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# Drivers Of Global Waterborne Disease Transmission Following Extreme Precipitation Events: A Systematic Review

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# Drivers of Global Waterborne Disease Transmission Following Extreme Precipitation Events:
# A Systematic Review

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## Abstract

Precipitation events such as hurricanes, typhoons, and heavy rainfall can have devastating impacts on water and sanitation infrastructure around the world and have led to large-scale waterborne outbreaks. As climate change amplifies the frequency and intensity of extreme weather events, it is also triggering an increase in waterborne disease transmission. This master's thesis consists of a systematic review of academic literature pertaining to extreme precipitation events and the pathways by which they trigger waterborne outbreaks.

A systematic review of the literature in PubMed was conducted to identify waterborne disease outbreaks associated with extreme precipitation. The initial search yielded 3,248 results for title and abstract screening, of which 173 full-text articles were subsequently retrieved and screened on inclusion criteria of extreme precipitation, waterborne disease outcomes, and importantly, discussion of mediators and mechanisms driving the association. Ultimately, 57 studies were included in the review, representing study locations in 73 countries. The waterborne diseases studied were primarily gastrointestinal illnesses and were caused by bacteria, viruses, and parasites. The most common pathogens studied included bacteria of the genera *Leptospira* (23%) and *Shigella* (11%), as well as parasites of the genus *Cryptosporidium* (11%). Heavy rainfall (33%) and flooding (32%) were the most common events associated with waterborne disease outbreaks.

Ultimately, the most common mediators of waterborne transmission following an extreme precipitation event were (1) hydro-ecological risk factors, related to runoff from industrial, agricultural, or environmental sources  (2) infrastructural risk factors, resulting from damage to or disruption of WASH (Water, Sanitation, and Hygiene) infrastructure, (3) socio-behavioral risk factors, arising from existing vulnerabilities or from changes in activities and behaviours, and (4) physical risk factors, due to contact with contaminated storm water or floodwaters. By examining and understanding these climate-related drivers of waterborne disease transmission, we can begin to envision better mitigation and prevention strategies to protect public health around the globe.

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## Introduction

The increasingly urgent threat of climate change has had profound impacts on meteorological patterns as well as socio-ecological systems. Among these, changes in the global hydrologic cycle have disrupted normal weather patterns and amplified the frequency and intensity of extreme weather events, floods, droughts and heatwaves.[1] While these meteorological changes have come with many significant human health impacts, one in particular – the exacerbation of extreme precipitation events – has been specifically associated with risk of waterborne disease transmission and burden.[2–4]

A major question that remains in our understanding of these associations is how exactly such precipitation influences waterborne disease outcomes and vulnerabilities, and what pathways or mediators are driving this association. Globally, and especially in low- and middle-income settings, mitigating the transmission of waterborne diseases is a crucial aspect of water, sanitation and hygiene (WASH) programming in public health.[5] Thus, it is highly relevant to study these pathways in order to prioritize prevention and mitigation efforts.

Much of the existing literature has highlighted the relationship between climate and health, and more specifically, between heightened precipitation events and waterborne disease transmission.[2,4] With a range of etiologies including unsafe drinking water, contact with contaminated water, or poor sanitation and hygiene options, waterborne diseases contribute to major health burdens across the world. In 2015, the Global Burden of Disease study attributed an estimated 1.2 million deaths and 71.7 million disability-adjusted life years (DALYs) to contaminated water.[6] Highly sensitive to climatic variability, this burden is likely to grow as precipitation events become more intense and unpredictable.

This systematic review aims to address two gaps in the study of waterborne disease transmission associated with extreme precipitation events. The first is that the study of these

specific climate events has generally remained limited to associations through epidemiological studies of disease outcomes, linking climate impact and its health outcomes, but without identifying the mediators that drive transmission and disease in this process, e.g., the specific mechanisms which create these vulnerabilities and drive these associations. For example, in the study of other types of infectious diseases, such as vector-borne diseases, researchers have been able to better highlight the mediating mechanism linking relevant climate events and infectious disease outcomes. Vector-borne diseases have been shown to thrive due to increased precipitation, primarily due to improved vector breeding grounds (e.g., more pools of stagnant water after storms),[7] but also in part due to changes in vector or reservoir behaviors (e.g., vector or reservoir migrations or population expansion following a climatic event).[8,9] These mechanisms have been evaluated numerous times, and in this way, the primary steps of the climate cascade are well-understood, such as the climate effect, the mechanisms of action, and the disease outcomes.[9,10] Thus, part of the aim of this review is to systematically assess and synthesize the mediators, or potential mechanisms, underlying the relationship between precipitation and waterborne disease. For waterborne disease transmission to be better understood and addressed, it is crucial that we better understand the mechanisms at hand.

The second gap this review aims to address is the greater use of a global, broad perspective. Existing reviews often highlight disease-specific or region-specific associations between climate events and infectious disease outbreaks.[11,12] Nevertheless, there is value in examining and synthesizing the global landscape and highlighting the mechanisms by which waterborne diseases are influenced by climate-change-related precipitation events at a global scale. By elucidating the climate-related drivers of waterborne disease outcomes, we can begin to consider mitigation and prevention strategies for vulnerable regions across the globe.

*Hypothesis & Rationale*

Studies in the existing literature outline mechanisms of waterborne disease transmission.[4,7,13] For each outbreak or disease transmission event, these mechanisms can vary, ranging from biological to behavioral, affecting the environment and engineering, and sometimes combining and overlapping considerably.[13] Thus, it is relevant to systematically examine the relationship between these mediators and their involvement in climate-related waterborne disease outbreaks.

We hypothesize that four primary mediators play a role in the fate of waterborne diseases, acting in of overlapping, interconnected, and compounding ways. These notably include (1) **hydro-ecological** factors**,** such as runoff from industry, agriculture, and environmental sources; (2) **infrastructural** factors, such as damage to or disruption of WASH infrastructure; (3) **physical** factors**,** including contact with stormwater or contaminated floodwaters; and (4) **socio-behavioral** factors, including the exacerbation of social vulnerabilities or change in activities caused by the extreme precipitation event. This review aims to systematically assess and synthesize the evidence surrounding these interconnected mediators and their broader implications for mitigation and prevention in the face of rapidly progressing climate change.

## Methods

**Search Strategy**

This search was conducted using PubMed as the primary source of peer-reviewed articles. The search terms, consisting of a waterborne disease domain and a precipitation domain, can be found in Supplemental Table 1. Search results were limited to English-language articles from February 18, 2013-February 17, 2023, to capture the most recent climate change impacts and developments, which are rapidly modifying the infectious disease landscape. Articles were screened based on titles and keywords, followed by an abstract review. Full-text versions of all remaining articles were subsequently downloaded and screened for inclusion.

**Inclusion and Exclusion Criteria**

Inclusion criteria were as follows:

- *Literature type:* Peer-reviewed, full-text primary research articles and epidemiological studies, including randomized-control, ecological, time-series, cohort, cross-sectional, observational, spatio-temporal studies.
- *Event:* Heavy precipitation or extreme weather events.
- *Outcome:* Outbreaks or increased incidence of waterborne disease, as previously defined
- *Population*: Any populations or regions of the world
- Particular interest was given to studies examining or theorizing about the specific mediators that could be underpinning the association between the weather event and the waterborne disease outcomes.

Exclusion criteria were as follows:

- *Literature type:* Inappropriate or irrelevant study designs or publication types, including review articles, protocol papers, pre-prints, and grey literature.

- *Event:* Other climate change impacts (eg: temperature increase, droughts, sea level rise, etc.); non-extreme seasonal/habitual weather events; floods without mention of extreme precipitation events causing them; precipitation not qualified as unusual or extreme

- *Outcome:* Food-borne, vector-borne, environmental diseases, or other diseases which are not primarily transmitted through water, *ie*: not waterborne as previously defined; projections of potential future cases

- *Population*: Non-human populations or non-human health outcomes

**Extraction**

After screening full-texts and obtaining a final body of included articles, the relevant data was extracted according to PRISMA guidelines and recorded into an Excel file. Data extraction categories and the corresponding coding can be found in Table 1.

**Quality Control**

The quality of included studies was evaluated based on study design, qualitative or quantitative outputs, and ascertainment of climate exposures, mediators and outcomes (systematic or not). Based on these criteria, the studies were subsequently assigned a quality rating of either "low," "moderate," or "high." Studies with ongoing surveillance or systematic ascertainment of climate exposures, outcomes and mediators received a rating of "high" quality. Studies with ongoing surveillance of two of these three components, but with non-systematic or interrupted ascertainment of the third, received a rating of "medium" quality. Studies without systematic ascertainment or ongoing surveillance for any of the components, or for only one of the three, received a rating of "low" quality in terms of the value of the evidence.

**Table 1: Data extracted from included articles.** *Data was extracted from 57 included articles and systematically recorded, coded and classified in a Microsoft Excel file.*

| Data Extraction Categories | Extraction classification category |
|---|---|
| Author | Name |
| Year of study | Year |
| Study location | Location, Country |
| Study design | Design and general characteristic<br>*(e.g.: retrospective cohort study)* |
| Duration of study | Study initiation month/year – study end month/year |
| Type of extreme precipitation event | Heavy precipitation / Extreme precipitation / Flooding following precipitation / Typhoon / Hurricane / El-Niño-related event / La Niña-related event |
| Pathogens studied or reported | Genus/species, or pathogen type<br>*(e.g. "Vibrio cholera", "gastrointestinal pathogen")* |
| Health outcomes being studied (cases, deaths, YLDs, hospitalizations…) | Description of health outcome<br>*(e.g.: "pediatric healthcare visits for gastrointestinal illness", "clinical and confirmed cases of leptospirosis")* |
| Outbreak size | Number of cases<br>(N/A if no outbreak reported) |
| Associations between extreme precipitation event and health outcome | Positive / negative / null<br>If quantified, numeric value<br>*(e.g. odds ratio, relative risk)* |
| Qualitative association between suspected mediator/driver and outbreak/disease incidence | Reports or descriptions of risk factors, drivers<br>*(e.g."runoff of fecal matter from nearby poultry farms contaminating stormwater")* |
| Quantitative association between suspected mediator/driver and outbreak/disease incidence | Measured levels of a mediator suggesting the presence of the mechanism: odds ratio, relative risk, spatial modeling, etc.<br>*(e.g. "high viral concentrations in floodwaters", "higher odds ratio among individuals drinking municipal tap water")* |

**Analysis**

Following data extraction and quality control, we conducted a descriptive analysis of the studies' locations, time periods, quality, event description, pathogen, outcomes assessment, and suspected mechanisms. This provided a profile of the characteristics of the articles obtained through our search, as well as highlight any potential gaps.

With these data extracted, we highlighted associations between extreme precipitation events and pathogens to establish the existing links between climate exposures and disease outcomes. Upon examining the reported mediators, we were able to identify key themes and categorize the mediators into four primary categories. A conceptual model was created to visually summarize the findings of this review and the categorization of mediators.

Finally, we also identified salient gaps in the literature with regard to study locations, pathogens, vulnerable populations, and overlooked mediators. Together, these findings can contribute to highlighting research gaps or informing public and global health recommendations for future research and interventions.

# Results

The initial literature search performed in PubMed yielded 3,248 results. (Fig. 1, Supp. Table 1) Following the title/abstract screening, 173 articles were retained based on the relevant inclusion and exclusion criteria, including study design and specific focus on waterborne diseases and extreme precipitation. Subsequently, a full-text screen was conducted to identify studies which discussed suspected or confirmed mediators of the relationship between waterborne disease and extreme precipitation events. Based on the pre-determined inclusion and exclusion criteria, 57 articles remained and were included in the final review.[14–70]
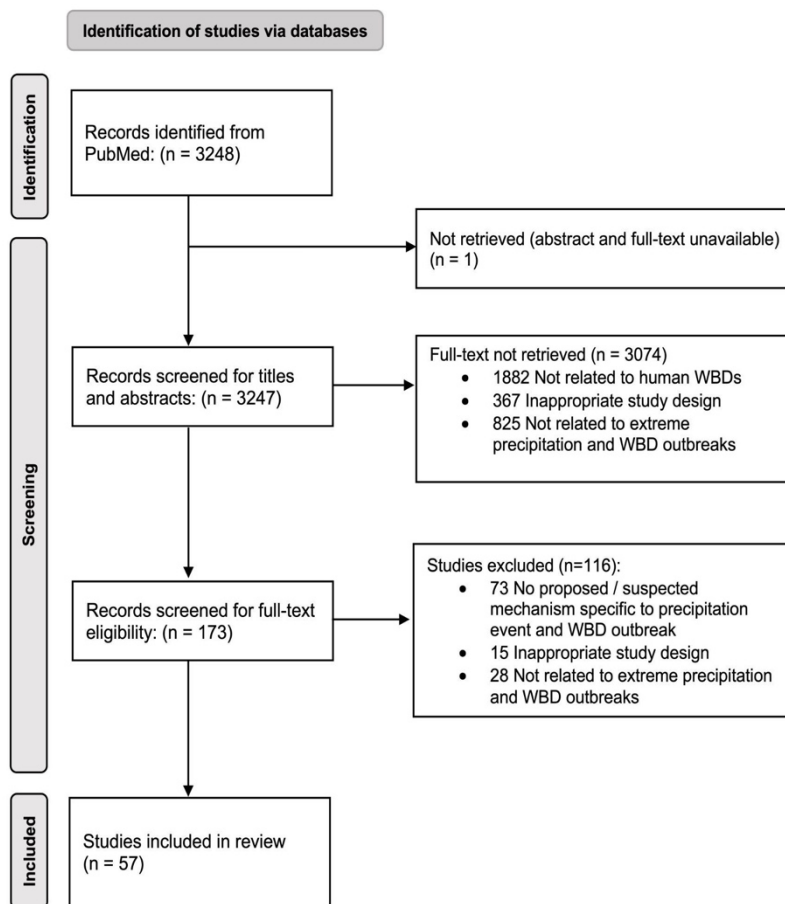


**Figure 1: PRISMA flow chart of Systematic Review Screening and Inclusion**
*Flowchart of the identification, abstract screening, full-text screening, and inclusion of studies in this systematic review.[79]*

The majority of studies were of high (46%) or medium (44%) quality, according to previously outlined criteria. Only 11% of studies were categorized as low quality (Supp. Table 2), and these were primarily case series, with little to no systematic ascertainment of extreme precipitation events or mediators. The higher prevalence of medium- or high-quality studies may be due to the fact that the inclusion criteria were stringent enough to typically require systematically ascertained, quantitative data in order to be included in the final review.

The articles consisted primarily of ecological studies (49%), most of which were time series studies (42%). Other study designs included cross-sectional studies (12%), cohort studies (14%), case-crossover (7%) and case-control studies (7%).



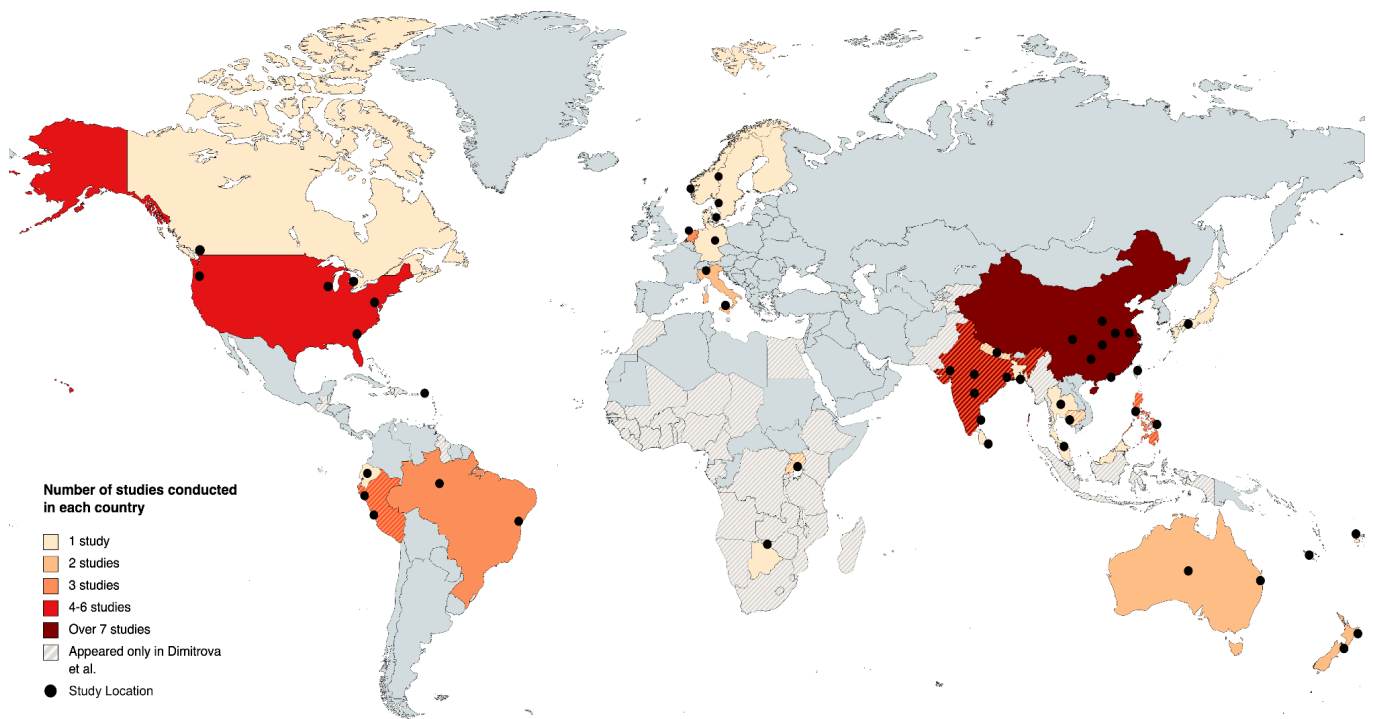**Figure 2. Global distribution of studies on waterborne diseases associated with extreme precipitation events.** *Studies were mapped according to the number of times they appeared in the included studies. Several countries, indicated by gray cross-hatching, appeared only in Dimitrova et al. Countries appearing in Dimitrova et al. as well as separate studies were cross-hatched in their corresponding count color.*

*Global Distribution*

The studies were conducted across 73 countries (Fig. 2). One study by Dimitrova *et al.*,[69] conducted a large-scale ecological study examining meteorological and health data from 51 low- and middle-income countries. The other 56 studies included locations in 28 countries. Across all studies (excluding the countries discussed only in Dimitrova *et al.*), the most common continents of study were Asia (42%), Europe (18%), and North America (12%). This distribution suggests a major gap in research in many low- and middle-income regions, notably in South America and Africa. Meanwhile, the range of publication dates was fairly evenly distributed, with the most common publication years being 2020 (14%) and 2018 (12%).

*Extreme Precipitation Events*

The most common precipitation events (Fig. 3, Supp. Table 4) were heavy precipitation and/or rainfall (33%) and flooding following precipitation (32%). The more intense, extreme events, such as tropical cyclones (hurricanes and typhoons), or ENSO-related events (El Niño and La Niña), were less frequent, appearing in 6 (11%) and 7 (12%) studies, respectively. This may reflect the lower frequency of very intense events compared to more moderate or seasonal ones, including monsoon events. Otherwise, it may also reflect the relative specificity of the terms used to classify precipitation events and their definitions (with "tropical cyclone" being a more specifically defined event than "heavy rainfall", for example).
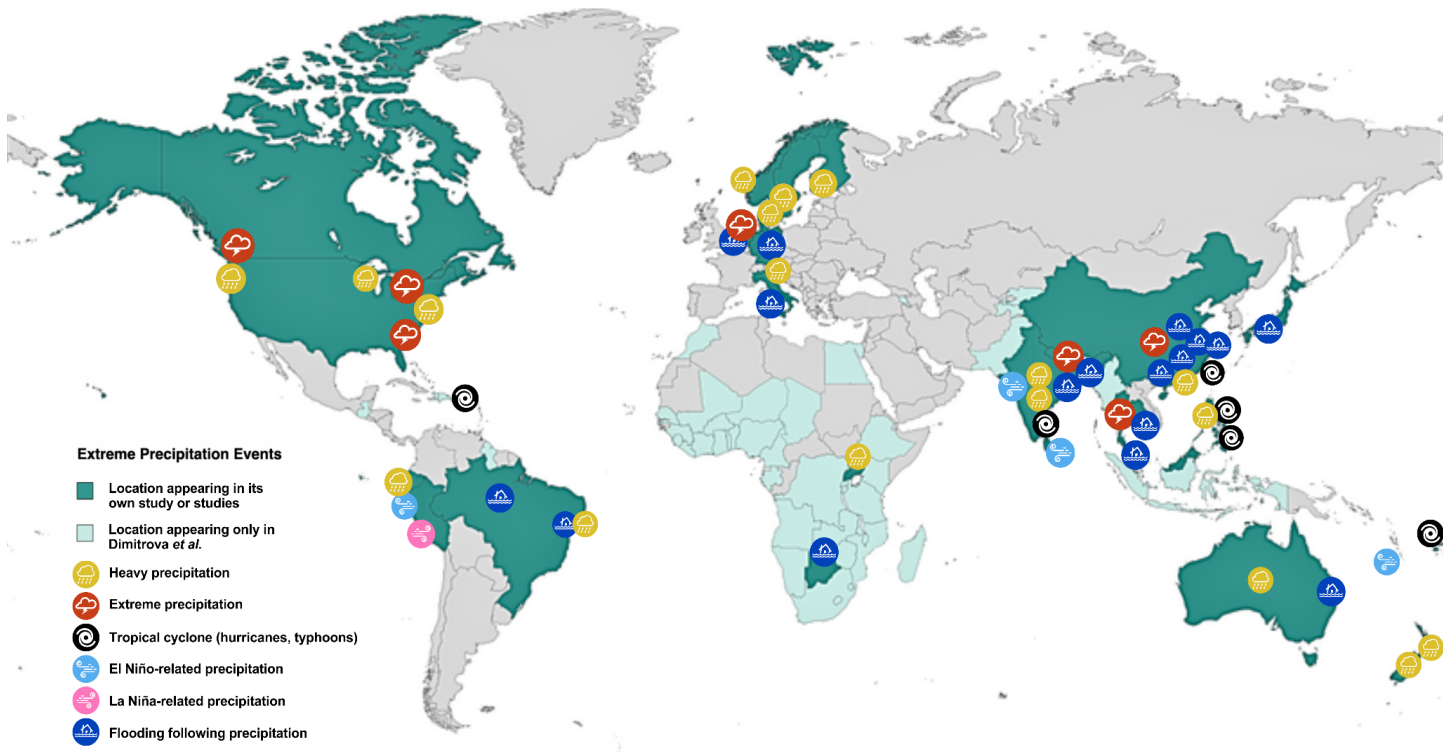
**Figure 3. Global distribution extreme precipitation events with reported waterborne disease outcomes.** *The precipitation events recorded in each study location are depicted with corresponding symbols. All countries included in Dimitrova et al. studied "heavy precipitation" events, and are not pictured as icons on this map.*

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## *Waterborne Pathogens & Disease Outcomes*

With respect to pathogens and diseases, 16 pathogenic organisms were studied or identified (Supp. Table 3). The most frequently identified pathogen among the 57 reports were the bacterium *Leptospira* and its infection, leptospirosis, with 13 studies (23%), followed by the bacterium *Shigella* (11%) and parasite *Cryptosporidium* (11%) with 6 studies each. The only larger category was that of gastrointestinal illnesses as a whole (designated by various titles, including acute diarrheal disease, gastroenteritis, etc.) for which a pathogen was not confirmed.

These unconfirmed or unspecified general gastrointestinal illnesses were the focus of 14 studies (25%) (Fig. 4).

Nearly all studies (96%) reported positive associations between waterborne disease and extreme precipitation events. Among those which reported quantitative outcomes, the relative risk of waterborne disease following an extreme precipitation event ranged anywhere from 1.13 to 11.47. [24,33] Twenty-nine studies reported discrete waterborne disease outbreaks, ranging from 2 cases to 8867 cases.[43,66] The remaining studies which did not report specific outbreaks were nearly all time-series or ecological studies spanning many years.

Only two studies, by Chong *et al*. and Wang *et al*., reported a negative association between the extreme precipitation event and cases.[14,62] They were included because they clearly reported and discussed which aspects of the suspected pathway had *not* been implicated. For example, Chong *et al*. clearly reported that the water infrastructure was confirmed to have not leaked or broken during the precipitation event, and also that the water supply, stormwater drainage and sewage management systems in Hong Kong are separate and independent.[14] Meanwhile, Wang *et al*. reported that the heavy rainfall had prevented outdoor activity and interpersonal contact for an extended period of time.[62] They also suspected that in this high-income urban setting, the city of Chongqing, China, heavy precipitation may have washed away many existing pools of pathogen growth. In both cases, the study locations were high-income, urbanized areas.[14,62]
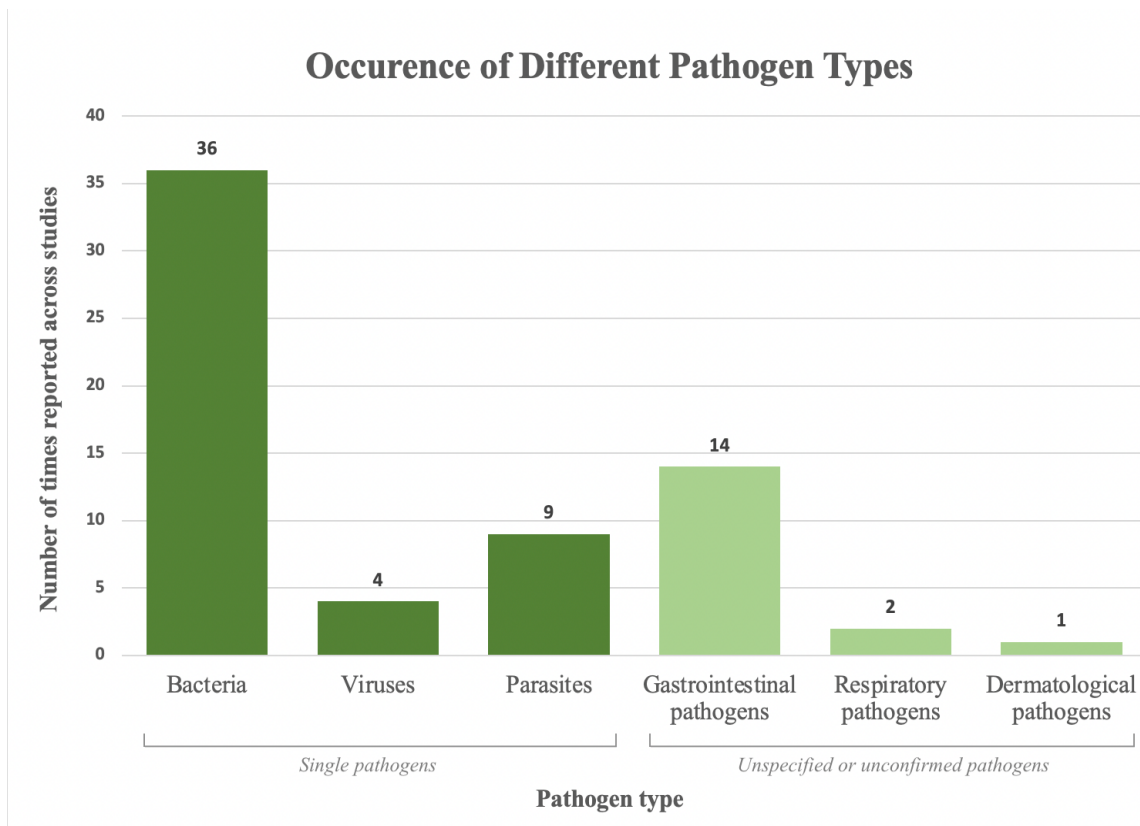
**Figure 4. Occurrence of pathogen causes of waterborne diseases associated with extreme precipitation events across 57 studies.** *The most frequently reported pathogen type was bacteria, followed by unspecified or unconfirmed gastrointestinal pathogens, and parasites. There were few reports of viruses, respiratory pathogens or dermatological pathogens.*

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***Suspected or Reported Mediators***

The most frequently reported pathway or suspected mediator of waterborne infection was infrastructural (ie: related to damage or disruption of WASH infrastructure), discussed in 38 papers (67%) (Table 2). The other pathways discussed most frequently were physical (ie: contact with floodwaters), hydro-ecological (ie: runoff from nonpoint sources), and socio-behavioral (ie: poverty, displacement, occupational or recreational activities), which were discussed in 24 (42%), 21 (39%) and 22 (37%) papers, respectively. The mediators most frequently reported for a waterborne pathogen were often reflective of the pathogen's typical modes of transmission. For

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example, *Leptospira*, a bacterium spread through contact with rodent urine,[52] was most frequently associated with contact with floodwaters, whereas *Shigella* and *V. cholera*, bacteria usually contracted through unsafe drinking water,[71,72] were most frequently associated with disrupted WASH infrastructure (Table 2).

### *At-Risk and Vulnerable Populations*

Numerous studies highlighted higher risks of infection among at-risk and vulnerable populations. Seven studies (12%) observed that, when stratified by age and sex, the risk of infection was typically higher among adult males. This is likely driven by the type of disease and mediator. Four of the seven studies were focused on leptospirosis, while the three others studied *V. cholera*, *Shigella*, and Hepatitis E. Most of the studies suspected that it could be due to men being tasked with post-flood assistance, repairs and clean-up, which typically entails wading through floodwaters or coming in contact with contaminated water.

Similarly, seven studies (12%) focused on pediatric outcomes, as children are among the most vulnerable and sensitive groups to waterborne infection. Four of the seven studies were focused on unspecified gastrointestinal illness, while the three others studied the enteroviral infection Hand, Foot and Mouth Disease (HFMD), as well as *Cryptosporidium* and *E. coli.*

One study, by Hines et al., also studied an outbreak of shigellosis among homeless persons in Oregon following an extreme precipitation event in 2015.[40] The outbreak of 105 cases was reported to be a consequence of social vulnerabilities, which can increase the risk of infectious waterborne disease.[40] It is crucial to shed light on these vulnerable populations in order to better prioritize, design and implement public health interventions to address waterborne disease transmission.

**Table 2: Reported mediators of the relationship between extreme precipitation events and waterborne diseases.** *Quantitative and qualitative data relating to the suspected drivers of waterborne disease transmission and the primary related pathogens were extracted from 57 studies and categorized thematically.*

| Suspected/Proposed Mediators | Studies involved (%) * | Examples of important pathways discussed | Selected pathogens related to mediator (%) ** | Assessment of mediator |
|---|---|---|---|---|
| **Hydro-ecological pathway** | 21 (37%) | - Runoff from concentrated animal feeding operations sources into drinking water<br>- Runoff from wildlife and environmental sources<br>- Runoff seeping into surface water or groundwater used as drinking water source<br>- Higher turbidity leading to insufficient or inadequate water treatment | *Cryptosporidium* (19%)<br>*Leptospira* (14%)<br>*Giardia* (10%)<br>*Campylobacter* (10%) | Quantitative (33%)<br><br>Qualitative (67%) |
| **Infrastructural pathway** | 38 (67%) | - Leaking or cracking of pipes or reservoirs<br>- Damage to wells and latrines<br>- Illicit cross-connections between sewage and drinking water supply systems | *Shigella* (16%)<br>*V. cholera* (13%)<br>*Cryptosporidium* (13%)<br>*Campylobacter* (8%)<br>*Giardia* (8%)<br>*Leptospira* (8%)<br>*E. histolytica* (5%)<br>*E. coli* (5%)<br>*Salmonella* (5%) | Quantitative (37%)<br><br>Qualitative (63%) |
| **Physical pathway** | 24 (42%) | - Contact with floodwater<br>- Post-flood cleanup activities<br>- Aerosolization of pathogens while driving or biking through floodwaters | *Leptospira* (54%)<br>*Shigella* (13%) | Quantitative (26%)<br><br>Qualitative (74%) |
| **Socio-behavioral vulnerabilities** | 22 (39%) | - Poverty leading to insufficient or nonexistent waste disposal systems<br>- Displacement after extreme climatic events<br>- Occupational exposure (ie: working in rice paddies) | *Leptospira* (32%)<br>*Shigella* (18%)<br>*E. histolytica* (9%) | Quantitative (23%)<br><br>Qualitative (77%) |

*does not sum to 100% due to involvement of multiple mediators per study; **does not sum to 100%, includes only primary selected pathogens affected by the reported mechanism
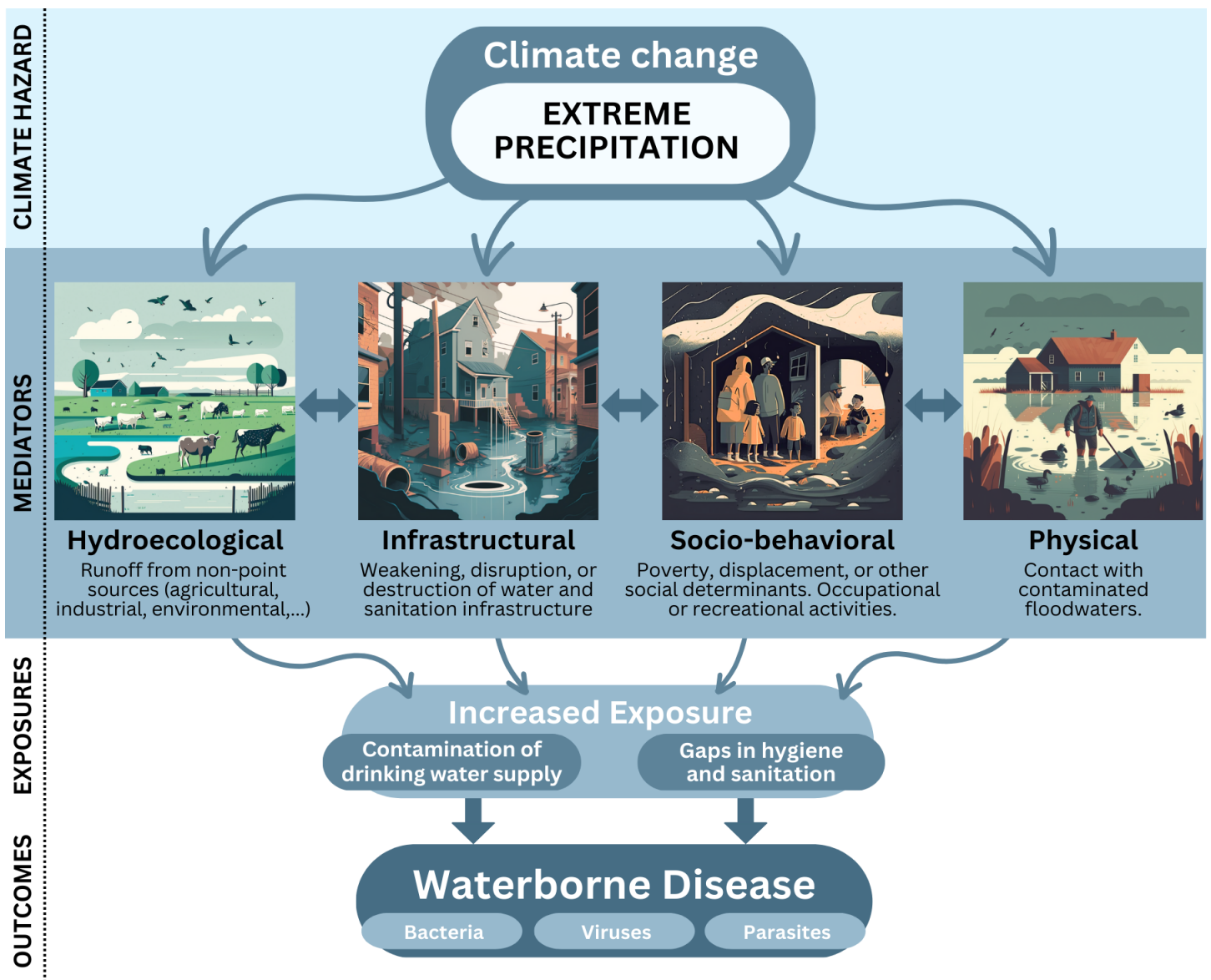
## Discussion



**Figure 5. Conceptual model of findings.** *The mediators reported in the 57 studies were synthesized into four primary categories and visualized in a conceptual model of the climate-disease cascade. This can help us better conceptualize potential mitigation and prevention areas for waterborne diseases.*

The most common precipitation events (Fig. 3, Supp. Table 4) tended to be heavy precipitation and flooding following precipitation, with the more extreme climatic events such as El Niño/La Niña and tropical cyclonic storms appearing less frequently. This could be due to the more precise definition of these events, such as ENSO-related events referring to the oscillation of ocean surface temperature which affect global weather and rainfall patterns, and tropical cyclones referring specifically to the low-pressure, rotating tropical storm systems that form hurricanes and typhoons.[34] Meanwhile, "heavy rainfall" and "flooding" are more general and therefore encompass a broader range of precipitation events, including monsoon-related precipitation events, which spanned multiple categories due to its wide range of possible impacts. This finding may also reflect the frequency of these storms in real life — in fact, more extreme storms may still be overrepresented in this review, appearing so often due to the severity of the storms and their impacts.

In terms of pathogens and diseases, the most frequently studied were *Leptospira* (21%), *Shigella* (11%) and *Cryptosporidium* (11%) (Supp. Table 3). This finding highlights not only the prevalence of different types of pathogens – bacterial and parasitic – but also their sensitivity to climate variability, as they were the etiology of numerous outbreaks following heavy precipitation events. That said, viruses were significantly less frequently discussed than bacteria and parasites, appearing in only 4 studies (7%) where a specific pathogen was reported (Fig. 4). This could be due to a number of factors, including greater sensitivity to heat inactivation in tropical climates, or washing away during precipitation events.[14,62]

Crucially, in the study of the mediators of waterborne disease transmission following extreme precipitation events, the infrastructural pathway was the most salient, by which disrupted WASH systems lead to drinking water contamination or gaps in sanitation and

contribute to an increase in waterborne disease incidence. Reported in 67% of studies, this pathway is among the most amenable to public health action or intervention and represents an opportunity for mitigation and prevention of waterborne disease outcomes.

The three other hypothesized mechanisms also appeared frequently and contributed to waterborne transmission. The physical pathways (*i.e.,* contact with floodwaters) were reported in 42% of studies, the hydro-ecological pathways (*i.e.,* runoff from nonpoint sources) were reported in 39%, and the socio-behavioral pathways (*i.e.,* poverty, displacement, occupational or recreational activities) were reported in 37% of studies. These findings support our hypothesis, which suggested that these four pathways were the primary mediators of the relationship between extreme precipitation events and waterborne disease transmission. Thus, extreme precipitation events can disrupt existing environmental, infrastructural, and social processes in a variety of overlapping, interconnected, and compounding ways, and by extension, impact waterborne disease transmission. Nevertheless, future research should be conducted to further quantify these associations and potentially establish more robust causal mechanisms.

The spatial distribution of the studies reviewed depicts key gaps in global research on waterborne diseases and their association with extreme precipitation events (Fig. 2). 56 of the studies covered study locations in 28 countries, and one study, by Dimitrova *et al.*, conducted a large-scale ecological study of data from 51 low- and middle-income countries, 45 of which were not covered by the other independent studies. When excluding the countries from Dimitrova *et. al*, only 2 African nations appear among the study locations. Meanwhile, research has shown that the African continent, and sub-Saharan Africa in particular, will suffer more frequent and intense meteorological changes due to climate change, which will likely trigger more unpredictable precipitation events and, by extension, waterborne disease outbreaks.[5,73] In a region with a majority of low- and middle-income countries with limited infrastructure, this

could have severe consequences for disease transmission and overall public health. With clear spatial gaps appearing on the map (Fig. 2), it is essential to promote further research in underrepresented regions to address those research gaps.

Despite these global gaps in distribution, many of the studies still focused on low-income cities, regions or countries, emphasizing many of the vulnerable communities within those areas who are at higher risk of infection due in many cases to social or infrastructural vulnerabilities. In addition, the study by Hines *et al.* even highlighted the vulnerabilities of low-income populations in high-income countries, as the outbreak of shigellosis was suspected to have been precipitated by a number of social vulnerabilities, including poverty, crowding in shelters, poor sanitation, and contamination of untreated drinking water. Another interesting finding that was encountered in several studies was the observation that, when stratified by age and sex, the risk of infection was typically higher among adult males, a reality mentioned in 12% of studies. Most of the studies highlighting this difference suspected that it could be due to men being given the task of cleaning up post-flood or wading through floodwaters to attend to their families' or neighbors' needs. Children, another major vulnerable population, were the focus of 12% of studies in this review. This is not unexpected, given that children – especially children under the age of 5 – are typically at higher risk of waterborne illness and death than adults.[14] Ultimately, it is relevant to consider these vulnerabilities, whether related to age, sex, or socio-economic status, when conducting research or implementing health interventions, as different populations and groups may have a wide range of needs.

One pathway which was not originally included in our hypothesis but appeared in several studies and require future research was the potential pathway of pathogen growth and survival. Nine studies (16%) discussed the theory that wetter conditions favored the growth, proliferation, and survival of pathogens in the environment. This could be due to favorable temperature and

humidity, greater availability of suspended nutrients, or the washing away of predators after heavy precipitation. While research exists supporting these mechanisms,[74–76] it could be relevant to integrate both epidemiological and microbiological fields of research and use these findings to further examine this microbial aspect of the relationship between extreme weather events and waterborne disease outbreaks.

The pathogens and illnesses encountered in these studies reflect the wide breadth of public health threats posed by waterborne agents. Consisting of bacteria, viruses, and parasites alike, the pathogens encountered in these studies require a variety of control mechanisms, each with their strengths, limitations, and implementation difficulties. For example, parasites such as *Cryptosporidium spp*. oocysts or *Giardia spp*. cysts are more resistant to water treatment processes such as chlorination, coagulation, and filtration and can therefore be difficult to treat if other methods such as UV treatment are unavailable.[77] Additionally, the ability for some pathogens such as *Legionella pneumophila* to remain suspended in aerosolized water droplets makes it both a respiratory pathogen and, in some cases, a gastrointestinal pathogen as well.[77] These findings call for an adaptable approach to public health prevention and mitigation, one that is prepared for outbreaks of different types, magnitudes, and etiologies.

Existing research suggests that the upstream drivers of waterborne outbreaks, extreme precipitation events, will become more frequent and intense as the global climate changes. This will likely increase the risk of these outbreaks, especially in regions and cities with aging or poorly designed infrastructure. Through the many biological, environmental, and social pathways discussed in this review, extreme precipitation events will pose a major threat to infectious disease health around the world. Even in regions where droughts occur, the flood-pulse dynamic of droughts followed by flooding — referred to as the "concentration-dilution hypothesis" and discussed in five studies (9%) in this review — is also likely to exacerbate

waterborne disease transmission.[45,78]  With climate impacts occurring more frequently and unpredictably, it is crucial to continue conducting research in order to inform mitigation and prevention strategies that take into account the climate sensitivity of waterborne disease transmission.

**Limitations**

This systematic review carries several limitations. First, the review was conducted by a single reviewer and with strict time constraints, which could have affected the profile of studies included in the review. In order to maintain rigor, however, this limitation was mitigated by adopting more stringent inclusion and exclusion criteria, in order to maximize efficiency and reduce the number of eligible studies. Additionally, this limitation restricted the number of articles which could realistically be reviewed, which could limit the scope or breadth of the study.  Another limitation of this study is the restriction to studies from the past 10 years. While this criterion was used for purposes of reviewer manageability, it nevertheless excluded numerous outbreaks and extreme precipitation events for which studies and data exist. Similarly, the sole use of PubMed and the restriction to English language studies may have excluded articles from different databases or from different regions of research, an important consideration when conducting a review of global health outcomes. Finally, the emphasis on precipitation and floods while excluding droughts may have unintentionally excluded certain findings, as the interaction of dry periods followed by extreme precipitation was mentioned in five studies but was not the focus of any studies in this review. Thus, studying the dynamics between drought and extreme precipitation events in relation to waterborne disease transmission could provide a more complete image of the mechanisms and mediators at play.

**Recommendations**

As previously mentioned, several gaps and opportunities appear in the literature examined in this review. The primary and most evident gap is an unequal distribution of studies between high-, middle-, and low-income regions and generalizability of the findings of the systematic review to LMICs. For example, many studies were in Europe and East Asia, which consist primarily of high- and middle-income communities. Meanwhile, studies were lacking in sub-Saharan Africa, which is experiencing more frequent and intense precipitation events and has serious infrastructural needs,[5] but which was only included in 3 of the articles examined in this review. Thus, additional research will be crucial to bridge this gap and better understand the public health threats, drivers, and needs of these regions.

**Conclusion**

Ultimately, waterborne diseases are among the most sensitive to climate change and its meteorological impacts across public and global health. When climate change disrupts current conditions, a vast array of social, ecological, and infrastructural vulnerabilities can combine and lead to major infectious disease outbreaks. Without concerted efforts to study, understand and address the risk factors underpinning waterborne disease transmission, we could miss an opportunity to prevent devastating outbreaks. Instead, we can choose to adapt mitigation and prevention strategies to account for climate change and its impacts. In doing so, we move toward socio-ecological resilience, protecting communities around the world from the burden of waterborne diseases.

# References

1.  Ebi, K. L. *et al.* Extreme Weather and Climate Change: Population Health and Health System Implications. *Annu. Rev. Public Health* **42**, 293–315 (2021).

2.  Cann, K. F., Thomas, D. R., Salmon, R. L., Wyn-Jones, A. P. & Kay, D. Extreme water-related weather events and waterborne disease. *Epidemiol. Infect.* **141**, 671–686 (2013).

3.  Levy, K., Woster, A. P., Goldstein, R. S. & Carlton, E. J. Untangling the Impacts of Climate Change on Waterborne Diseases: a Systematic Review of Relationships between Diarrheal Diseases and Temperature, Rainfall, Flooding, and Drought. *Environ. Sci. Technol.* **50**, 4905–4922 (2016).

4.  Sterk, A., Schijven, J., de Nijs, T. & de Roda Husman, A. M. Direct and indirect effects of climate change on the risk of infection by water-transmitted pathogens. *Environ. Sci. Technol.* **47**, 12648–12660 (2013).

5.  Tseole, N. P., Mindu, T., Kalinda, C. & Chimbari, M. J. Barriers and facilitators to Water, Sanitation and Hygiene (WaSH) practices in Southern Africa: A scoping review. *PloS One* **17**, e0271726 (2022).

6.  Forouzanfar, M. H. *et al.* Global, regional, and national comparative risk assessment of 79 behavioural, environmental and occupational, and metabolic risks or clusters of risks, 1990–2015: a systematic analysis for the Global Burden of Disease Study 2015. *The Lancet* **388**, 1659–1724 (2016).

7.  Semenza, J. C., Rocklöv, J. & Ebi, K. L. Climate Change and Cascading Risks from Infectious Disease. *Infect. Dis. Ther.* **11**, 1371–1390 (2022).

8.  Chan, N. Y., Ebi, K. L., Smith, F., Wilson, T. F. & Smith, A. E. An integrated assessment framework for climate change and infectious diseases. *Environ. Health Perspect.* **107**, 329–337 (1999).

9.  Cheng, A. *et al.* Analyzing the Potential Risk of Climate Change on Lyme Disease in Eastern Ontario, Canada Using Time Series Remotely Sensed Temperature Data and Tick Population

Modelling. *Remote Sens.* **9**, 609 (2017).

10. Garrido, R. *et al.* Potential impact of climate change on the geographical distribution of two wild vectors of Chagas disease in Chile: Mepraia spinolai and Mepraia gajardoi. *Parasit. Vectors* **12**, 478 (2019).

11. World Health Organization. Climate change and health research: current trends, gaps and perspectives for the future. (2021).

12. Karpagam, K. B. & Ganesh, B. Leptospirosis: a neglected tropical zoonotic infection of public health importance-an updated review. *Eur. J. Clin. Microbiol. Infect. Dis. Off. Publ. Eur. Soc. Clin. Microbiol.* **39**, 835–846 (2020).

13. Semenza, J. C. Cascading risks of waterborne diseases from climate change. *Nat. Immunol.* **21**, 484–487 (2020).

14. Chong, K. C. *et al.* A 21-year retrospective analysis of environmental impacts on paediatric acute gastroenteritis in an affluent setting. *Sci. Total Environ.* **764**, 142845 (2021).

15. Zellweger, R. M. *et al.* A 23-year retrospective investigation of Salmonella Typhi and Salmonella Paratyphi isolated in a tertiary Kathmandu hospital. *PLoS Negl. Trop. Dis.* **11**, e0006051 (2017).

16. Ventura, R. J., Muhi, E., de los Reyes, V. C., Sucaldito, M. N. & Tayag, E. A community-based gastroenteritis outbreak after Typhoon Haiyan, Leyte, Philippines, 2013. *West. Pac. Surveill. Response J. WPSAR* **6**, 1–6 (2015).

17. Maramraj, K. K. *et al.* A community-wide acute diarrheal disease outbreak associated with drinking contaminated water from shallow bore-wells in a tribal village, India, 2017. *BMC Public Health* **20**, 231 (2020).

18. Gilpin, B. J. *et al.* A large scale waterborne Campylobacteriosis outbreak, Havelock North, New Zealand. *J. Infect.* **81**, 390–395 (2020).

19. Ding, G. *et al.* A time-trend ecological study for identifying flood-sensitive infectious diseases in Guangxi, China from 2005 to 2012. *Environ. Res.* **176**, 108577 (2019).

20. Sheoran, P. *et al.* An outbreak investigation of acute Diarrheal Disease, Nagpur District, Maharashtra, India. *Indian J. Public Health* **65**, S14–S17 (2021).

21. Hu, X. *et al.* Assessment on the burden of bacillary dysentery associated with floods during 2005-2009 in Zhengzhou City, China, using a time-series analysis. *J. Infect. Public Health* **11**, 500–506 (2018).

22. Guzman Herrador, B. *et al.* Association between heavy precipitation events and waterborne outbreaks in four Nordic countries, 1992-2012. *J. Water Health* **14**, 1019–1027 (2016).

23. Tornevi, A., Axelsson, G. & Forsberg, B. Association between precipitation upstream of a drinking water utility and nurse advice calls relating to acute gastrointestinal illnesses. *PloS One* **8**, e69918 (2013).

24. Chhetri, B. K. *et al.* Associations between extreme precipitation and acute gastro-intestinal illness due to cryptosporidiosis and giardiasis in an urban Canadian drinking water system (1997-2009). *J. Water Health* **15**, 898–907 (2017).

25. Graydon, R. C. *et al.* Associations between extreme precipitation, drinking water, and protozoan acute gastrointestinal illnesses in four North American Great Lakes cities (2009-2014). *J. Water Health* **20**, 849–862 (2022).

26. Forbes, O., Hosking, R., Mokany, K. & Lal, A. Bayesian spatio-temporal modelling to assess the role of extreme weather, land use change and socio-economic trends on cryptosporidiosis in Australia, 2001-2018. *Sci. Total Environ.* **791**, 148243 (2021).

27. Fredrick, T. *et al.* Cholera outbreak linked with lack of safe water supply following a tropical cyclone in Pondicherry, India, 2012. *J. Health Popul. Nutr.* **33**, 31–38 (2015).

28. Bwire, G. *et al.* Cholera surveillance in Uganda: an analysis of notifications for the years 2007-2011. *J. Infect. Dis.* **208 Suppl 1**, S78-85 (2013).

29. Mendoza, M. T. *et al.* Clinical profile of patients diagnosed with leptospirosis after a typhoon: a multicenter study. *Southeast Asian J. Trop. Med. Public Health* **44**, 1021–1035 (2013).

30. Uejio, C. K. *et al.* Drinking water systems, hydrology, and childhood gastrointestinal illness in

Central and Northern Wisconsin. *Am. J. Public Health* **104**, 639–646 (2014).

31. Lai, H. *et al.* Effects of heavy rainfall on waterborne disease hospitalizations among young children in wet and dry areas of New Zealand. *Environ. Int.* **145**, 106136 (2020).

32. Phosri, A. Effects of rainfall on human leptospirosis in Thailand: evidence of multi-province study using distributed lag non-linear model. *Stoch. Environ. Res. Risk Assess. Res. J.* **36**, 4119–4132 (2022).

33. Ni, W. *et al.* Effects of the floods on dysentery in north central region of Henan Province, China from 2004 to 2009. *J. Infect.* **69**, 430–439 (2014).

34. Weinberger, D., Baroux, N., Grangeon, J.-P., Ko, A. I. & Goarant, C. El Niño Southern Oscillation and leptospirosis outbreaks in New Caledonia. *PLoS Negl. Trop. Dis.* **8**, e2798 (2014).

35. Ramírez, I. J. & Grady, S. C. El Niño, Climate, and Cholera Associations in Piura, Peru, 1991-2001: A Wavelet Analysis. *EcoHealth* **13**, 83–99 (2016).

36. Kuhn, K. G. *et al.* Epidemiological and serological investigation of a waterborne Campylobacter jejuni outbreak in a Danish town. *Epidemiol. Infect.* **145**, 701–709 (2017).

37. Owada, K. *et al.* Epidemiological Profile of a Human Hepatitis E Virus Outbreak in 2018, Chattogram, Bangladesh. *Trop. Med. Infect. Dis.* **7**, (2022).

38. Marinova-Petkova, A. *et al.* First Reported Human Cases of Leptospirosis in the United States Virgin Islands in the Aftermath of Hurricanes Irma and Maria, September-November 2017. *Open Forum Infect. Dis.* **6**, ofz261 (2019).

39. De Man, H. *et al.* Gastrointestinal, influenza-like illness and dermatological complaints following exposure to floodwater: a cross-sectional survey in The Netherlands. *Epidemiol. Infect.* **144**, 1445–1454 (2016).

40. Hines, J. Z. *et al.* Heavy precipitation as a risk factor for shigellosis among homeless persons during an outbreak - Oregon, 2015-2016. *J. Infect.* **76**, 280–285 (2018).

41. De Roos, A. J. *et al.* Heavy precipitation, drinking water source, and acute gastrointestinal illness in Philadelphia, 2015-2017. *PloS One* **15**, e0229258 (2020).

42. Carlton, E. J. *et al.* Heavy rainfall events and diarrhea incidence: the role of social and environmental factors. *Am. J. Epidemiol.* **179**, 344–352 (2014).

43. Vitale, M. *et al.* Human leptospirosis cases in Palermo Italy. The role of rodents and climate. *J. Infect. Public Health* **11**, 209–214 (2018).

44. Lau, C. L. *et al.* Human Leptospirosis Infection in Fiji: An Eco-epidemiological Approach to Identifying Risk Factors and Environmental Drivers for Transmission. *PLoS Negl. Trop. Dis.* **10**, e0004405 (2016).

45. Alexander, K. A., Heaney, A. K. & Shaman, J. Hydrometeorology and flood pulse dynamics drive diarrheal disease outbreaks and increase vulnerability to climate change in surface-water-dependent populations:  A retrospective analysis. *PLoS Med.* **15**, e1002688 (2018).

46. Mitsui, M. *et al.* Increased risk of Legionella pneumonia as community-acquired pneumonia after heavy rainfall in 2018 in west Japan. *J. Infect. Chemother. Off. J. Jpn. Soc. Chemother.* **27**, 1429–1435 (2021).

47. Hacker, K. P. *et al.* Influence of Rainfall on Leptospira Infection and Disease in a Tropical Urban Setting, Brazil. *Emerg. Infect. Dis.* **26**, 311–314 (2020).

48. Faccini, M. *et al.* Large community-acquired Legionnaires' disease outbreak caused by Legionella pneumophila serogroup 1, Italy, July to August 2018. *Euro Surveill. Bull. Eur. Sur Mal. Transm. Eur. Commun. Dis. Bull.* **25**, (2020).

49. Hyllestad, S. *et al.* Large waterborne Campylobacter outbreak: use of multiple approaches to investigate contamination of the drinking water supply system, Norway, June 2019. *Euro Surveill. Bull. Eur. Sur Mal. Transm. Eur. Commun. Dis. Bull.* **25**, (2020).

50. Smith, J. K. G., Young, M. M., Wilson, K. L. & Craig, S. B. Leptospirosis following a major flood in Central Queensland, Australia. *Epidemiol. Infect.* **141**, 585–590 (2013).

51. Mohd Radi, M. F. *et al.* Leptospirosis Outbreak After the 2014 Major Flooding Event in

Kelantan, Malaysia: A Spatial-Temporal Analysis. *Am. J. Trop. Med. Hyg.* **98**, 1281–1295 (2018).

52. Eyre, M. T. *et al.* Linking rattiness, geography and environmental degradation to spillover Leptospira infections in marginalised urban settings: An eco-epidemiological community-based cohort study in Brazil. *eLife* **11**, (2022).

53. Ramírez, I. J., Lee, J. & Grady, S. C. Mapping Multi-Disease Risk during El Niño: An Ecosyndemic Approach. *Int. J. Environ. Res. Public. Health* **15**, (2018).

54. Gertler, M. *et al.* Outbreak of Cryptosporidium hominis following river flooding in the city of Halle (Saale), Germany, August 2013. *BMC Infect. Dis.* **15**, 88 (2015).

55. Colston, J. *et al.* Pathogen-Specific Impacts of the 2011-2012 La Niña-Associated Floods on Enteric Infections in the MAL-ED Peru Cohort: A Comparative Interrupted Time Series Analysis. *Int. J. Environ. Res. Public. Health* **17**, (2020).

56. Mukhopadhyay, A. K. *et al.* Post-monsoon waterlogging-associated upsurge of cholera cases in and around Kolkata metropolis, 2015. *Epidemiol. Infect.* **147**, e167 (2019).

57. Lee, D., Chang, H. H., Sarnat, S. E. & Levy, K. Precipitation and Salmonellosis Incidence in Georgia, USA: Interactions between Extreme Rainfall Events and Antecedent Rainfall Conditions. *Environ. Health Perspect.* **127**, 97005 (2019).

58. Gao, L. *et al.* Projections of hepatitis A virus infection associated with flood events by 2020 and 2030 in Anhui Province, China. *Int. J. Biometeorol.* **60**, 1873–1884 (2016).

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

60. de Man, H. *et al.* Quantitative assessment of infection risk from exposure to waterborne pathogens in urban floodwater. *Water Res.* **48**, 90–99 (2014).

61. Iyer, V. *et al.* Role of extreme weather events and El Niño Southern Oscillation on incidence of Enteric Fever in Ahmedabad and Surat, Gujarat, India. *Environ. Res.* **196**, 110417 (2021).

62. Wang, P., Zhao, H., You, F., Zhou, H. & Goggins, W. B. Seasonal modeling of hand, foot, and mouth disease as a function of meteorological variations in Chongqing, China. *Int. J. Biometeorol.* **61**, 1411–1419 (2017).

63. Lin, C.-Y. *et al.* Serological investigation to identify risk factors for post-flood infectious diseases: a longitudinal survey among people displaced by Typhoon Morakot in Taiwan. *BMJ Open* **5**, e007008 (2015).

64. Mulder, A. C. *et al.* 'Sickenin' in the rain' - increased risk of gastrointestinal and respiratory infections after urban pluvial flooding in a population-based cross-sectional study in the Netherlands. *BMC Infect. Dis.* **19**, 377 (2019).

65. Chen, N.-T., Chen, Y.-C., Wu, C.-D., Chen, M.-J. & Guo, Y.-L. The impact of heavy precipitation and its impact modifiers on shigellosis occurrence during typhoon season in Taiwan: A case-crossover design. *Sci. Total Environ.* **848**, 157520 (2022).

66. Vieira, C. B. *et al.* The Impact of the Extreme Amazonian Flood Season on the Incidence of Viral Gastroenteritis Cases. *Food Environ. Virol.* **9**, 195–207 (2017).

67. Ehelepola, N. D. B., Ariyaratne, K. & Dissanayake, D. S. The interrelationship between meteorological parameters and leptospirosis incidence in Hambantota district, Sri Lanka 2008-2017 and practical implications. *PloS One* **16**, e0245366 (2021).

68. Matsushita, N. *et al.* The non-linear and lagged short-term relationship between rainfall and leptospirosis and the intermediate role of floods in the Philippines. *PLoS Negl. Trop. Dis.* **12**, e0006331 (2018).

69. Dimitrova, A., Gershunov, A., Levy, M. C. & Benmarhnia, T. Uncovering social and environmental factors that increase the burden of climate-sensitive diarrheal infections on children. *Proc. Natl. Acad. Sci. U. S. A.* **120**, e2119409120 (2023).

70. Davies, G. I. *et al.* Water-borne diseases and extreme weather events in Cambodia: review of impacts and implications of climate change. *Int. J. Environ. Res. Public. Health* **12**, 191–213 (2014).

71. Jones, N., Bouzid, M., Few, R., Hunter, P. & Lake, I. Water, sanitation and hygiene risk factors for the transmission of cholera in a changing climate: using a systematic review to develop a causal process diagram. *J. Water Health* **18**, 145–158 (2020).

72. Koutsotoli, A. D., Papassava, M. E., Maipa, V. E. & Alamanos, Y. P. Comparing *Shigella* waterborne outbreaks in four different areas in Greece: common features and differences. *Epidemiol. Infect.* **134**, 157–162 (2006).

73. Harrison, L., Funk, C. & Peterson, P. Identifying changing precipitation extremes in Sub-Saharan Africa with gauge and satellite products. *Environ. Res. Lett.* **14**, 085007 (2019).

74. Hashizume, M. *et al.* The Effect of Rainfall on the Incidence of Cholera in Bangladesh. *Epidemiology* **19**, 103–110 (2008).

75. Coffey, R., Paul, M., Stamp, J., Hamilton, A. & Johnson, T. A Review Of Water Quality Responses To Air Temperature And Precipitation Changes 2: Nutrients, Algal Blooms, Sediment, Pathogens. *J. Am. Water Resour. Assoc.* **55**, 844–868 (2018).

76. Alegbeleye, O. O. & Sant'Ana, A. S. Manure-borne pathogens as an important source of water contamination: An update on the dynamics of pathogen survival/transport as well as practical risk mitigation strategies. *Int. J. Hyg. Environ. Health* **227**, 113524 (2020).

77. Darby, J. & Buising, K. Could it be Legionella? *Aust. Fam. Physician* **37**, 812–815 (2008).

78. Kraay, A. N. M. *et al.* Understanding the Impact of Rainfall on Diarrhea: Testing the Concentration-Dilution Hypothesis Using a Systematic Review and Meta-Analysis. *Environ. Health Perspect.* **128**, 126001 (2020).

79. Page MJ, McKenzie JE, Bossuyt PM, Boutron I, Hoffmann TC, Mulrow CD, et al. The PRISMA 2020 statement: an updated guideline for reporting systematic reviews. BMJ 2021;372:n71. doi: 10.1136/bmj.n71

# Appendix

**Supplemental Table 1: Search Terms and Search Strategy**

| Search # | Query | Filters | Results |
|---|---|---|---|
| 1 | "water-borne"[TiAb] OR "water borne"[TiAb] OR waterborne[TiAb] OR "water-related"[TiAb] OR campylobacter*[TiAb] OR cryptosporidi*[TiAb] OR "entamoeba histolytica"[TiAb] OR "amoebic colitis"[TiAb] OR enterobacter*[TiAb] OR enterovirus*[TiAb] OR "escherichia coli"[TiAb] OR "e. coli"[TiAb] OR gastroenteritis[TiAb] OR giardi*[TiAb] OR "helicobacter pylori"[TiAb] OR "hepatitis a"[TiAb] OR "hepatitis e"[TiAb] OR legionell*[TiAb] OR leptospir*[TiAb] OR listeri*[TiAb] OR "naegleria fowleri"[TiAb] OR norovirus[TiAb] OR "pseudomonas aeruginosa"[TiAb] OR rotavirus[TiAb] OR salmonell*[TiAb] OR typhoid[TiAb] OR "enteric fever"[TiAb] OR schistosom*[TiAb] OR "cercarial dermatitis"[TiAb] OR shigell*[TiAb] OR dysentery[TiAb] OR toxoplasm*[TiAb] OR vibrio[TiAb] OR cholera[TiAb] OR yersinia[TiAb] OR yersiniosis[TiAb] | – | 814,748 |
| 2 | "Waterborne Diseases"[Mesh] | – | 234 |
| 3 | #1 OR #2 | – | 814,782 |
| 4 | "Climate change"[MeSH] OR "Cyclonic storms"[MeSH] OR "Floods"[MeSH] | – | 34,596 |
| 5 | "Climate change"[TiAb] OR "climate variability"[TiAb] OR "precipitation"[TiAb] OR "extreme weather"[TiAb] OR "hurricane*"[TiAb] OR "cyclon*"[TiAb] OR "typhoon*"[TiAb] OR "monsoon*"[TiAb] OR "tropical storm*"[TiAb] OR "tropical depression"[TiAb] OR "storm*"[TiAb] OR "rainfall"[TiAb] OR "rainstorm*"[TiAb] OR "flood*"[TiAb] OR "ENSO"[TiAb] OR "el niño"[TiAb] OR "la niña"[TiAb] | – | 197,205 |
| 6 | #4 OR #5 | – | 205,022 |
| 7 | #3 AND #6 | – | 6,743 |
| 8 | #3 AND #6 | English | 6,331 |
| 9 | #3 AND #6 | in the last 10 years, English | **3,248** |

**Supplemental Table 2: Study quality ratings and design of the 57 studies reviewed**

| Quality Rating | Number of studies (%)* | Study designs (% of category*) |
|---|---|---|
| High | 26 (46%) | Time-series (38%)<br>Cohort studies (27%)<br>Case-control studies (15%)<br>Cross-sectional studies (12%)<br>Case-crossover studies (4%)<br>Spatio-temporal analyses (4%)<br>Quantitative exposure assessment (4%) |
| Medium | 25 (44%) | Time-series (56%)<br>Case-crossover studies (12%)<br>Spatio-temporal analyses (8%)<br>Cross-sectional studies (8%)<br>Case-control studies (4%)<br>Ecological study (4%)<br>Case series (4%)<br>Longitudinal survey (4%) |
| Low | 6 (11%) | Case series (67%)<br>Cross-sectional studies (17%)<br>Cohort study (17%) |

*may not sum to 100%, due to rounding

**Supplemental Table 3: Pathogens reported in the 57 studies reviewed**

| Waterborne pathogen | Number of studies focused on pathogen (%)* | References |
|---|---|---|
| **Bacteria** | **36 (63%)** | |
| *Aeromonas hydrophila* | 1 (2%) | 16 |
| *Campylobacter* | 4 (7%) | 18, 36, 49, 60 |
| *Escherichia coli* | 2 (4%) | 45, 66 |
| *Enterococci* | 1 (2%) | 66 |
| *Legionella* | 2 (4%) | 46, 48 |
| *Leptospira* | 13 (23%) | 19, 29, 32, 34, 38, 43, 44, 47, 50, 51, 52 67, 68 |
| *Salmonella* | 2 (4%) | 15, 57 |
| *Shigella* | 6 (11%) | 19, 21, 33, 40, 59, 65 |
| *Vibrio Cholera* | 5 (9%) | 27, 28, 35, 53, 56 |
| **Viruses** | **4 (7%)** | |
| Enterovirus | 1 (2%) | 62 |
| Hepatitis A | 1 (2%) | 58 |
| Hepatitis E | 1 (2%) | 37 |
| Norovirus | 1 (2%) | 60 |
| **Parasites** | **9 (16%)** | |
| *Cryptosporidium spp.* | 6 (11%) | 24, 25, 26, 41, 54, 60 |
| *Entamoeba histolytica* | 2 (4%) | 33, 63 |
| *Giardia spp.* | 3 (5%) | 24, 25, 60 |
| **Gastrointestinal pathogen(s)** (unspecified or unconfirmed) | 14 (25%) | 14, 17, 20, 22, 23, 30, 31, 39, 42, 55, 61, 64, 69, 70 |
| **Respiratory pathogen(s)** (unspecified or unconfirmed) | 2 (4%) | 39, 64 |
| **Dermatological pathogen(s)** (unspecified or unconfirmed) | 1 (2%) | 39 |

*may not sum to 100% due to rounding and inclusion of multiple pathogens per study

**Supplemental Table 4: Extreme precipitation events reported in the 57 studies reviewed**

| Extreme Precipitation Event | Number of studies focused on event (%)* |
|---|---|
| Heavy precipitation/rainfall | 19 (33%) |
| Extreme precipitation/rainfall | 7 (12%) |
| Flooding following precipitation | 18 (32%) |
| ENSO-related precipitation (El Niño and La Niña) | 6 (11%) |
| Tropical cyclones (hurricanes and typhoons) | 7 (12%) |

*may not sum to 100% due to rounding

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