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Climate Change Impacts on Waterborne Diseases: Moving Toward Designing Interventions

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Abstract

Purpose: Climate change threatens progress achieved in global reductions of infectious disease rates over recent decades. This review summarizes literature on potential impacts of climate change on waterborne diseases, organized around a framework of questions that can be addressed depending on available data.

Recent findings: A growing body of evidence suggests that climate change may alter the incidence of waterborne diseases, and diarrheal diseases in particular. Much of the existing work examines historical relationships between weather and diarrhea incidence, with a limited number of studies projecting future disease rates. Some studies take social and ecological factors into account in considerations of historical relationships, but few have done so in projecting future conditions.

Summary: The field is at a point of transition, toward incorporating social and ecological factors into understanding the relationships between climatic factors and diarrheal diseases and using this information for future projections. The integration of these components helps identify vulnerable populations and prioritize adaptation strategies.

Keywords

Climate change; Diarrhea; Enteric diseases; Temperature; Rainfall; Social Vulnerability

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Compliance with Ethical Standards
Conflict of Interest

Karen Levy, Shanon M. Smith, and Elizabeth J. Carlton declare that they have no conflict of interest.

Human and Animal Rights and Informed Consent
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Introduction

Climate change is increasingly understood not just as an environmental issue but as a fundamental threat to human health and well-being. The health effects of climate change “threaten to undermine the gains made in public health and development during the past half-century” [e.g., 1].

Anthropogenic climate change has caused increases in the number of warm days and nights, and the frequency and intensity of both droughts and heavy rainfall events [2]. This has implications for waterborne diseases, as high temperatures can alter pathogen survival, replication and virulence, heavy rainfall events can mobilize pathogens and compromise water and sanitation infrastructure, and drought can concentrate pathogens in limited water supplies [3••]. The Intergovernmental Panel on Climate Change (IPCC) states that there is “very high confidence” that increased risks of food- and water-borne diseases can be expected “if climate change continues as projected across the representative concentration pathway (RCP) scenarios until mid-century” [4].

Waterborne diseases include many different types of infections that are transmitted via water, and include pathogens across a range of taxa (viruses, bacteria, protozoa, and helminths). These pathogens can cause an array of symptoms, including diarrhea, fever and other flu-like symptoms, neurological disorders, liver damage, and others. Here we focus on diarrheal diseases, which are commonly transmitted via waterborne pathways and comprise a substantial proportion of the global burden of diseases. [5, 6] Moreover, as diarrheal disease transmission is facilitated by insufficient or unsafe water, climate change has the potential to alter their distribution and incidence.

Due to the large burden of diarrheal diseases, even small changes in diarrheal disease risk due to climate change can have profound impacts on population health. Diarrheal diseases are the second leading cause of death in children under five worldwide, and the second greatest source of death and disability in low and middle income countries [7, 8, 5]. These health impacts are concentrated in young children in low-income settings, where pediatric diarrhea can lead to impaired growth and cognitive development, and trigger a cascade of ill health that reinforces poverty [9–11]. Globally, diarrhea morbidity and mortality is declining [5], but climate change may slow this downward trajectory, undermining multinational investments to reduce diarrheal disease burden, with impacts concentrated in some of the world’s most vulnerable populations.

The potential for climate change to affect diarrheal diseases was recognized starting with early efforts to estimate the impacts of anthropogenic climate change on human health [12, 13]. Diarrheal disease outbreaks have been associated with both heavy rainfall and dry periods [14–17], demonstrating that dry periods can concentrate enteric pathogens and precipitation can mobilize enteric pathogens, in both cases enabling contamination of drinking water sources and increasing chances of human-pathogen contact. Increases in hospital admissions in Lima, Peru during an El Niño warming event in the 1990s provided early epidemiological evidence of the potential for temperature anomalies to alter diarrheal disease incidence [18]. In the United States and Canada, waterborne disease outbreaks were found to often be preceded by extreme rainfall events [14, 17]. However, efforts to quantify the potential impacts of climate change on health have been hampered by, in the words of one research team, “the sparsity of empirical climate-health data” leading to uncertainties in the empirical relationships between climate and diarrheal diseases far greater than uncertainties in the projection of future climate [19].

Since these early efforts, a growing body of evidence suggests that climate change—particularly increases in high temperatures, heavy rainfall, flooding and drought—have the potential to alter the distribution of diarrheal diseases. We and others have found evidence of significant, positive associations between temperature and bacterial diarrhea, but not viral diarrhea [20••, 21•]; as well as evidence for increases in diarrhea following heavy rainfall events and flooding.

As the work describing associations between climate and diarrheal diseases grows, it is increasingly clear that the impacts of climate change on diarrheal diseases depend not simply on meteorological conditions, but on the underlying social and ecological contexts – from water and sanitation infrastructure to local pathogen distribution to social capital – that influence a population’s exposure, sensitivity and adaptive capacity. The complex interplay of climate, social vulnerability, ecology and health has been recognized and successfully incorporated into other areas of climate-health research. For example the vector-borne disease field showed early on the potential impact of climate change on future disease risk (e.g. [22–32]) and emphasized the importance of social (e.g. [33–41]) and environmental (e.g [37, 41–44]) dynamics in disease modeling to better reflect the epidemiological triad and to understand not only the effects on future disease rates but also to develop adaptation strategies under global change (e.g. [34, 45, 46]). Similarly, heat-related morbidity and mortality have been shown to vary by demographic characteristics (e.g. age, pre-existing conditions) as well as neighborhood infrastructure (e.g. access to air conditioning), leading to efforts to map high-risk populations and define effective adaptation strategies [47–49]. This has important implications for public health planning, as some populations may be particularly vulnerable to climate change than others. Incorporation of such underlying vulnerability will enable prioritization of interventions to reduce future disease risks in the most vulnerable populations.

In this review, we summarize the evidence describing the potential impacts of climate change on waterborne diseases, focusing primarily on diarrheal diseases due to their high burden of disease and the growing body of evidence demonstrating the potential impacts of climate change on diarrhea [e.g., [3••, 20••, 21•, 50, 51••, 52]]. We provide an organizing framework of types of questions that can be addressed depending on the types of data available, and summarize the literature addressing each of these questions, concluding with a discussion of what we view to be the most urgent research priorities while also highlighting current and future adaptation strategies.

It is time to shift the research questions

Our understanding of climate-disease relationships will depend on the types of data incorporated into analyses. **Table 1** provides an overview of the types of questions that we can answer based on the data included in quantitative models, and illustrates what we view to be an important transition in the field, from studies of basic associations to more complex approaches that can inform our understanding of causal processes and future vulnerability, and, ultimately, our ability to intervene to reduce vulnerability. Much of the existing work in this field examines historical relationships between observed weather and disease incidence (Question I), with a more limited number of studies projecting future disease rates (Question II). Some studies take mediating social and/or ecological factors into account in considerations of historical relationships (Question III), but very few have done so while also exploring social/ecological mediating factors or consequences of future conditions (Question IV). Below we review the literature organized by these four questions and argue that, given the state of the science and our need to identify effective interventions to reduce diarrheal disease burden in a changing climate, it is time to shift the research from studies of climate-disease associations historically (Question I) and in the future (Question II) towards studies that evaluate the social and environmental contexts that make a population vulnerable to climate change (Question III) and studies that evaluate the effectiveness of interventions to reduce vulnerability to waterborne disease transmission in a changing climate (Question IV)

Question I. What is the relationship between observed weather and waterborne disease incidence?

Most of the research in this field to date has been analyses of the historical relationships between observed weather conditions and waterborne disease incidence or prevalence. These are generally time series and/or spatial epidemiology studies [51••]. Extensive work has also been carried out on climate impacts on pathogen fate and transport in the environment [52].

Our research team recently published a systematic review and meta-analysis summarizing studies of the relationship between diarrheal diseases and four meteorological conditions that are expected to increase with climate change: ambient temperature, heavy rainfall, drought, and flooding [3••, 20••]. This review built upon and updated previously published reviews of: diarrhea – temperature relationships [12, 19]; extreme weather events and waterborne disease [50]; climatic influences on pathogens in the environment [52]; and specific diarrheal pathogens [53–58]. Key areas of agreement among the 141 articles that we reviewed were a positive association between ambient temperature and diarrheal diseases, with the exception of viral diarrhea, and an increase in diarrheal disease following heavy rainfall and flooding events. Insufficient evidence was available to evaluate the effects of drought on diarrhea [3••]. These associations were observed in low-, middle- and high-income countries. We found considerable evidence to support the biological plausibility of climate-diarrhea associations described above [3••] and other reviews further support these findings [50–52, 59]. Additional research published after our review provides further evidence to support the associations between diarrhea diseases and climate change: ambient temperature [60–64], heavy rainfall [22, 60–63, 65–69], drought [70], and flooding [71, 72].

From the systematic review, a subset of 26 articles provided quantitative estimates of the association of temperature and diarrhea that we were able to synthesize into a separate meta-analysis. This analysis indicated the relationship between temperature and diarrhea varies by pathogen taxa [20••]. We found a positive association between ambient temperature and all-cause diarrhea (incidence rate ratio (IRR) 1.07; 95% confidence interval (CI) 1.03, 1.10) and bacterial diarrhea (IRR 1.07; 95% CI 1.04, 1.10), but not viral diarrhea (IRR 0.96; 95% CI 0.82, 1.11). Only one study of protozoan diarrhea was identified. However, two independent reviews suggest a positive association between temperature and two major protozoan pathogens: cryptosporidium and giardia [53, 55].

There are several notable limitations in the above literature. Because most studies are secondary data analyses, publication bias is a concern [3••, 20••]. Sparsity of health data [59] and uncertainty in reporting [51••] are potential sources of error and may explain the uneven geographical distribution of studies [3••]. Guzman et al. (2015) [59] highlight issues related to sparse data and optimal choice of time lag. Moreover, Sterk et al. (2013) [52] point out that not all processes and pathogens are evenly covered by the literature. However, a prevailing theme is the need to adopt approaches that allow us to capture the complex causal pathways underlying the relationships between meteorological conditions and diarrheal diseases [3••, 51••, 73]. In addition, there is a need to evaluate the concurrent impacts of multiple meteorological exposures, such as the combined effects or interactions between temperature and rainfall.

Question II. How are waterborne disease rates expected to change under future climate scenarios?

For over a decade, scientists and policy makers have been interested in estimating the health impacts of climate change by projecting disease burden under future climate scenarios [1, 12]. Robust projections would enable estimates of deaths and disability averted through policies to reduce emissions; as well as identification of particularly vulnerable regions and prioritization of adaptation strategies for high-impact climate-sensitive diseases. One approach to this is the use of a comparative risk assessment framework, a method that has been widely used to estimate the global health impacts of an array of risk factors (from cigarette smoking to unsafe water and sanitation) [74–76]. The method is appealing in the context of climate health estimates, as it has the potential to provide quantitative estimates of disease burden under an array of future climate projections. The method requires estimates of disease burden, population exposure (in the case of climate change, this is defined as a given meteorological exposure under a future climate scenario), as well as estimated relationships between the exposure and outcome of interest. However, this last component has proven most challenging.

Early efforts to project disease burden under future climate scenarios used estimates of the relationship between climate and diarrheal diseases from studies designed to address Question I [12, 19, 76]. These estimates often depended upon single global parameters that assumed linear exposure-disease relationships and homogeneity across diarrheal pathogens and geographic regions. These projections were also limited by the sparse empirical climate-health data available, leading to “large uncertainties associated with future projections of diarrhea and climate change” [19]. As several of the original authors acknowledged and the more recent literature supports, the relationships between climate and enteric pathogens are complex and often non-linear, making future predictions a challenge. For diarrheal diseases, the direction of temperature-disease relationships varies by causative agent, with bacterial, protozoan, and viral diarrhea pathogens sometimes showing opposite patterns. For rainfall the effects are also often non-linear [3••]. A common theme that emerged from our systematic review is that the effects of heavy rainfall on diarrhea are magnified after dry periods, suggesting that models should incorporate antecedent conditions [3••].

Nonetheless, more recent work demonstrates possible approaches to projecting diarrheal disease burden under future climate scenarios. In Philipsborn et al. (2016) [21•] we projected almost 800,000 additional cases of enterotoxigenic *E. coli*-associated diarrhea in the near term, and 2.2 million additional cases by the end of the century under future climate scenarios in Bangladesh, using a comparative risk assessment approach [21•]. In this example we traded off a global scale-project for one that is specific to a region and pathogen. While these estimates depend on various assumptions and persistence of current water, sanitation and hygiene (WASH) and other conditions, and therefore have a high degree of uncertainty, they still illustrate the scale of potential public health impact that new climate scenarios could have on diarrheal disease incidence for one particular pathogen in one country. Adopting parameter estimates appropriate for defined subgroups may lead to more robust (albeit computationally intensive or regionally focused) projections.

Question III. How do social & environmental factors modify the association between weather and waterborne disease incidence?

A community’s vulnerability to climate change is determined not only by exposure to changing weather patterns, but also is a function of the community’s sensitivity and adaptive capacity **(Figure 1)**, i.e., the social and environmental conditions that affect pathogen exposure, host susceptibility, and a community’s ability to respond to stress. Mellor et al. (2016) [73] point out that there is a poor mechanistic understanding of the underlying disease transmission processes and substantial uncertainty surrounding current estimates, and argue that systems-based mechanistic approaches incorporating human, engineered and environmental components are needed.

Social factors related to sensitivity, such as water and sanitation infrastructure and healthcare access, and adaptive capacity, including available resources with which to intervene to prevent increased disease burden, are critical in determining the extent to which a population will experience the health impacts from changing climatic conditions, and how severe of an environmental exposure will cause a health effect. Low-income countries, with minimal water and sanitation infrastructure and poorly developed health systems, may experience health effects from even small changes in temperature or rainfall. Areas with minimal water and wastewater treatment are more vulnerable to the direct effects of these exposures, especially because baseline rates of disease are often high in these settings. High-income countries may still experience health impacts from changing meteorological conditions (e.g., [68•, 69]), but they are buffered by water and sanitation infrastructure that prevents transmission of waterborne diseases, leading to a higher threshold of exposure for impacts to be felt.

In terms of water service treatment and distribution, concerns for climate change focus on surface water sources (impairment and supply issues), as well as impacts on surface water treatment, groundwater sources, and water supply infrastructure. For sanitation services, climate change is expected to have “a mix of positive and negative” effects. The impacts will depend on the nature of changes that are likely to occur, and the type of technology in use, in a particular region. For example, for communities that rely on onsite sanitation systems regions with drying trends may experience reductions in groundwater contamination whereas regions annual rainfall increases or increased high intensity rainfall may be vulnerable to increased contamination. However, the literature on climate impacts on sanitation is vastly understudied [77••].

The IPCC recognizes the importance of broader factors in determining the health impacts of climate change, stating that “vulnerability encompasses a variety of concepts and elements including sensitivity or susceptibility to harm and lack of capacity to cope and adapt” [78]. Yet surprisingly few studies in this field included socio-economic indicators (e.g., access to water, index of poverty, age, education, human mobility) in their analysis, as documented by Lo Iacono et al. [51••] less than 10% of studies in their review included a variable related to index of deprivation/poverty, access to water/type of source water, land use, population density, education, or human mobility.

There are notable examples of where variables related to social vulnerability have been successfully included in analysis of climate-diarrhea relationships. Examples include considerations of variability in the relationship between meteorological conditions and diarrheal diseases by levels of household water treatment [79], population density [80•], increased vulnerability of subgroups [81, 82], and combined sewer overflows [68•, 69]. In low-income settings, studies have also examined factors such as water fetching distance [83], which could be exacerbated by drought, the impact of rainfall on fecal contamination of household wells [84], and water source switching from wells to source water during dry periods [85]. These studies go beyond establishing weather-disease associations to identify critical population vulnerabilities and incorporate them into analysis.

With respect to incorporation of variables related to environmental conditions, a handful of recent reviews and primary papers have an explicit focus on biological mechanisms and transmission processes underlying epidemiological associations between climatic factors and diarrhea. Most reviews in this area have been limited in geographical scope or focus on a particular transmission mode. Sterk et al. (2013) [52] carried out a systematic review of climate variables affecting pathogen input and behavior in aquatic environments, with a primary emphasis on The Netherlands. This review combines water-borne disease outbreak epidemiology with known pathogen behaviors illustrated in a conceptual model and highlights the need for quantitative modeling approaches to measure the sometimes counteracting effect of climate change on infection risks [52]. For example, summer droughts could concentrate pathogens due to lower river discharges, leading to increased infection risks, but could also increase inactivation of pathogens via increased temperatures and residence times, leading to decreased infection risks. Several other reviews have focused on risks to food safety as it relates to climate, which has been shown to influence environmental dispersal and persistence of foodborne pathogens [86–89]. In our systematic review, we developed a conceptual diagram illustrating potential causal pathways between meteorological conditions and diarrheal disease outcomes, based on literature supporting these biophysical and behavioral explanatory mechanisms [3••]. For example, heavy rainfall events may saturate subsurface soils, leading to mobilization of pathogens and increasing human contact with pathogens in low-income settings with minimal water treatment infrastructure. In settings with water treatment infrastructure, heavy rainfall events may increase turbidity of source water, overwhelming water treatment facilities.

Question IV. What interventions should be prioritized to reduce vulnerability to increased waterborne disease rates under future climatic conditions?

Early efforts to project disease burden under future climate scenarios (Question II) used parameter estimates from studies designed to address Question I. However, it is increasingly clear that the impact of climate on diarrheal diseases depends on social and environmental conditions that affect pathogen exposure, host susceptibility, and a community's ability to respond to stress (Question III). This justifies a more nuanced framing of the research questions to understand these modifying factors (Question IV). While this adds analytical complexity, social and environmental factors that are shown to modify relationships are the levers upon which we can act to ameliorate future negative impacts as well as variables we can use to define vulnerable populations. Lo Iacono et al. [51••] review some of the model structures available to address both environmental and social complexities, and we highlight a few recent papers that employ methods to incorporate social and environmental nuances into future projections.

Work by Hodges et al. (2014) demonstrates the potential of this approach [90•]. Based on evidence that the impact of temperature on waterborne-disease may be lower in populations with greater access to safe water and sanitation infrastructure, the authors projected waterborne disease burden across China under future emissions scenarios using three different data-driven water and sanitation infrastructure investment scenarios (maintenance, linear growth and exponential growth). For each future emissions scenario, waterborne disease burden was lowest under the most aggressive water and sanitation investment scenario, demonstrating the potential of water and sanitation interventions to reduce the risks posed by climate change. The approach provides a framework for understanding the potential of an adaptation strategy such as water and sanitation infrastructure investment to reduce climate vulnerability. Improved estimates of the role of water and sanitation, as well as other social and environmental variables, in modifying climate-disease relationships, will improve such projections and ultimately provide quantitative estimates of policy impacts, allowing evaluation of both emission reduction and adaptation strategies.

Mellor et al. 2016 [91] developed a partially mechanistic, systems approach to estimate future diarrhea prevalence and design adaptation strategies in Hubli-Dharwad, India, a city with an intermittent piped water supply exhibiting seasonal water quality variability vulnerable to climate change. They used an agent-based model [92], simulating the exposures and disease status of a set of individuals to estimate disease rates in a complex system, using downscaled global climate models, water quality data, quantitative microbial risk assessment, pathogen prevalence, precipitation data, and detailed information on diarrhea etiology. They estimated increases in diarrhea prevalence in the near and long term, and based on heterogeneities in response by pathogen, were able to suggest ceramic water filters over chlorination as the most effective climate adaptation strategy for water treatment in this setting. While computationally intensive, this approach allows the integration of diverse datastreams, from climate data to demographic data, and can account for complex, non-linear relations common in waterborne disease systems.

Another recent example comes from Stephen and Barnett [93] who used microsimulation models [94] to estimate the future health and economic costs of salmonellosis in Central Queensland from 2016 to 2036 under baseline and climate change scenarios. Similar to agent based models, these models simulate the exposures and disease status of individuals within a population and can account for changes in the size of the at-risk population due to transitions from one health state to another, as well as changes in higher- or lower-risk subpopulations due to demographic shifts, such as shifts in the underlying age structure of a population related to projected changes in birth and death rates. The models are based on increased foodborne transmission due to increased growth of *Salmonella* in food products, as well as increased waterborne transmission due to contamination of water sources as a function of altered rainfall. The authors estimate the years of quality life lost because of salmonellosis and its sequelae according to age, sex, and specific disease outcomes, after accounting for changes in incidence as a consequence of climate change, with the goal of informing strategies to reduce the incidence and costs of salmonellosis in the future. Results for salmonellosis through 2036 in Central Queensland suggest that health and economic costs are likely to be higher under the climate change scenario than under a scenario that assumes no changes in climate, and the findings help quantify the potential health and economic impacts of preventive measures such as food hygiene improvements.

Moving toward interventions

The social and environmental components of climate-disease relationships are particularly relevant because they drive disease dynamics (e.g., 80•), and they provide levers upon which we can act to ameliorate future negative impacts of climate change on disease risks. As our understanding of the relationship between climate change and waterborne diseases matures, we are increasingly able to evaluate the potential impacts of interventions to reduce disease risks from climate change. We argue that the most pressing research priorities in the field are to address the social and environmental components of climate-disease relationships (Question III) and project the impacts of interventions to reduce climate vulnerability (Question IV).

This requires focusing on causal pathways by which climate impacts pathogen exposure and disease outcomes, and employing systems-based approaches and process-based models that incorporate meteorological, health, demographic, engineering and environmental data [51••, 73]. Clarifying these pathways will allow for better design of intervention studies to reduce vulnerabilities in areas at risk of increased waterborne diseases as climate gradually changes, as well as in preparation for responding to meteorological extremes. Strategic research can help identify the areas most vulnerable to increases in disease risks and the interventions most likely to reduce vulnerability, making it possible to prioritize effective interventions in high risk communities, to build resilience to climate change.

Even in areas served by advanced sanitation and drinking water systems extreme precipitation events, flooding, and storm surges, which are increasing in frequency due to climate change, present an increased risk in infrastructure disruption, failure and/or exceedance of system capacity, [95–97]. Important early work by Curriero et al. (2001) [14] improved our understanding of the impacts of heavy rainfall on risk of waterborne disease outbreaks in the United States, and this now allows for adaptive management of water utilities. For example, in order to assess how future rainfall patterns might affect sewer capacity, Milwaukee was one of the first cities to integrate regional climate projections into its engineering models [98].

Conversely, public health programs focused on addressing social conditions should also consider how meteorological variables might affect the success of these programs. A recent analysis concluded that *not* including rainfall in estimates of the health impacts of WASH interventions can bias estimates of the intervention’s impact, suggesting that rainfall is an unappreciated confounder in child health intervention studies [99•].

Integrating knowledge of differing types of systems—biological, social, engineering—can improve our ability to estimate the health impacts of future climate conditions and extreme weather events and act to reduce vulnerability. This is a priority in both international and domestic contexts. Howard et al. (2016) [77••] review how water and sanitation services can be adapted or managed in the face of climate change. They highlight various mechanisms and planning processes to build climate resilience, including increased investment in water resources assessment and accounting; use of climate-resilient water safety plans as a risk management tool; a focus on utility management organization, with central support for decentralized management structures; and development of public-private partnerships to increase resilience of systems, including through investments in disaster risk reduction, delivery of services to the underserved, and use of microfinance and microinsurance mechanisms. The development of a water safety plan (WSP) outlined in the WHO Climate-resilient water safety plans [100•] provides a systematic framework to manage climate change risks with an emphasis on identification of hazardous events and the development and implementation of control measures. There are now many examples of plans for climate resilience from water utilities in developed countries, particularly Western Australia and The Netherlands, which primarily focus on alternative source development to produce lower-risk source waters. However, similar plans for lower income countries are lacking [77••]. Howard and Bartram have contributed useful work for these settings on the resilience of water and sanitation technologies and management systems under a number of climate scenarios [101, 102].

In addition to policy mechanisms to increase resilience of systems, some examples of engineering approaches include source, treatment, distribution, and point-of-use control measures that may be implemented to manage microorganism proliferation in drinking water. Examples include (but are not limited to) abstraction of source water from cooler depths; introduce or increase secondary booster disinfection; design or modify system to reduce residence times within pipes, and/or coat exposed pipes and tank roofs with white paint to reduce heat absorption resulting in reduced internal temperature thus reduced bacterial growth [100•].

Conclusions

Sufficient evidence has accrued to suggest that climate, especially heavy rainfall and high temperatures, have the potential to increase the risk of diarrheal diseases, one of the largest components of waterborne disease burden. Based on the accumulated evidence to date, we argue that the field is at a point of transition, from studies establishing associations between climatic conditions and water-borne disease outcomes (Question I) and simply projecting forward those associations (Question II), to studies that incorporate social and environmental processes (Question III), and incorporate these factors into future projections and adaptation planning (Question IV). Research efforts can now turn to identifying how and where to intervene to reduce risk in the most vulnerable populations.

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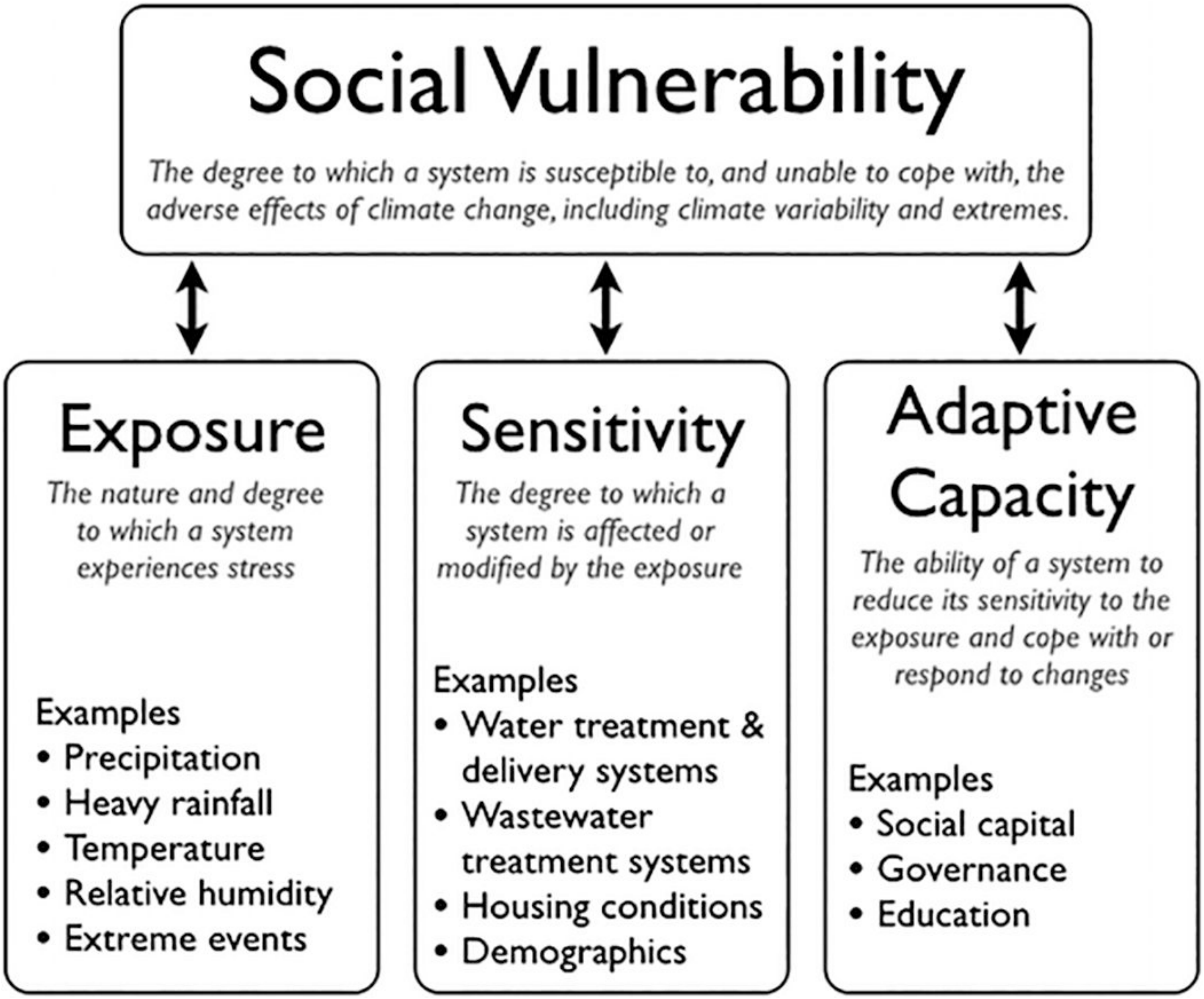

Figure 1.

Social vulnerability to climate change is a function not only of exposure to changing weather patterns, but also the community's sensitivity and adaptive capacity.

Table 1.

Research questions addressed by inclusion of data from different time points and inclusion of variables addressing different components of social and ecological vulnerability

	Historic Conditions	Future Conditions
Climatic Drivers	I. What is the relationship between observed weather and waterborne disease incidence?	II. How are waterborne disease rates expected to change under future climate conditions?
Climatic Drivers + Social/Ecological Mediators	III. How do social and/or ecological factors modify the association between observed weather and waterborne disease incidence?	IV. What interventions should be prioritized to reduce vulnerability to increased waterborne disease rates under future climatic conditions?