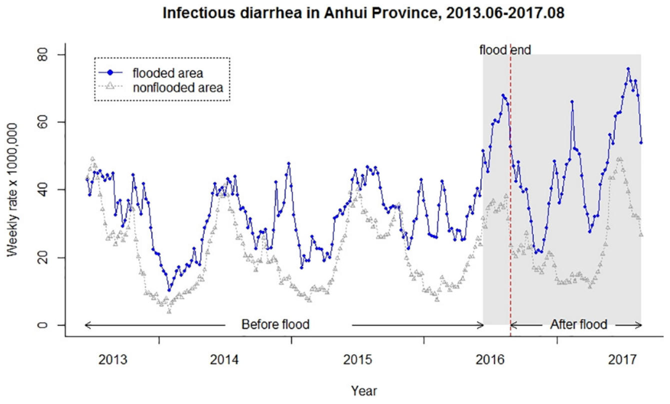

Fig. 2. Weekly rate of infectious diarrhea in flooded and non-flooded area from June 2013 to August 2017.

2.4. Sensitivity analysis

Sensitivity analyses were conducted by adding an interaction term between time and flood (slope change) to the main model to explore any slope changes and also to test the robustness of our findings. The results of sensitivity analyses remain similar to the main model (Supplementary Table 2). Results also indicated that slope change term is non-significant, so it is not included in the main model. In addition, the residual plots and partial autocorrelation function (PACF) plots of the deviance residuals of the main model are shown in Supplementary Fig. 1 to inform model fit.

3. Results

Overall, 274,621 infectious diarrheal cases from flooded areas and 129,356 cases from non-flooded areas were identified during our study period. Descriptive statistics of infectious diarrhea in these two areas are shown in Fig. 2 and Table 1. Fig. 2 shows there was a higher weekly infectious diarrhea rate in flooded areas compared to that in non-flooded areas. The rate of flooded areas increased when the flood occurred while that of non-flooded areas was relatively stable. Seasonality in the weekly infectious diarrhea rate was apparent in the both areas, usually peaking in summer and autumn, then gradually reducing.

Table 1 gives the case counts, rates, rate ratios (infectious diarrhea rate of flooded area divided by that of non-flooded area in the same time period) and ratios of rate ratios (rate ratios in the during-flood/after-flood periods compared with that in the before-flood period) of infectious diarrhea onset in different subgroups in the different periods. Regardless of time periods, the rates were particularly high in children under 5 years among all age groups. In the after-flood period, the rate of infectious diarrhea in children under 5 years was nearly 20 times greater than that of 15–44 year olds. Across all age combined, the rate ratio increased in total, with 1.49 before the flood, 1.61 during the flood and 1.83 after the flood, leading to a ratios of rate ratios of 1.08 during- and 1.22 after the flood. More specific, the ratio of rate ratios was found to increase after the flood in almost all subgroups except children under-5 and those aged 15–44. The ratio of rate ratios after the flood was highest in children aged 5–14, increasing from 1.29 to 1.85.

Fig. 3 shows the results of the ITS analysis conducted in the whole flooded areas (RR = 1.147, 95% CI: 1.077, 1.222) and in the non-flooded areas (RR = 1.028, 95% CI: 0.968, 1.091). A raised diarrheal risk was only found in the flooded areas, so the age- and gender-stratified analyses were only conducted in this area.

Table 2 presents the stratified analyses of cases in flooded areas. Gender-stratified analysis suggested that both females (RR = 1.175, 95% CI: 1.072, 1.287) and males (RR = 1.146, 95% CI: 1.072, 1.224) have increased diarrheal risks post-flood in flooded areas. As for age stratified analyses, the increased risks were significantly higher in all age groups, with 16.6%, 14.4%, 15.8% and 8.4% increases in children under-5, 15–44, 45–64 and those older than 65 age groups, respectively. Those aged 5–14 demonstrated the highest risk, with a 29.5% increase (RR = 1.295, 95% CI: 1.123, 1.562) in the aftermath of the flood.

Table 1
Case, rate, rate ratio and the ratios of rate ratios of infectious diarrhea in before-, during- and after-flood periods in the flooded and non-flooded areas.

	Case		Rate per 1000		Rate ratio[a]	Ratio of rate ratios[b]
	Flooded	Non-flooded	Flooded	Non-flooded		
Before the flood						
Gender						
Male	94,912	48,642	5.24	3.65	1.43	Ref.
Female	76,884	37,414	4.27	2.73	1.57	Ref.
Age						
< 5	73,846	24,471	39.99	11.76	3.40	Ref.
5–14	8700	5205	2.43	1.46	1.66	Ref.
15–44	37,162	20,083	2.32	1.66	1.39	Ref.
45–64	31,298	20,061	2.93	3.06	0.96	Ref.
≥ 65	20,790	16,236	5.26	5.91	0.89	Ref.
Total	171,796	86,056	4.76	3.18	1.49	Ref.
During the flood						
Gender						
Male	11,264	5214	0.62	0.39	1.59	1.11
Female	10,133	4724	0.56	0.34	1.63	1.04
Age						
< 5	6830	1514	3.70	0.73	5.08	1.49
5–14	827	384	0.23	0.11	2.14	1.29
15–44	6522	3106	0.41	0.26	1.58	1.13
45–64	4476	2756	0.42	0.42	1.00	1.04
≥ 65	2742	2178	0.69	0.79	0.88	0.98
Total	21,397	9938	0.59	0.37	1.61	1.08
After the flood						
Gender						
Male	44,726	18,180	2.47	1.37	1.81	1.26
Female	36,702	15,182	2.04	1.11	1.84	1.18
Age						
< 5	37,880	8703	20.51	4.18	4.91	1.44
5–14	4702	1519	1.31	0.43	3.07	1.85
15–44	16,689	8409	1.04	0.70	1.50	1.07
45–64	13,064	7939	1.22	1.21	1.01	1.05
≥ 65	9093	6792	2.30	2.47	0.93	1.05
Total	81,428	33,362	2.26	1.23	1.83	1.22

[a] Rate ratio: infectious diarrhea rate in the before-/during-/ or after-the flood period in flooded area compared with that in non-flooded area.

[b] Ratio of rate ratios: rate ratios in the during-/after-flood period compared with that in the before-flood period.

The city-stratified analyses show that the infectious diarrheal risk varied across cities post-flood. A significant rise of diarrheal risk was found in Xuancheng, Anqing, Chizhou, Hefei, and Maanshan, where increases of 46.0%, 38.7%, 19.8%, 13.3% and 12.3% were observed post-flood, respectively. A risk map (Fig. 4) based on the RRs of cities in flooded areas was determined. This conveys that cities located along the Yangzi River were generally at higher risk than those far away from the river after the flood. The results of the meta-regression quantified the negative association between the distance to Yangtze River and diarrheal risks post-flood ($\beta = -0.09$, P value = 0.01). The results indicated that one hundred kilometer decrease in the distance to the Yangtze river corresponds to increase 0.09 units in the terms of the average log relative risk of diarrhea post-flood.

To account for cities' heterogeneity, a random effects meta-analysis model was applied. Fig. 5 shows that the pooled estimates of the before-after change in infectious diarrheal risk at area-level, indicating that there was a significant 11% increase (RR = 1.11, 95% CI: 1.01, 1.23) of infectious diarrheal risk following the flood in flooded areas after taking cities' heterogeneity into account, whereas there was no significant before-after change (RR = 0.98, 95% CI: 0.87, 1.11) in non-flooded areas.

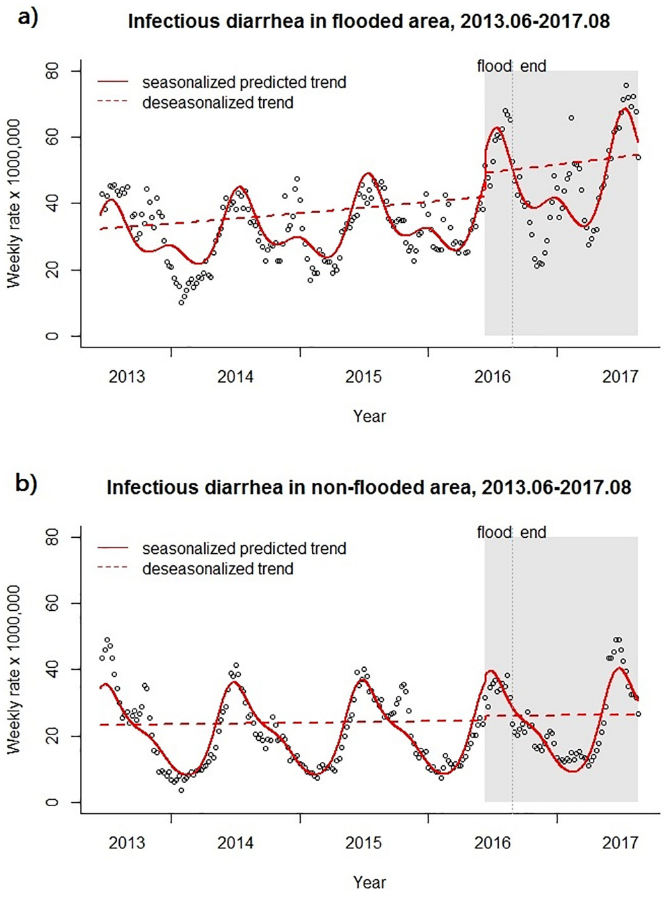

Fig. 3. Before-after change on infectious diarrhea risk of ITS model in flooded area (a); and in non-flooded area (b).

Table 2
Relative risk (RR) and 95% confidence interval (95% CI) for before-after change of infectious diarrheal risk post-flood **in flooded area** by subgroups.

	Relative risk	95% Confidence intervals
Total	1.147	(1.077, 1.222)*
Gender		
Male	1.146	(1.072, 1.224)*
Female	1.175	(1.072, 1.287)*
Age		
< 5	1.166	(1.072, 1.270)*
5–14	1.295	(1.123, 1.507)*
15–44	1.144	(1.054, 1.241)*
45–64	1.158	(1.064, 1.260)*
≥65	1.084	(1.008, 1.167)*
City		
Hefei	1.133	(1.044, 1.230)*
Wuhu	1.124	(0.992, 1.273)
Huainan	0.979	(0.850, 1.129)
Maanshan	1.123	(1.022, 1.233)*
Tongling	1.165	(0.814, 1.666)
Anqing	1.387	(1.193, 1.612)*
Huangshan	1.017	(0.887, 1.166)
Chuzhou	0.761	(0.668, 0.867)*
Luan	1.019	(0.907, 1.143)
Chizhou	1.198	(1.046, 1.372)*
Xuancheng	1.460	(1.326, 1.606)*

* Represents P value < 0.05.

4. Discussion

This is the first study to evaluate the health effects of the most recent devastating floods in China which affected Anhui province heavily. We conducted a province-wide analysis on the impacts of floods on infectious diarrhea at city-level and province-level applying an ITS design with a control series. Our study found a significant increase in diarrheal risk after flood at provincial level with high heterogeneity across the flooded cities, while no effect was found in non-flooded areas. The distance to the Yangtze River is found to be negatively associated with the diarrheal risk post-flood across cities. Cities near to the Yangtze River were identified as risk areas, and children aged 5–14 years old were found to be the age-group most at risk of diarrhea in flooded areas. Our findings provide more robust evidence to better understand the relationship between infectious diarrhea and floods in China.

The positive association between flood and diarrhea examined in this study is consistent with findings reported in many previous studies. A systematic review reported that 76% of articles found a positive relationship between flood and diarrhea (Levy et al., 2016). The positive association was detected in both developed (Brown and Murray, 2014; Marcheggiani et al., 2010; Schnitzler et al., 2007; Wade et al., 2004) and developing countries (Harris et al., 2008; Hashizume et al., 2008; Liu et al., 2018). Although the dominant pattern of this relationship was positive, some studies also reported no association between them. As an illustration of this, studies conducted in two cities in Anhui province, Hunan province found a positive association between flood and diarrhea (Ding et al., 2013; X. Liu et al. 2016) while another study in Qingdao found that there was no relationship between them (Zhang et al., 2016b). Both positive and non-significant association were observed in our city-stratified analyses, e.g., a positive association between diarrheal risk and flood was found in Hefei, Maanshan and Anqing while there was no association in Huainan Huangshan and Luan. Variation in effects may be due to different flood magnitude, population vulnerability, health care service and the levels of economic development in the affected areas (Brown and Murray, 2014; Lowe et al., 2013). However, a significant overall increase of diarrheal risk post-flood was found after considering the heterogeneity across cities in Anhui province, which is consistent with findings from a provincial wide analysis from Hunan, China (Liu et al., 2018).

The underlying mechanism of flood events increasing diarrhea risk may be that floodwater can mobilize pathogens from excreta in soil and transport them into surface water, and precipitation may also cause the pathogens resuspension in sediment or in soils and lower the quality of groundwater (Levy et al., 2016). Inundated floodwaters could also damage water supply and sewage disposal systems (WHO Regional Office for Europe, 2013). Thus, floods may cause deterioration in the water quality thereby exposing humans to contaminated water with infectious agents causing diarrhea. Moreover, risk factors such as direct contact with flood water (Schnitzler et al., 2007), exposure to food contaminated by flood, overcrowding during- and post-flood resettlement (Wakuma Abaya et al., 2009) and limited availability and access to healthcare services could also give rise to the increased diarrheal risk after flood occurrence.

Our study found that the distance to Yangtze River is negatively associated with diarrheal risk, with larger effects of flood on diarrhea in cities along the Yangtze River than those far away from the river. A similar finding was observed in a study conducted in Mexico (Jimenez-Sastre et al., 2012). In our cases, the reasons for this finding may be include the fact that the topography of cities near the Yangtze River is dominated by plain, which may prevent the flood from receding, and the depth of floodwater in cities near the river were deeper than those far away from it. A previous study showed that there was a significant increase in risk of gastroenteritis with depth of flooding (RR = 1.7, P

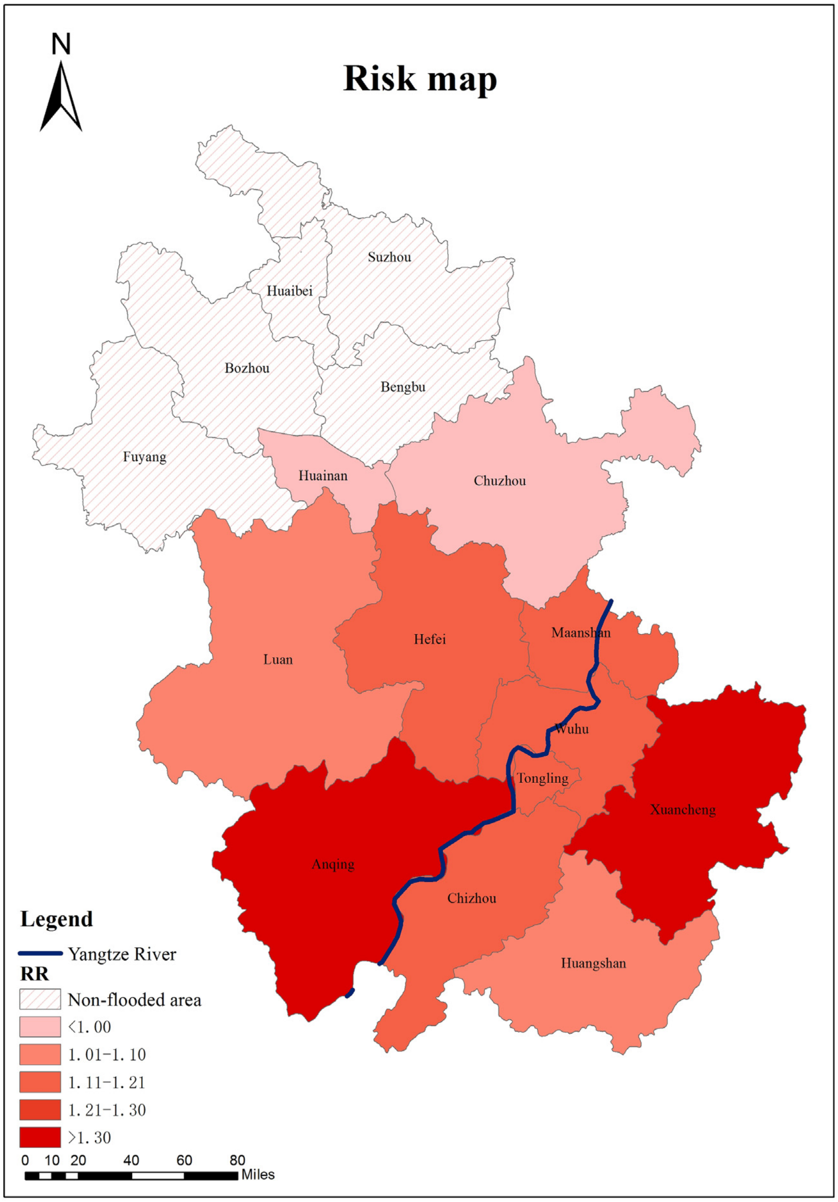

Fig. 4. Estimated risks of infectious diarrhea after the flood among flooded areas in Anhui Province.

for trend by flood depth = 0.04) (Reacher et al., 2004). A larger and deeper floodwater could lead to the poorer sanitation and hygiene, which can provide a suitable environment for infectious diarrheal pathogens to mobilize and spread. In particular, one plausible explanation of the extremely high risk in Xuancheng and Anqing is the close distance to the Yangtze river, and their less developed economy (Anhui Statistics Bureau, 2017). Liu et al. (2018) found that the effect of floods on infectious diarrhea was significantly higher in low economic settings compared to other regions in Hunan, China. Cities with higher economic levels may prepare more adequately in emergency response as well as better public health infrastructure and healthcare systems.

As for gender stratified analysis, the diarrheal risks of both men and women were found to rise after the flood and the risk for women was slightly higher. One explanation may be that women report more psychological symptoms (such as depression and anxiety) than men after extreme weather events (Bell et al., 2016; Lowe et al., 2013), and responsibilities of taking care of children and the elderly members of the family often falls on them. Psychological stress and fatigue caused by such heavy responsibilities may contribute to body function and immunity decline, which in turn may lead to higher susceptibility to infections.

Our study identified that children aged under 5 had the highest rates of diarrhea during whole study period among all age groups. This reflects that children under 5 have the greatest risks to gastrointestinal pathogens and are the most susceptible to diarrheal diseases, which is consistent with existing evidences (Carlton et al., 2012; Lim et al., 2012; World Health Organization, 2017). However, their relative risk after the flood did not increase as much as those aged 5–14 in our study. Reasons may be that those under 5 are preschool children who would have been well sheltered by their parents when the flood occurred, thus minimizing their expose to flood-contaminated water and food. Moreover, the intervention measures provided by local authorities would give highest priority to them, including measures such as providing access to clean bottled water and handwashing with soap, which are both proven to reduce risk (27%, 40% reduction respectively) of diarrhea in children under 5 years (Darvesh et al., 2017).

All age-groups were found to be affected by this severe flood on diarrhea, and children aged 5–14 years old were the most affected by this flood with a 29.5% increase of diarrheal risk post-flood. There is no consistent evidence of which age groups are at highest diarrheal risk

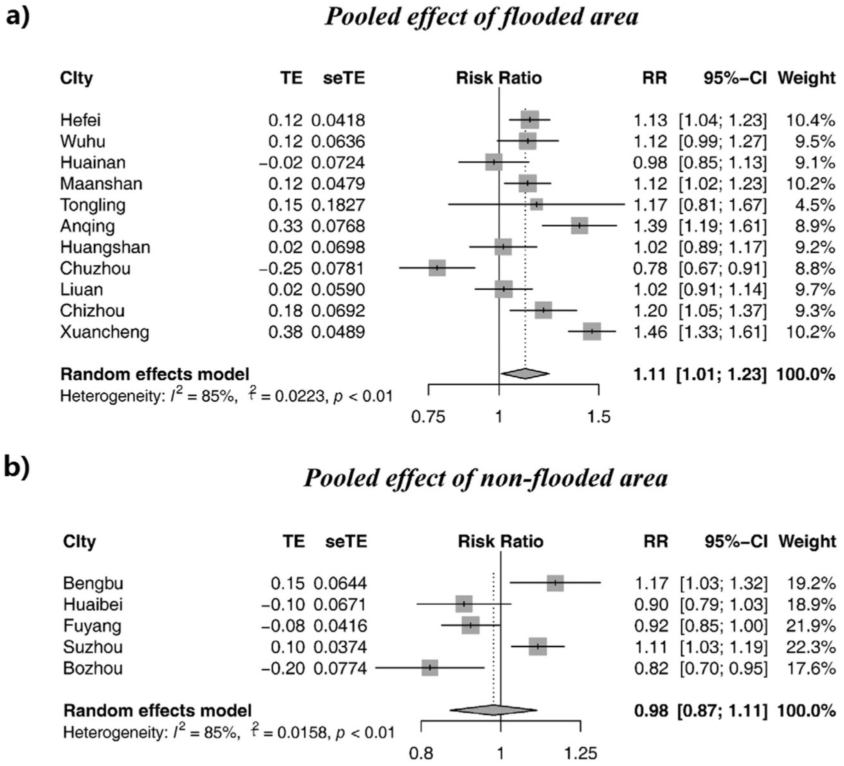

Fig. 5. Pooled estimates of relative risks for before-after change on infectious diarrhea post-flood in flooded area (a); and in non-flooded area (b).

increase in the aftermath of floods from previous studies. Children younger than 5 years were found to have higher risk of gastrointestinal symptoms after floods in some studies (Ding et al., 2013; Wade et al., 2004) while another study found that the effect of floods on dysentery increased significantly only among those aged 15–64 in China (Z.D. Liu et al. 2016). In contrast to those under 5 years, children aged 5–14 are school age children who may be separated from their parents or caregivers at the time of flood and have a wider range of activities than those under 5, which may heighten their exposure to floodwater and diarrheal pathogens. Furthermore, if alone they may not have adequate agency to respond to floods or to seek help if faced with a stressful event (WHO Regional Office for Europe, 2013), so there exists higher potential for them to be infected by a mass of pathogens which may increase the risk of gastrointestinal illnesses (Lowe et al., 2013; Wade et al., 2004). Moreover, their immature immune system may also contribute to the highest risk on diarrhea following the flood compared to adults. Age-stratified analysis also indicate that people aged 15–64 years old were at higher infectious diarrheal risk than those aged > 65 years. This may be because they took active part in relief work and engaged in the post-disaster reconstruction work more than the elderly.

The future health burden of infectious diseases may rise due to the increasing frequency and intensity of floods in a changing climate. It is reported that climate change is projected to delay China's progress towards reducing diarrhea and other water sanitation and hygiene (WASH)-attributable infectious disease burdens by 8–85 months by 2030 (Hodges et al., 2014), thus it is important for Chinese officials and the public to cope with infectious diarrhea. This study suggests that public health authorities should promote awareness about the dangers of infectious diarrhea when a flood occurs. More interventions (e.g. providing access to clean water, improving latrine infrastructure and improving the capacity of the health sector) should be provided to areas close to rivers or water bodies during and after floods. Children aged 5–14 years old should be recognized as highly vulnerable and be paid more attention and provided with better intervention measures as well, as may already be the case for children under 5 years.

Our study provides robust evidence on the causal nature of associations between flood and infectious diarrhea. The interrupted time-series design achieved good control for pre-existing trends, which is a failing of cross-sectional study designs (X. Liu et al. 2016; Schnitzler et al., 2007; Zhang et al., 2016a). Moreover, the sample size of our study is very large with almost 400 thousand cases from 16 cities in Anhui province. The pooled relative risk values were based on the results of 11 affected cities, which provide more power than previous studies based on one or two cities with small sample sizes (Ding et al., 2013; Z.D. Liu et al. 2016; Zhang et al., 2016b). Furthermore, compared with a recent multi-city study using a time-stratified design with a distributed lag non-linear model (DLNM) in Hunan province (Liu et al., 2018), we also assess 5 cities that have not been affected by the flood as a control group in our ITS design to adjust for other time-varying confounders such as concurrent events (Bernal et al., 2017), which was proved to strengthens the design and provides more trustworthy effects (Soumerai et al., 2015). Our observation that the risk of diarrhea was higher in cities in closer proximity to the flooded river also strengthens arguments for a causal relationship.

Several limitations of the present study should be acknowledged. First, any interventions initiated during and after the flood may have reduced the risk of some infectious diseases among the flood-affected population, but information on this was unavailable. It would be interesting to explore the effectiveness of specific interventions on health risk reductions during or after the flood in future analyses. Second, our result may under-estimate the flood effect on diarrhea since people with mild symptoms may not seek medical help, for example those live far away from hospital and other health institutions, resulting in under-reporting of diarrhea cases. Third, this study is an ecological study in nature. We can only divide the flood affected group and unaffected group according to the patient's residential address, but not all individuals in the flooded area were actually exposed to floods. More precise exposure evaluation could be achieved by remote sensing monitoring and geographic information system to ascertain individual households inundated by floodwaters. Alternatively, other research designs such as community surveys could be used to determine exposure. The above limitations would all serve to dilute true flood effects and so our observed results are despite the limitations rather than because of them.

5. Conclusions

The 2016 severe floods significantly increased the risks of infectious diarrhea in flooded areas in Anhui province, China. Diarrheal risks post-flood increased across cities as the distance to the river decreased, and children aged 5–14 years old were at higher risks of diarrhea post-flood. Our findings can help local health authorities better provide targeted and effective public health adaptation and intervention programs under the context of climate change.

Acknowledgement

This work was supported by the grant from the National Key R&D Program of China (grant number: 2018YFA0606200), China.

Competing interest

The authors declare no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.envint.2019.03.063.

References

Alderman, K., Turner, L.R., Tong, S., 2012. Floods and human health: a systematic review. Environ. Int. 47, 37–47.

Anhui Meteorology Administration, 2017. The Yearbook of Meteorological Disasters in Anhui Province. China Meteorological Press, Beijing, China.

Anhui Statistics Bureau, 2017. Statistical Yearbook of Anhui Province. edˆeds. China Statistics Press, Beijing.

Bell, J.E.; Herring, S.C.; Jantarasami, L.; Adrianopoli, C.; Benedict, K.; Conlon, K.; Escobar, V.; Hess, J.; Luvall, J.; Garcia-Pando, C.P.; Quattrochi, D.; Runkle, J.; Schreck, C.J., III. Ch. 4: Impacts of Extreme Events on Human Health. The Impacts of Climate Change on Human Health in the United States: A Scientific Assessment. Washington, DC: U.S. Global Change Research Program; 2016.

Bernal, J.L., Cummins, S., Gasparrini, A., 2017. Interrupted time series regression for the evaluation of public health interventions: a tutorial. Int. J. Epidemiol. 46, 348–355.

Brown, L., Murray, V., 2014. Examining the relationship between infectious diseases and flooding in Europe. Disaster Health 1, 117–127.

Carlton, E.J., Liang, S., McDowell, J.Z., Li, H., Luo, W., Remais, J.V., 2012. Regional disparities in the burden of disease attributable to unsafe water and poor sanitation in China. Bull. World Health Organ. 90, 578–587.

Darvesh, N., Das, J.K., Vaivada, T., Gaffey, M.F., Rasanathan, K., Bhutta, Z.A., Social Determinants of Health Study, T, 2017. Water, sanitation and hygiene interventions for acute childhood diarrhea: a systematic review to provide estimates for the Lives Saved Tool. BMC Public Health 17, 776.

Ding, G.Y., Zhang, Y., Gao, L., Ma, W., Li, X.J., Liu, J., Liu, Q.Y., Jiang, B.F., 2013. Quantitative analysis of burden of infectious diarrhea associated with floods in northwest of Anhui Province, China: a mixed method evaluation. PLoS One 8, e65112.

Global Burden of Disease, 2018. Global Burden of Disease Study 2017 (GBD 2017) Results. Institute for Health Metrics and Evaluation (IHME), Seattle, United States.

Guha-Sapir, D., Hoyois, P., Wallemacq, P., Below, R., 2016. Annual Disaster Statistical Review 2016: The Numbers and Trends. Centre for Research on the Epidemiology of Disasters (CRED), Brussels, Belgium.

Harris, A.M., Chowdhury, F., Begum, Y.A., Khan, A.I., Faruque, A.S.G., Svennerholm, A.-M., Harris, J.B., Ryan, E.T., Cravioto, A., Calderwood, S.B., Qadri, F., 2008. Shifting prevalence of major diarrheal pathogens in patients seeking hospital care during floods in 1998, 2004, and 2007 in Dhaka, Bangladesh. Am. J. Trop. Med. Hyg. 79, 708–714.

Hashizume, M., Wagatsuma, Y., Faruque, A.S.G., Hayashi, T., Hunter, P.R., Armstrong, B., Sack, D.A., 2008. Factors determining vulnerability to diarrhoea during and after severe floods in Bangladesh. J. Water Health 6, 323–332.

Hirabayashi, Y., Mahendran, R., Koirala, S., Konoshima, L., Yamazaki, D., Watanabe, S., Kim, H., Kanae, S., 2013. Global flood risk under climate change. Nat. Clim. Chang. 3, 816.

Hodges, M., Belle, J.H., Carlton, E.J., Liang, S., Li, H., Luo, W., Freeman, M.C., Liu, Y., Gao, Y., Hess, J.J., Remais, J.V., 2014. Delays reducing waterborne and water-related infectious diseases in China under climate change. Nat. Clim. Chang. 4, 1109–1115.

IPCC, 2014. Human health: impacts, adaptation, and co-benefits. In: Field, C.B., Barros, V.R., Dokken, D.J., Mach, K.J., Mastrandrea, M.D., Bilir, T.E., Chatterjee, M., Ebi, K.L., Estrada, Y.O., Genova, R.C., Girma, B., Kissel, E.S., Levy, A.N., MacCracken, S., Mastrandrea, P.R., White, L.L. (Eds.), Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jimenez-Sastre, A., Boldo-Leon, X., Priego-Alvarez, H., Quevedo-Tejero, E., Zavala-Gonzalez, M.A., 2012. Geographic distribution of dengue fever cases in flooded zones from Villahermosa, Tabasco, in 2010. Rev. Chil. Infectol. 29, 32–36.

Joshi, P.C., Kaushal, S., Aribam, B.S., Khattri, P., D'Aoust, O., Singh, M.M., Marx, M., Guha-Sapir, D., 2011. Recurrent floods and prevalence of diarrhea among under five children: observations from Bahraich district, Uttar Pradesh, India. Glob. Health Action 4.

Kondo, H., Seo, N., Yasuda, T., Hasizume, M., Koido, Y., Ninomiya, N., Yamamoto, Y., 2002. Post-flood-infectious diseases in Mozambique. Prehosp. Disaster Med. 17, 126–133.

Levy, K., Woster, A.P., Goldstein, R.S., Carlton, E.J., 2016. Untangling the impacts of climate change on waterborne diseases: a systematic review of relationships between diarrheal diseases and temperature, rainfall, flooding, and drought. Environ. Sci. Technol. 50, 4905–4922.

Lim, S.S., Vos, T., Flaxman, A.D., Danaei, G., Shibuya, K., Adair-Rohani, H., Amann, M., Anderson, H.R., Andrews, K.G., Aryee, M., Atkinson, C., Bacchus, L.J., Bahalim, A.N., Balakrishnan, K., Balmes, J., Barker-Collo, S., Baxter, A., Bell, M.L., Blore, J.D., Blyth, F., Bonner, C., Borges, G., Bourne, R., Boussinesq, M., Brauer, M., Brooks, P., Bruce, N.G., Brunekreef, B., Bryan-Hancock, C., Bucello, C., Buchbinder, R., Bull, F., Burnett, R.T., Byers, T.E., Calabria, B., Carapetis, J., Carnahan, E., Chafe, Z., Charlson, F., Chen, H.L., Chen, J.S., Cheng, A.T.A., Child, J.C., Cohen, A., Colson, K.E., Cowie, B.C., Darby, S., Darling, S., Davis, A., Degenhardt, L., Dentener, F., Des Jarlais, D.C., Devries, K., Dherani, M., Ding, E.L., Dorsey, E.R., Driscoll, T., Edmond, K., Ali, S.E., Engell, R.E., Erwin, P.J., Fahimi, S., Falder, G., Farzadfar, F., Ferrari, A., Finucane, M.M., Flaxman, S., Fowkes, F.G.R., Freedman, G., Freeman, M.K., Gakidou, E., Ghosh, S., Giovannucci, E., Gmel, G., Graham, K., Grainger, R., Grant, B., Gunnell, D., Gutierrez, H.R., Hall, W., Hoek, H.W., Hogan, A., Hosgood, H.D., Hoy, D., Hu, H., Hubbell, B.J., Hutchings, S.J., Ibeanusi, S.E., Jacklyn, G.L., Jasrasaria, R., Jonas, J.B., Kan, H.D., Kanis, J.A., Kassebaum, N., Kawakami, N., Khang, Y.H., Khatibzadeh, S., Khoo, J.P., Kok, C., Laden, F., Lalloo, R., Lan, Q., Lathlean, T., Leasher, J.L., Leigh, J., Li, Y., Lin, J.K., Lipshultz, S.E., London, S., Lozano, R., Lu, Y., Mak, J., Malekzadeh, R., Mallinger, L., Marcenes, W., March, L., Marks, R., Martin, R., McGale, P., McGrath, J., Mehta, S., Mensah, G.A., Merriman, T.R., Micha, R., Michaud, C., Mishra, V., Hanafiah, K.M., Mokdad, A.A., Morawska, L., Mozaffarian, D., Murphy, T., Naghavi, M., Neal, B., Nelson, P.K., Nolla, J.M., Norman, R., Olives, C., Omer, S.B., Orchard, J., Osborne, R., Ostro, B., Page, A., Pandey, K.D., Parry, C.D.H., Passmore, E., Patra, J., Pearce, N., Pelizzari, P.M., Petzold, M., Phillips, M.R., Pope, D., Pope, C.A., Powles, J., Rao, M., Razavi, H., Rehfuess, E.A., Rehm, J.T., Ritz, B., Rivara, F.P., Roberts, T., Robinson, C., Rodriguez-Portales, J.A., Romieu, I., Room, R., Rosenfeld, L.C., Roy, A., Rushton, L., Salomon, J.A., Sampson, U., Sanchez-Riera, L., Sanman, E., Sapkota, A., Seedat, S., Shi, P.L., Shield, K., Shivakoti, R., Singh, G.M., Sleet, D.A., Smith, E., Smith, K.R., Stapelberg, N.J.C., Steenland, K., Stockl, H., Stovner, L.J., Straif, K., Straney, L., Thurston, G.D., Tran, J.H., Van Dingenen, R., van Donkelaar, A., Veerman, J.L., Vijayakumar, L., Weintraub, R., Weissman, M.M., White, R.A., Whiteford, H., Wiersma, S.T., Wilkinson, J.D., Williams, H.C., Williams, W., Wilson, N., Woolf, A.D., Yip, P., Zielinski, J.M., Lopez, A.D., Murray, C.J.L., Ezzati, M., 2012. A comparative risk assessment of burden of disease and injury attributable to 67 risk factors and risk factor clusters in 21 regions, 1990–2010: a systematic analysis for the Global Burden of Disease Study 2010. Lancet (London, England) 380, 2224–2260.

Liu, X., Liu, Z., Zhang, Y., Jiang, B., 2016a. Quantitative analysis of burden of bacillary dysentery associated with floods in Hunan, China. Sci. Total Environ. 547, 190–196.

Liu, Z.D., Li, J., Zhang, Y., Ding, G.Y., Xu, X., Gao, L., Liu, X.N., Liu, Q.Y., Jiang, B.F., 2016b. Distributed lag effects and vulnerable groups of floods on bacillary dysentery in Huaihua, China. Sci. Rep. 6, 29456.

Liu, Z., Zhang, F., Zhang, Y., Li, J., Liu, X., Ding, G., Zhang, C., Liu, Q., Jiang, B., 2018. Association between floods and infectious diarrhea and their effect modifiers in Hunan province, China: a two-stage model. Sci. Total Environ. 626, 630–637.

Lowe, D., Ebi, K.L., Forsberg, B., 2013. Factors increasing vulnerability to health effects before, during and after floods. Int. J. Environ. Res. Public Health 10, 7015–7067.

Marcheggiani, S., Puccinelli, C., Ciadamidaro, S., Della Bella, V., Carere, M., Francesca Blasi, M., Pacini, N., Funari, E., Mancini, L., 2010. Risks of water-borne disease outbreaks after extreme events. Toxicol. Environ. Chem. 92, 593–599.

Milojevic, A., Armstrong, B., Hashizume, M., McAllister, K., Faruque, A., Yunus, M., Kim Streatfield, P., Moji, K., Wilkinson, P., 2012. Health effects of flooding in rural Bangladesh. Epidemiology 23, 107–115.

Ministry of Water Resources of China, 2016. China Water and Drought Disaster Bulletin. (edˆeds. Beijing, China; 2016).

Phung, D., Guo, Y., Nguyen, H.T., Rutherford, S., Baum, S., Chu, C., 2016. High temperature and risk of hospitalizations, and effect modifying potential of socio-economic conditions: a multi-province study in the tropical Mekong Delta Region. Environ. Int. 92-93, 77–86.

Phung, D., Tran, P.D., Nguyen, L.H., Do, C.M., Rutherford, S., Chu, C., 2017. The impact of prevention and control of infectious disease law on diarrhoea control: a 5-year evaluation in multiple provinces in Vietnam. Health Policy Plan. 32, 1347–1353.

Reacher, M., McKenzie, K., Lane, C., Nichols, T., Kedge, I., Iversen, A., Hepple, P., Walter, T., Laxton, C., Simpson, J., 2004. Health impacts of flooding in Lewes: a comparison of reported gastrointestinal and other illness and mental health in flooded and non-flooded households. Commun. Dis. Public Health 7, 39–46.

Schnitzler, J., Benzler, J., Altmann, D., Mucke, I., Krause, G., 2007. Survey on the population's needs and the public health response during floods in Germany 2002. J.

Public Health Manag. Pract. 13, 461–464.

Schwartz, B.S., Harris, J.B., Khan, A.I., Larocque, R.C., Sack, D.A., Malek, M.A., Faruque, A.S., Qadri, F., Calderwood, S.B., Luby, S.P., Ryan, E.T., 2006. Diarrheal epidemics in Dhaka, Bangladesh, during three consecutive floods: 1988, 1998, and 2004. Am. J. Trop. Med. Hyg. 74, 1067–1073.

Soumerai, S.B., Starr, D., Majumdar, S.R., 2015. How do you know which health care effectiveness research you can trust? A guide to study design for the perplexed. Prev. Chronic Dis. 12, E101.

Troeger, C., Forouzanfar, M., Rao, P.C., Khalil, I., Brown, A., Reiner, R.C., Fullman, N., Thompson, R.L., Abajobir, A., Ahmed, M., Alemayohu, M.A., Alvis-Guzman, N., Amare, A.T., Antonio, C.A., Asayesh, H., Avokpaho, E., Awasthi, A., Bacha, U., Barac, A., Betsue, B.D., Beyene, A.S., Boneya, D.J., Malta, D.C., Dandona, L., Dandona, R., Dubey, M., Eshrati, B., Fitchett, J.R.A., Gebrehiwot, T.T., Hailu, G.B., Horino, M., Hotez, P.J., Jibat, T., Jonas, J.B., Kasaeian, A., Kissoon, N., Kotloff, K., Koyanagi, A., Kumar, G.A., Rai, R.K., Lal, A., El Razek, H.M.A., Mengistie, M.A., Moe, C., Patton, G., Platts-Mills, J.A., Qorbani, M., Ram, U., Roba, H.S., Sanabria, J., Sartorius, B., Sawhney, M., Shigematsu, M., Sreeramareddy, C., Swaminathan, S., Tedla, B.A., Jagiellonian, R.T.M., Ukwaja, K., Werdecker, A., Widdowson, M.A., Yonemoto, N., Zaki, M.E., Lim, S.S., Naghavi, M., Vos, T., Hay, S.I., Murray, C.J.L., Mokdad, A.H., 2017. Estimates of global, regional, and national morbidity, mortality, and aetiologies of diarrhoeal diseases: a systematic analysis for the Global Burden of Disease Study 2015. Lancet Infect. Dis. 17, 909–948.

Wade, T.J.; Sandhu, S.K.; Levy, D.; Lee, S.; LeChevallier, M.W.; Katz, L.; Colford, J.M., Jr. Did a severe flood in the Midwest cause an increase in the incidence of gastrointestinal symptoms? Am. J. Epidemiol. 2004;159:398–405.

Wagner, A.K., Soumerai, S.B., Zhang, F., Ross-Degnan, D., 2002. Segmented regression analysis of interrupted time series studies in medication use research. J. Clin. Pharm. Ther. 27, 299–309.

Wakuma Abaya, S., Mandere, N., Ewald, G., 2009. Floods and health in Gambella region, Ethiopia: a qualitative assessment of the strengths and weaknesses of coping mechanisms. Glob. Health Action 2.

WHO Regional Office for Europe, 2013. In: Menne, B., Murray, V. (Eds.), Floods in the WHO European Region: Health Effects and Their Prevention. WHO Regional Office for Europe, Copenhagen, Denmark.

World Health Organization, 2017. Diarrhoeal Disease Fact Sheets.

Zhang, F., Ding, G., Liu, Z., Zhang, C., Jiang, B., 2016a. Association between flood and the morbidity of bacillary dysentery in Zibo City, China: a symmetric bidirectional case-crossover study. Int. J. Biometeorol. 60, 1919–1924.

Zhang, F., Liu, Z., Gao, L., Zhang, C., Jiang, B., 2016b. Short-term impacts of floods on enteric infectious disease in Qingdao, China, 2005–2011. Epidemiol. Infect. 144, 3278–3287.