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The Complex Epidemiological Relationship between Flooding Events and Human Outbreaks of Mosquito-Borne Diseases: A Scoping Review

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Background: Climate change is expected to increase the frequency of flooding events. Although rainfall is highly correlated with mosquito-borne diseases (MBD) in humans, less research focuses on understanding the impact of flooding events on disease incidence. This lack of research presents a significant gap in climate change–driven disease forecasting.

Objectives: We conducted a scoping review to assess the strength of evidence regarding the potential relationship between flooding and MBD and to determine knowledge gaps.

Methods: PubMed, Embase, and Web of Science were searched through 31 December 2020 and supplemented with review of citations in relevant publications. Studies on rainfall were included only if the operationalization allowed for distinction of unusually heavy rainfall events. Data were abstracted by disease (dengue, malaria, or other) and stratified by post-event timing of disease assessment. Studies that conducted statistical testing were summarized in detail.

Results: From 3,008 initial results, we included 131 relevant studies (dengue $n=45$, malaria $n=61$, other MBD $n=49$). Dengue studies indicated short-term (<1 month) decreases and subsequent (1–4 month) increases in incidence. Malaria studies indicated post-event incidence increases, but the results were mixed, and the temporal pattern was less clear. Statistical evidence was limited for other MBD, though findings suggest that human outbreaks of Murray Valley encephalitis, Ross River virus, Barmah Forest virus, Rift Valley fever, and Japanese encephalitis may follow flooding.

Discussion: Flooding is generally associated with increased incidence of MBD, potentially following a brief decrease in incidence for some diseases. Methodological inconsistencies significantly limit direct comparison and generalizability of study results. Regions with established MBD and weather surveillance should be leveraged to conduct multisite research to *a*) standardize the quantification of relevant flooding, *b*) study nonlinear relationships between rainfall and disease, *c*) report outcomes at multiple lag periods, and *d*) investigate interacting factors that modify the likelihood and severity of outbreaks across different settings. https://doi.org/10.1289/EHP8887

Introduction

Mosquito-borne diseases (MBD) cause a significant proportion of infectious disease morbidity and mortality globally. Although declines in the disease burden of some, chiefly malaria (Cibulskis et al. 2016), have been achieved in the past several decades, others such as dengue (Messina et al. 2019) and West Nile virus (WNV; Chancey et al. 2015) have increased substantially in geographic range and incidence. Newly emerging MBD such as Zika and chikungunya viruses have become pandemics within just the last decade (Chang et al. 2016a), whereas others like Rift Valley fever (RVF) virus and WNV remain persistent threats. In the coming decades, models predict that global warming will cause regional shifts in the distribution of key vector species, leading to an overall global increase in the risks of MBD that will be more severe at 2°C than 1.5°C of warming (IPCC 2018). Changes in average temperature and rainfall patterns are also anticipated to be accompanied by increased frequency and intensity of extreme weather events, such as tropical cyclones (cyclones, hurricanes, and typhoons), floods, and unusually heavy rainfall events (IPCC 2012; U.S. Global Change Research Program 2018). Increasing sea level rise is further linked to increasing risk of tsunami-related flooding (Li et al. 2018; Shao et al. 2019). How these extreme weather events will influence the distribution and level of MBD has not been consistently evaluated and may differ by disease and for the same disease in different geographic, social, or temporal contexts.

Floods are described in myriad ways worldwide depending on location (land surface, geomorphology, hydrology) and duration. For example, in the United States, the National Flood Insurance Program (NFIP) describes a flood as “A general and temporary condition of partial or complete inundation of two or more acres of normally dry land area or of two or more properties . . . from: overflow of inland or tidal waters; unusual and rapid accumulation or runoff of surface waters from any source; mudflow; or collapse or subsidence of land along the shore of a lake or similar body of water as a result of erosion or undermining caused by waves or currents of water exceeding anticipated cyclical levels that result in a flood as defined above” (NFIP 2015). The U.S. National Weather Service issues a flood warning for “flooding that lasts 6 h or more over a general area and/or affects mainstream rivers that is a threat to life/property,” whereas a flash flood warning is for flooding that produces a life or property threat over a period of 0–6 h (National Weather Service n.d.). The World Meteorological Organization recognizes the challenges of forecasting and defining flash floods worldwide, and the organization promotes a focus on intensity of rainfall and the impact of rainfall on saturated soils (World Meteorological Organization 2021). The Flash Flood Guidance System with Global Coverage (FFGS) is designed to assist with forecasting implementation worldwide (https://public.wmo.int/en/projects/ffgs). The inherent variability in defining floods in different global contexts presents challenges for standardization and generalization in studies of their impacts, including impacts on MBD.

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MBD transmission is regulated by a complex set of environmental and social determinants that affect the proliferation, survival, and interactions of pathogens, mosquito species, and host(s) (Parham et al. 2015). The dynamic of each specific pathogen–vector–host relationship is unique. One commonality, however, is the need for an aquatic habitat for immature life stages of the mosquito (Foster and Walker 2019). Rainfall, humidity, and temperature affect habitat availability, mosquito development time, fecundity, feeding behaviors, and survival (Christophers 1960; Clements 1992; Morin et al. 2013). Recently, much attention has been directed toward predicting how climate change–associated shifts in these factors will drive temporal and geographic changes in MBD risk (Akpan et al. 2019; Caminade et al. 2014a; Hertig 2019; Kamal et al. 2018; Kraemer et al. 2019; Liu-Helmersson et al. 2019; Messina et al. 2019; Monaghan et al. 2018; Ryan et al. 2019; Samy et al. 2016). Often these predictions focus on how projected average temperature and, less commonly, rainfall patterns may change temporal and geographic risk. Many studies have compared long-term rainfall and disease surveillance data but modeled precipitation as a linear predictor variable without exploring potential nonlinearity after extreme rainfall events. However, some evidence suggests that heavy rainfall can actually flush out oviposition sites, particularly in the immediate time periods following these events (Benedum et al. 2018). Models that fit rainfall as a linear predictor may miss such nonlinear impacts of flood events linked to heavy rainfall.

In fields that study MBD, we characterize vectorial capacity, a measure that quantifies transmission risk, as comprising multiple parameters, including *a*) mosquito density, *b*) the human-biting rate, *c*) survival of the mosquito, *d*) the extrinsic incubation period, and *e*) vector competence. As illustrated in Figure 1, we hypothesize many direct and indirect influences on these parameters during flooding and inundation events that could contribute to variation of the effects of flooding on different pathogens and for the same pathogen in different spatial or temporal settings. Mosquito density may be positively or negatively influenced, depending on characteristics of the local mosquito vectors and other contextual factors. For instance, although higher frequency or intensity of extreme flooding events may increase available immature-stage mosquito habitat by creating more stagnant water pools or spreading detritus that may serve as a habitat for container-breeding mosquitoes, the relationship may be neither linear nor temporally consistent if breeding sites are flushed out in the short term. These relationships would not necessarily generalize to other MBDs transmitted by mosquito species that breed in larger pools. Another example is coastal flooding from storm surges that may leave large areas of land inundated with flood waters, but many important vector species cannot breed easily in high-salinity water (Kengne et al. 2019); thus the context of flooding events is critical. Overall, the impacts of flooding events on mosquito density may be mediated by factors such as the typical climate (e.g., rainfall, temperature, humidity) patterns of the region, the salinity of the water, local water storage practices, lag period of consideration after the event, and human mitigation/vector control efforts.

Survival of the adult mosquito and the extrinsic incubation period for the disease link to a singular epidemiologically relevant concept, survival past the extrinsic incubation period. Higher humidity conditions are associated with increased mosquito survival at high temperatures (Schmidt et al. 2018). Following rainfall and flooding events, humidity would be anticipated to be high, though in tropical environments, the increase may not be large. If coupled with limited temperature changes, it is theoretically possible that more mosquitoes could survive past the extrinsic incubation period after flooding than before it. Alternately, although adult mosquitoes can avoid being killed by raindrops in flight, they can be killed by them when flying too close to the ground (Dickerson et al. 2012). Finally, vector competence for transmission of a specific pathogen should remain unaffected, but as noted above, flooding and inundation events could alter the species composition in an area toward or away from a more competent vector species.

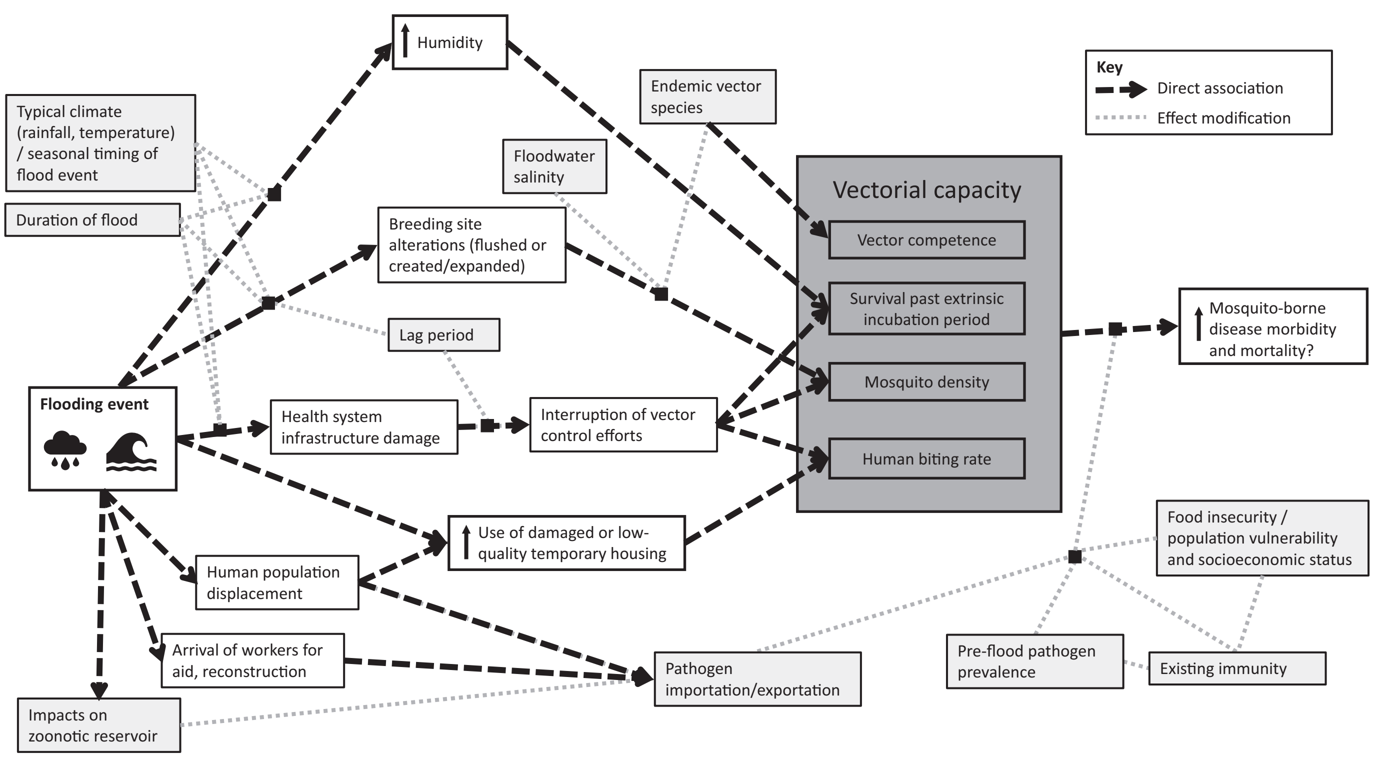

Figure 1. Hypothesized conceptual diagram of key factors that link flooding and human mosquito-borne disease frequency.

Furthermore, much research on rainfall has focused on changes in mosquito population distributions as the primary outcome rather than human disease incidence, but mosquito abundance does not always directly correlate with intensity of pathogen transmission (Barrera et al. 2019; Ernst et al. 2017; Mori et al. 2018), because other parameters of vectorial capacity may influence the disease dynamics. For instance, the human-biting rate may also be influenced by flooding. Vector–human contact is mediated by the built environment. Flooding and inundation events, particularly those associated with hurricanes, may degrade housing quality, leading to more penetrable housing and increased vector–human contact (Crandell et al. 1993; Massarra et al. 2021). Such events may also displace individuals to outdoor, semipermanent locations, depending on the extent of damage, and further reduce barriers to vector–human contact (Loebach and Korinek 2019). A complex constellation of social and socioeconomic factors influence the frequency of mosquito contacts with humans and potential zoonotic hosts, such as housing construction quality (Tusting et al. 2015), population density (Schmidt et al. 2011), land use (Norris 2004; Steiger et al. 2016), and access to interventions, such as mosquito repellent and breeding site management (McCall et al. 2009). We hypothesize that such factors will also mitigate the impacts of flooding on incidence of different diseases in different social/geographic contexts (Figure 1).

Given the challenges in predicting the specific timing and location of weather disaster events, we argue that strong epidemiological evidence regarding a causal relationship between extreme events and MBD frequencies requires study sites with systematic disease surveillance, enabling testing of trends over time, rather than solely descriptive or reactionary reports of perceived outbreaks following extreme events. However, in the wake of a disaster, infrastructure damages can make it particularly challenging to monitor resulting infectious disease burdens, even in places where predisaster data are regularly collected (Iwata et al. 2013). Thus, although a direct relationship between flooding and mosquito-borne disease transmission has often been assumed, data to support generalizable causal inferences have been limited, and there has been no systematic aggregation of the full body of evidence to this point. Understanding the potential strength, direction, and timing of these causal relationships is critical for disaster response preparedness and prediction of disease frequencies in the context of climate change. Therefore, we undertook a scoping review of the associations between extreme rainfall or flooding events and MBD frequencies in human populations. The goals of the review were to characterize the potential relationship, to determine the gaps in knowledge, and to better inform future projections of disease risk.

Methods

Search Strategy

We undertook a scoping review of the literature to identify all primary published data relating to the occurrence of MBD in humans after flooding events. To better understand how inundation events influence MBD, we took a broad view, including flooding due to heavy rainfall, flooding associated with the El Niño–Southern Oscillation (ENSO) or Pacific Decadal Oscillation (PDO), and flooding of land due to other disasters like tsunamis. The methods were guided by the Preferred Reporting Items for Systematic Reviews and Meta-Analyses–Extension for Scoping Reviews (PRISMA-ScR) statement (Tricco et al. 2018). Anticipating high variability in study designs and available data, we planned a qualitative summary without a specific meta-analysis. We searched PubMed, Embase, and Web of Science for all studies included through 31 December 2020, with no lower limit on publication date. The search used flood-related terms as the exposure and mosquito-borne disease terms as the outcome, as follows:

Exposure: (flood OR tsunami OR typhoon OR "tropical storm" OR hurricane OR "El Nino" OR "La Nina" OR ((extreme OR heavy OR unseasonal) AND (rain OR rainfall OR precipitation)) OR monsoon OR "storm surge" OR (disaster AND (climate OR weather)) OR ENSO OR PDO)

AND

Outcome: (((mosquito OR mosquitos OR mosquitoes OR mosquito-borne OR mosquitoborne OR "mosquito borne" OR vector OR vectors OR vectorborne OR vector-borne OR "vector borne" OR aedes OR anopheles OR culex) AND (disease OR infection)) OR "west nile virus" OR chikungunya OR dengue OR zika OR "yellow fever" OR "lymphatic filariasis" OR elephantiasis OR malaria OR Plasmodium OR "rift valley" OR encephalitis)

Throughout the course of screening and data abstraction, we regularly scanned bibliographies of relevant studies to identify and screen additional potentially relevant citations that had not appeared in the initial search results.

Study Selection

This review aimed to gather and assess the data available on any effects of flooding events on MBD rates in human populations, so the main inclusion criteria were *a*) primary reports of human health data relating to one or more MBD (even if the reported case count was zero) that *b*) evaluated flood disasters or very high rainfall events as an exposure. Retrospective outbreak reports were expected, given that many studies are conducted only following a disaster because of the short time frame for forecasting the event, and we anticipated a lack of consistency or formality across reports of potentially relevant data. Thus, the search included nearly all study designs, and we planned for a primarily qualitative summary of the literature. We also elected not to restrict the review to certain dates or geographies.

Exclusion criteria were developed before reviewing search results (Table 1). One of the challenges of this review was the large variety in how flooding and heavy rainfall were operationalized as exposures. Some studies reported on the impacts of specific extreme events (meteorological and other) that could lead to excess water presence on land, e.g., specific locally designated floods, tropical cyclones (hurricanes, typhoons, or cyclones), and tsunamis; others compared disease surveillance data to climatological monitoring data like daily, weekly, or monthly rainfall. Because heavy rainfall is a common cause of flooding, we included the latter for this review if the study operationalized rainfall variables in a way that allowed for nonlinear effects at high thresholds (e.g., using splines), which could potentially distinguish effects of flooding from those of average rainfall conditions. For example, included studies of heavy rainfall could quantify disease impacts when rainfall amount exceeded a study-specific threshold per time period or a threshold of deviation from local averages. Studies modeling rainfall only as a continuous linear predictor of disease and those describing typical seasonal variability were excluded. This selection method could potentially have excluded pertinent results from areas where flooding is common at all rainfall amounts due to poor drainage conditions, but in most cases the reporting of an average increase in cases per unit rainfall does not enable a distinction of rainfall amounts that would be sufficient to cause flooding events where water covers atypical land areas.

Table 1. Exclusion criteria for the scoping literature review of flood and mosquito-borne disease.

Category	Exclusion criteria
Exposures	No flood-related exposure/study of regular annual rainfall variation
	El Niño Southern Oscillation without assessment of flood events
Outcomes	No vector-borne disease outcomes
	Vector-borne disease with a non-mosquito vector
	Mosquito surveillance only (i.e., no human health data)
	Systems/response studies without human health outcome data
Design	Nonhuman species/*in vitro* study
	Case reports
	Reviews without primary data
	Corrections/revisions to other articles
	Opinion pieces/editorials/news articles
	Conference abstracts
	Predictive simulations without primary data
Logistics	Duplicates
	Full text not available
	Untranslated foreign language (i.e., not in English, French, Spanish, Italian, or Portuguese)

Titles and abstracts of identified studies were each scanned for eligibility by two reviewers, with any discrepancies resolved by a third reviewer. Full texts were not accessible for 16 citations (see Excel Table S3). All remaining full-text documents that could not be excluded based on the title and abstract alone were obtained for further consideration. All full texts in English, French, Spanish, Italian, or Portuguese were then reviewed by two reviewers for final inclusion in the qualitative summary using the same inclusion/exclusion criteria, with a third reviewer again resolving any discrepancies.

Data Abstraction

Data were abstracted from relevant studies into preestablished templates in two phases. The first phase involved only key elements to help broadly categorize available data. These key elements included study continent, country/geographic region, years of data collection, mosquito genus/species, disease(s), and brief characterization of flooding operationalization. Given the specificity of the ecological niches of mosquito species and the social-cultural context of public health and disaster response systems, we elected to aggregate studies by disease for the next phase of data abstraction. This aggregation has limitations, because many pathogens can be vectored by multiple mosquito species. For example, dozens of mosquito species are competent vectors of human malaria parasites, each of which has different vector competence, behaviors, and interactions with humans (Foster and Walker 2019). The initial abstraction revealed that studies could be divided into three general disease categories for the second phase of data abstraction: *a*) dengue, *b*) malaria, and *c*) other.

Three teams of researchers then completed the second phase of detailed, narrative data abstraction within each disease category, including additional fields on the specific study location, typical climate, study design, source of disease data, details on the definition of the exposure, comments on the preflood disease frequency, and the postflood disease frequency. Latency time to postflood impacts, if reported, was abstracted in five broad windows of time: acute (within 1 wk), subacute (1 wk–1 month), medium term (1–4 months), long term (4 months–1 y), and subsequent years. Flooding exposure groups were retroactively classified as *a*) heavy rainfall metrics (above average rainfall, rainfall exceeding a threshold, flooded land/waterlogging/"flushing"); *b*) major flooding events [specific "flood" events, tropical cyclones (cyclones, hurricanes, or typhoons), tsunami]; or *c*) other/unspecified (see Table 2 for details). Studies in which a statistical test was performed and reported for the association between flood and MBD were considered higher-quality evidence and were evaluated in detail for this paper. Team leaders then reviewed all abstracted data and compiled final summary tables and narratives. Full details of the screening and abstraction on all citations are available in Excel Tables S1 (detailed exclusion criteria), S2 (title/abstract screening), S3 (full text screening), S4 (initial data abstraction), S5 (dengue detailed data abstraction), S6 (malaria detailed data abstraction), S7 (detailed data abstraction on other diseases), and S8 (details on studies screened from the reference lists of relevant studies).

Results

The search resulted in 2,876 de-duplicated citations, with an additional 132 potentially relevant novel citations identified through a review of the reference lists of screened papers, for a total of 3,008 publications screened (Figure 2). Of these, 131 studies were deemed relevant and included in the overall qualitative synthesis.

There was considerable variability in the operationalization of "flood" exposure. We categorized included studies based on whether they evaluated flooding from specific events ("Major flooding events"), which tended to be dichotomous identification of presence or absence of an event during a specific window of time, or whether they operationalized the exposure as heavy rainfall deviating from average or exceeding study-specific thresholds ("Heavy rainfall metrics"), which tended to involve analysis of a continuous variable in the form of rainfall, river height, or area of land covered by water. Details on some of the specific metrics found in the literature are presented in Table 2.

Forty-five studies reported on dengue, 61 reported on malaria, and 49 reported on other MBD, primarily RVF, WNV, Japanese encephalitis (JE), and Murray Valley encephalitis (MVE) (Table 3), with some studies reporting on multiple disease categories. Dengue and malaria studies predominantly used data from Asian countries, with a considerable number of malaria studies also reporting data from African countries. Studies reporting on other diseases were more evenly distributed across continents, though there were few studies on flood and any MBD from Europe or South America. At least one study on flooding and MBD from 52 countries or major geographic entities (Figure 3) was included, though only 9 of these countries were the subject of 5 or more published studies on the topic: India (16 studies), the United States (12 studies for the continental United States and 5 from Puerto Rico alone), Australia (11 studies), Sudan (8 studies), Kenya (7 studies), China (7 studies), Pakistan (6 studies), Indonesia (5 studies), and Tanzania (5 studies). Because our goal was to capture all published evidence related to extreme rainfall and flooding events, there was a large variety in study design and quality of included studies. Studies reporting potential outbreak occurrence that coincided with floods but lacking a comparison group (either from before the flood or in a comparable geographic area) for hypothesis testing were common. Only 51 studies from 24 nations/geographic entities had any studies that provided a statistical analysis quantifying the impact of flooding on MBD frequencies, with the majority of these reporting on dengue (Table 3; Figure 3D).

There were also differences in the time frames studied for potential effects. As described in the methods, timing of effects on disease incidence post flooding were grouped for this review as acute (within 1 wk), subacute (1 wk–1 month), medium term (1–4 months), long term (>4 months–1 y), subsequent years (>1 y), or unspecified. The largest body of evidence was reported for the medium term (24 dengue publications, 26 malaria publications, and 22 other disease publications), closely followed by the subacute

Table 2. Examples of flood operationalization metrics used by studies included in this scoping review.

Category assigned in this review	Description of flood operationalization	Example studies
Major flooding events		
Specific flood event(s)	Single events described as floods, e.g., Heavy rains and flash flooding that were the "worst in 25 years"	(Elsanousi et al. 2018; Gao et al. 2016)
	Presence/absence of flood dichotomized weekly based on times when news and development authorities reported "nearly all major city roads impassable due to flood"	(Carvajal et al. 2018)
	Presence/absence of flood dichotomized for each 10-d period based on recording in the "Yearbooks of Meteorological Disasters Information Data set"	(Ding et al. 2019)
	Number of floods in a country in a year as recorded by the Emergency Events Database (EM-DAT) of the Center for Research on the Epidemiology of Disasters (CRED)	(Kaur et al. 2020)
Tropical cyclones (cyclone, hurricane, or typhoon)	Single events described as a type of tropical cyclone (e.g., Hurricane Mitch, Hurricane Katrina)	(Caillouët et al. 2008, Campanella, 1999)
	Exposure period was days that a city experienced a tropical cyclone with a level-7 wind circle and above, satisfying one of three additional rainfall or windspeed criteria	(Zheng et al. 2017)
Tsunami	Single events described as tsunamis	(Briët et al. 2006; Manimunda et al. 2011)
Heavy rainfall metrics		
Above average rainfall	Deviation (in millimeters) from the average or median cumulative rainfall over a time period (i.e., monthly, weekly, seasonal)	(Arcari et al. 2007; Kakarla et al. 2019; Pramanik et al. 2020)
	4-month cumulative rainfall anomaly (difference from average each month, summed for 4-month exposure periods)	(Anyamba et al. 2012)
	Heavy rainfall years (where monthly average total rainfall was 183% or 205% higher than previous 3 y)	(Himeidan et al. 2007)
	Number of very heavy precipitation days in a year (annual count of days with precipitation ≥ 20 mm)	(Méndez-Lázaro et al. 2014)
	Total rainfall from extremely wet days (days with rainfall >99th percentile)	(Méndez-Lázaro et al. 2014)
	Maximum 24-h rainfall that occurred during a month	(Yuan et al. 2019)
Rainfall exceeding a threshold	Daily, weekly, or monthly cumulative rainfall exceeding study-specific thresholds	(Cabrera and Taylor 2019; Chen et al. 2012; Chien and Yu 2014; Liyanage et al. 2016; Zhang et al. 2016)
	A week of heavy rainfall defined as weeks with 1+ days of >50 mm rainfall	(Soverow et al. 2009)
	Cumulative rainfall over a time period, evaluated for non-linearity (shifts in slope at high values)	(Ramadona et al. 2016; Singh et al. 2020; Xiao et al. 2018)
	Monthly rainfall over 6 months that was ≥ 2.5 standard deviations above average	(Lowe et al. 2018)
Flooded land/waterlogging/ "flushing"	River gage height, river level	(Mori et al. 2018; Tall and Gatton 2020; Wolfarth-Couto et al. 2020)
	Flooding and waterlogging events (dichotomized). Flooding = "an overflow of surface runoff that submerges towns and farmland, which is often caused by long-lasting heavy storms." Waterlogging = "submergence, wet damage, moisture damage, and is often caused by long lasting rainfall without a heavy precipitation intensity."	(Ding et al. 2014)
	Monthly flood discharge (in mm^3/month)	(Chirebvu et al. 2016)
	Flood extent measured as area covered by water that is not normally covered by water based on satellite images (e.g., in square kilometers, or calculating "normalized flooding index")	(Chirebvu et al. 2016; Rattanavong et al. 2020; Saulnier et al. 2018)
	Dichotomized at the household level based on whether or not residents reported "stagnant water around households for 3-5 days" following a flood	(Nsereko et al. 2020)

term (17 dengue publications, 24 malaria publications, and 19 other disease publications); however, 14 dengue publications, 20 malaria publications, and 42 publications for other diseases reported no results that could be linked to a specific lag period after the flooding. Most studies that specified time from event reported data for only one of the timing windows used in this review (Excel Table S9). Only 22 studies reported disease frequency results for at least three of our defined post-flood lag periods: 8 dengue studies, 11 malaria studies, and 3 studies on other diseases.

Dengue

Overview. The 45 publications that reported on dengue were predominantly from Asian countries or territories (Table 3); all nations or territories that had three publications or more were located in Asia, with the exception of Puerto Rico, which had four dengue-related publications (Figure 3). Most studies that reported the local vector species indicated the presence of *Aedes aegypti* ($n = 20$) with four reporting the co-occurrence of *Ae. albopictus* and one reporting the co-occurrence of *Ae. taeniorhynchus* (Excel Table S9). Of all publications, regardless of whether a statistical analysis was performed, 16 (36%) reported no clear impact of flooding on dengue, 13 (29%) reported an increase, 5 (11%) reported a decrease, and 11 (24%) reported both decreases and increases, depending on the specific flooding metric or the window of lag time reported (Excel Table S9). A summary of the findings of studies that included statistical analyses of these associations is presented below and shown in Table 4; the summary findings of all dengue studies can be found in Excel Table S9.

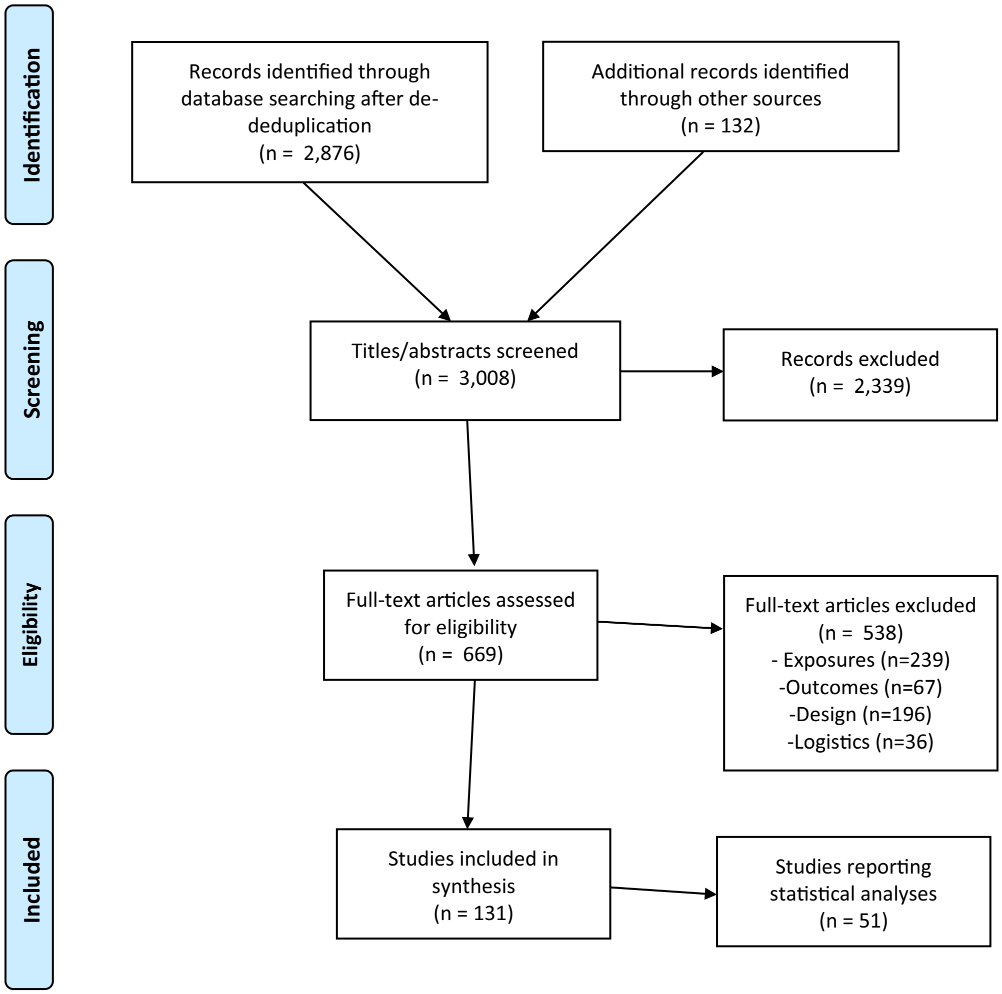

Figure 2. PRISMA 2009 flow diagram for the scoping review of flood and mosquito-borne disease (From Moher D, Liberati A, Tetzlaff J, Altman DG, The PRISMA Group (2009). Preferred Reporting Items for Systematic Reviews and Meta-Analyses: The PRISMA Statement. PloS Med 6(7):e1000097. Doi:10.1371/journal.pmed1000097). Note: See Excel Table S1 for a detailed list of reasons for exclusion.

Major flooding events. Five studies reported statistical analyses of the impacts of major flooding events on dengue, with inconsistent results (Table 4). Tropical cyclones were reported to statistically significantly ($p < 0.05$) increase risk for dengue fever in one large study of 65 such storms in southeastern China between 2005 and 2011, though the time frame of the effects was not specified (Zheng et al. 2017). A study from the Philippines tracked 5 years of dengue cases in relation to major flooding events as identified through social media warnings issued by the Metropolitan Manila Development Authority when "nearly all major roads … are impassable due to flood" and found the highest positive correlation between flood weeks and dengue cases reported after 6 wk ($r = 0.29$), but the primary goal of the paper was a methodological comparison of modeling techniques for prediction of dengue cases, and it did not present details on quantification of the association between flood and dengue for each model or at other studied lag periods (Carvajal et al. 2018). A study from Indonesia found that the prevalence of dengue hemorrhagic fever was statistically significantly higher ($p < 0.05$) 1 month after a major flood at 0.7% in comparison with a "preflood" prevalence of 0.2% (Sudaryo et al. 2020). However, two studies of major flooding events reported decreases in subsequent dengue cases: one that compared case counts before and after a major flood in the Solomon Islands (Natuzzi et al. 2016) and one that compared dengue counts to hurricane frequency and above average rainfall data from 26 y in Puerto Rico (Jury 2008). Both studies reported that major dengue outbreak years did not consistently occur in years with major floods or frequent hurricanes, and the Puerto Rican study additionally noted that cases peaked with average July–December rainfall and tended to decrease rapidly with increases in above-average rainfall, though neither identified these decreases as statistically significant.

Heavy rainfall metrics. Fifteen dengue publications reported statistical analyses on the impacts of flooding as approximated by heavy rainfall metrics (e.g., rainfall exceeding a specific threshold, above average cumulative rainfall) (Table 4). These studies differed dramatically in their methods for defining heavy rainfall, for performing statistical analyses, and for reporting results. For instance, two studies from Taiwan reported on dengue responses following "torrential" rainfall in the range of ~300 mm in a single day (Chen et al. 2012; Chien and Yu 2014), whereas studies from India (Kakarla et al. 2019) and Sri Lanka (Liyanage et al. 2016) used rainfall thresholds in the range of 100 – 350 mm per week. Others investigated cases after months of "exceptionally wet" weather based on total rainfall more than 2.5 standard deviations from average (Lowe et al. 2018), during cumulative 3-month seasons based on an index of deviation from the seasonal average (Pramanik et al. 2020), after weeks with increasing numbers of predicted

Table 3. Characteristics of included studies by disease category.

Category	Dengue studies *n*	Dengue studies References	Malaria studies *n*	Malaria studies References	Other studies[a] *n*	Other studies[a] References
Total[b]	45	(Arcari et al. 2007; Aumentado et al. 2015; Balaraman et al. 2005; Beatty et al. 2007; Benedum et al. 2018; Bich et al. 2011; Cabrera and Taylor 2019; Carvajal et al. 2018; Chakravarti and Kumaria 2005; Chang et al. 2016b; Chen et al. 2012; Chharang et al. 2018; Chien and Yu 2014; Dietz et al. 1990; Gao et al. 2016; Giribabu et al. 2020; Guha-Sapir and van Panhuis 2009; Hasan and Bambrick 2013; Jury 2008; Kakarla et al. 2019; Knope et al. 2013; Langkulsen et al. 2020; Liyanage et al. 2016; Lowe et al. 2018; McCarthy et al. 1996; Méndez-Lázaro et al. 2014; Natuzzi et al. 2016; Nelms et al. 1993; O'Leary et al. 2002; Pan American Health Organization 1998, 1999; Parekh et al. 2020; Pradutkanchana et al. 2003; Pramanik et al. 2020; Ramadona et al. 2016; Rattanavong et al. 2020; Rigau-Perez et al. 2001; Roy et al. 2018; Ruiz et al. 2018; Saulnier et al. 2018; Sudaryo et al. 2020; Xiang et al. 2017; Xiao et al. 2018; Yuan et al. 2019; Zheng et al. 2017)	61	(Afzal and Sultan 2013; Ahmed et al. 2011; Ansari and Nasir 1958; Asari et al. 2000; Balaraman et al. 2005; Barclay and Coulter 1988; Beatty et al. 2007; Bissell 1983; Bouma and Dye 1997; Boyce et al. 2016; Briët et al. 2005, 2006; Brown et al. 1998; Campanella 1999; Cedeno 1986; Chan et al. 2017; Chastel 2007; Chirebvu et al. 2016; Cissoko et al. 2020; Ding et al. 2014, 2019; Eke et al. 2006; Elsanousi et al. 2018; Emmelin et al. 2009; Gao et al. 2016; Giribabu et al. 2020; Guha-Sapir and van Panhuis 2009; Himeidan et al. 2007; Kaur et al. 2020; Knope et al. 2013; Kolachi et al. 2013; Kondo et al. 2002; Krishnamoorthy et al. 2005; Kumari et al. 2009; Kuraishy and Haider 1961; Lindsay et al. 2000; Linthicum et al. 2010; Maes et al. 2014; Manimunda et al. 2011; Mason and Cavalie 1965; Mathur et al. 1992; McCarthy et al. 1996; Memon et al. 2014; Muriuki et al. 2012; Nandi and Sharma 2000; Natuzzi et al. 2016; Nelms et al. 1993; Noor et al. 2013; Nsereko et al. 2020; Pan American Health Organization 1998, 1999; Pawar et al. 2008; Ramirez 2019; Russac 1986; CDC 1989; Sunder Rao et al. 1960; Wolfarth-Couto et al. 2020; Woodruff et al. 1990; Zheng et al. 2017)	49	(Anders et al. 1994; Anderson 1954; Anderson et al. 1958; Anyamba et al. 2009, 2012, 2014; Balaraman et al. 2005; Barrera et al. 2019; Beatty et al. 2007; Broom et al. 2003; Caillouët et al. 2008; Caminade et al. 2014b; Chen et al. 2012; Chretien et al. 2008; Cordova et al. 2000; Day and Curtis 1999; Ding et al. 2019; Doggett et al. 2001; El Mamy et al. 2011; Gao et al. 2016; Gilliland et al. 1995; Giribabu et al. 2020; Grossi-Soyster et al. 2017; Gudo et al. 2016; Harrison et al. 2009; Hopkins et al. 1975; Hubálek et al. 2000, 2005; Knope et al. 2013; Lehman et al. 2007; Linthicum et al. 1999, 2010; McCarthy et al. 1996; McDonnell et al. 1994; Mori et al. 2018; Nasci and Moore 1998; Nderitu et al. 2011; Nielsen et al. 2002; Rattanavong et al. 2020; Reeves et al. 1964; Roiz et al. 2015; Ruiz et al. 2018; Selvey et al. 2014; Singh et al. 2020; Sorensen et al. 2017; Soverow et al. 2009; Sow et al. 2014; Tall and Gatton 2020; Zhang et al. 2016)
Studies presenting statistical analyses on the relationship between flood and mosquito-borne disease	20	(Arcari et al. 2007; Benedum et al. 2018; Cabrera and Taylor 2019; Carvajal et al. 2018; Chen et al. 2012; Chien and Yu 2014; Jury 2008; Kakarla et al. 2019; Liyanage et al. 2016; Lowe et al. 2018; Méndez-Lázaro et al. 2014; Natuzzi et al. 2016; Pramanik et al. 2020; Ramadona et al. 2016; Roy et al. 2018; Saulnier et al. 2018; Sudaryo et al. 2020; Xiao et al. 2018; Yuan et al. 2019; Zheng et al. 2017)	17	(Boyce et al. 2016; Briët et al. 2006; Campanella 1999; Chirebvu et al. 2016; Cissoko et al. 2020; Ding et al. 2014, 2019; Elsanousi et al. 2018; Gao et al. 2016; Himeidan et al. 2007; Kaur et al. 2020; Lindsay et al. 2000; Manimunda et al. 2011; Natuzzi et al. 2016; Nsereko et al. 2020; Saulnier et al. 2018; Zheng et al. 2017)	13	(Anyamba et al. 2012; Caillouët et al. 2008; Chen et al. 2012; Ding et al. 2019; Gao et al. 2016; Grossi-Soyster et al. 2017; Knope et al. 2013; Mori et al. 2018; Rattanavong et al. 2020; Singh et al. 2020; Soverow et al. 2009; Tall and Gatton 2020; Zhang et al. 2016)
Geographic region[c]						
Europe	0		0		3	(Hubálek et al. 2000, 2005; Roiz et al. 2015)
North America	10	(Beatty et al. 2007; Dietz et al. 1990; Jury 2008; Lowe et al. 2018; Méndez-Lázaro et al. 2014; Nelms et al. 1993; O'Leary et al. 2002; Pan American Health Organization, 1998, 1999; Rigau-Perez et al. 2001)	8	(Beatty et al. 2007; Bissell, 1983; Campanella 1999; Mason and Cavalie 1965; Nelms et al. 1993; Pan American Health Organization, 1998, 1999; Saenz et al. 1995)	13	(Anders et al. 1994; Barrera et al. 2019; Beatty et al. 2007; Caillouët et al. 2008; Day and Curtis 1999; Gilliland et al. 1995; Harrison et al. 2009; Hopkins et al. 1975; Lehman et al. 2007; Mori et al. 2018; Nasci and Moore, 1998; Reeves et al. 1964; Soverow et al. 2009)
South America	3	(Cabrera and Taylor 2019; Parekh et al. 2020; Ruiz et al. 2018)	6	(Bouma and Dye 1997; Cedeno 1986; Linthicum et al. 2010; Ramirez 2019; Russac 1986; Wolfarth-Couto et al. 2020)	2	(Ruiz et al. 2018; Sorensen et al. 2017)

Table 3. (*Continued.*)

Category	Dengue studies *n*	Dengue studies References	Malaria studies *n*	Malaria studies References	Other studies[a] *n*	Other studies[a] References
Africa	1	(McCarthy et al. 1996)	18	(Barclay and Coulter 1988; Boyce et al. 2016; Brown et al. 1998; Chirebvu et al. 2016; Cissoko et al. 2020; Eke et al. 2006; Elsanousi et al. 2018; Emmelin et al. 2009; Himeidan et al. 2007; Kondo et al. 2002; Lindsay et al. 2000; Linthicum et al. 2010; Maes et al. 2014; McCarthy et al. 1996; Noor et al. 2013; Nsereko et al. 2020; CDC 1989; Woodruff et al. 1990)	14	(Anyamba et al. 2009, 2012, 2014; Caminade et al. 2014b; Chretien et al. 2008; El Mamy et al. 2011; Grossi-Soyster et al. 2017; Gudo et al. 2016; Linthicum et al. 1999, 2010; McCarthy et al. 1996; Nderitu et al. 2011; Nielsen et al. 2002; Sow et al. 2014)
Asia	27	(Arcari et al. 2007; Aumentado et al. 2015; Balaraman et al. 2005; Benedum et al. 2018; Bich et al. 2011; Chakravarti and Kumaria 2005; Chang et al. 2016b; Chen et al. 2012; Chharang et al. 2018; Chien and Yu 2014; Gao et al. 2016; Giribabu et al. 2020; Guha-Sapir and van Panhuis 2009; Kakarla et al. 2019; Langkulsen et al. 2020; Liyanage et al. 2016; Pradutkanchana et al. 2003; Pramanik et al. 2020; Ramadona et al. 2016; Rattanavong et al. 2020; Roy et al. 2018; Saulnier et al. 2018; Sudaryo et al. 2020; Xiang et al. 2017; Xiao et al. 2018; Yuan et al. 2019; Zheng et al. 2017)	25	(Afzal and Sultan 2013; Ahmed et al. 2011; Ansari and Nasir 1958; Balaraman et al. 2005; Briët et al. 2005, 2006; Chastel, 2007; Ding et al. 2014, 2019; Gao et al. 2016; Giribabu et al. 2020; Guha-Sapir and van Panhuis 2009; Kolachi et al. 2013; Krishnamoorthy et al. 2005; Kumari et al. 2009; Kuraishy and Haider 1961; Manimunda et al. 2011; Mathur et al. 1992; Memon et al. 2014; Muriuki et al. 2012; Nandi and Sharma 2000; Pawar et al. 2008; Saulnier et al. 2018; Sunder Rao et al. 1960; Zheng et al. 2017)	9	(Balaraman et al. 2005; Chen et al. 2012; Chretien et al. 2008; Ding et al. 2019; Gao et al. 2016; Giribabu et al. 2020; Rattanavong et al. 2020; Singh et al. 2020; Zhang et al. 2016)
Australia/Pacific Islands	4	(Carvajal et al. 2018; Hasan and Bambrick 2013; Knope et al. 2013; Natuzzi et al. 2016)	4	(Asari et al. 2000; Chan et al. 2017; Knope et al. 2013; Natuzzi et al. 2016)	10	(Anderson, 1954; Anderson et al. 1958; Anyamba et al. 2014; Broom et al. 2003; Cordova et al. 2000; Doggett et al. 2001; Knope et al. 2013; McDonnell et al. 1994; Selvey et al. 2014; Tall and Gatton 2020)
Type of flooding exposure						
Heavy rainfall metrics						
Above-average rainfall	8	(Arcari et al. 2007; Hasan and Bambrick 2013; Jury, 2008; Kakarla et al. 2019; Méndez-Lázaro et al. 2014; Pramanik et al. 2020; Roy et al. 2018; Yuan et al. 2019)	8	(Barclay and Coulter 1988; Bouma and Dye 1997; Cedeno, 1986; Chirebvu et al. 2016; Emmelin et al. 2009; Himeidan et al. 2007; Linthicum et al. 2010; Noor et al. 2013)	19	(Anderson, 1954; Anderson et al. 1958; Anyamba et al. 2009, 2012, 2014; Broom et al. 2003; Chretien et al. 2008; Cordova et al. 2000; Doggett et al. 2001; Gudo et al. 2016; Linthicum et al. 1999, 2010; McDonnell et al. 1994; Mori et al. 2018; Nderitu et al. 2011; Reeves et al. 1964; Selvey et al. 2014; Sorensen et al. 2017; Sow et al. 2014)
Rainfall exceeding a threshold	9	(Cabrera and Taylor 2019; Chen et al. 2012; Chien and Yu 2014; Langkulsen et al. 2020; Liyanage et al. 2016; Lowe et al. 2018; Ramadona et al. 2016; Xiang et al. 2017; Xiao et al. 2018)	0		5	(Chen et al. 2012; Day and Curtis 1999; Singh et al. 2020; Soverow et al. 2009; Zhang et al. 2016)
Flooded land/ waterlogging/ “flushing”	3	(Benedum et al. 2018; Rattanavong et al. 2020; Saulnier et al. 2018)	6	(Chirebvu et al. 2016; Cissoko et al. 2020; Ding et al. 2014; Nsereko et al. 2020; Saulnier et al. 2018; Wolfarth-Couto et al. 2020)	7	(Doggett et al. 2001; Gudo et al. 2016; McDonnell et al. 1994; Mori et al. 2018; Rattanavong et al. 2020; Reeves et al. 1964; Tall and Gatton 2020)

Table 3. (*Continued.*)

Category	Dengue studies		Malaria studies		Other studies[a]	
	n	References	n	References	n	References
Major flooding events						
Specific flood event(s)	12	(Bich et al. 2011; Carvajal et al. 2018; Chharang et al. 2018; Dietz et al. 1990; Gao et al. 2016; Knope et al. 2013; McCarthy et al. 1996; Natuzzi et al. 2016; Parekh et al. 2020; Pradutkanchana et al. 2003; Ruiz et al. 2018; Sudaryo et al. 2020)	27	(Afzal and Sultan 2013; Ahmed et al. 2011; Ansari and Nasir 1958; Boyce et al. 2016; Brown et al. 1998; Ding et al. 2019; Eke et al. 2006; Elsanousi et al. 2018; Gao et al. 2016; Kaur et al. 2020; Knope et al. 2013; Kolachi et al. 2013; Kondo et al. 2002; Lindsay et al. 2000; Maes et al. 2014; Mathur et al. 1992; McCarthy et al. 1996; Memon et al. 2014; Nandi and Sharma 2000; Natuzzi et al. 2016; Pawar et al. 2008; Ramirez 2019; Russac 1986; Saenz et al. 1995; CDC 1989; Sunder Rao et al. 1960; Woodruff et al. 1990)	17	(Anders et al. 1994; Anderson et al. 1958; Broom et al. 2003; Ding et al. 2019; El Mamy et al. 2011; Gao et al. 2016; Gilliland et al. 1995; Harrison et al. 2009; Hopkins et al. 1975; Hubálek et al. 2000, 2005; Knope et al. 2013; McCarthy et al. 1996; Nasci and Moore 1998; Nielsen et al. 2002; Roiz et al. 2015; Selvey et al. 2014)
Tropical cyclones (cyclone, hurricane, or typhoon)	12	(Aumentado et al. 2015; Beatty et al. 2007; Chang et al. 2016b; Giribabu et al. 2020; Jury 2008; Knope et al. 2013; Nelms et al. 1993; Pan American Health Organization 1999; Rigau-Perez et al. 2001; Zheng et al. 2017)	12	(Beatty et al. 2007; Bissell 1983; Campanella 1999; Chan et al. 2017; Giribabu et al. 2020; Knope et al. 2013; Kuraishy and Haider 1961; Mason and Cavalie 1965; Nelms et al. 1993; Pan American Health Organization 1999, 1998; Zheng et al. 2017)	7	(Barrera et al. 2019; Beatty et al. 2007; Caillouët et al. 2008; Cordova et al. 2000; Giribabu et al. 2020; Knope et al. 2013; Lehman et al. 2007)
Tsunami	2	(Balaraman et al. 2005; Guha-Sapir and van Panhuis 2009)	10	(Asari et al. 2000; Balaraman et al. 2005; Briët et al. 2005, 2006; Chastel 2007; Guha-Sapir and van Panhuis 2009; Krishnamoorthy et al. 2005; Kumari et al. 2009; Manimunda et al. 2011; Muriuki et al. 2012)	1	(Balaraman et al. 2005)
Other or unspecified flooding	1	(Chakravarti and Kumaria 2005)	0		3	(Caminade et al. 2014b; Grossi-Soyster et al. 2017; Ruiz et al. 2018)

[a]Other diseases included: Japanese encephalitis (8 studies (Balaraman et al. 2005; Chen et al. 2012; Ding et al. 2019; Gao et al. 2016; Knope et al. 2013; Rattanavong et al. 2020; Singh et al. 2020; Zhang et al. 2016)), Murray Valley Encephalitis (8 studies (Anderson, 1954; Anderson et al. 1958; Anyamba et al. 2014; Broom et al. 2003; Cordova et al. 2000; Doggett et al. 2001; Knope et al. 2013; Selvey et al. 2014)), Barmah Forest virus (2 studies (Doggett et al. 2001; Knope et al. 2013)), Ross River virus (4 studies (Doggett et al. 2001; Knope et al. 2013; McDonnell et al. 1994; Tall and Gatton 2020)), Rift Valley Fever (12 studies (Anyamba et al. 2009, 2012, 2014; Caminade et al. 2014b; Chretien et al. 2008; El Mamy et al. 2011; Gudo et al. 2016; Linthicum et al. 1999, 2010; McCarthy et al. 1996; Nderitu et al. 2011; Sow et al. 2014)), West Nile (or Kunjin) virus (13 studies (Beatty et al. 2007; Broom et al. 2003; Caillouët et al. 2008; Cordova et al. 2000; Doggett et al. 2001; Harrison et al. 2009; Hubálek et al. 2000, 2005; Knope et al. 2013; Lehman et al. 2007; McCarthy et al. 1996; Mori et al. 2018; Soverow et al. 2009)), Western Equine Encephalitis (4 studies (Anders et al. 1994; Gilliland et al. 1995; Nasci and Moore 1998; Reeves et al. 1964)), Eastern Equine Encephalitis (2 studies (Gilliland et al. 1995; Nasci and Moore 1998)), St. Louis Encephalitis (7 studies (Anders et al. 1994; Day and Curtis 1999; Gilliland et al. 1995; Hopkins et al. 1975; Lehman et al. 2007; Nasci and Moore 1998; Reeves et al. 1964)), Yellow fever (2 studies (Chretien et al. 2008; Knope et al. 2013)), Chikungunya (6 studies (Giribabu et al. 2020; Grossi-Soyster et al. 2017; Knope et al. 2013; McCarthy et al. 1996; Roiz et al. 2015; Ruiz et al. 2018)), Zika virus (3 studies (Barrera et al. 2019; Ruiz et al. 2018; Sorensen et al. 2017)), and one study each of Tahyna virus (Hubálek et al. 2005), Sindbis virus (Hubálek et al. 2005), Batai virus (Hubálek et al. 2005), La Crosse encephalitis (Gilliland et al. 1995), and lymphatic filariasis (Nielsen et al. 2002).
[b]Counts may not sum to expected totals as studies could count toward multiple categories.
[c]One study that included a global analysis of 79 nations was not reported in the section by continent (Kaur et al. 2020).

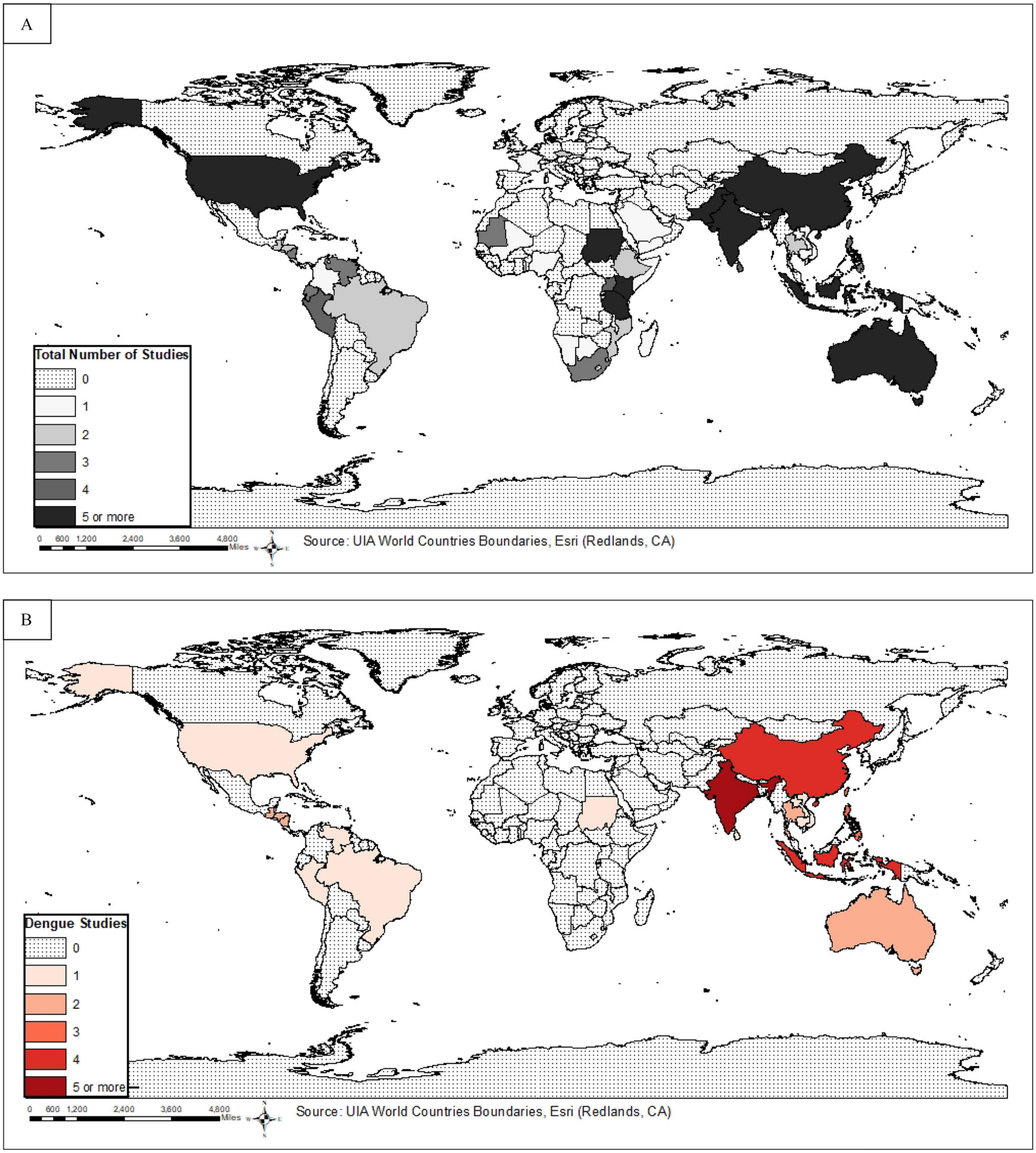

Figure 3. Number of studies on flood and mosquito-borne disease occurrence by country as (A) total, (B) dengue, (C) malaria, and (D) studies with statistical hypothesis testing of the association between flood and mosquito-borne disease (see Excel Table S10 for data).

"flushing" events (Benedum et al. 2018), or compared years based on the maximum 24-h rainfall within different months (Yuan et al. 2019). Such methodological variability limited our ability to quantitatively compare study results. Nonetheless, we qualitatively observed a pattern of decreases in rates of dengue in the acute (<1 wk) and subacute term (1 wk–1 month) after heavy rainfall but increases in the medium term (1–4 months). Only one study reported results on dengue incidence in the long term (>4 months–1 y) and found a statistically significant decrease above a threshold of heavy rainfall in Barbados (Lowe et al. 2018).

Malaria

Overview. Though sub-Saharan Africa experiences the greatest malaria burden globally, 18 of 61 total malaria studies reported on malaria risk following heavy rainfall and flooding in sub-Saharan Africa, whereas 25 studies were conducted in Asia (Table 3). Most studies ($n = 37$, 61%) did not indicate species or subspecies of *Anopheles* mosquitoes. Of all 61 publications, 18 (30%) reported no clear impact of flooding on malaria cases, 34 (56%) reported increases in malaria cases, 4 (7%) reported decreases, and 5 (8%) reported both increases and decreases

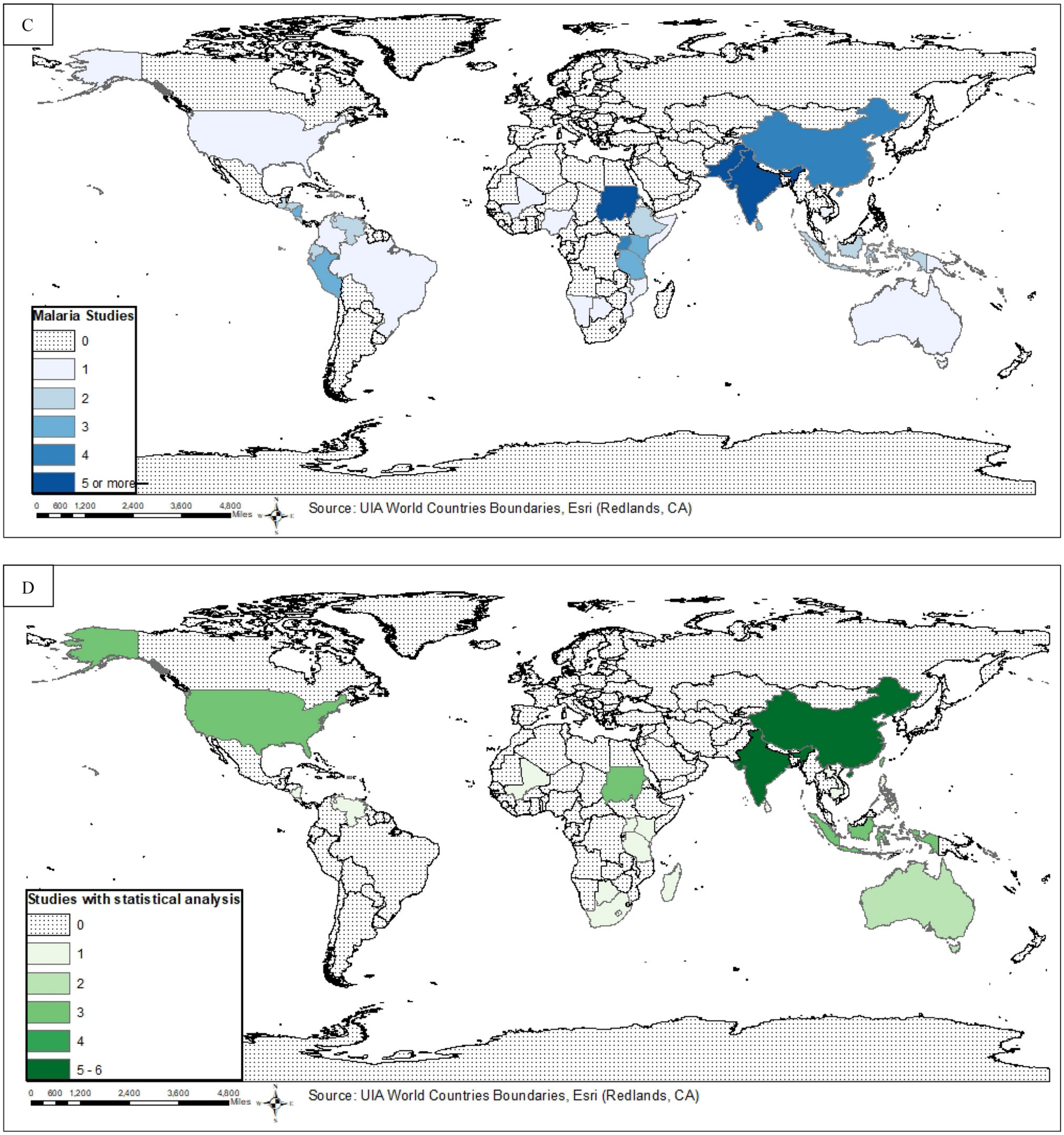

Figure 3. (*Continued.*)

depending on the specific flooding metric or the window of lag time (Excel Table S9). A summary of the findings of studies that included statistical analyses is described below and presented in Table 5; the summary findings of all malaria studies can be found in Excel Table S9.

Major flooding events. Of studies with relevant statistical analyses, a greater proportion of the malaria studies than dengue studies analyzed the relationship with major flooding events (as opposed to heavy rainfall metrics), with eight reporting on malaria after specific flood events/periods (Boyce et al. 2016; Ding et al. 2014, 2019; Elsanousi et al. 2018; Gao et al. 2016; Kaur et al. 2020; Lindsay et al. 2000; Natuzzi et al. 2016), two reporting after tropical cyclones (Campanella 1999; Zheng et al. 2017), and two reporting after tsunamis (Briët et al. 2006; Manimunda et al. 2011). The reported impacts on malaria were inconsistent, with a greater number of publications reporting statistically significant ($p < 0.05$) increases than decreases in case numbers, especially in African studies, but no obvious temporal lag pattern in studies that reported timing of impacts as was observed for dengue. Mediating factors like disaster response efforts, landscape, water salinity, and mosquito species were suggested by the authors to play important roles in some context-specific outcomes in some of these studies, though impacts of these mediating factors were not quantified in statistical models.

A study of disease patterns following 65 cyclones in China that reported a statistically significant increase in dengue fever

Table 4. Key findings of the relationship between heavy rainfall/flooding and dengue based on studies that performed a statistical analysis.

Study/reference	Country	Reported vector(s)	Flood exposure category	Lag time between flooding and disease results				
				Acute <1 wk	Subacute 1 wk–1 month	Medium term >1–4 month	Long term >4 month–1 y	Unspecified time
Major flooding events								
Zheng et al. 2017	China	NR	TC-CY	—	—	—	—	Increase*
Carvajal et al. 2018	Philippines	*Ae.ae*	FE	—	—	Increase	—	—
Sudaryo et al. 2020	Indonesia	NR	FE	—	Increase*	—	—	—
Natuzzi et al. 2016	Solomon Is.	NR	FE	Decrease	No impact	Decrease	Decrease	—
Jury 2008	U.S. (PR)	*Aedes* sp.	AR, TC-HR	—	—	—	—	Decrease
Heavy rainfall metrics								
Kakarla et al. 2019	India	*Ae.ae, Ae.al*	RT	Decrease	Decrease	Increase*	—	—
Roy et al. 2018	India	*Ae.ae, Ae.al*	AR	Decrease	—	Increase	—	—
Pramanik et al. 2020	India	*Aedes* sp.	AR	—	Increase/ Decrease[b]	Increase/ Decrease[b]	—	—
Liyanage et al. 2016	Sri Lanka	*Ae.ae, Ae.al*	RT	Decrease	Decrease	Increase*	—	—
Saulnier et al. 2018[a]	Cambodia	NR	FL	No impact	No impact	No impact	—	—
Benedum et al. 2018	Singapore	*Ae.ae*	FL	Decrease*	Decrease*	Increase*	—	—
Ramadona et al. 2016	Indonesia	*Ae.ae*	RT	Decrease	Increase	Increase*	—	—
Arcari et al. 2007	Indonesia	*Ae.ae, Ae.al*	AR	—	—	Increase*	—	—
Xiao et al. 2018	China	*Aedes* sp.	RT	—	—	Increase/ Decrease[b]	—	—
Chen et al. 2012	Taiwan	*Ae.ae*	RT	—	—	Increase*/ Decrease*[b]	—	—
Chien and Yu 2014	Taiwan	*Aedes* sp.	RT	—	Decrease*	Increase*	—	—
Yuan et al. 2019	Taiwan	*Ae.ae*	AR	—	—	—	—	Decrease*
Méndez-Lázaro et al. 2014	U.S. (PR)	*Aedes* sp.	AR	—	—	—	—	No impact
Lowe et al. 2018	Barbados	*Ae.ae*	RT	Increase	Increase*	Increase	Decrease*	—
Cabrera and Taylor 2019	Venezuela	*Ae.ae*	RT	—	Decrease	—	—	—

Note: Exposure categories: —, No results reported; AR, above average rainfall; ER, extreme monsoon/rainy season; FE, flood events (specific); FL, flooded land, waterlogging, or "flushing"; RT, rainfall exceeding a specified threshold; TC, tropical cyclones (CY, cyclone; HR, hurricane; TY, typhoon); TS, tsunami. *Indicated by study authors as a statistically significant difference at $p < 0.05$. Other: Ae.ae, *Aedes aegypti*; Ae.al, *Aedes albopictus*; NR, not reported; PR, Puerto Rico; U.S., United States.
[a]Saulnier (2018) reported malaria and dengue cases in combination as "vector-borne diseases."
[b]Mixed results may stem from the use of different study sites, differences across time within the window, or differences in results by flooding metric.

found a statistically significant decrease in risk for *Plasmodium vivax* malaria in the subacute period after cyclones (1 wk–1 month) (Zheng et al. 2017). This decrease corresponded with findings in a study from the Solomon Islands that reported a decrease in the number of malaria cases in the months following a flash flood in the capital city when compared with the previous year (Natuzzi et al. 2016) and a study that found significantly decreased prevalence of parasitemia and splenomegaly overall in a Tanzanian area 10 months after major ENSO-related flooding (Lindsay et al. 2000). Another study in Guangxi, China, investigated changes in 39 diseases in a surveillance system following 10-d periods in which a flood was determined to be present or absent by the Yearbooks of Meteorological Disasters in China and Chinese Agrimeteorological Disasters Information Database; floods were not found to have an impact on malaria incidence at any lag period, but the incidence in the area was relatively low at an annual average of 0.219 per 100,000 (Ding et al. 2019). However, five publications reported a statistically significant increase in malaria incidence in the subacute or medium term after singular flooding events: one following Hurricane Mitch in Nicaragua (Campanella 1999), two following an extreme flash flood in Anhui Province, China (Ding et al. 2014; Gao et al. 2016), and one each following major flash floods in Uganda (Boyce et al. 2016) and Sudan (Elsanousi et al. 2018). Campanella et al. noted that aggressive surveillance efforts after the hurricane may have contributed to improved case detection post flood in Nicaragua, rather than true case increases (Campanella 1999), whereas Natuzzi et al. suggested that the aggressive surveillance and vector-control efforts post flood may have helped to explain their findings of decreased incidence in the Solomon Islands (Natuzzi et al. 2016).

In addition to differences based on flood surveillance and human intervention responses, the nature of the specific flooding events and geographic context may also contribute to variability in reported findings. For instance, tsunamis are associated with high salinity flooding from ocean water (Villholth et al. 2005). Two studies following the December 2004 tsunami reported opposing long-term findings. One study from Sri Lanka reported lower incidence of malaria in 2005 than in 2004, suggesting that the tsunami did not negatively affect the downward trend in incidence that began in the year 2000 (Briët et al. 2006). The other reported a statistically significant increase in malaria incidence in the Nicobar Islands of India (Manimunda et al. 2011). These studies noted context-specific factors that could have contributed

Table 5. Key findings of the relationship between heavy rainfall/flooding and malaria based on studies that performed a statistical analysis.

Citation	Country	Reported vector(s)	Flood exposure category	Lag time between flood and disease results					
				Acute <1 wk	Subacute 1 wk–1 month	Medium term >1–4 months	Long term >4 months–1 y	Very long >1 y	Unspecified time
Major flooding events									
Kaur et al. 2020	Global (79 nations)	*Anopheles* sp.	FE	—	—	—	—	—	Increase*
Boyce et al. 2016	Uganda	*Anopheles* sp.	FE	—	Increase	Increase*	Increase*	—	Increase*
Elsanousi et al. 2018	Sudan	*An. arabiensis*	FE	—	—	Increase*	—	—	—
Lindsay et al. 2000	Tanzania	*An. gambiae s.l.*	FE	—	—	—	Increase / Decrease*[d]	—	—
Campanella 1999	Nicaragua	*Anopheles* sp.	TC-HR	—	Increase*	—	—	—	—
Natuzzi et al. 2016	Solomon Is.	NR	FE	Decrease*	Decrease*	Decrease*	Increase	—	—
Zheng et al. 2017	China	NR	TC-CY	—	Decrease*	—	—	—	—
Ding et al. 2014[a]	China	*An. sinensis*	FE	Increase*	Increase*	No impact	—	—	—
Gao et al. 2016[a]	China	NR	FE	—	Increase*	—	—	—	—
Ding et al. 2019	China	NR	FE	No impact	No impact	No impact	No impact	—	—
Manimunda et al. 2011	India	*An. sundaicus*	TS	—	—	—	Increase*	Increase	—
Briët et al. 2006	Sri Lanka	Multiple[b]	TS	—	—	Decrease	Decrease	—	—
Heavy rainfall metrics									
Chirebvu et al. 2016	Botswana	*Anopheles* sp.	FL, AR	Increase*/ Decrease*[d]	Increase / Decrease[d]	Decrease*	Increase*/ Decrease*[d]	—	—
Nsereko et al. 2020	Uganda	*An. gambiae s.l.*	FL	—	—	Increase	—	—	Increase*
Himeidan et al. 2007	Sudan	*An. arabiensis*	AR	—	—	—	—	—	Increase*/ Decrease*[d]
Cissoko et al. 2020	Mali	NR	FL	—	—	Increase	—	—	Increase*
Saulnier et al. 2018[c]	Cambodia	NR	FL	No impact	No impact	No impact	—	—	—

Note: Exposure categories: —, No results reported; AR, above average rainfall; ER, Extreme monsoon/rainy season; FE, flood events (specific); FL, flooded land, waterlogging, or "flushing"; NR, not reported; RT, rainfall exceeding a specified threshold; TC, tropical cyclones (CY, cyclone; HR, hurricane; TY, typhoon); TS, tsunami. *Indicated by study authors as a statistically significant difference at $p < 0.05$.

[a]These two studies reported different analyses for the same case data source from a major flooding event in July 2007 in Anhui Province.

[b]Reported species included: *Anopheles subpictus*, *An. culicifacies*, *An. vagus*, and *An. varuna*.

[c]Saulnier (2018) reported malaria and dengue cases in combination as "Vector-borne diseases".

[d]Mixed results may stem from the use of different study sites, differences across time within the window, or differences in results by flooding metric.

to the differences in the reported impact of the tsunami (or lack thereof) on malaria incidence, including differences in local vector species and pre-tsunami parasite endemicity. Briët et al. suggested that the lack of impact of the tsunami on malaria incidence may have been attributable to the absence of *Anopheles sundaicus*, a species that breeds successfully in brackish waters like those brought by the tsunami, in Sri Lanka and the fact that the affected area generally had low and unstable incidence (Briët et al. 2006). On the other hand, Manimunda et al. noted that *An. sundaicus* was the predominant vector in the Nicobar Islands and that malaria was highly endemic to the area prior to the arrival of the tsunami (Manimunda et al. 2011). They also hypothesized that cases increased due to widespread destruction of homes, which drove the local populations inland and into temporary housing structures, increasing their exposure to mosquito bites, and which prompted an influx of vulnerable workers from mainland areas with lower endemicity who had less immune protection from the parasite (Manimunda et al. 2011).

Heavy rainfall metrics. Evidence regarding the effects of other heavy rainfall metrics on malaria was even more limited and inconsistent than the evidence following specific major disaster events, with only five studies presenting statistical analyses. Of these, interpretation was severely limited for one, which combined dengue and malaria cases together as "vector-borne diseases" (Saulnier et al. 2018). Evidence from two of the other studies (Chirebvu et al. 2016; Himeidan et al. 2007) reported mixed results, with statistically significant decreases and increases in malaria after heavy rainfall depending on the metrics, lag period, and analytical methods. For instance, Chirebvu et al. reported the association between clinical malaria cases diagnosed at a village health center in Botswana and flood measured as both cumulative monthly millimeters of rain and maximum extent of area flooded by annual river overflow in square kilometers (Chirebvu et al. 2016). Rain contributing to stream/river discharge was associated with a significant increase in malaria cases in the acute terms (lag of 0 months) but with a significant decrease after a lag of 3–5 months. Flood extent had nearly the opposite pattern, with a significant decrease in the short term (decreased for lags of 0–3 months) but significant increase in the long term (after lags of 5 and 6 months) (Chirebvu et al. 2016). Such complex findings from a single study highlight the challenges of comparing results across different studies and contexts. Of the remaining two studies, Cissoko et al. reported statistically significantly ($p < 0.05$) higher malaria incidence for people who lived in the proximity of a river delta in Mali that tended to flood in comparison with those living in other areas (Cissoko et al.

Table 6. Key findings of the relationship between heavy rainfall/flooding and Japanese encephalitis, West Nile virus, Barmah Forest virus, Rift Valley fever, Ross River virus, and chikungunya based on studies that performed a statistical analysis.

Citation	Country	Reported vector(s)	Flood exposure category	Lag time between flood and disease results: Acute <1 wk	Subacute 1 wk–1 month	Medium term >1–4 month	Long term >4 month–1 y	Unspecified time
Japanese encephalitis								
Gao et al. 2016	China	NR	FE	—	Increase*/ Decrease*[a]	—	—	—
Ding et al. 2019	China	NR	FE	Increase*	—	—	—	—
Zhang et al. 2016	China	*Cx. tritaeniorhynchus*	RT	—	Increase*	—	—	—
Chen et al. 2012	Taiwan	*Ae. aegypti*	RT	—	Increase*/ Decrease*[a]	—	—	—
Rattanavong et al. 2020	Lao PDR	NR	FL	—	Increase*	No impact	No impact	Increase
Singh et al. 2020	India	NR	RT	—	—	—	—	Decrease
West Nile virus								
Caillouët et al. 2008	U.S. (LA, MS)	NR	TC-HR	—	Increase	—	Increase*	—
Soverow et al. 2009	U.S.	NR	RT	Increase*	Increase*/no impact	—	—	—
Mori et al. 2018	U.S. (ND)	*Cx. tarsalis*	AR, FL	—	—	—	—	No impact
Barmah Forest virus								
Knope et al. 2013	Australia, Pacific Islands	NR	FE, TC-CY	—	—	—	—	Increase
Rift Valley fever								
Anyamba et al. 2012	East Africa, Sudan, S. Africa, Madagascar	NR	AR	—	—	Increase*	—	—
Ross River virus								
Knope et al. 2013	Australia	Multiple	FE, TC-CY	—	—	—	—	Increase
Tall and Gatton 2020	Australia	NR	FL	—	—	Increase*	—	—
Chikungunya								
Grossi-Soyster et al. 2017	Kenya	*Ae. aegypti*	NS	—	—	—	—	Increase*

Note: Studies were found for other mosquito-borne diseases, but none that reported a statistical analysis of the flood and mosquito-borne disease relationship for inclusion in this table: Murray Valley encephalitis, St. Louis encephalitis, Western equine encephalitis, Eastern equine encephalitis, lymphatic filariasis, Tahyna bunyavirus, Sindbis virus, Batai virus, Zika virus, La Crosse virus, or yellow fever. Details on these studies can be found in Excel Table S9. Exposure categories: —, No results reported; AR, above average rainfall; ER, extreme monsoon/rainy season; FE, flood events (specific); FL, flooded land, waterlogging, or "flushing"; RT, rainfall exceeding a specified threshold; TC, tropical cyclones (CY, cyclone; HR, hurricane; TY, typhoon); TS, tsunami. Other: LA, Louisiana; MS, Mississippi; ND, North Dakota; NR, not reported; U.S., United States. *Indicated by study authors as a statistically significant difference at $p < 0.05$.
[a]Mixed results may stem from the use of different study sites, differences across time within the window, or differences in results by flooding metric.

2020). Similarly, during an outbreak investigation following a major flood in Uganda, Nsereko et al. found cases had significantly ($p < 0.05$) higher odds of exposure to stagnant water around the home for 3–5 d after flooding in comparison with controls (Nsereko et al. 2020). Neither study reported their statistical results in a way that could be linked to a specific lag period, though the Uganda outbreak investigation indicated that the outbreak began approximately 40 d after the flood (Nsereko et al. 2020).

Other Diseases

In addition to malaria and dengue, we identified 17 other MBD that were investigated across 49 studies that reported on flooding: 12 reporting on RVF; 13 on WNV or Kunjin virus; 8 each on MVE and JE; 7 on St. Louis encephalitis (SLE); 6 on chikungunya; 4 each on Western equine encephalitis (WEE) and Ross River virus (RRV); 3 on Zika virus; 2 each on Barmah Forest virus (BFV), Eastern equine encephalitis (EEE), and yellow fever; and 1 each on Tahyna virus, Sindbis virus, Batai virus, La Crosse encephalitis, and lymphatic filariasis (Table 3). These reports tended to be highly geographically specific. For instance, MVE, RRV, and BFV occur only in Australia and the Pacific Islands (Reed 2018; Smith et al. 2011) and were correspondingly reported only in studies from Australia. RVF was reported only in studies from Africa and the Middle East, where it is endemic (Reed 2018; Samy et al. 2017). Finally, WWW, EEE, and SLE were reported only in flood-related studies from the United States, though they occur more broadly in the Americas and the Caribbean (Corrin et al. 2021; Kopp et al. 2013; Kumar et al. 2018).

Summarizing the results for this group of studies is challenging due to the variability in the epidemiology of each disease, the limited number of studies/cases, and the general lack of comparison group data and statistical analyses. As of 2019, the published literature indicates little to no evidence supporting an association between flood and human infections with WEE (Anders et al. 1994; Gilliland et al. 1995; Nasci and Moore 1998; Reeves et al. 1964), EEE (Gilliland et al. 1995; Nasci and Moore 1998), La Crosse virus (Gilliland et al. 1995), Tahyna virus (Hubálek et al. 2000), Sindbis virus (Hubálek et al. 2005), Batai virus (Hubálek et al. 2005), or lymphatic filariasis (Nielsen et al. 2002), though the possibility cannot be excluded due to the limitations of the evidence. Studies weakly and inconsistently indicated possible associations between floods and chikungunya (Giribabu et al. 2020; Grossi-Soyster et al. 2017; Knope et al. 2013; McCarthy et al. 1996; Roiz et al. 2015; Ruiz et al. 2018), Zika (Barrera et al. 2019; Ruiz et al. 2018; Sorensen et al. 2017), yellow fever (Chretien et al. 2008; Knope et al. 2013), and SLE viruses (Anders et al. 1994; Day and Curtis 1999; Gilliland et al. 1995; Hopkins et al. 1975; Lehman et al. 2007; Nasci and Moore 1998; Reeves et al. 1964), but the amount of evidence was limited, statistical analyses were generally absent or failed to achieve significance, and strength of evidence was therefore low. Though only one study reported the result of a statistical significance test (Anyamba et al. 2012), flooding seems to be particularly notable as a cause of human outbreaks of MVE, RRV, BFV, and RVF. All but one study reported that outbreaks of these diseases occurred following flooding or unusually heavy rainfall, though heavy rainfall did not guarantee an outbreak (Anderson 1954; Anderson et al. 1958; Anyamba et al. 2009, 2012, 2014; Broom et al. 2003; Caminade et al. 2014b; Chretien et al. 2008; Cordova et al. 2000; Doggett et al. 2001; El Mamy et al. 2011; Gudo et al. 2016; Knope et al. 2013; Linthicum et al. 1999, 2010; McCarthy et al. 1996; McDonnell et al. 1994; Nderitu et al. 2011; Selvey et al. 2014; Sow et al. 2014). Key findings of all studies are summarized in Excel Table S9.

Most studies with statistical testing of "other" MBD were reported for JE and WNV, though there were two for RRV and one each for RVF, chikungunya, and BFV. All studies on diseases other than malaria or dengue that reported statistical testing are summarized in Table 6. The three analytical studies on WNV were all from U.S. data. Two of the three studies reported statistically significant ($p < 0.05$) increases in WNV cases. One was based on rapid increases in case counts following Hurricane Katrina in "hurricane-affected" counties/parishes in comparison with previous years (Caillouët et al. 2008). The second, a case-crossover study using data from 17 states, found statistically significant ($p < 0.05$) increases in WNV for the first 3 wk after a week with at least 1 day of heavy rainfall >50 mm (Soverow et al. 2009). The third study found that recent rainfall was not a significant predictor of WNV cases in North Dakota, but that river gage height (corresponding to overflow) was negatively associated with *Culex tarsalis* mosquito counts at lags of zero weeks and at 1 y, suggesting potential washout of breeding sites (Mori et al. 2018).

Most of the six studies of JE presented results for the subacute term (1 wk – 1 month after flooding). In their case-crossover analysis comparing dates after a major flood in Anhui Province, China, to the same dates in other years, Gao et al. reported a maximum odds ratio (OR) of 4.50 [95% confidence interval (CI): 1.40, 7.60] at an 11-d lag after the flooding began but reported an overall statistically significant decrease in JE associated with the flood in the analysis of the first month post flooding (OR = 0.58, 95% CI: 0.47, 0.71) (Gao et al. 2016). Zhang et al. reported a statistically significant increase in JE from a case-crossover analysis using nine specific flood events in Sichuan, China, but found that the strongest effect was at a lag of 23–24 d (OR = 2.0, 95% CI: 1.14, 3.52) (Zhang et al. 2016). A third case-crossover analysis studying JE cases after floods in Guangxi, China, reported that the strongest relationship overlapped with the 10-d blocks identified dichotomously as having a flood or not (classified as the acute period) and reported a statistically significant increase in case incidence (multivariate adjusted OR = 2.334, 95% CI: 1.119, 4.865) (Ding et al. 2019). The reason for the discrepancies is not clear, given the methodological similarities of these three studies. A study in Taiwan reported that there was a statistically significant positive association with torrential amounts of rainfall (201–350 mm/d) and incidence of JE after 14 d (relative risk = 4.26), but they found no cases occurring after extreme torrential rain (>350 mm/d) (Chen et al. 2012). This finding led the authors to hypothesize a positive association between rainfall and JE but with a threshold above which rainfall washes out breeding sites and decreases risk, echoing the hypothesis from the Mori et al. study of WNV (Mori et al. 2018). A recent study from Lao PDR performed two separate analyses of JE and flooding, both using satellite images to calculate a normalized flooding index (NFI) for villages and for 2-km, 5-km, and 10-km buffers around individual residences (Rattanavong et al. 2020). Their ecological analysis comparing the incidence rates of hospitalizations for JE from villages by quartile of NFI for the 8-y study period found a slight elevation in the OR for the two highest quartiles, but the differences were not statistically significant (OR for fourth quartile vs. first quartile = 1.26, 95% CI: 0.54, 2.95) (Rattanavong et al. 2020). They also conducted a retrospective epidemiological analysis comparing the NFI quartile for buffers around the residences of hospitalized JE cases to control patients hospitalized for central nervous system disease of a different etiology, which we identified as an example of a hospital-based case–control analysis. They reported statistically significantly increasing ORs by quartile of NFI for JE during the month of case admission at a buffer of 10 km (OR for fourth quartile vs. first quartile = 3.06, 95% CI: 1.04, 8.96) (Rattanavong et al. 2020). Finally, a study from India reported that an overall positive association between rainfall and JE hospitalizations and deaths appeared to reverse, becoming negatively associated with heavy rainfall greater than 100 mm in a day (Singh et al. 2020).

Discussion

The results of our scoping review provide some evidence that flooding and extreme rainfall can increase MBD, but the dearth of high-quality evidence undermines the strength of the conclusions. Event-to-transmission timing differed among disease systems. Incidence of malaria generally increased in all reported time frames (acute, mid, and long term), whereas dengue incidence declined during the acute phase but increased approximately 1 month after the extreme weather event. The overall low epidemiological rigor of included studies indicates that extreme caution is warranted in interpreting these relationships. Our work underscores the complex impacts climate change may have on MBD through the pathway of extreme flooding events, though the lack of methodological consistency precluded quantitative analysis and exploration of potential mediating factors, such as other local climate and weather conditions, socioeconomic characteristics of the human population, extent of flood damages, vector species, and other entomological factors. We recommend that future infectious disease risk projections consider the impacts of changing climate variability, including increasing frequency of flooding and more severe tsunamis triggered by rising sea levels, in addition to projected changes in average temperature and rainfall that are already commonly examined. More rigorous studies will need to be conducted to identify parameters for inclusion in transmission predictions under climate change scenarios.

As more research in this area is conducted, we believe it is critical to address three fundamental limitations to the current body of literature on this topic. First, there must be investment in surveillance and research capacity where the impact is likely to be the greatest. Research is underrepresented in the low-income, low-resource regions where MBD pose the greatest threats. For instance, although sub-Saharan Africa accounts for 94% of malaria burden and deaths (WHO 2020), only 40% of malaria articles included in this review were focused on countries in sub-Saharan Africa. Further, the literature on dengue had very little representation from Latin American countries, which suffer a significant dengue burden (Zeng et al. 2021), and none from sub-Saharan Africa, where reporting and detection have been limited (Buchwald et al. 2020) but where models predict an increasing burden as the climate changes (Messina et al. 2019). Second, this review highlights the need for standards to ensure systematic reporting of relevant and accurate epidemiological data in papers to facilitate integration and comparisons among regions. The goal of many of these studies was often a locally specific predictive model, so even those that did perform statistical analyses were not undertaken or presented in a way that supported generalizable causal inferences. Finally, disease outcome end points, such as case numbers, should be presented in the context of surveillance systems or consistent data collection processes. Outbreaks identified by the included studies may be biased by the reactionary nature of much of the included research—namely, that outbreaks were identified because surveillance efforts increased following a natural disaster. Relatively few studies reporting on flood events were based on analyses comparing data collected consistently during nonflood conditions. Studies that did use longer-term data to assess trends between rainfall and disease incidence, especially for dengue, often reported the association with rainfall only as a linear predictor, making it impossible to delineate the impact of discrete flooding events. Strengthening public health surveillance systems to consistently monitor disease incidence before and after acute events is needed to better quantify flood impacts.

Dengue

Although it was one of the most widely studied diseases of interest, the identified relationship between flooding and dengue incidence was inconclusive. Overall, we observed a trend toward decreased incidence in the first month following the extreme rainfall/flooding event, followed by a statistically significant increase in cases between 1 and 4 months after the event. These trends are biologically plausible. The primary vector reported in the studies with species information available was *Ae. aegypti*, which is known to be the primary vector globally (Foster and Walker 2019). As container breeders, *Ae. aegypti* exploits artificial habitats that may overflow in acute rainfall events, effectively washing out maturing larvae and pupae and reducing transmission in the immediate aftermath (Benedum et al. 2018; Seidahmed and Eltahir 2016), though laboratory experiments have not confirmed the hypothesis (Koenraadt and Harrington 2008). However, increased debris and more numerous water-holding containers following the acute stage after a flood could lead to later increases in breeding sites and vector abundance. Even where study designs and epidemiological rigor were strong, a consistent issue was lack of reported surveillance data or accounting for vector species and the circulating dengue serotype(s). It is unclear whether there could have been increases related to the introduction of a new serotype that was unrelated to the weather event. Natuzzi et al. suggested that previous outbreaks of a particular dengue serotype may preclude new flood-related outbreaks due to high levels of population immunity (Natuzzi et al. 2016). The serotypes of cases were not reported in most of the identified literature. Reporting of serotypes should become standardized to help disentangle these precursors to increasing transmission. Many studies did not specify the vector subspecies and/or presumed the major vector was *Ae. aegypti*, though distribution of other *Aedes* vectors has increased dramatically in the past few decades (Benedict et al. 2007). Dengue surveillance is also a prime example of the critical need to consider multiple time points following an extreme rainfall/flooding event to study the effect on both mosquitoes and humans. Study designs do not necessarily allow enough time to determine virus circulation in the mosquito (extrinsic incubation period) or in humans (intrinsic incubation period) (e.g., Zheng et al. 2017). Further, some studies we identified relied on the same sources of data and therefore were not independent contributors to the overall strength of evidence. Finally, few studies examined linkages between extreme weather events and other viruses vectored by *Aedes*, including Zika and chikungunya, so it was difficult to determine whether the biological pathway of fluctuating immature habitat availability may influence dengue incidence.

Malaria

First, in studies from malaria endemic regions (i.e., areas where malaria transmission is typically stable or seasonal), there was more evidence for outbreaks after a flooding or rainfall related disaster in comparison with areas with low and unstable transmission prior to flooding. Second, water salinity (i.e., salt water vs. fresh water), modified by events like tsunamis or storm surges that bring salt water inland, might result in no change or decreased malaria incidence post event than heavy rainfall, which leads to freshwater flooding events. It is possibly for this reason that results were heterogenous following cyclones, tsunamis, and hurricanes, whereas heavy rainfall and general flooding events tended to be associated with higher malaria risk.

Salinity of water is a possible moderator, especially where seawater is brought farther inland by storm surge associated with extreme weather events such as hurricanes and cyclones. This effect could be mediated by the species of malaria vector in the area. For example, *An. sundaicus* is known as a brackish-water mosquito and reported to breed in a wide range of habitats, including saline water and water with organic pollution (Sinka et al. 2011; Syafruddin et al. 2020), whereas water salinity limits the breeding success for other vector species (Kengne et al. 2019). However, most of the studies we included did not identify which vector species were responsible for transmission in the study area.

The aftermath of the flood event may be more important for mosquito abundance than the event itself because initial flooding might flush out vector breeding grounds. However, if floodwaters do not recede quickly, the provision of more breeding areas may be a modifying factor in the occurrence of increased malaria in addition to population displacement and widespread malnutrition following natural disasters. Overcrowding conditions and malnutrition both increase malaria risk (Alton and Rattanavong 2004; Bannister-Tyrrell et al. 2017; Das et al. 2018), and the combination of increased mosquito breeding with these demographic and social changes could increase likelihood of outbreaks.

Other Mosquito-Borne Diseases

We found relatively limited evidence pertaining to the relationship of flooding with MBD other than dengue and malaria. Studies that performed statistical hypothesis testing on the relationship were found mainly for JE and WNV, from which no clear patterns emerged, though results tended to be suggestive of increases in incidence after flooding. Most studies on flood and other MBD reported descriptively on human disease outbreaks without surveillance data for statistical testing in comparison with unaffected areas or to time periods without floods. Furthermore, outbreak reports have been inconsistent in providing details to quantify flood extent or define the timeline of impacts on human disease incidence.

Despite a lack of statistical testing, flooding has been commonly linked to several human outbreaks of the zoonotic diseases MVE, RRV, BFV, and RVF. As the key mosquito vectors that transmit these viruses are floodwater mosquitoes, laying their eggs adjacent to water on wet soil to later emerge during a flooded state (Webb 2013), it is not surprising that they are noted to be associated with zoonotic outbreaks. However, flooding events are not universally associated with human outbreaks of these diseases, and other factors may be critical to regulating whether zoonotic outbreaks spill over into human populations. For example, RVF research indicates that seroprevalence and severe disease may be associated with occupational exposures to blood of infected animals, instead of direct transmission from mosquitoes (Anyangu et al. 2010; Nyakarahuka et al. 2018). For

RRV, population dynamics among kangaroo hosts may significantly influence human outbreak potential (Carver et al. 2010). Although more research on mediating factors is needed, flooding in areas endemic for RRV, MVE, RFV, and BFV should prompt increased surveillance or prevention efforts to detect and interrupt epidemics in both humans and animal reservoirs.

Data Quality and Generalizability: Recommendations

We identified relatively few studies that could be considered truly comparable for a quantitative synthesis or meta-analysis due to wide variability in methodology and reporting. This finding indicates a wider problem with only collecting post-event data (vs. constant surveillance), especially for regions at highest risk for a flooding disaster event. Even papers that did report statistical hypothesis testing lacked consistency in the modeling methods, methods of defining and reporting weather and climate variables (particularly for extreme events like flooding), and methods of reporting the results for disease–flood associations. This methodological variability challenged our attempts to systematically summarize and interpret results, even for studies that investigated the same events or geographic locations. A primary example of this phenomenon was that many studies compared rainfall to weekly dengue incidence, and yet no two were alike in operationalization of the key variables or in their statistical approaches; for instance, some measured the extent of flooding in square kilometers of land covered by water from satellite images, others as rainfall exceeding varying thresholds in varying time periods, and others as rainfall significantly deviating from average, etc. Another review of climate-driven malaria epidemics also found imprecise incidence measurements and highly varying statistical analysis techniques in the literature, complicating the potential for valid generalizations (Mabaso and Ndlovu 2012). These methodological differences may exist because the goal of most of the studies was not to achieve broader causal inferences about the relationships but rather to build locally useful predictive models. However, such an approach limits the generalizability of these studies to support predictions of flood impacts in other settings, which is especially problematic for low-resource regions where populations are most vulnerable to climate change and infectious disease but little local research has been conducted to date.

Based on gaps identified in this scoping review, we have several recommendations to further investigate causal associations between weather-related flooding and other natural disaster events on MBD risk:

- **Design:** Studies should use a design that involves a comparison group, enabling statistical testing rather than just descriptive outbreak reports. Example designs can include *a*) ecological studies that compare disease incidences in flood-affected areas to similar flood-unaffected areas or from preflood to postflood dates; *b*) ecological case-crossover designs that compare the frequency or intensity of flood exposures preceding major disease outbreaks to the frequency/intensity of flood exposures in previous weeks, months, or the same weeks/months in previous years; *c*) individual-level cross-sectional, case–control, or case-crossover studies that compare exposure to floods in those with disease to those without disease (case–control) or to their own exposure to flood at other time points (case-crossover); or *d*) individual-level cohort studies that leverage either ongoing research studies or demographic surveillance systems data to compare disease risks in flooded vs. nonflood time points or between similar geographic areas affected vs. unaffected by flooding.
- **Case detection:** Studies should rely on a well-defined, consistent case detection and enrollment procedure, preferably using an existing active or passive disease surveillance system. Any necessary changes in methodology for confirming cases should be detailed clearly, including laboratory methods performed, to adjust for variation in sensitivity and specificity of the test and the system.
- **Investment in surveillance and research capacity:** Further investment is critically needed to build local research capacity and surveillance systems in the geographic areas currently most at risk for transmission of MBD. Health inequities are stark and will increase under the current climate change trajectory (Ebi et al. 2018; Ebi and Hess 2020; Smith et al. 2014). Knowledge base and capacity must be built to mitigate these disparities.
- **Flooding definitions:** It is not possible to proscribe a standardized definition for flooding. The World Meteorological Organization encourages the use of locally specific guidelines as to what constitutes a flood, because this depends on terrain, drainage, typical weather, and other local conditions (World Meteorological Organization 2021). For studies reporting on the occurrence of distinct flooding events, these locally relevant definitions should be clearly reported, preferably with reference to typical weather patterns in the area. Furthermore, most studies rely on secondary analysis of meteorological variables collected by other sources, limiting available options. Flood severity metrics should either be described for a singular event or included in analyses comparing multiple flood events. These can include the duration of persistent flood waters, measures of population affected, or extent of land area affected. When the only available secondary measure of flooding is cumulative daily or monthly rainfall amounts, studies should consider using splines or a categorical analysis to fit potential nonlinear effects in the case of heavy rainfall that leads to flooding that may flush out typical breeding sites. With increasing availability of remotely sensed satellite data, such results could be enhanced by the quantification of land areas covered by water during flood periods where water is not normally present, such as calculating a normalized differential water index (NDWI) (Sivanpillai et al. 2021).
- **Vectors:** Studies should comment on the known endemic vector species, even when vectors are not being captured directly and, when possible, incorporate vector monitoring or entomological indices into study.
- **Lag periods:** Studies should quantify effects at various lag periods following flooding events, to include acute (within 1 wk), sub-acute (1 wk–1 month), medium term (1–4 months), long term (>4 months–1 y), and subsequent years, or more detailed time points if possible. In particular, studies that examine long-term effects due to lags in recovery or changes in vector ecology and human susceptibility are currently lacking in the literature.
- **Bias assessments:** Future analyses should comment on or adjust for potential biases that may be introduced by major population or systems changes subsequent to the occurrence of major disasters. For instance, human migration patterns following flood may have significant impacts on population denominators for disease incidence calculations; disaster events may reduce the accuracy of case detection and reporting; or, conversely, emergency relief systems may increase screening and identification of infected individuals, particularly if the flooding leads to informal housing settlements for displaced individuals.
- **Collaboration/generalizability:** We recommend attempts to systematically collect and analyze data across multiple sites and diseases using standard methods. We also recommend

that studies attempt to quantify socioenvironmental and human behavioral factors that may confound or modify relationships between flooding and disease risk—an influence that is assumed but not quantified in the literature (Banu et al. 2011). Important potential mediating variables may include socioeconomic status of the population, especially things like population density and housing structure quality, which regulate the extent of human–mosquito contact; proximity to zoonotic host species where relevant; baseline endemicity of different MBDs; extent of structural damage and population displacement; extent of vector control efforts; and other climate and weather factors like season, typical rainfall patterns, temperature, and humidity. Investigating these potential mediating factors across multiple sites will improve our ability to generalize such results to areas with limited local data availability and refine our strategies for disaster response.

- **Data integration:** There is an urgent need to have routine integration of disparate data systems to facilitate investigations into extreme weather events and infectious disease (and other public health) outcomes. Although this review focuses on primarily precipitation-driven events and MBD outcomes, it also highlights current limitations more broadly in integration of data related to biodiversity of vectors and zoonotic health species, weather and climate data, social systems and behaviors, public health and medical infrastructure and support, and disease monitoring and surveillance (both human and animal). Questions regarding the role of extreme heat events on disease systems and influence of shocks to food systems on pathogen transmission and human susceptibility, etc., will all require an integrative One Health approach to data that harmonizes spatial and temporal scales.

Strengths and Limitations

Although there have been numerous partial reviews of this topic, to our knowledge this is the first systematic attempt to review the quantitative and qualitative data available on flooding and MBD incidence. Key strengths of this review include the comprehensive search effort and breadth of languages considered ($n=5$), although exclusion of other languages may have led to missed information. Our search strategy was broadly inclusive and had good specificity (21.9% of initial results for title/abstracts went to full text review). However, the literature we identified had limited interpretability pertaining to our research question due to inconsistencies in study design, analysis, and reporting, especially regarding temporality of measured disease end points, which indicates a strong level of detection bias. Individual publications that presented results as outbreak case studies in the absence of any comparison group, metrics on the event, or statistical testing made little if any contribution to the overall strength of evidence presented in this review.

Additionally, the effects of human activity/response and other mediating variables are likely important but were not addressed consistently and comparably in the identified literature, e.g., vector control measures, rescue workers introducing a disease to a previously isolated population, human migration, and immunity. Finally, we did not include studies of ENSO impacts unless flooding was specifically indicated; therefore, ENSO-related variability may merit additional review.

The inclusion of tsunami events may not seem directly relevant to climate-related natural disasters. However, with climate change–induced sea level rise and the decline of protective reef ecosystems, there are indirect associations between climate change and increased tsunami risk (Shao et al. 2019). Given that 40% of the world's population lives within 100 km of coastal areas (Office for Coastal Management, National Oceanic and Atmospheric Administration 2020), vector-borne disease dynamics following inundation with brackish water merit further exploration.

Public Health Implications

Our scoping review highlights a general need for improved surveillance systems in the most vulnerable global areas. Strong foundational knowledge of which types of flooding events lead to increases for particular diseases under which temporal and geographic contexts will be helpful in disaster planning, surveillance, and management. For example, prioritizing measuring malaria risk and implementing prevention and control strategies following flooding events after heavy rainfall may be more important than after tsunamis, cyclones, and hurricanes. There may be a brief respite in dengue case incidence immediately following flooding, though vector-control measures should be intensified in the first week or two following floods to prevent a subsequent spike in cases. However, gaps in the quality of the evidence found in this review highlight key domains where surveillance and research can focus to obtain more consistent pre-event numbers for reliable comparisons. First, population denominators should consider predisaster measurements for comparison after the event, confirming the importance of disease surveillance systems. Second, clearer reporting of specific timing of disease or outcome incidence post flooding will help clarify the complex and dynamic trends in risk at different latency periods in the aftermath of these events. Third, attempts should be made to share data and pursue methodological consistency to improve generalizability of study findings about flood and MBD associations. As the effects of climate change amplify, it is likely that competency differences between vector species will become more apparent, meaning that species and subspecies identification is critical in future work.

Conclusions

An overall positive relationship between flooding and incidence of malaria, dengue, and other MBD likely exists, but the current literature on the topic is insufficient to make interpretations about the strength and precise timing of these relationships. This review emphasizes the need for rigor and consistency in research methods for improved natural disaster planning and preparation regarding MBD and other disease systems susceptible to increasingly common extreme weather events.

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