REVIEW ARTICLE

FOSSIL-FUEL POLLUTION AND CLIMATE CHANGE
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Waterborne Diseases That Are Sensitive to Climate Variability and Climate Change

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All stages of the fossil-fuel life cycle are a threat to human health, yet global overdependence on fossil fuel continues unabated, despite ambitious international agreements to lower greenhouse-gas emissions substantially by 2030. According to the World Health Organization, “The modern addiction to fossil fuels is not just an act of environmental vandalism. From the health perspective, it is an act of self-sabotage.”[1] A rapid transition to renewable energy is critically needed, but access to clean energy remains a challenge, particularly in the Global South, where close to 1 billion people are served by health care facilities without access to reliable energy services.[2]

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The average global temperature has already increased by 1.15°C since the Industrial Revolution, with the oceans having absorbed 90% of this excess heat, and records of average global ocean temperature were broken in May, June, July, and August 2023 (Fig. S1 in the Supplementary Appendix, available with the full text of this article at NEJM.org).[3] This warming disturbs the hydrologic cycle — the continuous movement of water from earth to the atmosphere and back again.[4] Specifically, the increase in temperature augments evaporation from the ocean, artificially increasing atmospheric water vapor, the most abundant greenhouse gas. Global land precipitation has increased in conjunction with these disturbances in the hydrologic cycle, as evidenced by a surge in the severity of very wet events. The moisture that had evaporated from the ocean reached California as an atmospheric river of heavy rains and flooding in January 2023 and as Hurricane Hillary, with a year’s precipitation in 1 day, in August 2023. Hydrologic cycle variability also includes the opposite extreme, with more frequent and severe droughts.[5]

Intensification of the hydrologic cycle can have implications for waterborne pathogens because their exposure pathways are intricately linked to local climate and weather (Fig. 1 and Table 1).[6] However, the environmental and climatic drivers of transmission differ among pathogens, in that certain waterborne pathogens can replicate outside the host (e.g., salmonella and vibrio), whereas others cannot (e.g., campylobacter, cryptosporidium, and norovirus) (Table 1).[7] A change in climatic conditions can therefore have direct or indirect effects on transmission, depending on the pathogen.

CLIMATE-SENSITIVE PATHWAYS FOR WATERBORNE DISEASES

INCREASED TEMPERATURE

An increase in ambient temperature influences the transmission of waterborne pathogens through direct effects on their growth, survival, and infectivity, as well as through indirect effects on their environmental fate and the behaviors that place persons at risk for exposure (Table 1 and Fig. 1). Climate-sensitive waterborne

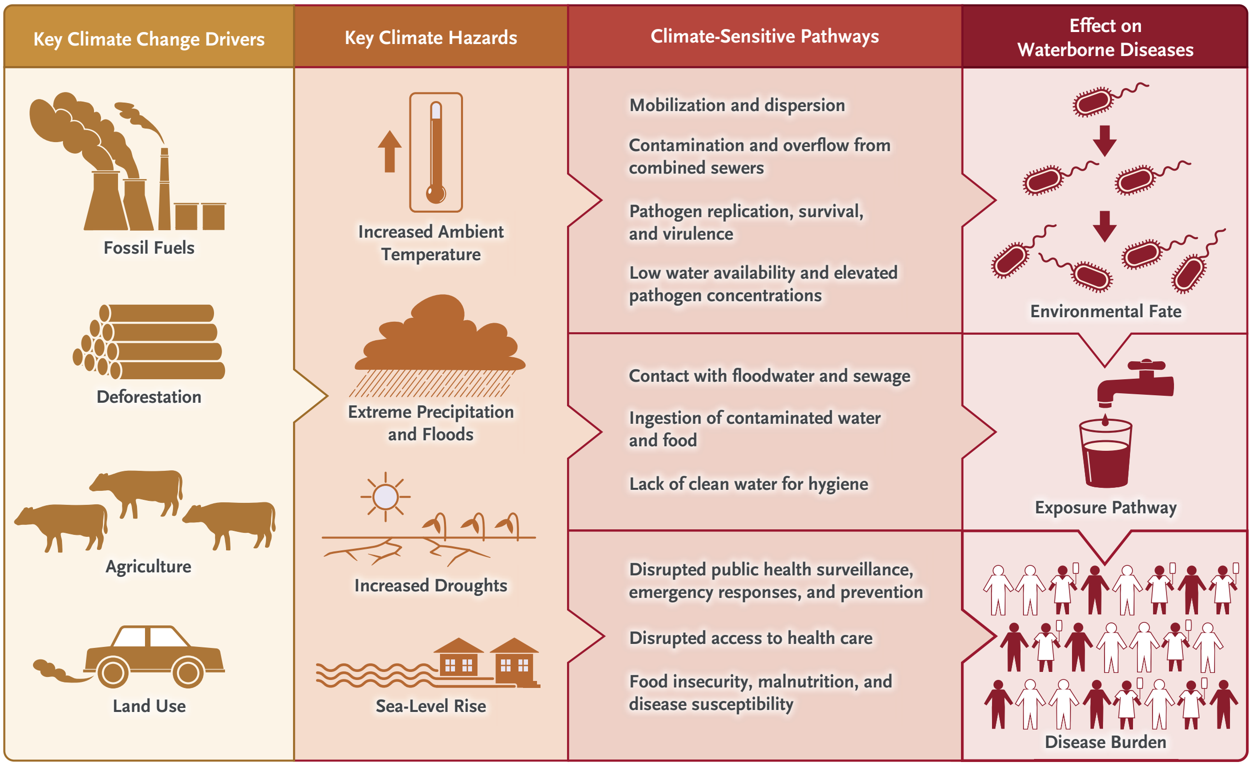

Figure 1. Pathways by Which Climate Change Drives the Burden of Waterborne Diseases.
Shown are the key drivers and hazards of climate change and the pathways by which these processes influence the environmental fate of waterborne pathogens, increase exposures of people to pathogens, and ultimately enhance the disease burden in vulnerable populations.

diseases have a distinct seasonal pattern, whereby warm summer months are associated with an increased incidence of bacterial diarrheal infections — specifically, salmonellosis and campylobacteriosis — owing to the increased fitness or reproductive success of the pathogens at higher temperatures.[8-10] Moreover, during or outside the summer months, higher air temperature is associated with an elevated incidence of diarrheal diseases, although this relationship varies according to the pathogen.[7,11,12] A majority of studies have shown a positive association between temperature and diarrhea caused by bacterial pathogens.[7,11,12] In contrast, most studies show that infections with viral pathogens such as rotavirus are less common with higher temperatures, a finding that is consistent with their heat lability (Table 1).[7,11,12]

Although higher air temperatures may improve the efficiency of microbial processing (and thus water purification) at water treatment plants, extreme heat can have adverse effects on water purification, inhibiting chlorination and ultraviolet irradiation of potable water, by increasing solubilization of organic matter and water turbidity (Table 1). Hot weather also increases water demand for drinking, hygiene, and sanitation at a time when supplies might be stretched thin, which can further increase the likelihood of human exposure to pathogens.

EXTREME PRECIPITATION AND FLOODING

Extreme precipitation can mobilize and redistribute sediments contaminated with fecal pathogens from upland pastures and fields and transport them to streams, rivers, and lakes (Table 1 and Fig. 1).[13] In urban settings, runoff from streets and other impermeable surfaces can transport pathogens to downstream collection systems and discharge them into surface water or marine environments.[14] The density of pathogenic organisms is higher in runoff if the extreme precipitation

Table 1. Effects of Climate Change Hazards on Selected Waterborne Diseases.*

Climate Hazard and Pathogen	Environmental Effects on Pathogen	Effects on Human Exposure and Disease Risk
Increase in air and water temperature		
Typhoidal and nontyphoidal salmonella, shigella, *Vibrio cholerae*	Increased survival and growth, with infectivity retained in warm water	Increased because of higher pathogen burden in water sources and prolonged transmission season, affecting contact rates
Salmonella, shigella	Expression of virulence genes at higher temperature but repression at lower temperature	Increased because of exposure to more infectious pathogens
V. vulnificus, *V. parahaemolyticus*, *Naegleria fowleri*	Increased survival and growth of marine bacteria, resulting in bacterial blooms in coastal waters	Increased because of prolonged transmission season, affecting contact rates (e.g., recreational water use)
N. fowleri, acanthamoeba species	Increased growth or enhanced survival, with infectivity retained in warm, untreated fresh water (e.g., nutrient-rich lakes, ponds, and reservoirs)	Increased because of higher pathogen burden in water sources
Rotavirus, norovirus, cryptosporidium, *Giardia lamblia*	Die-off of pathogens and reduced infectivity in warm water	Decreased because of lower pathogen burden in water sources
Legionella	Enhanced growth and survival in biofilms on air-conditioning units, water heaters, or water delivery systems	Increased because of higher pathogen burden and dispersion by contaminated air-conditioning units or aerosolization by showerheads
Bacterial, protozoan, viral, and parasitic pathogens	Water purification may be more efficient as a result of improved disinfection with chlorination at higher temperatures; water purification may be less efficient if organic matter is solubilized at higher temperatures, which increases water turbidity in treatment plants, inhibiting chlorination and ultraviolet irradiation of potable water	Decreased or increased, depending on effects on pathogen burden in potable water
Precipitation and flooding		
Cryptosporidium, *G. lamblia*	Increased discharge from water treatment plants, industry, and animal-feeding operations due to flooding and infrastructure damage	Increased because of higher pathogen burden in water sources
V. cholerae, hepatitis A virus, other fecal pathogens	Compromised WASH infrastructure (e.g., wells and potable water sources) due to damage from flooding and extreme events	Increased because of higher pathogen burden in water sources
Leptospira, staphylococcus, hepatitis A virus, rotavirus	Increased pathogen mobilization and transport due to stormwater runoff and sewage overflow	Increased because of more frequent exposure to contaminated surface water (e.g., floodwater) and soil (e.g., mud)
Escherichia coli O157:H7 and other fecal pathogens from animal and human sources	Increased runoff from non–point sources (e.g., livestock manure, wildlife, or septic system); groundwater contamination with fecal pathogens during heavy precipitation in regions with insufficient water treatment; overwhelmed water treatment, resulting in contamination of water sources and river and lake sediments	Increased because of higher pathogen concentrations in surface water
Drought		
Fecal pathogens	Insufficient treatment options (e.g., home chlorination) when water sources, storage, or both are shifted during droughts	Increased because of higher pathogen burden in water sources and decreased hand hygiene with reduced water availability
Storm surge or sea-level rise		
Fecal pathogens, including vibrio species, from human, environmental, and animal sources	Suspension and dispersion of pathogens and contamination of drinking water during storm surges	Increased because of higher pathogen burden in water sources

* For an annotated version of this table with references, see Table S1 in the Supplementary Appendix. WASH denotes water, sanitation, and hygiene.

event is preceded by extended dry periods.[15] Stormwater runoff from a heavy precipitation event carries both particulate matter and fecal waste, particularly in areas that lack functioning sewers. Combined sewers that collect runoff are at risk for overflow (Fig. 1), releasing wastewater into the environment, inundating the water intake of wastewater treatment plants, and overwhelming or damaging treatment infrastructure. Cases of water treatment failure or contamination of source water leading to exposures of persons in the catchment area to climate-sensitive waterborne diseases are well documented in the United States, northern Europe, the United Kingdom, and Canada.[16-19] In both resource-rich and resource-scarce regions of the world, drainage is not designed for unusually intense precipitation, and through a sequence of cascading events, flooding can ensue.[6,20] Flooding can inundate low-lying infrastructure in the flood plain, such as critical health care facilities, compromising the delivery of care, as happened in 2012 during Hurricane Sandy, when hospitals and emergency services in New York had to be evacuated because of flooding and power outages.

Droughts

Whereas climate change is projected to cause increased precipitation in many parts of the world, other regions will experience increased droughts. With reduced precipitation and increased evapotranspiration, groundwater and surface water decline, thereby concentrating pathogens.[21] Diminished river volume, with elevated pathogen concentrations, coincides seasonally with higher water demand (Table 1 and Fig. 1). High pathogen concentrations in surface water can then overwhelm water treatment plants, especially older ones. Moreover, whereas high pressures are normally maintained in water lines to prevent exogenous contamination from leaking parallel sewer lines, these pressures are not maintained during times of water scarcity, facilitating the entry of fecal contaminants and posing a risk of large-scale population exposures to waterborne pathogens.[22]

Data on the association between drought and waterborne disease outcomes are limited.[23-25] However, in a study in which a standardized precipitation evapotranspiration index for drought was used and the incidence of diarrhea among children under the age of 5 years was calculated from health surveys in 51 low- and middle-income countries, the estimated risk of diarrhea increased by 5% with a mild drought that lasted 6 months and by 8% with a severe drought.[26] The risk of diarrhea was reduced if water and soap were available at handwashing sites. Yet the frequency of handwashing declines significantly during periods of drought as compared with other times, as a result of reduced water availability (Table 1 and Fig. 1).[27]

Storm Surges and Sea-Level Rise

The unrelenting sea-level rise associated with climate change poses a long-term challenge to the lives and safety of millions of people that can only partly be addressed with dykes, causeways, land reclamation, and aquifer protection (Table 1 and Fig. 1). Storm surges, another manifestation of climate change, can cause catastrophic damage and floods. After Hurricane Katrina made landfall on the U.S. Gulf Coast in 2005, vibrio infections resulting from exposure of wounds to floodwaters were observed.[28] Similarly, a cholera outbreak followed the massive flooding that occurred when Cyclone Idai struck the southeastern coast of Africa at Beira, Mozambique, in 2019.[29]

Burden of Waterborne Disease Attributable to Climate Change

Every year, 1.4 million people die from diseases attributable to a lack of safe water, sanitation, and basic hygiene in households, health care facilities, and schools.[30] Over the course of the last three decades, diarrhea has remained the third leading cause of the disease burden among children under the age of 10 years, but the incidence of diarrhea declined by 68% between 1990 and 2019, in part because of improved access to WASH (water, sanitation, and hygiene), access to care, vaccination, and improved nutrition.[31]

Climate change threatens to offset these public health gains. The annual number of temperature-attributable excess deaths due to enteric infections is projected to be between 10,000 and almost 75,000 by 2050–2065, under an optimistic scenario (temperature rise kept under 2°C by 2100) and a pessimistic scenario (temperature rise of 3° to 4°C by 2100), respectively.[32] These estimates take into account the differential effects of temperature on enteric bacteria and viruses but not the effects of additional climate change (besides temperature anomalies) on climate-sensitive waterborne diseases. Nonetheless, the discrepancy in the projected enteric infection rates between these two scenarios highlights the impact that investment in public health interventions and health care, as well as substantive reductions in the use of fossil fuels, can have in reducing the burden of climate-sensitive waterborne diseases.

EXAMPLES OF CLIMATE-SENSITIVE WATERBORNE DISEASES

Four climate-sensitive waterborne pathogens of public health importance are discussed below. These and other examples are included in Table 1.

NON–*VIBRIO CHOLERAE* VIBRIO SPECIES

Vibrio bacteria are part of marine environments and thrive in warm, brackish water (a mixture of fresh and salt water) (Table 1 and Fig. 2). There are several pathogenic vibrio species, of which *V. parahaemolyticus* and *V. vulnificus* are among the most common sources of food poisoning in the United States. Both pathogens can also cause wound infections, which can progress — especially among persons with chronic liver disease or immunocompromising conditions — to necrotizing fasciitis, the need for amputation, septicemia, and death. With increasing sea-surface temperatures, these vibrio species have expanded toward northern latitudes. The northernmost outbreak of *V. parahaemolyticus*, which occurred in 2004 in Alaska, was associated with a warmer-than-normal ocean temperature at oyster farms.[33] The warming of the Baltic Sea has been associated with mounting numbers of vibrio infections among recreational water users exposed at beaches during hot summer days (Fig. 2).[34] Transmission in the Baltic Sea is projected to further increase and expand to northern latitudes in the coming decades.[34] *V. vulnificus* is also projected to expand to every U.S. state along the eastern seaboard by 2080 under scenarios of medium-to-high greenhouse-gas emissions.[35]

VIBRIO CHOLERAE

Cholera, due to *V. cholerae* O1 or O139 infection, causes epidemic diarrhea in resource-limited regions that lack a WASH infrastructure (Table 1 and Fig. 2). Infection results in profuse watery diarrhea and vomiting, dehydration, and a risk of circulatory collapse and death. Transmission occurs through the fecal–oral route. Children younger than 5 years of age are at highest risk because they lack preexisting natural anticholera immunity. Fecal contamination of the water supply can occur during heavy precipitation events that carry the pathogen from latrines into surface water. Approximately 2.9 million cases of *V. cholerae* and 95,000 associated deaths are reported annually, characteristically in low-income communities with inadequate sanitation and a lack of access to care (e.g., vigorous rehydration).[36] Cholera has two forms: an endemic form occurring with a background rate in the population and distinct seasonal peaks, and an epidemic form involving exogenous introduction of the pathogen into an unexposed population. The convergence of extreme precipitation[37] and high temperatures[38] (both of which are more frequent with climate change) and a deficient WASH infrastructure[39,40] that is further challenged by extreme weather establishes the conditions favoring large-scale cholera outbreaks (Fig. 2).[41,42]

CRYPTOSPORIDIUM

The protozoan cryptosporidium can complete its lifecycle within a single host. Humans, livestock, and wildlife are all hosts. Oocysts are excreted in feces and can survive in the environment for several months in moist soil or water and endure both heat and cold (Table 1 and Fig. 2). Infectious oocysts can be spread through the fecal–oral route, by direct contact with an infected person, or through contaminated food and water. In healthy persons, cryptosporidiosis causes diarrhea that resolves spontaneously, but in immunocompromised persons, the infection can cause profuse, watery diarrhea that may be life-threatening. In the Global South, cryptosporidium is an important cause of diarrhea and death in children under 5 years of age and is associated with malnutrition and stunted growth.[43] During heavy rainfall, cryptosporidium washes into waterways, where it can contaminate water treatment plants (Fig. 2).[44] In 1993, severe rains in Milwaukee contaminated the public water plant with cryptosporidium oocysts because of water treatment failure, resulting in the largest reported cryptosporidium outbreak in the United States.[45]

LEPTOSPIRA

Leptospirosis is caused by the bacterium leptospira, which infects a wide range of hosts, in-

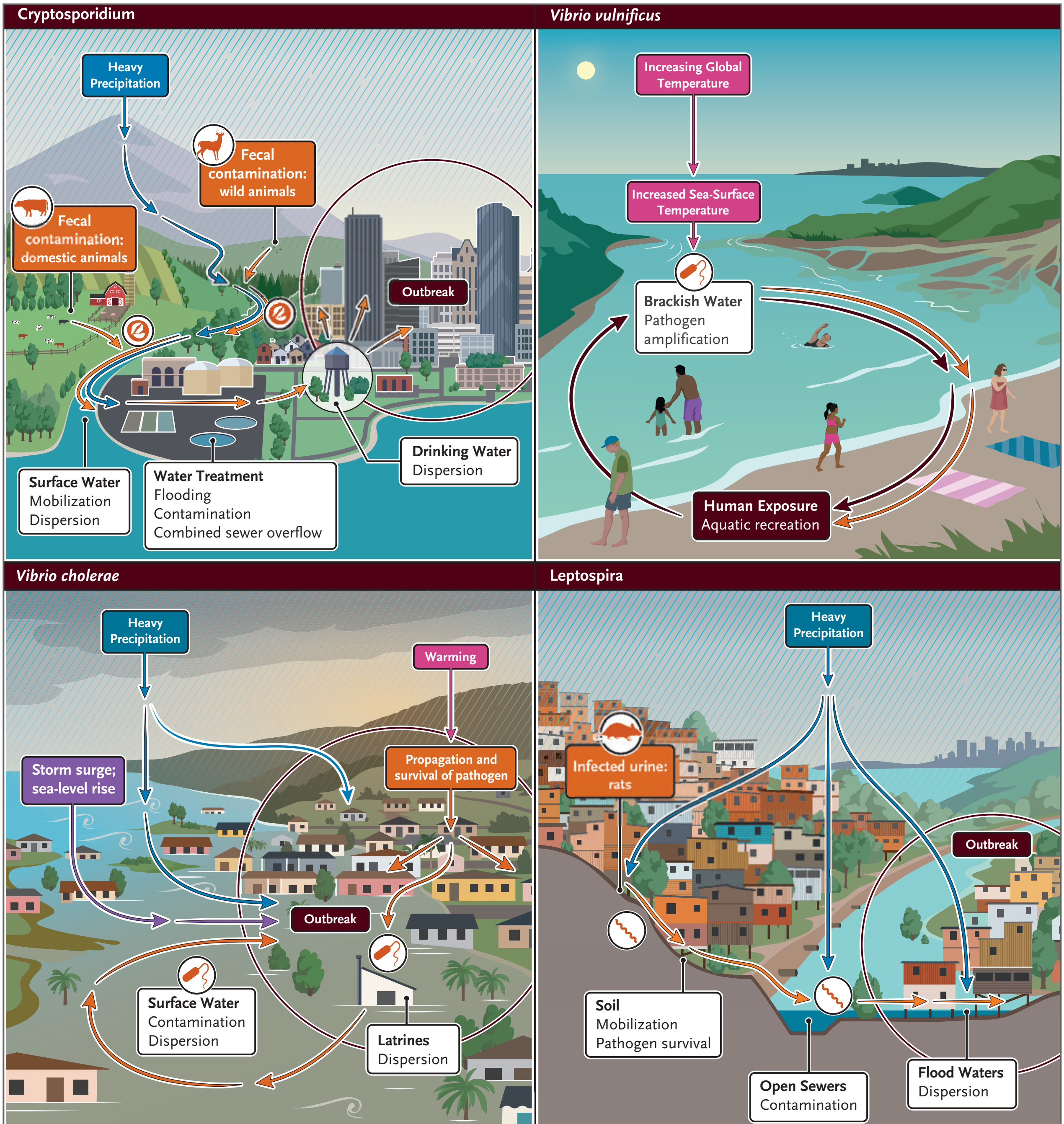

Figure 2. Examples of the Effects of Climate Change on Disease Transmission.

In the case of cryptosporidiosis, heavy rain, particularly early in the season, flushes cryptosporidium parasites in wildlife or livestock feces from the watershed into surface-water sources, where the parasites enter water treatment plants. Cryptosporidium oocytes can survive chlorination and be dispersed by the water distribution system, potentially causing large outbreaks. *Vibrio vulnificus* are aquatic bacteria that are part of the brackish marine ecosystem (e.g., estuaries), where they thrive at an elevated sea-surface temperature. Recreational water users can be exposed during warm summer days. A damaged or deficient sanitary system can disperse *V. cholerae* to surface-water sources, an effect that is exacerbated by climate-intensified heat, extreme precipitation, storm surges, and rising sea levels. Community transmission can propagate a large outbreak and contaminate the entire WASH (water, sanitation, and hygiene) infrastructure. Flooding of urban areas, particularly unplanned and low-income neighborhoods, during heavy rain events can mobilize leptospira bacteria in the urine from reservoir animals and contaminate urban environments. Exposure to the pathogenic bacteria can result in large outbreaks.

cluding humans, cattle, pigs, dogs, and rodents (Table 1 and Fig. 2). Leptospira are spread through the urine of infected animals and can survive for months in water or soil. Infection causes fever, headaches, and muscle pains but can progress to severe complications, such as Weil's disease (acute jaundice, bleeding, and kidney failure), severe pulmonary hemorrhage syndrome, or meningitis. Spillover transmission to humans typically occurs during contact with contaminated water, soil, or food. In overcrowded urban settlements with inadequate infrastructure, where people live in proximity to animal and environmental reservoirs of infection, leptospirosis transmitted by rats is a serious public health problem.[46] Floodwaters after heavy rain or extreme, transient warming in sea-surface temperatures (occurring with El Niño–Southern Oscillation) can be contaminated with leptospira and result in large outbreaks, as observed in urban centers in Brazil and South Pacific islands[47,48] (Table 1 and Fig. 2).

INEQUITIES IN IMPACTS OF CLIMATE-SENSITIVE WATERBORNE DISEASES

Climate change magnifies inequities in the burden of waterborne diseases because of its synergistic impacts on structural vulnerabilities, such as a poor WASH infrastructure, weak public health surveillance and response, and inadequate access to health care (Fig. 3). Globally, there are roughly 2 billion people without access to safely man-

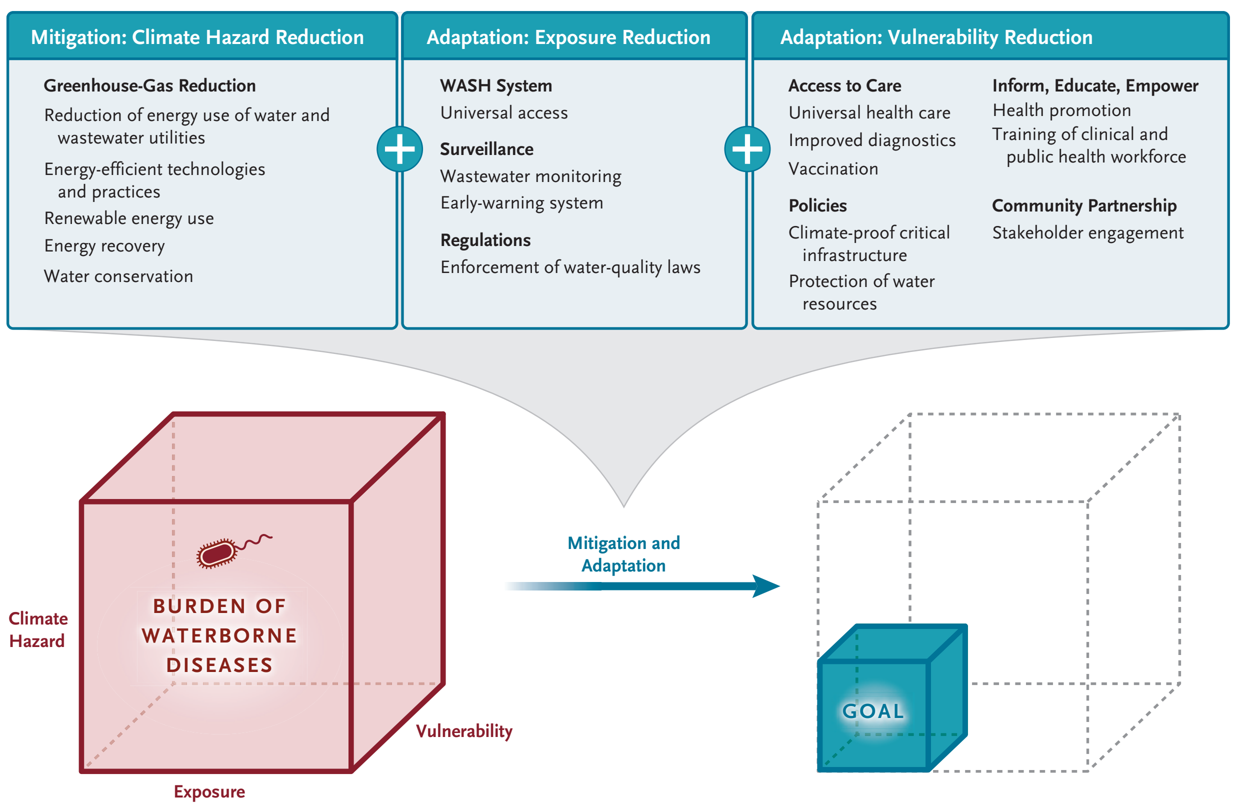

Figure 3. Reducing the Burden of Climate-Sensitive Waterborne Diseases through Mitigation of and Adaptation to Climate Change.
Mitigation aims to reduce the risk from climate hazards through greenhouse-gas reductions, particularly in high-emitting sectors but also in the water sector. Adaptation aims to reduce the risk of exposure through indicator-based surveillance for climate-sensitive waterborne diseases, enhanced event-based detection of outbreaks, monitoring of environmental and climatic precursors of disease for early-warning systems, outbreak investigation and response, and enforcement of water-quality laws. Adaptation also aims to reduce vulnerability through policies that protect the WASH system; improve access to health care; promote research on the detection, treatment, and prevention of climate-sensitive waterborne diseases; and inform, educate, and empower communities and stakeholders.

aged drinking water services, mainly in the Global South.[49]

Rapid urbanization in low- and middle-income countries has led to an expansion of informal settlements characterized by poor housing that is often built on precarious land and lacks adequate sewage and rainwater drainage systems (Fig. 2). For the approximately 1 billion people worldwide who are living in these conditions, extreme rainfall events with flooding result in

Table 2. Adaptive Strategies Addressing Key Vulnerabilities Regarding Climate-Sensitive Waterborne Diseases (WBDs).*

Vulnerability	Selected Opportunities for Adaptation
	Surveillance and monitoring
Limited surveillance capacity to detect WBD outbreaks triggered by climate hazards	Establish integrated surveillance systems and early-warning systems for climate-sensitive WBDs, with capacity to monitor: • meteorologic factors (e.g., rainfall, temperature) that trigger or contribute to disease spread; • environmental conditions (e.g., sea-surface salinity) that can trigger prompt investigation of suspected cases and control measures (e.g., closure of contaminated recreational water sites); • physical properties of surface- and drinking-water quality (e.g., temperature, turbidity, pH, chlorine, conductivity) that may promote microbial growth and survival and efficiency of water treatment and purification and enable authorities to protect the water supply (e.g., ultraviolet disinfection of water supplies); • microbial agents (bacterial, viral, and parasitic) in potable water sources and wastewater, identified in real time through PCR testing, NGS, ELISA, and biosensors; • social media for references of symptoms or WBDs (e.g., hashtags, keywords). Develop capacity for rapid point-of-use field detection, mobile detection of waterborne pathogens with a suitcase laboratory (and nanopore-sequencing technology) to identify and confirm outbreaks in difficult-to-reach settings and vulnerable populations).
	Health care system
Unprepared health infrastructures	Identify climate hazards that will affect health care facilities and their catchment populations and assess vulnerabilities. Strengthen resilience by implementing the 10 components of the WHO operational framework.† Reinforce the 10 essential public health functions.‡
	Diagnosis
Multiple causative agents for climate-sensitive WBDs and outbreaks	Develop and use improved multiplex diagnostic testing: • PCR and LAMP — highly sensitive and specific tests used for the diagnosis of waterborne pathogens such as cryptosporidium and giardia; • metagenomic sequencing — high-throughput sequencing that can detect genetic material in patient samples, including bacteria, viruses, fungi, and parasites; may be used in broad screening where diagnosis is unclear; • mass spectrometry — identifies proteins and peptides in patient samples and may be useful in diagnosis of waterborne pathogens (e.g., legionella); • biosensors — highly sensitive and specific devices to detect specific pathogens (e.g., *Escherichia coli*, salmonella) in patient samples in real time.
	Access to safe water
Vulnerable water supply systems	Implement risk management approaches through water safety plans. Identify risks to water safety and associated risks of hazardous events (e.g., outbreaks). Determine and validate control measures (e.g., water disinfection), reassess, and prioritize risk. Consider the long-term impacts of climate change and upgrade plans accordingly.
	Access to safe sanitation
Lack of access to or inadequate sanitation systems	Implement risk management approaches through sanitation safety plans that identify climate-related hazards, assess existing control measures, and expose risks. Identify and prioritize health risks from climate-sensitive WBDs along the sanitation chain, from toilet to storage, conveyance, treatment, and end use or disposal. Control highest risks along the sanitation chain with the use of technology upgrades, changes in management and operation, behavior change measures, and policy and regulatory measures..

Table 2. (Continued.)

Vulnerability	Selected Opportunities for Adaptation
	Key research gaps
Marginalized groups and Global South	In Central Asia, North and Central Africa, South America, and other regions where climate data are not readily available (because of the lack of monitoring stations, infrastructure, technology, financial resources, or technical expertise), generate evidence base through technology transfer, capacity building, and financial assistance.
Additional vulnerabilities	Develop tools (e.g., Quantitative Microbial Risk Assessment) to estimate risk of adverse effect (e.g., infection, illness, or death from WBD exposure). Predict risks of WBD under different climate change scenarios to better understand possible future impacts on disease burden. Assess resilience of WASH-based interventions to climate hazards and their usefulness in reducing the impacts of climate change on WBDs. Generate evidence based on effects of climate change mitigation and adaptation on WBD risks.

* For an annotated version of this table with references, see Table S2 in the Supplementary Appendix. ELISA denotes enzyme-linked immunosorbent assay, LAMP loop-mediated isothermal amplification, NGS next-generation sequencing, PCR polymerase chain reaction, and WHO World Health Organization.

† The 10 components of the WHO framework are as follows: leadership and governance; health workforce; vulnerability, capacity, and adaptation assessment; integrated risk monitoring and early warning; health and climate research; climate-resilient and sustainable technologies and infrastructure; management of environmental determinants of health; climate-informed health programs; emergency preparedness and management; and climate and health financing.

‡ The 10 essential public health functions are as follows: monitoring; outbreak investigation and response; informing, educating, and empowering communities and stakeholders; fostering of interagency and community partnerships; development of policies; enforcement of laws and regulations; assurance of access to care; assurance of a competent workforce; evaluation and continuous quality improvement of public health functions; and research.

exposure to waterborne diseases, including parasitic infections, bacterial diarrheal diseases, and leptospirosis.[30,50,51] Furthermore, the inhabitants typically lack access to essential treatments when facing threats such as cyclone-associated cholera epidemics and rainfall-associated outbreaks of leptospirosis.[29,47]

In upper-income countries, climate change–driven warming and more intense storms have a disproportionate impact on waterborne disease risks in low-income communities and communities of color, in part owing to antiquated and inadequate potable water systems in many of these communities. For example, vulnerable inner-city populations are particularly susceptible to outbreaks of legionellosis, such as the outbreak that occurred in Flint, Michigan, in 2014, when a change in the water source and temperature led to increased release of iron from an antiquated water distribution system, which in turn promoted the growth of *Legionella pneumophila* in the potable water supply.[52]

Conversely, drought jeopardizes the availability of fresh water in urban areas.[53,54] Extreme drought, intermittent precipitation, and elevated air temperatures are projected to cause water shortages for 1 billion urban dwellers in the near future,[55,56] especially groups that already vulnerable. Asymmetric and unsustainable water consumption by privileged segments of society[57,58] drains limited water resources and compromises the ability of socioeconomically disadvantaged populations to meet basic water needs.[59] Low-income rural populations are similarly deprived of water sources for irrigation and agricultural activities, which has implications for food security (Fig. 1).[55] More equitable redistribution of water resources and restrictions on the use of water for amenities are critical measures for addressing climate change–related inequities.

MEDICAL AND PUBLIC HEALTH INTERVENTIONS

Historically, public health practice has successfully interrupted transmission pathways for climate-sensitive waterborne diseases through WASH, but these achievements are increasingly threatened by climate hazards.[60] Adapting to the rapidly increasing risks of waterborne disease from climate change builds on the 10 essential public health functions.[61] The charge is to climate-proof our medical and public health systems across multiple levels, ensuring an integrated response in individual- and population-level interventions. However, successful adaptation to climate change hinges on educating the clinical and public health workforce about the health threats from climate change — for example, as part of medical and public health school curricula, postgraduate training programs, and continuing education. Advocacy by the medical and public health establishment will be key in advancing climate change policies and regulations — and their enforcement — to safeguard health at the population level.

Adaptive strategies for addressing the challenges posed by climate change–related waterborne diseases include effective early-warning systems that integrate surveillance of climatic conditions, detection of pathogens in wastewater, enhanced case-based detection, and cutting-edge technologies for laboratory diagnosis (Table 2 and Fig. 3).[6,60] Current surveillance is limited by the complexity of diagnostic testing and the diversity of bacterial, viral, and parasitic agents to be monitored. Wastewater monitoring of nucleic acids or biomarkers from waterborne pathogens in effluents offers cost-effective and real-time surveillance of community transmission.[62] In a review of worldwide outbreaks caused by protozoa, cryptosporidium and giardia accounted for the vast majority of outbreaks,[63] and both are detectable in wastewater.[64] Wastewater monitoring can detect community transmission before case-based surveillance identifies outbreaks, serving as an early-warning system (Table 2 and Fig. 3).[65,66]

Climatic conditions can be monitored to predict the likelihood that certain waterborne pathogens will pose a health risk.[6] As an example, the ECDC (European Centre for Disease Prevention and Control) Vibrio Map Viewer, an environmental monitoring system that detects climatic suitability for noncholera vibriosis, has been operationalized in Europe, where these infections do not constitute a reportable disease.[34,67] Sea-surface temperature and salinity in marine environments are remotely sensed globally in real time. A 5-day forecasting function calculates whether conditions could be suitable for pathogenic vibrio bacteria that thrive in warm, brackish coastal water.[34] Alerts about environmental suitability in certain coastal areas are sent to public health authorities with options for intervention.[34] Examples of protective strategies include beach closures and alerts to health care providers and the public, warning at-risk persons to avoid exposure to vibrio bacteria from recreational water use or consumption of raw seafood. The success of an integrated early-warning system relies on community engagement in decision making, preparedness, and response.[68]

Ongoing research is needed to refine climate models in order to assess the specific effects of climate change. An important limitation is that climate data are often not available in areas populated by socially and economically marginalized groups, exacerbating existing health inequities. Effective diagnostics and treatments, as well as vaccinations (currently available for cholera, hepatitis A, typhoid fever, and rotavirus infection), are indispensable tools to reduce the burden of climate-sensitive waterborne diseases (Table 2 and Fig. 3).[69,70]

CLIMATE CHANGE MITIGATION

Minimizing harms from climate change–related waterborne diseases requires a prompt and equitable transition away from fossil fuels in all sectors. Although such a transition is especially critical in sectors with the highest emissions (e.g., energy and transportation), it is also important for water and wastewater utilities, which are responsible for 3 to 7% of greenhouse-gas emissions (Fig. 3).[71] In addition, the water management sector consumes 4% of global electricity for abstraction (i.e., extraction of water from natural sources), conveyance, and treatment, a rate projected to double by 2040 as a result of increasing desalination of salt water (Table 2 and Fig. 3).[72] However, by 2040, this energy use could be reduced by 15% through more efficient water use, such as reuse of wastewater and reduction in unnecessary water consumption and waste.[73] Moreover, energy-positive treatment plants that generate methane as an energy source from organic material in wastewater may reduce the overall energy consumption of the water sector.[74]

CONCLUSIONS

Climate change has already intensified environmental turmoil, with substantial ramifications for health and health care systems,[75] including increased risks of several waterborne diseases. These risks are projected to continue to increase in the near future, should the global community fail to take strong and immediate action to mitigate greenhouse-gas emissions and institute adaptive strategies. Climate-proofing water treatment and distribution systems, as well as our health care delivery systems, is critical for preventing, preparing for, and managing climate-sensitive waterborne diseases.[6,60] Beyond continued work on developing and better deploying vaccines and effective therapies for waterborne diseases, developing integrated early-warning systems with the use of climatic or environmental precursors of disease can help contain or prevent disease outbreaks.[6,60] Finally, reducing waterborne diseases requires safe and equitable access to water and sanitation for all segments of the world's population, a goal that can be met by returning to basic public health principles, ensuring climate resilience in water infrastructure, and rapidly transitioning from our dependence on fossil fuels.

Disclosure forms provided by the authors are available with the full text of this article at NEJM.org.

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REFERENCES

1. Huet N. WHO joins global call for a binding treaty to end 'self-sabotage' of addiction to fossil fuels. Euronews. September 14, 2022 (https://www.euronews.com/next/2022/09/14/who-joins-global-call-for-a-binding-treaty-to-end-self-sabotage-of-addiction-to-fossil-fue).
2. Romanello M, Di Napoli C, Green C, et al. The 2023 report of the Lancet Countdown on health and climate change: the imperative for a health-centred response in a world facing irreversible harms. Lancet (in press).
3. Record-breaking North Atlantic Ocean temperatures contribute to extreme marine heatwaves. Copernicus. July 6, 2023 (https://climate.copernicus.eu/record-breaking-north-atlantic-ocean-temperatures-contribute-extreme-marine-heatwaves).
4. Allen MR, Ingram WJ. Constraints on future changes in climate and the hydrologic cycle. Nature 2002;419:224-32.
5. Gründemann GJ, van de Giesen N, Brunner L, van der Ent R. Rarest rainfall events will see the greatest relative increase in magnitude under future climate change. Commun Earth Environ 2022;3:235.
6. Semenza JC. Cascading risks of waterborne diseases from climate change. Nat Immunol 2020;21:484-7.
7. Semenza JC, Herbst S, Rechenburg A, et al. Climate change impact assessment of food- and waterborne diseases. Crit Rev Environ Sci Technol 2012;42:857-90.
8. Yun J, Greiner M, Höller C, Messelhäusser U, Rampp A, Klein G. Association between the ambient temperature and the occurrence of human Salmonella and Campylobacter infections. Sci Rep 2016;6:28442.
9. Djennad A, Lo Iacono G, Sarran C, et al. Seasonality and the effects of weather on Campylobacter infections. BMC Infect Dis 2019;19:255.
10. Lake IR, Colón-González FJ, Takkinen J, et al. Exploring campylobacter seasonality across Europe using the European surveillance system (TESSy), 2008 to 2016. Euro Surveill 2019;24:1800028.
11. Levy K, Woster AP, Goldstein RS, Carlton EJ. 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 2016;50:4905-22.
12. Lo Iacono G, Armstrong B, Fleming LE, et al. Challenges in developing methods for quantifying the effects of weather and climate on water-associated diseases: a systematic review. PLoS Negl Trop Dis 2017;11(6):e0005659.
13. Schijven JF, de Roda Husman AM. Effect of climate changes on waterborne disease in the Netherlands. Water Sci Technol 2005;51:79-87.
14. Semenza JC, Caplan JS, Buescher G, Das T, Brinks MV, Gershunov A. Climate change and microbiological water quality at California beaches. Ecohealth 2012;9:293-7.
15. Coffey R, Benham B, Krometis L-A, Wolfe ML, Cummins E. Assessing the effects of climate change on waterborne microorganisms: implications for EU and U.S. water policy. Hum Ecol Risk Assess 2014;20:724-42.
16. Curriero FC, Patz JA, Rose JB, Lele S. The association between extreme precipitation and waterborne disease outbreaks in the United States, 1948-1994. Am J Public Health 2001;91:1194-9.
17. Guzman Herrador B, de Blasio BF, Carlander A, et al. Association between heavy precipitation events and waterborne outbreaks in four Nordic countries, 1992-2012. J Water Health 2016;14:1019-27.
18. Nichols G, Lane C, Asgari N, Verlander NQ, Charlett A. Rainfall and outbreaks of drinking water related disease and in England and Wales. J Water Health 2009;7:1-8.
19. Thomas KM, Charron DF, Waltner-Toews D, Schuster C, Maarouf AR, Holt JD. A role of high impact weather events in waterborne disease outbreaks in Canada, 1975–2001. Int J Environ Health Res 2006;16:167-80.
20. Semenza JC, Rocklöv J, Ebi KL. Climate change and cascading risks from infectious disease. Infect Dis Ther 2022;11:1371-90.
21. Schijven J, Bouwknegt M, de Roda Husman AM, et al. A decision support tool to compare waterborne and foodborne infection and/or illness risks associated with climate change. Risk Anal 2013;33:2154-67.
22. Semenza JC, Roberts L, Henderson A, Bogan J, Rubin CH. Water distribution system and diarrheal disease transmission: a case study in Uzbekistan. Am J Trop Med Hyg 1998;59:941-6.
23. Fang X, Ai J, Liu W, et al. Epidemiology of infectious diarrhoea and the relationship with etiological and meteorological factors in Jiangsu Province, China. Sci Rep 2019;9:19571.

24. Ikeda T, Kapwata T, Behera SK, et al. Climatic factors in relation to diarrhoea hospital admissions in rural Limpopo, South Africa. Atmosphere 2019;10:522.
25. Epstein A, Benmarhnia T, Weiser SD. Drought and illness among young children in Uganda, 2009–2012. Am J Trop Med Hyg 2020;102:644-8.
26. Wang P, Asare E, Pitzer VE, Dubrow R, Chen K. Associations between long-term drought and diarrhea among children under five in low- and middle-income countries. Nat Commun 2022;13:3661.
27. Emont JP, Ko AI, Homasi-Paelate A, Ituaso-Conway N, Nilles EJ. Epidemiological investigation of a diarrhea outbreak in the South Pacific Island nation of Tuvalu during a severe La Niña–associated drought emergency in 2011. Am J Trop Med Hyg 2017;96:576-82.
28. Vibrio illnesses after Hurricane Katrina — multiple states, August–September 2005. MMWR Morb Mortal Wkly Rep 2005;54:928-31.
29. Chen WH, Azman AS. Mitigating cholera in the aftermath of cyclone Idai. Am J Trop Med Hyg 2019;101:960-2.
30. United Nations Children's Fund (UNICEF). Triple threat: how disease, climate risks, and unsafe water, sanitation and hygiene create a deadly combination for children. UNICEF. March 2023 (https://www.unicef.org/reports/triple-threat-wash-disease-climate).
31. GBD 2019 Diseases and Injuries Collaborators. Global burden of 369 diseases and injuries in 204 countries and territories, 1990-2019: a systematic analysis for the Global Burden of Disease Study 2019. Lancet 2020;396:1204-22.
32. Chua PLC, Huber V, Ng CFS, et al. Global projections of temperature-attributable mortality due to enteric infections: a modelling study. Lancet Planet Health 2021;5(7):e436-e445.
33. McLaughlin JB, DePaola A, Bopp CA, et al. Outbreak of *Vibrio parahaemolyticus* gastroenteritis associated with Alaskan oysters. N Engl J Med 2005;353:1463-70.
34. Semenza JC, Trinanes J, Lohr W, et al. Environmental suitability of Vibrio infections in a warming climate: an early warning system. Environ Health Perspect 2017;125:107004.
35. Archer EJ, Baker-Austin C, Osborn TJ, et al. Climate warming and increasing Vibrio vulnificus infections in North America. Sci Rep 2023;13:3893.
36. Clemens JD, Nair GB, Ahmed T, Qadri F, Holmgren J. Cholera. Lancet 2017;390:1539-49.
37. Constantin de Magny G, Murtugudde R, Sapiano MR, et al. Environmental signatures associated with cholera epidemics. Proc Natl Acad Sci U S A 2008;105:17676-81.
38. Jutla A, Whitcombe E, Hasan N, et al. Environmental factors influencing epidemic cholera. Am J Trop Med Hyg 2013;89:597-607.
39. Taylor DL, Kahawita TM, Cairncross S, Ensink JH. The impact of water, sanitation and hygiene interventions to control cholera: a systematic review. PLoS One 2015;10(8):e0135676.
40. Sasaki S, Suzuki H, Fujino Y, Kimura Y, Cheelo M. Impact of drainage networks on cholera outbreaks in Lusaka, Zambia. Am J Public Health 2009;99:1982-7.
41. Ali M, Nelson AR, Lopez AL, Sack DA. Updated global burden of cholera in endemic countries. PLoS Negl Trop Dis 2015;9(6):e0003832.
42. Severe K, Alcenat N, Rouzier V. Resurgence of cholera in Haiti amidst humanitarian crises. N Engl J Med 2022;387:2389-91.
43. Khalil IA, Troeger C, Rao PC, et al. Morbidity, mortality, and long-term consequences associated with diarrhoea from Cryptosporidium infection in children younger than 5 years: a meta-analyses study. Lancet Glob Health 2018;6(7):e758-e768.
44. Semenza JC, Nichols G. Cryptosporidiosis surveillance and water-borne outbreaks in Europe. Euro Surveill 2007;12(5):E13-E14.
45. Mac Kenzie WR, Hoxie NJ, Proctor ME, et al. A massive outbreak in Milwaukee of cryptosporidium infection transmitted through the public water supply. N Engl J Med 1994;331:161-7.
46. Ko AI, Galvão Reis M, Ribeiro Dourado CM, Johnson WD Jr, Riley LW, Salvador Leptospirosis Study Group. Urban epidemic of severe leptospirosis in Brazil. Lancet 1999;354:820-5.
47. Cunha M, Costa F, Ribeiro GS, et al. Rainfall and other meteorological factors as drivers of urban transmission of leptospirosis. PLoS Negl Trop Dis 2022;16(4):e0007507.
48. Weinberger D, Baroux N, Grangeon J-P, Ko AI, Goarant C. El Niño southern oscillation and leptospirosis outbreaks in New Caledonia. PLoS Negl Trop Dis 2014;8(4):e2798.
49. Kashiwase H, Fujs T. World Water Day: two billion people still lack access to safely managed water. World Bank. March 23, 2023 (https://blogs.worldbank.org/opendata/world-water-day-two-billion-people-still-lack-access-safely-managed-water).
50. Bethony J, Brooker S, Albonico M, et al. Soil-transmitted helminth infections: ascariasis, trichuriasis, and hookworm. Lancet 2006;367:1521-32.
51. Garchitorena A, Sokolow SH, Roche B, et al. Disease ecology, health and the environment: a framework to account for ecological and socio-economic drivers in the control of neglected tropical diseases. Philos Trans R Soc Lond B Biol Sci 2017;372:20160128.
52. Rhoads WJ, Garner E, Ji P, et al. Distribution system operational deficiencies coincide with reported Legionnaires' disease clusters in Flint, Michigan. Environ Sci Technol 2017;51:11986-95.
53. Zhang X, Chen N, Sheng H, et al. Urban drought challenge to 2030 sustainable development goals. Sci Total Environ 2019;693:133536.
54. Dilling L, Daly ME, Kenney DA, et al. Drought in urban water systems: learning lessons for climate adaptive capacity. Clim Risk Manag 2019;23:32-42.
55. Flörke M, Schneider C, McDonald RI. Water competition between cities and agriculture driven by climate change and urban growth. Nat Sustain 2018;1:51-8.
56. Greve P, Kahil T, Mochizuki J, et al. Global assessment of water challenges under uncertainty in water scarcity projections. Nat Sustain 2018;1:486-94.
57. Savelli E, Mazzoleni M, Di Baldassarre G, Cloke H, Rusca M. Urban water crises driven by elites' unsustainable consumption. Nat Sustain 2023;6:929-40.
58. Rusca M, Savelli E, Di Baldassarre G, Biza A, Messori G. Unprecedented droughts are expected to exacerbate urban inequalities in Southern Africa. Nat Clim Chang 2023;13:98-105.
59. Savelli E, Rusca M, Cloke H, Di Baldassarre G. Drought and society: scientific progress, blind spots, and future prospects. Wiley Interdiscip Rev Clim Change 2022;13(3):e761.
60. Semenza JC, Paz S. Climate change and infectious disease in Europe: impact, projection and adaptation. Lancet Reg Health Eur 2021;9:100230.
61. Semenza JC, Menne B. Climate change and infectious diseases in Europe. Lancet Infect Dis 2009;9:365-75.
62. Zahedi A, Monis P, Deere D, Ryan U. Wastewater-based epidemiology-surveillance and early detection of waterborne pathogens with a focus on SARS-CoV-2, cryptosporidium and giardia. Parasitol Res 2021;120:4167-88.
63. Ma J-Y, Li M-Y, Qi Z-Z, et al. Waterborne protozoan outbreaks: an update on the global, regional, and national prevalence from 2017 to 2020 and sources of contamination. Sci Total Environ 2022;806:150562.
64. Razzolini MTP, Breternitz BS, Kuchkarian B, Bastos VK. Cryptosporidium and giardia in urban wastewater: a challenge to overcome. Environ Pollut 2020;257:113545.
65. King B, Fanok S, Phillips R, Lau M, van den Akker B, Monis P. Cryptosporidium attenuation across the wastewater treatment train: recycled water fit for purpose. Appl Environ Microbiol 2017;83(5):e03068-16.

66. Morin CW, Semenza JC, Trtanj JM, Glass GE, Boyer C, Ebi KL. Unexplored opportunities: use of climate-and weather-driven early warning systems to reduce the burden of infectious diseases. Curr Environ Health Rep 2018;5:430-8.
67. Lindgren E, Andersson Y, Suk JE, Sudre B, Semenza JC. Public health. Monitoring EU emerging infectious disease risk due to climate change. Science 2012;336:418-9.
68. Semenza JC. Lateral public health: advancing systemic resilience to climate change. Lancet Reg Health Eur 2021;9:100231.
69. Aliabadi N, Antoni S, Mwenda JM, et al. Global impact of rotavirus vaccine introduction on rotavirus hospitalisations among children under 5 years of age, 2008-16: findings from the Global Rotavirus Surveillance Network. Lancet Glob Health 2019;7(7):e893-e903.
70. Qadri F, Wierzba TF, Ali M, et al. Efficacy of a single-dose, inactivated oral cholera vaccine in Bangladesh. N Engl J Med 2016;374:1723-32.
71. Trommsdorf C. Can the water sector deliver on carbon reduction? International Water Association. October 7, 2015 (https://iwa-network.org/can-the-water-sector-deliver-on-carbon-reduction/).
72. The United Nations world water development report 2020: water and climate change. Paris: UNESCO, 2020.
73. Freyberg T. Denmark kick-starts energy-positive wastewater treatment project. WaterWorld Magazine. February 5, 2016 (https://www.waterworld.com/wastewater/article/16202924/denmark-kickstarts-energypositive-wastewater-treatment-project).
74. Maktabifard M, Zaborowska E, Makinia J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. Rev Environ Sci Biotechnol 2018;17:655-89..
75. Haines A, Ebi K. The imperative for climate action to protect health. N Engl J Med 2019;380:263-73.