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Association of natural flood disasters with infectious diseases in 168 countries and territories from 1990 to 2019: A worldwide observational study

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ABSTRACT

Background: Natural flood disasters have a devastating effect on society, but the comprehensive assessment of their association with infectious diseases is lacking. We aimed to comprehensively assess the association of natural flood disasters with new cases and deaths of different infectious disease globally from 1990 to 2019, and provide scientific evidence for early warning and measures for the prevention and control of outbreaks and endemic of potential infectious disease following natural flood disasters.

Methods: We used data on natural flood disasters from international disaster database from 1990 to 2019. Data on infectious diseases were from the Global Burden of Disease Study 2019. Quasi-Poisson generalized linear models (quasi-Poisson GLM) were used to calculate the effects size, after controlling other confounders.

Results: From 1990 to 2019, natural flood disasters occurred on 47,368 cumulative days in 168 countries and territories, resulting in a total of 242,516 deaths and affecting 3.55 billion people. The duration of floods showed a trend of increase, with an average increased rate of 5.14% per year (Estimated annual percentage change [EAPC] =5.14%, 95% CI: 3.57%-7.16%; $p < 0.05$). The incidence rates of most infectious diseases showed decreasing trends in the past 30 years (all $p < 0.05$), except for dengue (with an EAPC of 1.06%, 95%CI: 0.90%-1.23%). In the multivariable models, increased number of new cases of acute hepatitis A, acute hepatitis E, dengue, malaria, measles, meningitis, typhoid and paratyphoid, tuberculosis, and upper respiratory infections were significantly correlated with the longer duration of floods (all $p < 0.05$). Increased lasting days of flooding were associated with increased number of deaths from lower respiratory tract infections (0.173%), measles (0.126%), typhoid and paratyphoid (0.043%), tetanus (0.245%), and tuberculosis (0.154%, all $p < 0.05$).

Conclusions: Natural flood disasters were associated with increased new cases and deaths of enteric infections, neglected tropical diseases, and respiratory infections. Concerted efforts should be made to design better strategies for adaptation to prevent and control the outbreak of floods-related infectious disease and reduce their impact on health and life.

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1. Introduction

Floods were the most prevalent events (44% percentage of occurrences) among all natural disasters, and the number of major floods doubled from 1389 events between 1980 and 1999 to 3254 events between 2000 and 2019. [1] Natural flood disasters affect more people than any other environmental hazard and hinder sustainable development, with serious health, social, and economic consequences. [2,3] A previous study showed that over 500,000 deaths occurred, and nearly 3 billion people were affected by floods during 1980–2009 across the world. [4] Moreover, it is shown that under current conditions, more people than previously known are exposed to flood risks, with 1.81 billion people directly exposed to 1-in-100-year floods. [5] In 2015, the Sendai Framework for Disaster Risk Reduction 2015-2030 was adopted at the third UN World Conference on Disaster Risk Reduction which highlighted that inability to understand and manage systemic risk was a challenge for the achievement of the Sendai Framework and the SDGs. [1] The UN Office for Disaster Risk Reduction (UNDRR) called for a substantial reduction in direct disaster losses as well as secondarily-associated infectious diseases, social and economic losses that the responsibility should be shared by the stakeholders.

Infectious diseases following natural flood disasters could occur as a result of the prolonged secondary effects of the disaster, mostly when there was an interruption of public health measures resulting from destruction of the local infrastructure, such as drinking water contamination, which is the most frequent concern from an infectious disease perspective. Many historical outbreaks of post-flood infectious diseases have been reported, including diarrhea, cholera, bacillary dysentery, dengue, malaria, and acute respiratory infection. [6–14] For example, the 1998 flood in Bangladesh ravaged approximately 60% of the land which had affected over 30 million people and increased rates of diarrheal illness were reported following the 1998 Bangladesh floods. [8,15] However, there are also some examples without any documented outbreaks of infectious disease when significant flooding and subsequent water system damage occurred. [16–18] Therefore, there were still gaps in studies on the association of natural flood disasters with infectious diseases, and a lack of quantified analysis of association between natural flood disasters and new cases and deaths of different infectious diseases still exist.

A better understanding of the risk of secondarily-associated infectious diseases is important to strengthen disaster risk governance, manage the risk, and enhance preparedness for effective response to prevent and control outbreaks of infectious diseases. However, the extent to which natural flood disasters are associated with new cases and deaths of different infectious diseases on a global scale during the past three decades is not well understood. In this study, we aimed to estimate the association of natural flood disasters with new cases and deaths of different infectious disease globally from 1990 to 2019. This study covers countries worldwide, contains data for a 30-year period, and provides a comprehensive view of the trends of natural flood disasters and their association with different kinds of infectious diseases in the three decades immediately preceding the COVID-19 pandemic.

2. Methods

2.1. Study design and data sources

This was a worldwide observational study which covered all the countries and territories that had reported natural flood disasters from 1990 to 2019. We used disaster-related data from the international disaster database (https://www.emdat.be/), namely the Emergency Events Database (EM-DAT). EM-DAT was launched with the initial support of the World Health Organization (WHO) and the Belgian Government by the Centre for Research on the Epidemiology of Disasters in 1988. The main objective of the database is to serve the purposes of humanitarian action at national and international levels and to rationalize decision-making for disaster preparedness, as well as provide an objective base for vulnerability assessment and priority setting. [19] EM-DAT contains essential core data on the occurrence and effects of different kinds of disasters in the world from 1900 to the present day, which is compiled from various sources, including UN agencies, non-governmental organizations, insurance companies, research institutes, and press agencies. [19] If the administrative boundary of the national unit was changed during the study period, the administrative boundary of 2022 was used. 36 out of 204 countries and territories that did not record any deaths or affected people from natural disasters caused by flooding from 1990 to 2019 were excluded in this study, yielded 168 countries and territories in the final analysis. Countries and territories included and excluded from the study were shown in the Appendix S1.1. The study did not involve any human participant and/or animal that no ethics approval or informed consent was needed.

2.2. Natural flood disasters

Flood was defined as the overflow of water from a stream channel onto normally dry land in the floodplain (riverine flooding), higher-than-normal levels along the coast and in lakes or reservoirs (coastal flooding), as well as ponding of water at or near the point where the rain fell (flash floods). [19] In the EM-DAT database, the natural flood disaster was one of the hydrological disasters (including flood, landslide, and wave action), which were defined as hazards caused by the occurrence, movement, and distribution of surface and subsurface freshwater and saltwater. According to the EM-DAT database, for a natural flood disaster to be entered into the database, at least one of the following criteria must be fulfilled: ten or more people reported killed, hundred or more people reported affected, declaration of a state of emergency, or call for international assistance. [19,20].

We used the following variables in the EM-DAT database, including country (countries in which the disaster has occurred), date (when the disaster occurred and ended), disaster type (flood disasters or not), duration (days the disaster lasted), death (number of people who lost their life because the event happened), affected (number of people who were injured, homeless, or required immediate assistance during a period of emergency, i.e., basic survival needs such as food, water, shelter, sanitation and immediate medical assistance).

2.3. Infectious diseases

We used data on infectious diseases from 1990 to 2019 by year and location from the Global Health Data Exchange Query tool (http://ghdx.healthdata.org/gbd-results-tool) of the Global Burden of Disease Study 2019 (2019 GBD study). [21,22] The 2019 GBD study provided data of disease burden of 369 diseases and injuries in 204 countries and territories from 1990 to 2019. Specific methods of GBD study 2019 estimation process for the incidence of infectious diseases were described elsewhere. [22] Briefly, the 2019 GBD study modeled infectious diseases burden using DisMod-MR version 2.1, a Bayesian meta-regression tool that uses a compartmental model structure with a series of differential equations that synthesize sparse and heterogeneous epidemiologic data for infectious diseases. Data of the GBD study has been widely used to explore the association between exposures and health outcomes globally. [23].

According to the previous literature on potential infectious diseases following natural disasters, we selected four major categories of infectious disease (level 2 causes), including enteric infections, HIV/AIDS and sexually transmitted infections, neglected tropical diseases and malaria, and respiratory infections and tuberculosis, and 13 specific infectious diseases (level 3 causes), including acute hepatitis A, acute hepatitis E, dengue, diarrheal diseases, leishmaniasis, lower respiratory infections, malaria, measles, meningitis, tetanus, tuberculosis, typhoid and paratyphoid, and upper respiratory infections from the 2019 GBD study database in this study. [10,24] Yearly new cases, new deaths, incidence rate and mortality rate of the selected infectious disease were obtained from the Global Health Data Exchange Query tool. Appendix S1.2 showed the infectious diseases included in the study.

2.4. Covariates

We used data of socio-economic characteristics, socio-demographic characteristics, and health resources as covariates. The human development index (HDI), a composite socio-economic indicator of life expectancy, income and education level to reflect socio-economic status level in different countries and territories, was extracted from the UN open database (http://data. Un.org/Default.aspx). The number of populations, population density, gross domestic product (GDP), the number of beds per thousand population were extracted from the World Bank (https://data.Worldbank.org/indicator). The share of people who have access to safe drinking water and the share of the population with access to handwashing facilities were from WHO/UNICEF Joint Monitoring Programme (https://washdata.org/data). The socio-demographic index (SDI), a composite indicator of income per capita, average years of schooling for those aged 15 and above, and total fertility rate under the age of 25, was also extracted from the GBD study database. [25].

2.5. Statistical analysis

In the descriptive analysis, given the difference in population size and the fluctuation of population size in different years and countries, we calculated the rates of people affected by flood per 100,000 people (PAF) and the rates of death by flood per 100,000 people (PDF) by using the number of deaths caused by natural flood disasters, the total number of people affected by natural flood disasters and the total number of populations of each country in each year. The PAF and PDF rate were calculated by dividing the number of people affected by the population size in the calendar year (and expressed as a rate per 1000).

To reflect the trends of rates, we calculated the estimated annual percentage change (EAPC), a summary and widely used indicator to show the trend and annual change over a specified time interval. [25,26] A regression line was fitted to the natural logarithm of rates using the formula $y = \alpha + \beta x + \varepsilon$, where y refers to ln (rates) and x refers to calendar year. EAPC was calculated as $100 \times (e^{\beta} - 1)$ and its 95% confidence intervals (CIs) were also calculated to assess the temporal trend of the rates. If the EAPC estimation and its 95% CIs were both >0 (or both <0), the rates were deemed to be in an increasing trend (or a decreasing trend) in the given time interval. We calculated incidence rate and mortality rate of infectious diseases in 168 countries using the formula $Rates = \frac{\sum_{i=1}^{168} cases\ or\ deaths}{\sum_{i=1}^{168} population} \times 100,000$ in each year.

In the multivariable regression analysis, we used the quasi-Poisson generalized linear model (quasi-Poisson GLM) [27] to calculate the effects of flooding on new cases and deaths of infectious diseases after controlling for potential confounders, and considered the overdispersion trend of data on new cases and deaths. The quasi-Poisson GLM is the most common way to deal with overdispersion for counts. [28] For a quasi-Poisson GLM, the variance is a linear function of the mean, and weights are directly proportional to the mean. [28] The formula was as follows: $\log(Y(t)) = \alpha + \log(\text{offset}(\text{Population})) + \beta_1 \text{Duration}_{ij} + \beta_2 \text{PDF} + \beta_3 \text{PAF} + \text{Country}_j + \text{HDI} + \text{SDW} + \text{HF} + \text{Beds}$, where Y(t) refers to the expected number of new case or deaths on day t, and an offset for population in a specific year was included in the model to interpret the results in terms of the infectious diseases in the specific country. Moreover, α refers to the intercept; β refers to the regression coefficient; Duration refers to days of flood duration in the year i of country j; PDF refers to flood deaths per 100,000 people in the year i of country j; PAF represents the number of people affected by floods per 100,000 people in the year i of country j; Country_j represents the categorical variable of the country j; HDI refers to the human development index in the year i of country j; SDW refers to the share of people have access to safe drinking water in the year i of country j; HF refers to the share of the population with access to handwashing facilities in the year i of country j; Beds refers to the number of beds per thousand population in the year i of country j. Effect size were indicated as a percentage change (%) in the number of cases (new cases or new deaths) caused by each 1 unit change in duration, PDF and PAF. To examine the robustness of our results, we used the data of infectious diseases from all 204 countries and territories, instead of 168 countries and territories, to fit the model in the sensitivity analyses. Moreover, we controlled for SDI in the multivariable regression models instead of HDI to assess the stability of the results.

All analyses were performed using R software (version 4.0.4). All tests were two-sided, and a value $P < 0.05$ was considered statistically significant.

3. Results

3.1. Natural flood disasters

From 1990 to 2019, natural flood disasters occurred on 47,368 cumulative days in 168 countries and territories, resulting in a total of 242,516 deaths and affecting 3.55 billion people (Table 1). The PDF was 0.13 per 100,000 people and PAF was 1835.49 per 100,000 people in the past 30 years. The duration of floods showed a trend of steady increase, rising at an average rate of 5.14% per year (EAPC=5.14%, 95% CI: 3.57%-7.16%; $p < 0.05$). However, the number of deaths, the number of people affected by floods, PDF, and PAF all showed decreasing trends, with EAPC of −0.79%, −3.05%, −2.00% and −4.13%, respectively ($p < 0.05$). The trends of the number of deaths, the number of people affected by floods, PDF, and PAF over time in 168 countries at the global level and at country and territory level from 1990 to 2019 were shown in Appendix S2.1-S2.2.

The spatial and temporal distribution of total deaths and the number of people affected by floods differed in 168 countries and territories between 1990 and 2019, as shown in Appendix S2.1-S2.2. During 1990-2019, Venezuela, India and China had the largest total number of flood-related deaths, with Venezuela having the highest PDF (5.79 per 100,000 people), followed by Bhutan (1.57 per 100,000 people) and Tajikistan (1.47 per 100,000 people). China, India and Bangladesh were the top three countries with the largest number of people affected by floods, with PAF highest (5,622.73 per 100,000 people) in China, followed by Cambodia (4,025.36 per 100,000 people) and Bangladesh (3,839.13 per 100,000 people). From 1990 to 2019, PDFs increased the most in Nigeria, Serbia, and Niger, with EAPC of 10.94% (95% CI: 2.81%-19.72%), 10.84% (95% CI:

Table 1
The total number of people affected by flood and EAPC of the impacts of natural flood disasters in 168 countries from 1990 to 2019.

Variables	1990	2019	1990-2019	EAPC (%, 95%CI)
Duration of flood (days)	379	2141	47,368	5.14 (3.57 to 7.16)
Number of deaths	2636	5935	242,516	−0.79 (−2.80 to 1.27)
Number of people affected	57,295,645	58,909,822	3,546,956,531	−3.05 (−5.53 to −0.51)
PDF (per 100,000 people)	0.05	0.08	0.13	−2.00 (−3.82 to −0.14)
PAF (per 100,000 people)	1093.56	771.10	1835.49	−4.13 (−6.53 to −1.66)

Notes: PAF, rates of people affected by flood per 100,000 people; PDF, rates of death by flood per 100,000 people; EAPC, estimated annual percentage change; CI, confidence interval.

5.52%-16.42%), and 10.48% (95% CI: 5.18%-16.04%), respectively (all $p < 0.05$). PAFs had the fastest growth in Niger, Nigeria and Angola, with EAPC of 50.73% (95% CI: 28.88%- 76.28%), 44.00% (95% CI: 20.65%-71.86%) and 37.63% (95% CI: 15.53%-63.96%), respectively (all $p < 0.05$).

3.2. New cases and deaths of infectious diseases

Trends of global cases of four major categories and 13 specific infectious diseases from 1990 to 2019 were shown in Appendix S3.1-S3.17. The changes in the number of new cases and incidence rates of four major categories and 13 specific infectious diseases between 1990 and 2019 were shown in Appendix Table S3. As for four major categories of infectious diseases, the new cases of enteric infections, neglected tropical diseases and malaria, and respiratory infections showed increased trends from 1990 to 2019, with EAPC all above 0 ($p < 0.05$), while the incidence rates of these diseases showed decreasing trends from 1990 to 2019, with EAPC all below 0 ($p < 0.05$). In terms of the specific infectious diseases, the number of new cases of acute hepatitis A, acute hepatitis E, dengue, lower and upper respiratory infections increased, while the number of new cases of leishmania, malaria, measles, meningitis and tuberculosis decreased in the past 30 years (all $p < 0.05$). The incidence rates of most infectious diseases showed decreasing trends in the past 30 years (all $p < 0.05$), except for dengue (with an EAPC of 1.06%, 95% CI: 0.90%-1.23%). Changes in the numbers of new cases and incidence rates of infectious diseases from 1990 to 2019 in 168 countries were shown in the Fig. 1. Changes in the numbers of new cases and incidence rates in each country from 1990 to 2019 were shown in Appendix S3.18-S3.30.

Trends of global deaths of four major categories and 13 specific infectious diseases from 1990 to 2019 were shown in Appendix S3.1-S3.17. The changes in the number of deaths and mortality rates of four major categories and 13 specific infectious diseases

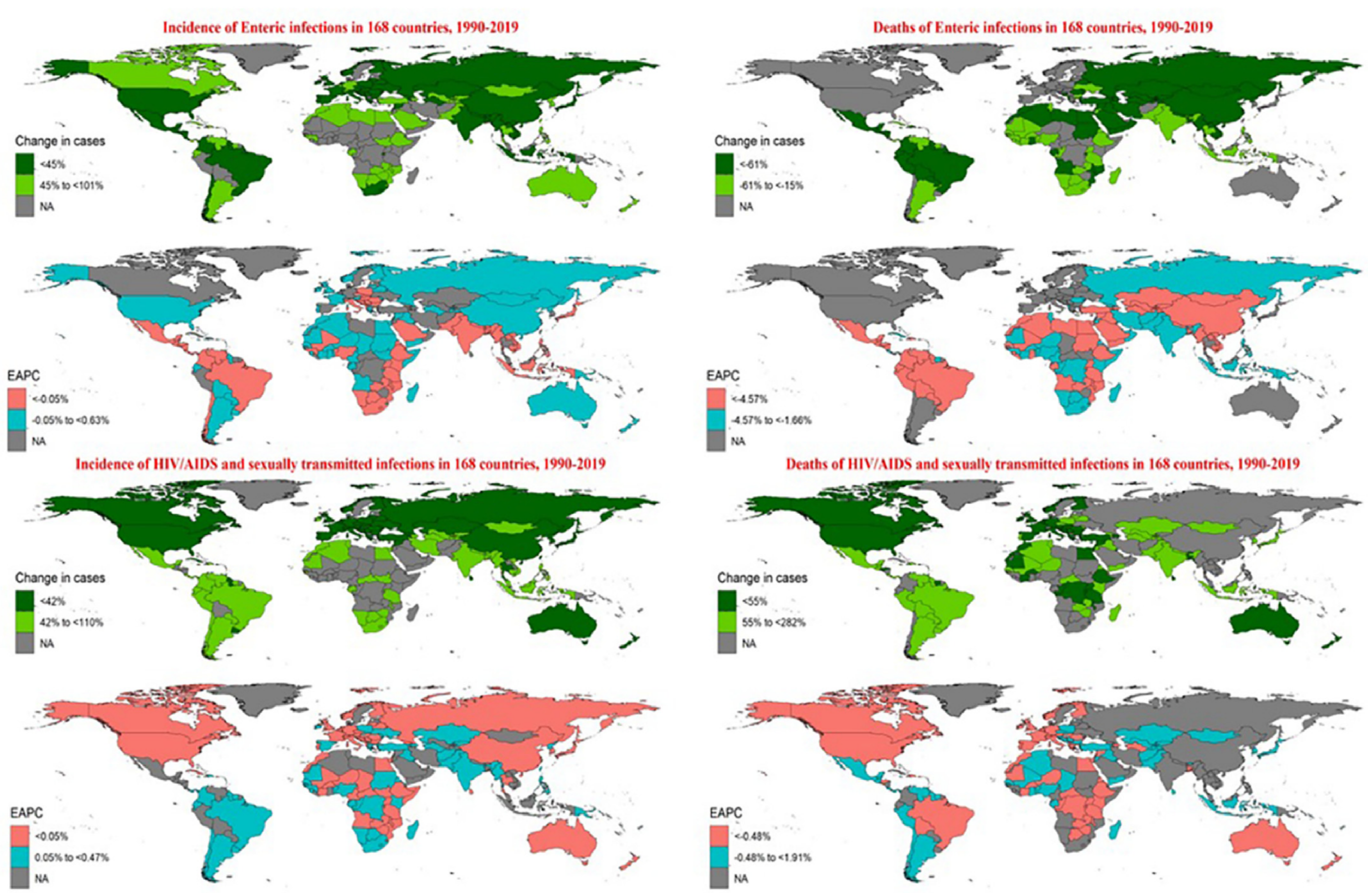

Fig. 1. Changes in the numbers and EAPC of new cases and deaths for four categories of infectious diseases in 168 countries, 1990-2019. HIV/AIDS, human immunodeficiency virus/ Acquired Immune Deficiency Syndrome; EAPC, estimated annual percentage change.

between 1990 and 2019 were shown in Appendix Table S4. As for four major categories of infectious diseases, the number of deaths and mortality rates of enteric infections, neglected tropical diseases and malaria, and respiratory infections all showed decreasing trends from 1990 to 2019, with EAPC below 0 (all $p < 0.05$). In terms of the 13 specific infectious diseases, the number of deaths all showed decreasing trends during the past 30 years, except for dengue showing an increased trend with EAPC of 0.28% (95% CI: 0.06%-0.48%). The mortality rates of all the 13 specific infectious diseases showed decreasing trends in the past 30 years (EAPC ranged from to −0.14% to −9.25%, all $p < 0.05$). Changes in the numbers of deaths and mortality rates of infectious diseases from 1990 to 2019 in 168 countries were shown in the Fig. 2. Changes in the numbers of deaths and mortality rates in each country from 1990 to 2019 were shown in Appendix S4.1.

The correlation between EAPC of incidence and deaths of infectious diseases and HDI in 2019 at the country and territorial levels was shown in the Figs. 3–4 and Appendix S5. There was a positive correlation between EAPC of incidence and HDI among all the four major categories of infectious diseases (ρ ranged from 0.19 to 0.55, all $p < 0.05$), suggesting that these infectious diseases increased faster in countries with higher levels of HDI from 1990 to 2019. However, EAPC of incidence was negatively correlated with HDI in hepatitis A (ρ = −0.19, p=0.02) and tuberculosis (ρ = −0.35, $p < 0.001$), suggesting that these diseases increased faster in countries with lower levels of HDI from 1990 to 2019. EAPC of deaths and HDI were positively correlated in diarrhea disease (ρ = 0.36, $p = 0.017$) and measles (ρ = 0.18, $p = 0.03$), while negatively correlated in acute hepatitis A (ρ = 0.20, $p = 0.02$), meningitis (ρ = 0.42, $p < 0.001$) and tuberculosis (ρ = 0.46, $p < 0.001$).

3.3. Association of natural flood disasters with new cases of infectious diseases

The associations of flood duration, PDF, and PAF with new cases of infectious diseases by multivariable quasi-Poisson GLM regression models were shown in the Table 2. The multivariable quasi-Poisson GLM regression models showed when the duration of natural flood disasters increased by one day, the number of new cases of neglected tropical diseases and malaria, and respiratory infections and tuberculosis would increase by 0.042% (95% CI: 0.024%-0.060%) and 0.010% (95% CI: 0.004%-0.017%), respectively. Increased number of new cases of acute hepatitis A, acute hepatitis E, dengue, malaria, measles, meningitis, tuberculosis, typhoid and paratyphoid, and upper respiratory infections were significantly correlated with the longer duration of floods (all $p < 0.05$). Each unit increase in PDF was associated with a 0.001% (95% CI: 0.0007%-

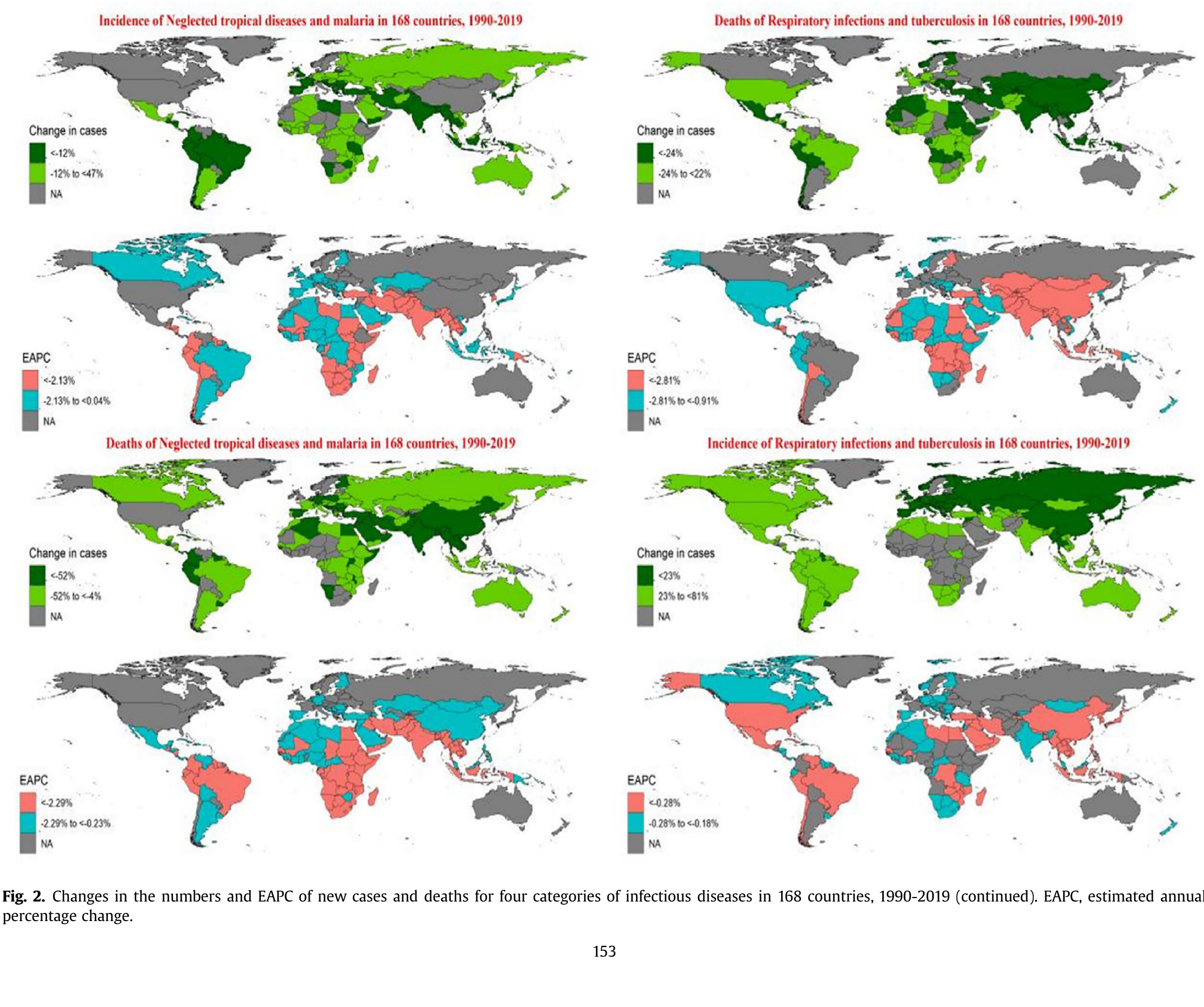

Fig. 2. Changes in the numbers and EAPC of new cases and deaths for four categories of infectious diseases in 168 countries, 1990-2019 (continued). EAPC, estimated annual percentage change.

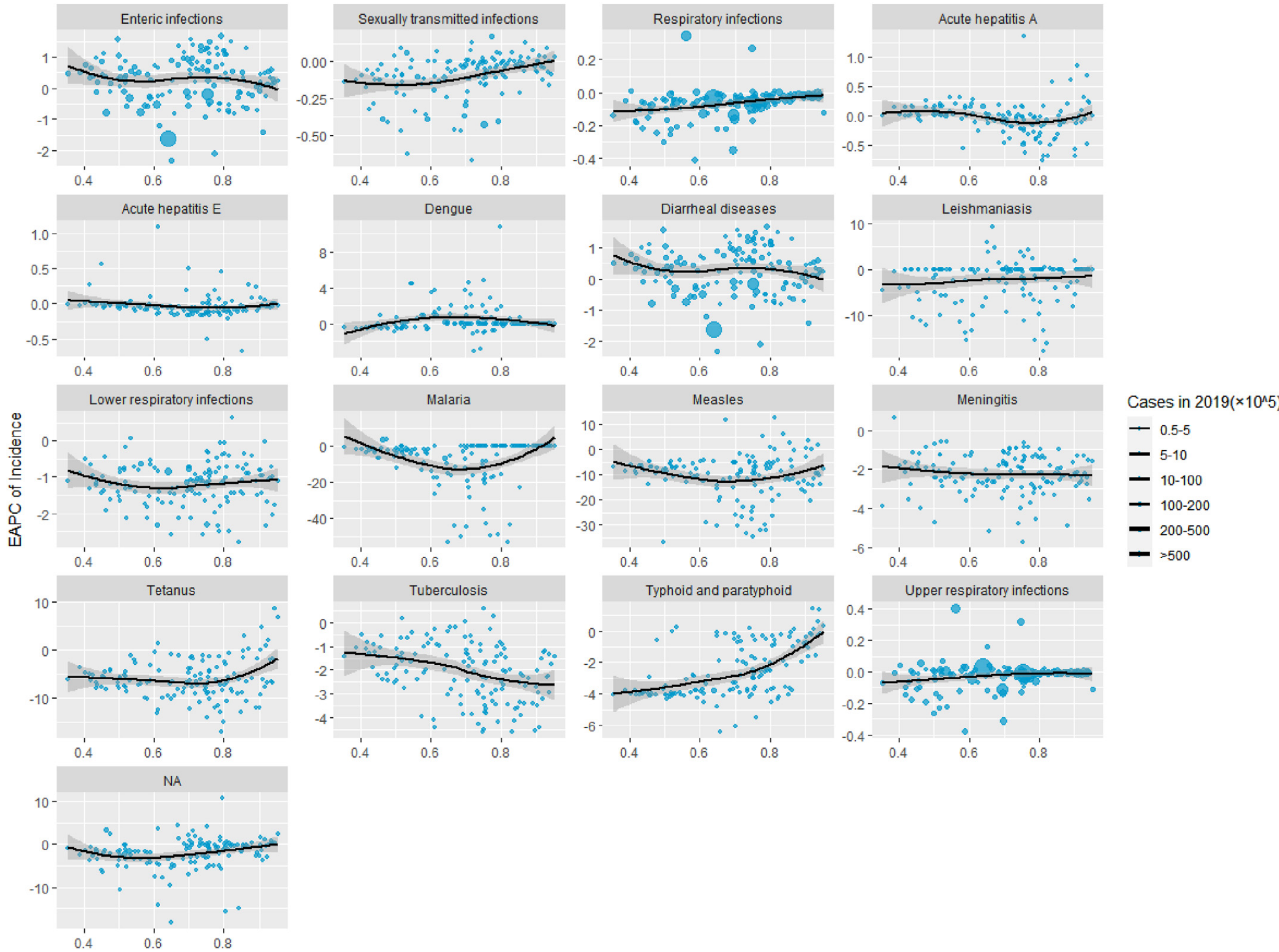

Fig. 3. Correlation between EAPC of incidence of infectious diseases and HDI in 2019 at the country and territorial levels.
Notes: The circles represent countries that were available on HDI data. The size of circle is increased with the cases of infectious.

0.0014%) increase in the number of new cases of enteric infections. To be specific, increased in PDF was associated with higher number of new cases of acute hepatitis A, acute hepatitis E, diarrheal diseases, and malaria (all $p < 0.05$). Each unit increase in PAF was associated with a 0.030% (95% CI: 0.024%-0.035%) increased number of new cases of neglected tropical diseases, and with a 0.028% (95% CI: 0.022%-0.035%) increase in malaria. The results were stable in the sensitivity analysis.

3.4. *Association of natural flood disasters with deaths of infectious diseases*

In the multivariable quasi-Poisson GLM regression models, each unit increase in duration, PDF and PAF of natural flood disasters was associated with 0.098% (95% CI: 0.055%-0.140%), 0.0008% (95% CI: 0.00009%-0.0015%) and 0.020% (95% CI: 0.0003%-0.039%) increase in the number of new deaths from respiratory infections and tuberculosis, respectively (Table 3). As for specific infectious diseases, increased lasting days of flooding were associated with increased number of deaths from lower respiratory tract infections (0.173%), measles (0.126%), typhoid and paratyphoid (0.043%), tetanus (0.245%), and tuberculosis (0.154%, all $p < 0.05$). Increased PDF was associated with increased numbers of deaths from lower respiratory infections (0.002%) and measles (0.0013%) in the multivariable models (all $p < 0.05$). The results were stable in the sensitivity analysis.

4. Discussion

To the best of our knowledge, this was the first study that estimated the association between natural flood disasters and the new cases and deaths of different infectious disease among 168 countries globally from 1990 to 2019, which provided a comprehensive view on the trends of natural flood disasters and their association with different kinds of infectious diseases in the past three decades immediately preceding the COVID-19 pandemic. We found that natural flood disasters were associated with increased new cases and deaths of enteric infections, neglected tropical diseases, and respiratory infections in this study. One possible explanation is that natural flood disasters might lead to infectious disease outbreaks because of substantial population displacement and exacerbate synergic risk factors (change in the environment, in human conditions and in the vulnerability to existing pathogens) for disease transmission after natural flood disasters. [11] Our finding could provide scientific evidence for early warning and making measures for the prevention and control of outbreaks and endemic of

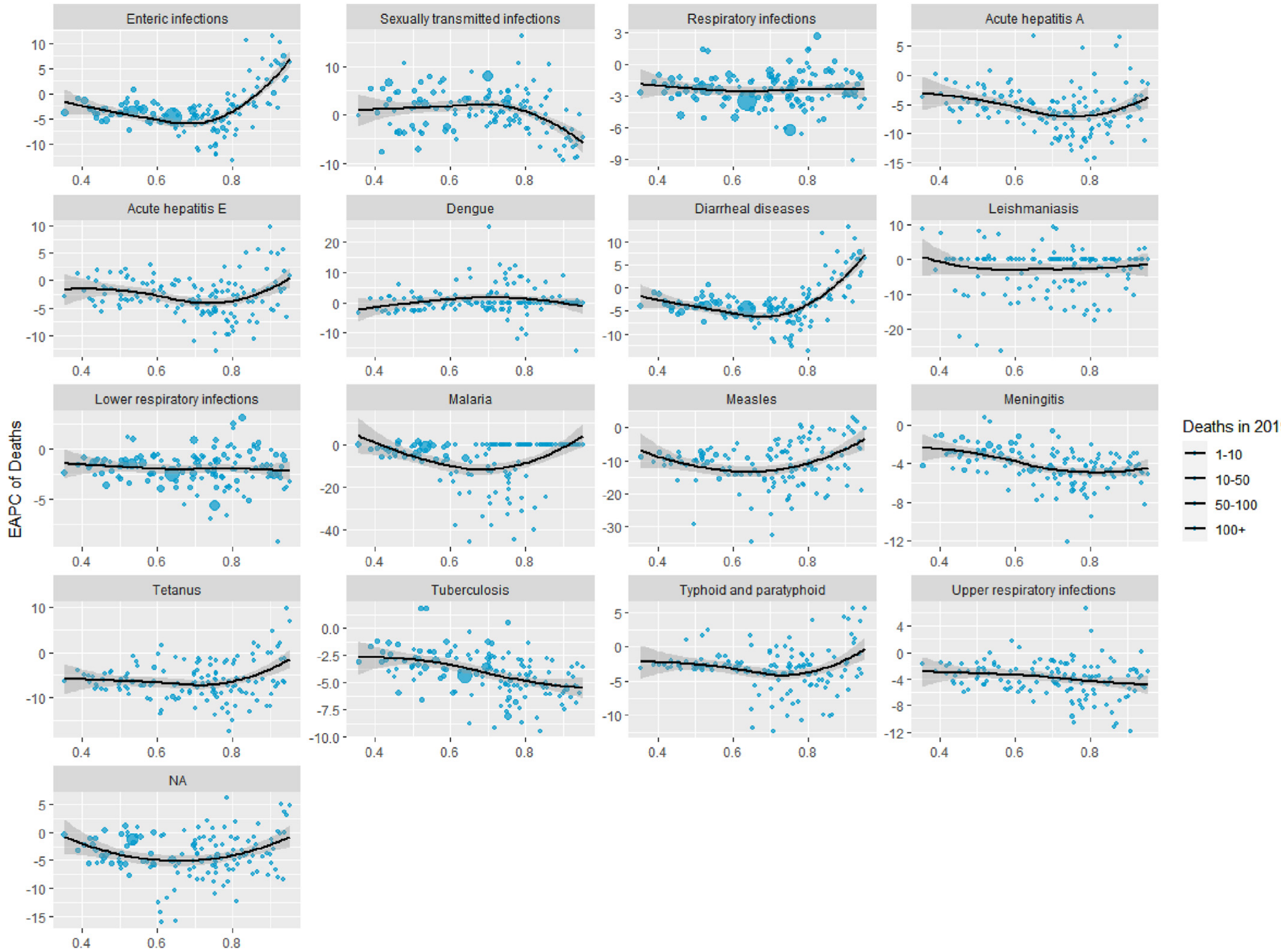

Fig. 4. Correlation between EAPC of deaths of infectious diseases and HDI in 2019 at the country and territorial levels.
Notes: The circles represent countries that were available on HDI data. The size of circle is increased with the cases of infectious.

potential infectious disease following natural flood disasters.

We found that natural flood disasters occurred on 47,368 cumulative days in 168 countries and territories, resulting in a total of 242,516 deaths and affecting 3.55 billion people from 1990 to 2019. A large proportion of population could be affected by the natural flood disasters, leading to injured, homelessness, or even deaths. Immediate assistance is required to meet the basic survival needs (such as food, water, shelter, sanitation and immediate medical assistance) in emergencies. Although the number of deaths, people affected by floods, PDF, and PAF had declined during the past three decades because of advances in medical technology and improvement of emergency medical rescue resources, the duration of floods still continued to rise, which might be related to accelerated global warming. [29] As is widely recognized that global warming is exacerbated by excessive land use, air pollution, and other human behaviors that destroy the natural environment. We found that China had the highest number of people affected by floods, which was consistent with previous studies. [30] Floods are among the most frequent natural disasters in China. [30] For example, a serious natural flood disaster unfortunately threatened the lives and homes of people in 27 out of 31 provinces across central and southern China in July 2020 and authorities in China issued alerts for heavy rainfall for 41 consecutive days. [31] Moreover, the compound events of natural disasters and pandemic occurred during the COVID-19 pandemic demonstrated the vulnerability of healthcare systems worldwide. 339 people died in the urban flood occurring in Zhengzhou, China on July 20, 2021, with a 1 h rainfall of 202 mm. [32] For the management of urban floods, road connectivity will decline more dramatically as rainfall increases, thus more adaptive traffic management is required to address such storms in the case area. [33] Besides, better levees, enlarged reservoirs, improved early-warning systems and disaster risk analysis could guide strategies for managing disasters. [34].

In the present study, the incidence rates of most infectious diseases showed decreasing trends in the past 30 years, except for dengue with an EAPC of 1.06%, which was in line with the results of previous studies. [35] Dengue, as a neglected tropical disease, is the most common mosquito-borne viral disease and has brought a heavy socioeconomic burden globally. [36,37] To reduce the disease burden of dengue, WHO put forward the global strategy for dengue prevention and control 2012–2020. [37] Given the increased incidence of dengue, more efforts focusing on dengue need to be carried out to achieve the goal of dengue elimination. The main prevention and control strategy of dengue infection is vector control currently. [38] Some studies recently reported that existing control measures were ineffective at curbing the increasing global trends on the incidence of dengue. Comprehensive combined prevention and control measures and promotion on vaccination

Table 2
Association between natura flood disasters and new cases of infectious diseases estimated changes with 95% confidence intervals in cases percentage change (%) associated with each 1 unit increase in duration, PDF and PAF among 168 countries, 1990-2019.

Causes	Duration (%, 95%CI)	PDF (%, 95%CI)	PAF (%, 95%CI)
Major categories of infectious diseases (level 2 causes)			
Enteric infections	0.006 (-0.003 to 0.015)	0.001* (0.0007 to 0.0014)	−0.005 (-0.013 to 0.004)
HIV/AIDS and sexually transmitted infections	0.023 (-0.012 to 0.033)	0.0004 (-0.0001 to 0.0007)	−0.005 (-0.013 to 0.002)
Neglected tropical diseases and malaria	0.042* (0.024 to 0.060)	0.0003 (-0.0002 to 0.0008)	0.030* (0.024 to 0.035)
Respiratory infections and tuberculosis	0.010* (0.004 to 0.017)	0.0002 (-0.00003 to 0.0004)	−0.003 (-0.011 to 0.005)
Specific infectious diseases (level 3 causes)			
Acute hepatitis A	0.010* (0.002 to 0.019)	0.0004* (0.0001 to 0.0006)	−0.004 (-0.009 to 0.002)
Acute hepatitis E	0.020* (0.012 to 0.027)	0.0003* (0.0002 to 0.0006)	−0.005 (-0.012 to 0.003)
Dengue	0.0098* (0.0007 to 0.0190)	0.0002 (-0.0003 to 0.0006)	−0.363 (-1.889 to 1.186
Diarrheal diseases	0.0062 (-0.0030 to 0.0154)	0.001* (0.0007 to 0.0014)	−0.0047 (-0.0134 to 0.0040)
Leishmaniasis	0.0353 (-0.0097 to 0.0803)	−0.0013 (0.0022 to −0.0003)	0.0003 (-0.0730 to 0.0736)
Lower respiratory infections	−0.0024 (-0.0091 to 0.0043)	0.0001 (-0.0002 to 0.0004)	0.0006 (-0.0060 to 0.0063)
Malaria	0.080* (0.050 to 0.110)	0.0008* (0.00009 to 0.00157)	0.028* (0.022 to 0.035)
Measles	0.145* (0.111 to 0.179)	−0.003 (-0.004 to 0.001)	0.043 (-0.072 to 0.158)
Meningitis	0.035* (0.021 to 0.049)	0.000 (-0.0005 to 0.0005)	−0.002 (-0.012 to 0.007)
Tetanus	0.102 (— to —)	0.002 (-94.272 to 1645.724)	−2.328 (— to —)
Tuberculosis	0.020* (0.011 to 0.030)	−0.0002 (-0.0006 to 0.0002)	−0.007 (-0.025 to 0.010)
Typhoid and paratyphoid	0.011* (0.007 to 0.016)	−0.0001 (-0.0002 to 0.0001)	0.0001 (-0.145 to 0.146)
Upper respiratory infections	0.012* (0.005 to 0.019)	0.0002 (-0.00005 to 0.00037)	−0.003 (-0.011 to 0.005)

Notes: PDF, rates of death by flood per 100,000 people; PAF, rates of people affected by flood per 100,000 people; CI, confidence interval; "—" indicates that the value is an outlier. The models were adjusted for population, year, country, duration, human development index (HDI), share of people have access to safe drinking water, share of the population with access to handwashing facilities, and the number of beds per thousand population. *$p < 0.05$.

strategies are crucial for this disease. [39,40].

When examined the association of natural flood disasters with new cases of infectious diseases, we found that increased number of new cases of acute hepatitis A, acute hepatitis E, dengue, malaria, measles, meningitis, tuberculosis, typhoid and paratyphoid, and upper respiratory infections were significantly correlated with the longer duration of floods. The similar correlation of floods and these infectious diseases had been reported in previous studies. [41–48] One possible explanation is that infection by enteric infections and neglected tropical diseases can be caused by poor access to clean water and sanitation after the disasters. [11,49] Another possible explanation is that individuals are more prone to be exposed to vectors that insect bites and stings are also frequently observed because of the damage of floods on forests and plants. [11] Therefore, adequate supplies of water per person for drinking, bathing, washing and for excreta disposal, as well as management of solid wastes, are of vital importance in preventing outbreaks of diarrheal diseases and other vector-borne diseases.

It was worth noting that malaria was all significantly associated with the duration, PDF and PAF of floods. Malaria is still a public health threat for people living in malaria-endemic areas, especially for children under 5. [25] Standing water caused by natural flood disasters creates a breeding site for mosquitoes; and overcrowded conditions and temporary shelter might increase mosquito bite frequencies thus promoting the transmission cycle. [11] Given that malaria is preventable and curable and has an obvious relationship with floods, malaria should be paid more attention to avoid being infected following natural flood disasters. Vector control, such as insecticide-treated mosquito nets and specifically long-lasting insecticide-impregnated nets, could effectively reduce malaria transmission at the community level. [25].

In this study, we found that each unit increase in the duration, PDF and PAF of natural flood disasters was associated with 0.098%, 0.0008% and 0.020% increase in the number of new deaths from respiratory infections, respectively. As for specific infectious diseases, increased lasting days of flooding were associated with an increased number of deaths from lower respiratory tract infections (0.173%), measles (0.126%), typhoid and paratyphoid (0.043%), tetanus (0.245%), and tuberculosis (0.154%). Although natural flood disasters do not directly transmit infectious diseases and the primary cause of death in the aftermath of a natural flood disaster is noninfectious, [11] infectious diseases have been reported as important causes of morbidity among flood-afflicted individuals. [45] Lower respiratory infections are well-known as a leading cause of morbidity and mortality around the world. [50] Although substantial progress has been found in the reduction of lower respiratory infection burden, the progress was not equal across countries and territories. [50] The results of our study suggested that emergency medical rescue and timely treatment of infectious diseases should be strengthened to reduce the deaths caused by infectious diseases after floods, especially for lower respiratory tract infections.

Table 3
Association between natural flood disasters and deaths of infectious diseases estimated changes with 95% confidence intervals in deaths percentage change (%) associated with each 1 unit increase in duration, PDF and PAF among 168 countries, 1990-2019.

Causes	Duration (%, 95%CI)	PDF (%, 95%CI)	PAF (%, 95%CI)
Major categories of infectious diseases (level 2 causes)			
Enteric infections	−0.016 (-0.048 to 0.015)	−0.0002 (-0.0009 to 0.0005)	0.007 (-0.006 to 0.020)
HIV/AIDS and sexually transmitted infections	0.0001 (-0.035 to 0.035)	0 (-0.0006 to 0.0006)	0.002 (-0.011 to 0.015)
Neglected tropical diseases and malaria	−0.011 (-0.041 to 0.018)	−0.0001 (-0.0007 to 0.0006)	0.007 (-0.006 to 0.020)
Respiratory infections and tuberculosis	0.098* (0.055 to 0.140)	0.0008* (0.00009 to 0.0015)	0.020* (0.0003 to 0.039)
Specific infectious diseases (level 3 causes)			
Acute hepatitis A	0.017 (-0.021 to 0.055)	−0.0003 (-0.0012 to 0.0005)	0.005 (-0.019 to 0.029)
Acute hepatitis E	0.018 (-0.016 to 0.052)	0 (-0.0007 to 0.0007)	0.005 (-0.005 to 0.014)
Dengue	0.02 (-0.009 to 0.049)	−0.0001 (-0.0008 to 0.0005)	0.004 (-0.007 to 0.014)
Diarrheal diseases	0.025 (-0.001 to 0.050)	−0.0003 (-0.0008 to 0.0003)	−0.008 (-0.033 to 0.017)
Leishmaniasis	0.025 (-21.689 to 27.760)	0.0003 (-0.551 to 0.555)	−0.401 (-99.999 to 0.000097)
Lower respiratory infections	0.173* (0.117 to 0.228)	0.002* (0.0005 to 0.0026)	−0.021 (-0.154 to 0.112)
Malaria	−0.011 (-0.056 to 0.034)	−0.0005 (-0.0016 to 0.0007)	0.004 (-0.005 to 0.014)
Measles	0.126* (0.072 to 0.181)	0.0013* (0.0005 to 0.0021)	0.020 (-0.002 to 0.041)
Meningitis	0.127 (— to —)	0.002 (-85.472 to 588.374)	−2.881 (— to —)
Tetanus	0.245* (0.159 to 0.330)	−0.0002 (-0.0032 to 0.0003)	0.001 (-0.016 to 0.019)
Tuberculosis	0.154* (0.076 to 0.231)	−0.011 (-0.014 to 0.009)	0.043 (-0.036 to 0.123)
Typhoid and paratyphoid	0.043* (0.013 to 0.072)	−0.0005 (-0.0012 to 0.0002)	0.033 (-0.241 to 0.307)
Upper respiratory infections	0.034 (-0.050 to 0.118)	−0.0002 (-0.0004 to 0.0028)	0.015 (-0.220 to 0.250)

Notes: PDF, rates of death by flood per 100,000 people; PAF, rates of people affected by flood per 100,000 people; CI, confidence interval; "—" indicates that the value is an outlier. The models were adjusted for population, year, country, duration, human development index (HDI), share of people have access to safe drinking water, share of the population with access to handwashing facilities, and the number of beds per thousand population. *$p < 0.05$.

This study had several limitations. First, this is an ecological study by linking aggregated data on new cases and deaths of infectious diseases as well as natural flood disasters that might cause ecological fallacies in this study. Nevertheless, our findings could provide important clues for conducting further studies based on individual data as well as early warning of preparedness and response of potential outbreak of infectious disease following natural flood disasters in the future. Second, other potential confounders (such as individual behavior, history of diseases, history of vaccinations, implementation of rescue and treatment measures) could not be included in the multivariable models. Third, limitations of using the GBD database are not avoidable. We could not do further analysis (such as seasonal analysis) because only yearly data was available on the new cases and deaths of infectious diseases globally; when the original data are sparse or missing, the burden of disease was estimated by the models, which may have affected the accuracy of the morbidity and mortality in these areas; [22] and we were not able to analyze differences at the sub-national level, which may affect the interpretation of the results in countries with uneven development in terms of resource allocation, economic level and medical and health conditions, etc. Despite all the limitations of the GBD database, we found that longer duration of floods was associated with an increased number of new cases and new deaths of certain infectious diseases, which filled the gaps of studies on the association between natural flood disasters and infectious diseases, and quantified the association of natural flood disasters with new cases and deaths of different infectious diseases. Fourth, we did not analyze the lag time pattern in our study due to the fact that the data we used were annual, and it is generally believed that the annual data cannot be used to estimate the lag time pattern. In future research, it is necessary to conduct further research on the association between floods and infectious diseases at the sub-national level, while considering the impact of floods on different age groups, and the seasonal impact of floods on infectious disease outbreaks.

5. Conclusions

The duration days of natural flood disasters continued to rise in the past three decades and natural flood disasters were associated with increased new cases and deaths of enteric infections, neglected tropical diseases, and respiratory infections. Policymakers, scientists, and the public should cooperate together and make concerted effects to design better strategies for adaptation to prevent and control the outbreak of floods-related infectious diseases and reduce their impact on health and life. Rapid provision of clean water and sanitation facilities, prompting vector controls, avoiding exposure to contaminated environments, wearing protective devices, and education about potential related risk on occurrence and deaths of infectious diseases and prevention are important. In the context of global warming, the risk of floods caused by extreme weather factors increases, and the prevention and control of disasters-related infectious diseases has become more important than ever before. Targeted intervention studies are needed in the future, especially in areas with limited resources.

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CRediT authorship contribution statement

Qiao Liu: searched the literature, collected the data, analyzed the data, interpreted the results, Writing – original draft, contributed equally as first authors, revised the paper. **Jie Yuan:** searched the literature, collected the data, analyzed the data, interpreted the results, Writing – original draft, contributed equally as first authors, revised the paper. **Wenxin Yan:** revised the paper. **Wannian Liang:** revised the paper. **Min Liu:** conceived of the study, Writing – review & editing, supervised the study, interpreted the results, contributed equally as corresponding authors. **Jue Liu:** Conceptualization, designed the study, Supervision, interpreted the results, contributed equally as corresponding authors.

Declaration of competing interest

Wannian Liang is the editor-in-chief for Global Transitions, Min Liu and Jue Liu are Editorial Board members for Global Transitions, and all of them were not involved in the editorial review or the decision to publish this article. All authors declare that there are no competing interests.

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Appendix A. Supplementary data

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