COLLOQUIUM REPORT

Water, Waterborne Pathogens and Public Health: Environmental Drivers

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Water, Waterborne Pathogens and Public Health: Environmental Drivers

Report on an American Academy of Microbiology and American Geophysical Union Colloquium held on December 5 & 6, 2024.

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Executive Summary

Humans were once nomadic, constantly moving in search of resources. However, the Industrial Revolution marked a significant turning point. We chose to abandon our wandering ways and establish permanent settlements, creating communities designed to meet our diverse needs. Water, an elemental necessity for life, continued to be a crucial resource. Yet we failed to foresee how fluctuations in water availability would profoundly affect the ecology of environmentally sensitive pathogens, thereby impacting human health in unforeseen ways. This oversight has led to complex challenges in managing water resources and safeguarding public health functions.

With more than 3.5 million deaths each year attributable to waterborne pathogens, it is a critical time to question our ability to understand the relationships between water and public health, particularly to the etiological pathways in which environmentally sensitive pathogens interact with human populations and have resulted in major pandemics of our times. We also need to provide introspection on the very basic tenet of life: is safe water a right or a privilege? This report seeks scientific scholarship and evidence to answer this question, with particular emphasis on waterborne pathogens as the key indicators of safe water available for humans.

This report is based on the deliberations of experts who participated in a colloquium on December 5 and 6, 2024, organized by the American Academy of Microbiology, the honorific leadership group and think tank within the American Society for Microbiology (ASM), and the American Geophysical Union (AGU). These experts, from various fields and sectors, focused on how changes in water and the environment affect the spread of infectious diseases. They reviewed current knowledge and identified key gaps in understanding the relationship between water and disease-causing microorganisms in today's world. They identified several key issues to enhance public health.

- **Expand collaboration and engagement.** Experts in earth sciences, microbiology, hydrology and public health along with community leaders need to collaborate.
- **Strengthen water systems.** Modern and resilient water infrastructure allows for improved water safety, reduced disease risk and sustainable economic benefits.
- **Improve knowledge sharing.** Integrate data systems that link Earth observations and weather parameters with public health information for proactive public health support.

Introduction

All living organisms, from the tiniest microbes to the largest mammals, rely on water for survival. However, availability and quality of this crucial resource are increasingly unpredictable due to various factors. Microbes, including those that cause disease, play a vital role in water systems and are essential for maintaining life on Earth.

Several factors contribute to the variability of water resources.

- **Variable weather patterns.** Enhanced variability in weather and climate processes is altering precipitation and temperature, affecting water availability.
- **Pollution.** Industrial, agricultural and urban pollution are contaminating water sources, making them unsafe.
- **Population growth.** Increasing human populations are putting more pressure on water resources, leading to shortages and conflicts.

These changes not only limit the availability of clean water but also create new pathways for humans to interact with pathogens. As water becomes scarcer and more polluted, the risk of waterborne diseases increases. To build a resilient response to these health challenges, it is crucial to understand how environmental changes impact waterborne pathogens. This involves studying the interactions between weather, water and climate processes. The goal is to generate knowledge for a deeper understanding of these dynamics, so that we can develop strategies to protect public health and ensure sustainable water management for future generations.

Globally, 1 in 3 people do not have access to safe consumable water.

More than 3.5 million deaths are attributed to waterborne pathogens annually (Wellcome 2024). Globally, 1 in 3 people do not have access to safe consumable water, putting a vast number of people at risk of waterborne pathogens (UNICEF 2019). Microorganisms, such as viruses, bacteria and protists, are found in all water systems. A subset of microbes can cause disease when humans drink or interact with water contaminated by those microbes, known as waterborne pathogens. Waterborne diseases include a range of illnesses caused by pathogens such as *Vibrio cholerae* (cholera), *Salmonella* (typhoid fever), Hepatitis A, Norovirus, *Giardia lamblia* and *Cryptosporidium*. These diseases can lead to severe health outcomes, including diarrhea, which is a leading cause of death among children under 5 years old.

In the United States, waterborne diseases affect over 7 million people annually, resulting in approximately 601,000 emergency department visits, 118,000 hospitalizations and 6,630 deaths. The direct healthcare costs associated with these illnesses are estimated to be around 3.33 billion USD per year. Globally, the World Health Organization (WHO) estimates that 1.4 million deaths and 74 million disability-adjusted life years (DALYs) could have been prevented with safe water, sanitation and hygiene (WASH) services in 2019. Unsafe WASH services are linked to 69% of all diarrheal deaths and 356,000 deaths from acute respiratory infections.

Innovations in public sanitation systems in the 19th century, such as the development of sewage systems and water treatment facilities, greatly reduced the burden of waterborne diseases and death. However, aging infrastructure and increasingly extreme weather events pose severe risks to safe drinking water for a growing global population. Water-related weather events are expected to increase in frequency, intensity and duration, via excessive rainfall, floods and droughts. These events can lead to contamination of water supplies, exacerbating spread of waterborne diseases. Addressing the global burden of waterborne diseases requires significant investment in modernizing water infrastructure and improving access to safe water and sanitation. This is crucial to reduce the health and economic impacts of these preventable illnesses.

More recently, in 2024 alone, water-related natural disasters, such as flooding, cyclones and hurricanes, caused more than 8,700 deaths and over 550 billion USD in damage globally (Global Water Monitor 2025). These storms heighten microbial pathogen exposure, thereby increasing the risk of infection. Skin, gastrointestinal and respiratory infections have increased after severe storms (Liang and Messenger 2018; Lynch and Shaman 2023). In addition, warming temperatures are associated with increased incidence of vector-borne and waterborne infections (Levy et al. 2016; Paz 2024). Globally, the number of waterborne infections is rising and expected to increase because of aging sanitation systems and more extreme weather events (Levy et al. 2018; Kunz et al. 2024).

More than 4 billion people globally, the majority of whom live in low- and middle-income countries, access water from unmonitored and unsafe sources (Greenwood et al. 2024). Building more robust water surveillance systems can increase pathogen monitoring and reduce outbreaks. In addition, environmental data linked with public health

information can be used to develop predictive models to anticipate waterborne disease outbreaks and thereby offer proactive warnings of local health risks from contaminated water.

This report is based on deliberations of experts in microbial sciences, infectious disease, hydrology and climate science who participated in a colloquium on December 5 and 6, 2024. The event was organized by the American Academy of Microbiology, which is the honorific leadership group and think tank within the American Society for Microbiology, and the American Geophysical Union. The colloquium was also supported by the Association for the Sciences of Limnology and Oceanography.

Participants focused on the critical role of water and environmental variability in the transmission and distribution of infectious pathogens. They reviewed the current understanding of and outlined key knowledge gaps about the interplay of water and pathogenic microorganisms in today's world. Discussions highlighted the impact of extreme weather events and aging infrastructure on water safety and public health. From their discussions, the participants developed a holistic strategy for managing water resources and leveraging global data to improve human health and well-being. They identified several key issues to enhance public health.

- **Modernizing water infrastructure.** Investing in advanced water treatment and distribution systems to ensure safe drinking water.
- **Enhancing surveillance and monitoring.** Implementing robust systems to track water quality and pathogen presence.
- **Promoting interdisciplinary research.** Encouraging collaboration across microbial sciences, hydrology and climate science to address complex challenges.
- **Improving public awareness and engagement.** Raising awareness about the importance of safe water and sanitation practices and engaging with local communities to co-develop collaborative solutions.

The report underscores the urgency of addressing the global burden of waterborne diseases through coordinated efforts and innovative solutions. Integrating scientific knowledge and technological advancements can mitigate the risks posed by waterborne pathogens and enhance global health outcomes.

A Brief History of Sanitation, Public Health and Waterborne Diseases

Water treatment dates back to ancient civilizations, with early methods like solar radiation, boiling and filtration recorded in India (2000 B.C.E.) and Minoa (3200–1100 B.C.E.) (Mala-Jetmarova et al. 2015). Greek (eight to sixth century B.C.E.) and Roman (100 B.C.E. to 500 A.D.) civilizations had long-distance aqueducts and the ancient Incan city of Macchu Picchu (1450–1540 A.D.) had a sophisticated water conveyance system (Wright et al. 1997; Mala-Jetmarova et al. 2015). The first well-documented large pumped water supply system was developed in the late 16th century to pump water from the River Thames to the London population (Mala-Jetmarova et al. 2015).

The River Thames in London also played a major role in the history of our understanding of waterborne disease transmission. Previously, diseases such as typhoid and cholera, which are now known to be caused by exposure to polluted water, were believed to be transmitted by sewer gas "miasma" (literally "foul air") (Barnes 2002). The focus of wastewater management at that time was based on separation of odiferous materials (Beach 2022). John Snow's 1854 cholera investigation in London pioneered modern epidemiology, demonstrating the link between consumption of contaminated water and disease (Johnson 2006).

The advent of drinking water distribution and treatment systems occurred concurrently with the "epidemiological transition" observed in the early 20th century, when mortality rates fell precipitously and life expectancy rose. Although collection of waste and conveyance for discharge were recognized as alleviating immediate concerns, it was soon realized that the disposal of waste into bodies of water could result in contamination of the receiving waters. Water contamination led to diseases associated with degraded potable and recreational water. Municipalities pursued strategies of longer offshore pumping of waste and/or relocation of drinking water sources.

At the turn of the century, major cities began to incorporate various aspects of modern water treatment and distribution systems into their municipal water supply services. The first large-scale municipal water system in the U.S. was built in Philadelphia at the dawn of the 19th century (Cutler and Miller 2005). Many large cities subsequently followed in Philadelphia's footsteps and by 1940 most major U.S. cities had built filtration plants. Furthermore, the "urban penalty," i.e., the higher mortality rates in urban populations, disappeared during this period (Cutler and Miller 2005). Before 1900, the leading cause of death was infectious disease. By 1940, chronic conditions such as heart disease and cancer took the lead as causes of death (Anderson et al. 2018).

Originally developed to reduce discoloration and turbidity, the advantage for public health by water filtration was increasingly recognized. Chlorination, introduced in the early 20th century, provided a major advance. Jersey City was the first municipality in the U.S. to chlorinate its water supply. This approach quickly gained in popularity because of its cost-effectiveness (Anderson et al. 2018). In conjunction with these water treatment measures, municipalities also began to recognize the importance of source water protection, to ensure clean water delivery to water treatment facilities (Fig. 1). Economic analysis has suggested that provision of clean water was responsible for nearly half the total mortality reduction in major cities, three-quarters of infant mortality reduction and nearly two-thirds of child mortality reduction (Cutler and Miller 2005). These improvements cannot be fully disentangled from other concurrent advances in urban areas, such as improvements in food safety, housing quality and nutrition, but it is widely believed that filtering and chlorinating drinking water was a major factor in the notable decline in typhoid mortality (Anderson et al. 2018).

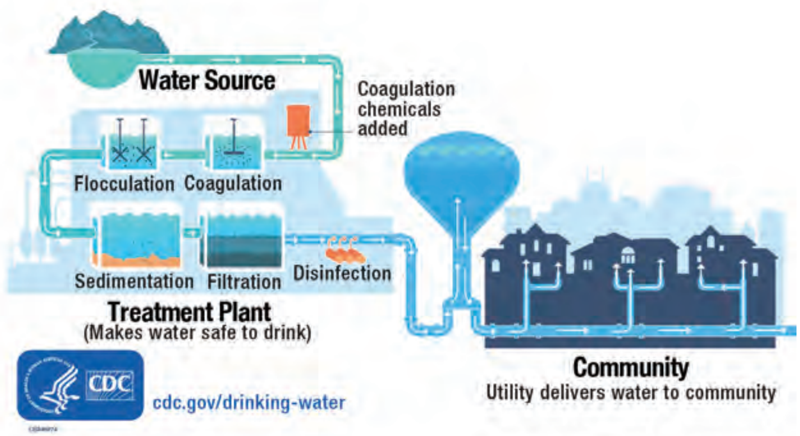


Figure 1: General water treatment process. Source: CDC.

At the same time, treatment of wastewater also improved, moving from direct discharge of sewage to rivers to conveyance of wastewater to treatment plants in recognition that water treatment alone was not adequately protective of public health (Tarr et al. 1984). One of the first wastewater treatment plants using chemical precipitation was brought online in the U.S. in Worcester, Massachusetts in the late 1800s. Activated sludge technology was described in the early 1900s and the first of large-scale activated sludge wastewater treatment plants were built shortly thereafter. With increasing population and concern for environmental protection, further innovation in wastewater treatment occurred. These can be broadly characterized as follows.

- **Primary treatment.** Larger, coarser solids are physically removed, most frequently by gravity settling.
- **Secondary treatment.** Biological processes are used for degradation of organic material. This also results in reduction of pathogens by various mechanisms. The most common processes are trickling filters and activated sludge.
- **Advanced/tertiary treatment.** Further treatment by combinations of chemical, physical, and/or biological processes removes nutrients and trace organic compounds and achieves greater reduction of pathogens. With higher levels of tertiary treatment, the effluent can be suitable as a source of water supply. These processes include addition of chemical coagulants or precipitants, sand filtration, membrane filtration, activated carbon treatment and chemical oxidation.
- **Disinfection.** This may be done after secondary or tertiary treatment to achieve high levels of pathogen reduction, allowing discharge into recreational waters or in proximity to drinking water intakes. The disinfection processes most commonly used are chlorination, ozonation and ultraviolet light irradiation.

Current Impact of Environmental Factors on Water, Waterborne Pathogens and Public Health

Impact on Water and Water Microbes

Projections estimate that global clean water demand will increase by 55% by 2050 due to rapid urbanization and environmental changes (Panhwar et al. 2022). This surge in demand is driven by factors such as manufacturing, thermal electricity generation and domestic use (Boretti and Rosa 2019). Many factors impact the availability of water resources, such as competition between communities seeking access, environmental pollution, temperature, ocean acidification and precipitation.

Heavy precipitation events, which are becoming more frequent, can overwhelm stormwater infrastructure and water reservoirs, leading to flooding. Conversely, decreased precipitation can result in droughts that deplete water resources. Both scenarios pose significant challenges to natural and engineered water systems (Berg and Hall 2015). For instance, floods caused nearly 100,000 deaths and affected 1.6 billion people between 2002 and 2021 (UNESCO 2024). Droughts, on the other hand, impacted over 1.4 billion people and caused 170 billion USD in economic losses during the same period (UNESCO 2024).

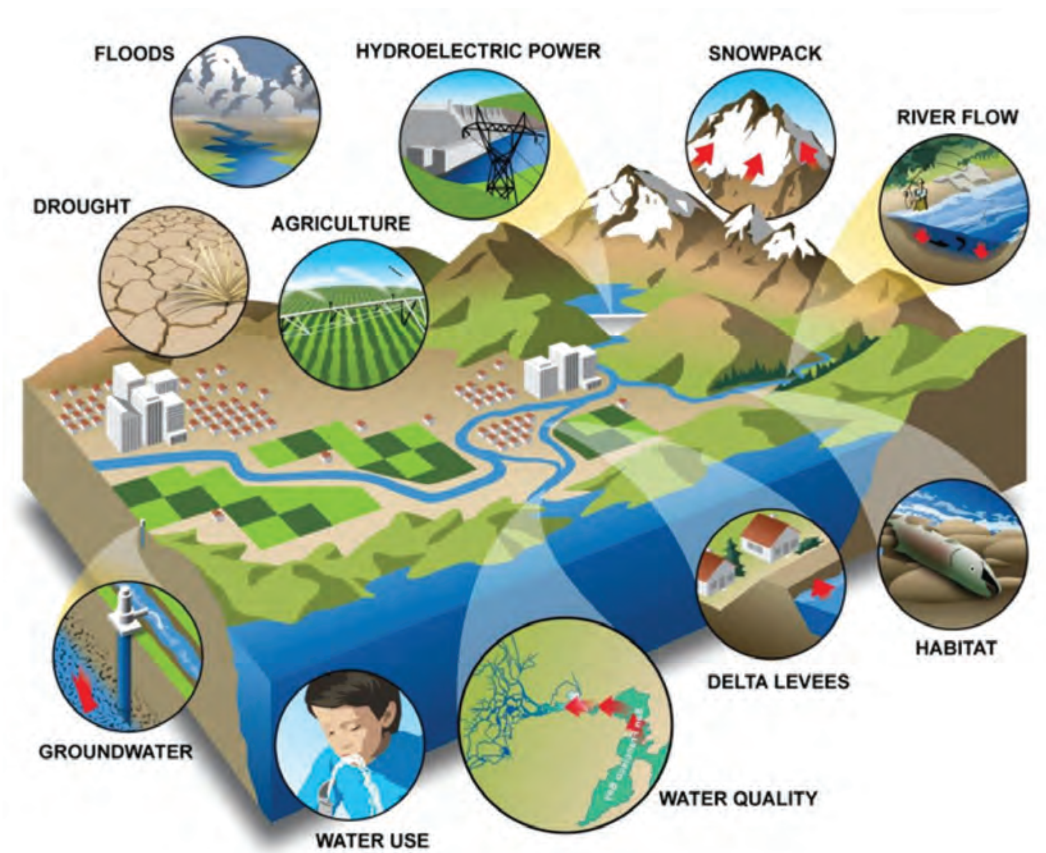


Figure 2: Impacts of environmental drivers on water resources and society. Source: California – Department of Water Resources.

Water quality degradation exacerbates water stress and demand for water resources suitable for human use (Fig. 2). Wastewater infrastructure is particularly vulnerable to extreme weather, which can reduce treatment efficiency (Infrastructure Report Card 2025). Environmental variables like temperature and drought can increase biological oxygen demand and make waste streams more difficult to treat (Motesaddi et al. 2025). Reduced rainfall can also increase corrosion in conveyance systems due to high concentration of pollutants, anaerobic conditions or higher salinity (Hughes et al. 2021). Rising sea levels and intensified rainfall can disrupt resident microbes in various environments, further complicating water management (Hamlington et al. 2024). Wastewater treatment plants (WWTPs) are also susceptible to extreme weather. Increased rainfall, rising temperatures and earlier snowmelt runoff can lead to untreated sewer overflows and increased flooding, which compromise the efficiency of WWTPs and raise energy consumption and maintenance costs (Zouboulis and Tolkou 2014). Additionally, the scarcity of water resources due to environmental change necessitates increased wastewater reuse, further complicating treatment processes. These statistics highlight the urgent need for improved water management strategies to address the growing demand and the impacts of environmental changes

The dependence on water of several infectious disease agents is well recognized.

Aquatic microorganisms are diverse and include members of all domains of life. They are key players in major biogeochemical cycles and ecosystems, including primary productivity (conversion of energy into organic compounds), nutrient recycling and water quality. The aquatic ecosystem harbors pathogenic microbes, including viruses, bacteria, fungi, cyanobacteria and microeukaryotes. Many are highly sensitive to changing conditions, with environmental drivers that include temperature, pH, salinity, resource availability, physical mixing, etc. Because species and their strains have different environmental responses, some may increase in abundance and others decline under given environmental conditions. Species whose traits enable fitness under given conditions are winners and the others are losers (Dutkiewicz et al. 2013). Different responses of microbes to changing environmental parameters induce changes in microbial community composition and function, including pathogens (Litchman et al. 2015; Cavicchioli et al. 2019; Kapetanović et al. 2024; Seymour and McLellan 2025).

For example, toxic, bloom-forming cyanobacteria in fresh water can have higher temperature tolerance, hence are favored by higher water temperatures (Thomas et al. 2016; Huisman et al. 2018; Litchman 2023). Increasing biomass of toxic cyanobacteria in lakes, rivers and coastal oceans is associated with poor water quality and negative consequences for animal and human health and local economies (Hamilton et al. 2014; Chorus and Welker 2021). Cyanobacterial toxins can contaminate drinking water sources, negatively affect recreational activities and change aquatic food webs (Hamilton et al. 2014; Chorus and Welker 2021). Thus, an entire ecosystem can deteriorate, with increased prevalence of waterborne pathogens due to stimulation of growth by environmental factors, namely, high temperature and hydrological change (Levy et al. 2018). Pathogenic microbial taxa may be preferentially selected, e.g., some bacterial pathogens increase and viral pathogens decrease in number with increasing temperature (Chua et al. 2022).

The dependence on water of several infectious disease agents is well recognized. Bertuzzo and Mari (2017) provide a listing of infectious diseases associated with hydrology, namely, flooding, droughts and intense rainfall, the latter linked to diarrhea, cholera, schistosomiasis, micro- and macro-parasite infection, malaria, yellow fever, dengue and other illnesses. Water-related infectious disease outbreaks are catalogued in the Global

Infectious Disease and Epidemiology Network (GIDEON). Beyond hydrology, GIDEON lists diseases correlated with population density and socioeconomic vulnerability (Yang et al. 2012). Precipitation, water availability and temperature are considered most important, with respect to infectious disease outbreaks.

Extreme climatic events have been associated with profound changes in composition and dynamics of aquatic microbial communities (Philippot et al. 2021). Effects on microbes that occur after natural disasters comprise a "disaster microbiology," where infections rise after extreme weather events (Smith and Casadevall 2022). If conditions are close to or beyond tolerance limits of the microbes, richness and diversity of microbial communities decline (Teittinen et al. 2022). Species-poor communities have proven more vulnerable to perturbation, with lower potential for maintaining key functions, such as productivity, nutrient recycling, stability, etc. (Schmidt et al. 2020; Seidel et al. 2022; Teittinen et al. 2022). Understanding and predicting reorganization of aquatic microbial communities during changing environments are key to maintaining and enhancing global human well-being.

Despite the many effects of environmental drivers on microbes, they have a strong capacity in adapting to novel conditions (Lenski 2017). Microbes can evolve to have higher temperature optima when subjected to extremely warm temperatures or a tolerance to low pH and toxic compounds (O'Donnell et al. 2018; Scheuerl et al. 2020; Mathivanan et al. 2021). The microbial adaptive capacity, with respect to novel environments, depends in large part on abiotic drivers and biotic interactions (Scheuerl et al. 2020; Aranguren-Gassis et al. 2019). Also, adaptive capacity differs among microbes, with the challenge being to determine the capacity of aquatic microbes to adapt to many environmental drivers simultaneously and also to understand how their community composition and diversity may change in the future (Levin and Bergstrom 2000).

Waterborne Infections After Extreme Weather in Florida Case Study

Florida's climate is becoming hotter and wetter, a trend that has been observed over the past few decades (Florida Climate Center). More common extreme weather events, such as hurricanes and heavy rainfall, can overwhelm stormwater infrastructure and force coastal waters into inland areas, leading to flooding and contamination of water sources with waterborne pathogens. The common waterborne pathogens include *Cryptosporidium, Giardia, Legionella, Naegleria* and *Vibrio vulnificus,* the latter being a flesh-eating bacterium (Florida Department of Health 2021). Waterborne infections have increased after severe storms. For example, Hurricane Ian in 2022 led to a surge in *Vibrio vulnificus* infections in Florida, as floodwaters carried the bacteria into residential areas. Increasing sea surface temperatures and altering precipitation patterns have contributed to the proliferation of *Vibrio vulnificus.*

The rise of waterborne pathogens remains a significant concern for Florida since many large cities are within 10 miles of the active coast. In Florida, waterborne diseases are spread by swallowing, breathing or having contact with contaminated water from wells, cooling systems, swimming pools, lakes, rivers and the ocean. These pathogens pose serious health risks. The cost of treating waterborne pathogens in states like Florida is substantial, reflecting a current vulnerability to waterborne diseases due to frequent extreme weather events (NOAA National Centers for Environmental Information). Direct healthcare costs of waterborne illnesses in the U.S. amount to approximately 3.3 billion USD annually (Collier et al. 2021). This includes costs associated with emergency department visits, hospitalizations and deaths caused by various pathogens such as *Legionella, Cryptosporidium* and *Vibrio vulnificus* (Collier et al. 2021). Drinking water exposures are associated with 40% of hospitalizations and 50% of deaths from waterborne diseases, primarily linked to pathogens that produce biofilms, like *Legionella* and nontuberculous mycobacteria, costing the U.S. 1.39 billion USD annually (DeFlorio-Barker et al. 2021).

Changing weather patterns and the rise of waterborne pathogens in Florida highlight an urgent need for improved water management strategies and proactive adaptation to environmental change. Effective collaboration among stakeholders, including scientists, health professionals and community members, is essential to develop comprehensive strategies to adapt to these changes and safeguard local public health. Integration of innovative technologies, appropriate region-specific specifications and proactive public health programs are critical to addressing the evolving challenges of extreme weather and associated pathogens in the water.

Public Health Impact

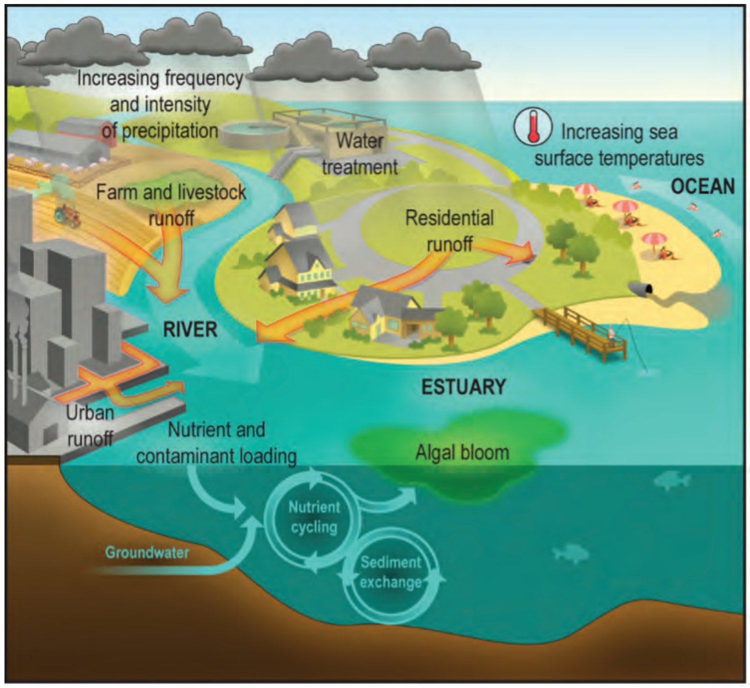
The environment plays a significant role in disease transmission. Rising temperatures, shifting precipitation patterns and extreme weather events influence spread of pathogens and infectious disease (Fig. 3) (Bell et al. 2018). Extreme weather events drive pathogen transmission by increasing exposure, degrading water quality and reducing sanitation effectiveness (Patz et al. 2008; LaKind et al. 2016). Simply stated, floodwaters spread contamination from human and animal waste and droughts reduce the ability of water bodies to dilute pollutants. These extremes result in the spread of infectious diseases, highlighting a critical link between hydrology and infectious disease. Thus, where combined with an aging water infrastructure, the ability of water systems to protect against spread of disease is severely weakened (Olds et al. 2018).

Wastewater systems are increasingly vulnerable to changing weather patterns, which can significantly affect efficiency and reliability. Their failure pose significant risk to public health since untreated or partially treated sewage discharged into local waterways will contaminate the water source and increase risk of waterborne disease. For example, hurricanes and floods have caused widespread power outages and the bypassing of billions of gallons of untreated sewage into water bodies (Kenward et al. 2013). Adaptive strategies, such as infrastructure upgrade, technological innovation and energy-efficient design, are essential to ensure wastewater system resilience and provide safe water.

Although there has been progress in understanding how environmental parameters affect public health and influence water-related health issues associated with waterborne pathogens, significant knowledge gaps remain. An effective response to changes in temperature, humidity and other climate parameters is needed because they influence microbial evolution, particularly antimicrobial resistance. Since weather extremes drive sequential weather events like flooding and drought, how they influence pathogen spread and impact treatment systems needs attention.

Contamination of coastal aquatic environments also occurs with recreational activities. Crowded beaches contribute to fecal pollution of the water and spread of antibiotic

Figure 3. Links among environmental drivers, water quality and exposure to waterborne pathogens. Source: U.S. Global Change Research Program.



resistance genes (Toubiana et al. 2021). Relatively little is known about direct risk to public health, especially during heat waves.

Many case datasets compiled for specific infectious diseases lack sufficient resolution to determine climate-related outbreaks, making it very difficult to link environmental conditions to the emergence of a specific disease. Stronger surveillance and an expanded monitoring system are essential for an effective public health system. Specific public health information needed includes climate-related stressors that influence disease transmission, especially challenges to sanitation. When floods spread contaminants to soil or water and droughts retain and accumulate pathogens in high concentrations, both of which occur in tandem, the complex conditions created make predicting the outcome very difficult. Thus, to respond effectively to both ongoing and emerging threats, public health systems must be dynamic, proactive and adaptable.

In summary, both infrastructure and the assessment of current threats require strengthening. Wastewater infrastructure in particular is susceptible to both extreme weather and changes in precipitation resulting in reduced treatment efficiency. For example, warmer temperatures allow increased biofilm formation in water pipes and faster decay rates for chlorine. Because private wells are not subject to the same safety standards as public water systems, landowners are responsible for monitoring. There is a critical need for education, outreach and testing to minimize risk of contaminated water (Peer et al. 2024). Smaller municipal systems require aging infrastructure to be upgraded and monitoring established to identify and mitigate threat. Thus, risk and vulnerability assessment are crucial to identify areas of concern and to forecast geographic locations with higher risk in coming decades (Ebi et al. 2021).

Future Prospects for Water, Waterborne Pathogens and Public Health

Predictive Models for Outbreaks and Health Risk

More than 4 billion people worldwide do not have access to safe drinking water; hence solutions to bolster sanitation infrastructure and predict waterborne health risks will have to adapt to local needs (Greenwood et al. 2024). Environmental and public health data integrated into infectious disease models can inform public health decisions and reduce waterborne disease (see the *Vibrio* case study). Earth observation and sensing data systems that are easily accessible, integrated with public health information and reflect local conditions are examples of using "environmental intelligence" to inform resilience and mitigation options for public health.

Earth Observations and Sensing

Studies have highlighted linkages between hydrology, the water cycle and infectious diseases. Hydrological indicators have been used to monitor mosquito-borne West Nile virus transmission (Shaman and Day 2005). Increase in infectious disease is evident after hydrologic disasters such as floods and droughts (Liang and Messenger 2018). However, many studies were either regional in nature, based on models or conducted over short time periods. Since infectious disease outbreaks generally are regional in geography, there is always a potential for spread and therefore continental scale analysis is required. In addition, most regions of the world lack in situ observations of critical environmental parameters, e.g., precipitation, soil moisture and standing water, or the data are not publicly available.

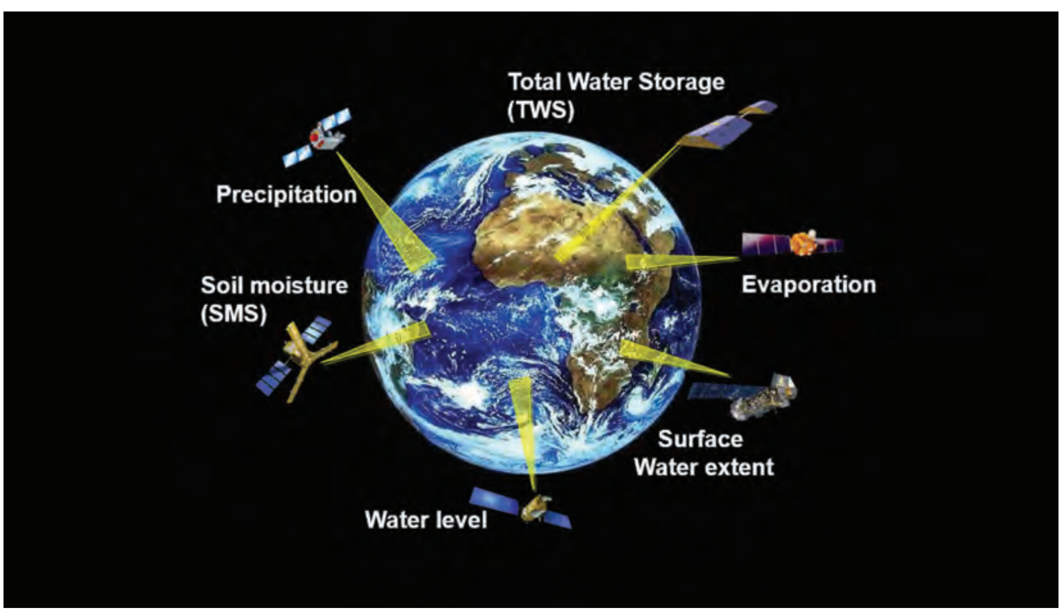


Figure 4. Examples of hydrological Earth observations. Source: Space4Water Portal.

Publicly available Earth observations help regional, continental and global analysis (Fig. 4). Data are generally available for the past two to three decades, thereby ensuring temporal continuity in analysis (see the Vibrio case study). Quantification of the water cycle that includes flux (precipitation) and storage (standing water and soil moisture) is essential to informing disease models, specifically for prediction, and are of significant public health value. These Earth observations are easily accessible to users and require little or no background knowledge of remote sensing theory or data structure, which makes it easy to use in public health research and application. Data sets can be used for stand-alone analysis and/or as input to infectious disease models.

- **Precipitation:** The Global Precipitation Measurement (GPM) mission is an extension of the Tropical Rainfall Measuring Mission (TRMM) that provides global scale rainfall and snow estimates. It was launched in February 2014 and has been providing precipitation retrievals of 0.1° resolution and several timescales, from 30 minutes to daily, on a global scale (60°S–60°N), for better understanding of rain and snow processes under normal or extreme conditions, as well as for improving accuracy of hydrology and weather models (Hou et al. 2014). The Integrated Multi-satellitE Retrievals for GPM contains data from the early and most recent precipitation estimates from TRMM (2000–2015) and GPM (2014–present) (Huffman et al. 2015).

- **Soil Moisture:** The Soil Moisture Active Passive mission provides medium spatial resolution and frequently revisits the soil moisture and freeze/thaw state on a global scale. It operates on a near-polar Sun-synchronous orbit with 6 a.m./p.m. overpass times and has a constant incidence angle of 40° degrees, as well as a 1000-km-wide swath that allows a 2–3 day global revisit (McNairn et al. 2014; Chan et al. 2016; Chan et al. 2018; Colliander et al. 2017). Meanwhile, the Soil Moisture and Ocean Salinity satellite carries an L-band radiometer to observe topsoil layer soil moisture and sea surface salinity.

- **Surface Water:** The ability to observe the location of water bodies and pooling, or surface water extent, especially during flood events, is essential for infectious disease models and studies. Space-borne remote sensing applications from missions such as Sentinel-1, Landsat, the Cyclone Global Navigation Satellite System and the Surface Water and Ocean Topography provide large-scale surface water extent mapping. Through the combination of multiple missions, global surface water extent can be observed nearly daily, providing timely and accurate information on water body dynamics.

Accessing real-time data on pathogen dynamics will help improve epidemic predictive models. Yet, research is still needed to understand better the relationship between viral dynamics in wastewater and a disease outbreak and how to refine the sampling strategy according to the level of information sought. Furthermore, wastewater-based epidemiology provides useful information to inform public health decisions at the national, local, city and regional levels. Clearly, it should be a component of public health strategy.

Vibrio Outbreak Case Study as an Example of Using Satellite Data to Improve Public Health

Members of the genus *Vibrio* are naturally occurring in aquatic environments and play an important role in carbon and nitrogen cycling, as well as other significant biogeochemical processes (Colwell et al. 1977; Joseph et al. 1982; Le Roux and Blokesch 2018). While *Vibrio* spp. are generally present in larger numbers in coastal waters, their abundance is strongly influenced by environmental factors, notably temperature and salinity (Brumfield et al. 2021). Additionally, these bacteria exist as commensals or symbionts of various aquatic invertebrates, including crustaceans, zooplankton and bivalves (Lovelace et al. 1968; Huq et al. 1983; Brumfield et al. 2023). Given their ecological significance, eradication of *Vibrio* spp. is not feasible.

Predictive modeling has transformed public health strategies by integrating environmental, microbiological and sociological data to anticipate outbreaks of waterborne pathogens, particularly *Vibrio cholerae,* the etiological agent of pandemic cholera, and *Vibrio vulnificus,* a major cause of vibriosis and wound infection (Colwell 1996; Jacobs et al. 2014; Jamal et al. 2024). The presence and proliferation of *Vibrio* spp., and thus their transmission, are closely linked to environmental factors such as temperature, salinity and chlorophyll concentration (Brumfield et al. 2021; Jamal et al. 2024). First proposed in the 1990s, satellite-based remote sensing and machine learning models now enable real-time risk assessment and proactive intervention strategies (Colwell 1996).

Improvements in satellite technology, coupled with an increasing number of advanced Earth-orbiting satellites, have facilitated development of predictive models for assessing the risk of *Vibrio* infections using near real-time environmental and sociological data. These early-warning systems provide decision makers with the ability to deploy health personnel and allocate resources to high-risk areas. Predictive modeling for cholera outbreaks has been successfully implemented in Haiti, Zimbabwe, Nepal, Ukraine, Yemen and, more recently, Malawi (Khan et al. 2017; Jutla et al. 2015; Khan et al. 2018; Usmani et al. 2022; Usmani et al. 2023; Jutla et al. 2023). When paired with early intervention measures at both individual and large-scale levels, these models have contributed to a reduction in case fatality rates of cholera (Akanda et al. 2012). Similar predictive frameworks have been applied to *V. vulnificus* in the Chesapeake Bay and non-cholera *Vibrio* spp. in the Baltic Sea (Jacobs et al. 2014; Levy 2018). These models assist in forecasting favorable conditions for *Vibrio* growth, thereby supporting timely public health measures, such as targeted water treatment, vaccine distribution and community education programs. However, refining predictive algorithms remains a challenge due to regional environmental variability and human behavioral factors. Moreover, predicative modeling depends on groundtruth observations for algorithm training, yet data on non-cholera Vibrio spp. remain limited, primarily derived from studies conducted in developed countries. Future modeling efforts should incorporate sociological and behavioral data related to waterborne pathogen exposure, including recreational and occupational activities.

Effective management of *Vibrio* outbreaks requires strengthening local infrastructure for water quality monitoring, sanitation and public health surveillance. Integration of pathogen surveillance methods, including whole genome sequencing and metagenomics, with environmental monitoring, provides a robust framework for early detection and response. Case studies indicate that improving water safety infrastructure, especially in vulnerable coastal and estuarine regions, significantly reduces *Vibrio*-related morbidity and mortality.

For example, simple, community-driven water management strategies, such as filtration techniques to remove copepods, the *Vibrio* host, have proven effective in regions with limited resources (Colwell et al. 2003). Additionally, localized data collection can refine global predictive models by incorporating region-specific variables that influence the dynamics of *Vibrio* populations and human behavior (Brumfield et al. 2023).

Public Health Data

To enhance water safety, public health organizations and researchers will need to focus on improving surveillance and harmonizing data systems to foster better integration of Earth observations with public health data. This will provide opportunities to improve understanding of these relationships, as well as leverage machine learning and other analytical tools to assess emerging threats.

There exists a large amount of publicly available information on waterborne disease outbreaks. For instance, the U.S. Centers for Disease Control and Prevention (CDC) hosts the Waterborne Disease and Outbreak Surveillance Reporting system and the European Centre for Disease Prevention and Control (ECDC) provides surveillance and updates on food- and waterborne diseases. However, these data are not always well integrated with local environmental information. Monitoring systems should be reevaluated to enhance environmental data integration. For example, reporting systems could emphasize individual event tracking and higher-resolution data to capture dynamic changes better (see the malaria case study). This information should be integrated with structured metadata frameworks and descriptive ontologies to support programmatic assessment and predictive models. It will be critical to secure and enhance information resources and harness the burgeoning array of quantitative tools for real-time disease monitoring and public health support. At the same time, it should be recognized that microbial outbreaks and the models used for their identification are dynamic in nature. As digital infrastructure is built for earlier and more sensitive detection, these systems must also be adaptable to emerging pathogens with genetic exchange and changes in the underlying modeling technologies for their prediction. Additionally, clinical records are highly regulated with little public access, making it more difficult and time intensive to connect records of illness to larger outbreaks or environmental factors. Data systems that ensure patient privacy while enabling real-time data sharing on outbreaks need to be developed and integrated into waterborne pathogen monitoring systems. This goal requires investment; however, the health and economic benefits will be enormous.

Figure 5. WHO protocol for developing and establishing a water-related infectious disease surveillance system. Source: WHO Regional Office for Europe 2019.

For seamless integration among different systems, data harmonization and reporting standards will be necessary to ensure scientists from many different disciplines, e.g., public health, microbiology, hydrology and climate science, can all utilize the same data sets effectively. The World Health Organization (WHO) outlined consistent standards for monitoring, reporting and managing waterborne infections (Fig. 5) (WHO Regional Office for Europe 2019). Likewise, other initiatives such as the National Microbiome Data Collective have aimed to create a framework for standardizing and structuring metadata data collected for these microbial samples (genomics, microbiome, proteomics or metabolomics) (Vangay et al. 2021). Supporting public health systems to apply these standards worldwide can provide valuable information to track and monitor outbreaks.

Though waterborne diseases are a global problem, solutions that meet local needs and conditions merit priority. Each region has a unique set of factors, such as average temperature range, precipitation level, geography, established infrastructure and population. In addition, incidence and occurrence of specific waterborne pathogens vary significantly across countries, regions and communities. Monitoring and data systems need to be tailored to specific factors of each region and aligned with their public health system. Given that resources for monitoring are limited, citizen and community science initiatives including sequencing at the edge can play a valuable role in expanding data collection and improving long-term monitoring. These efforts should engage with local stakeholders to co-develop systems that meet the needs of the local community.

The rising incidence and geographic expansion of waterborne infections highlight the need for proactive, data-driven public health interventions. By integrating predictive models with localized water safety initiatives, health agencies can mitigate risks associated with waterborne pathogens while promoting sustainability of the aquatic ecosystem. Specifically, water-related infection disease data collected thus far can be used to augment foundation models, which could then be fine-tuned to address specific geographic or pathogen constraints. Continued advancements in high-resolution environmental monitoring, coupled with community engagement and infrastructure investment, will be essential to ensuring water safety and reducing the global burden of waterborne infections.

Malaria Case Study for Linking Clinical and Environmental Data to Improve Public Health

Malaria continues to impose a heavy burden of morbidity and mortality throughout much of the developing world. The disease is complex with 5 species of the protozoan *Plasmodium* causing human malaria and around 70 species of *Anopheles* mosquitoes capable of *Plasmodium* transmission (Phillips et al. 2017; Escobar et al. 2020). This diversity of pathogens and vectors enables outbreaks of malaria in a broad range of settings, including coastal brackish regions, tropical forests, dry savannahs and more mountainous habitats, where environmental conditions determine the complement of *Anopheles* species present, their prevalence and when during the year there is sufficient vector biting activity to support transmission.

In the years since first identification of *Plasmodium* and description of its complex life cycle and transmission by *Anopheles* mosquitoes, there has been an abundance of studies describing ecology of the *Anopheles* mosquito and *Plasmodium,* their dependence on environmental conditions and epidemiology of the disease (Laveran 1881; Marchiafava and Celli 1885; Ross 1898; Bignami 1898; Grassi et al. 1899). These data informed design and use of therapeutics and prophylaxes to treat and prevent human infection, development and deployment of mosquito control measures, such as habitat remediation, insecticide, larvicide, and bed netting and selection of resistance to control measures in both *Plasmodium* and *Anopheles.* This research has supported numerous attempts to eradicate malaria, including the WHO Global Malaria Eradication Program (1955–1969) and the WHO-led Roll Back Malaria (RBM) project (WHO 1999).

The first 20 years of the RBM were highly successful, yielding substantial reduction in malaria morbidity and mortality. However, in recent years, the gains have stagnated (WHO 2023). Renewed efforts to provide enhanced surveillance, analytics and projections will be needed. Malaria surveillance has always been complicated because of incomplete records of human infection and outcomes and sparse data on larval and adult mosquito abundance and human movement. These data inadequacies reflect the impoverished settings in which malaria is often most burdensome, where clinical services and record keeping are limited. However, tools for improved surveillance are solvable. Electronic health record keeping, centralized through Ministries of Health and distributed to local clinics, is more abundant than ever in countries impacted by malaria. Satellite and phone records documenting environmental conditions and human movement are available and citizen-informed science now enables in-field collection of local data at scale. It is imperative for public health and safety that such data collection is maintained, that domestic and international investment in such tools continues, or increases, and that these data are made available in a coordinated and accessible manner to support public health policy and practice. These information sources provide the basis for data-driven research and operational analytics and forecasting in collaboration with in-country clinical and public health personnel. With advances in computing and growth of AI and other quantitative methods, the means for interrogating vast troves of data to develop new drugs, execute precision in both medicine and public health and generate real-time simulations of intervention outcomes and forecasts of future disease burden have never been greater.

Sustainable and Updated Infrastructure that Promotes Public Health and Economic Benefits

The lack of sufficient water, sanitation and hygiene (WASH) services worldwide results in estimated annual economic losses totaling 260 billion USD, which encompasses healthcare costs and productivity loss as well as premature deaths and wider socioeconomic damage (Hutton et al. 2012; World Bank 2016). The reported economic losses from inadequate WASH services significantly underestimate the true burden since they fail to include indirect expenses like reduced agricultural productivity (see the water reuse case study) and environmental-related vulnerabilities along with educational setbacks caused by child diarrheal cases.

Economic Highlights

- **$260 Billion Annual Global Losses:** Attributed to inadequate water and sanitation infrastructure (Hutton et al. 2012; World Bank 2016).
- **$4.30 Return per $1 Invested:** In water and sanitation improvements (Hutton and Haller 2004; WHO 2012).
- **$600 Million/Year in Avoidable Health Costs:** Due to unmonitored private wells in the U.S. (Peer et al. 2024).

In the U.S., extreme weather events have significant financial and public health implications especially regarding waterborne disease transmission. Annually, waterborne diseases in the U.S. result in approximately 7.2 million illnesses and 6,630 deaths, with

a direct healthcare cost estimated at 3.3 billion USD per year (Collier et al. 2021). Tropical cyclonic storms in the U.S. between 1996 and 2018 led to a 48% rise in Shiga toxin producing *Escherichia coli* infections one week post-storm, a 42% increase in Legionnaires' disease two weeks after storm events, and a 52% surge in cryptosporidiosis cases during storm weeks (Lynch and Shaman 2023). Beyond healthcare expenses, natural disasters impose extensive economic burdens from destruction of transportation, health care, residential and commercial infrastructure.

Science-based multisectoral interventions represent investments that deliver substantial benefit-to-cost ratios. According to the WHO, investment in water and sanitation infrastructure generates economic returns of $4.30 for every $1 spent through decreased disease burden and better productivity (Hutton and Haller 2004). In high-risk environments, including areas prone to increasingly occurring extreme weather events, the return can be as high as 7:1, underscoring the importance of implementing data-driven and scalable solutions adapted to local needs.

Investment in water and sanitation infrastructure generates economic returns of $4.30 for every $1 spent.

Engineered systems for safe drinking water benefit society by reducing infections, thus lowering public health costs (Collier et al. 2021; WHO 2023). However, current water systems are aging and operating beyond their designed lifespan. These systems can be impacted by extreme weather events, such as flooding or heat waves, overwhelming the systems and lowering efficacy of overall treatment. Since 1980, the U.S. has experienced over 400 weather and climate disasters, each with damages exceeding 1 billion USD, culminating in a total cost surpassing 2.1 trillion USD (Smith 2020). Specifically, floods, often linked to waterborne disease outbreaks, caused approximately 135 billion USD in damages between 1990 and 2022 (Liu et al. 2024). The annual average of extreme weather events for 1980–2024 was 9, while the average for the past 5 years

(2020–2024) was 23 (Smith 2020). As extreme weather events are by no means lessening in frequency, the future holds critical challenges for public health preparedness and water system infrastructure. Investments in water infrastructure are needed that take changing environmental parameters and extreme weather events into account. This includes building more decentralized solutions that address region-specific geographical and environmental conditions and meet the needs of the local community.

Microbes underpin wastewater infrastructure and are potential targets to counter the stressors of environmental variability and the economic and ecosystem costs associated with infrastructure failures. Estimates made by the U.S. Environmental Protection Agency in the 2022 Clean Watersheds Needs Survey found that 630 billion USD is needed to bring wastewater infrastructure up to standard operating levels, even without considering the additional pressure of extreme weather events. Li et al. described city level adaption actions for multiple environmental challenges but emphasized the need for future modeling efforts to pinpoint effective strategies (Li et al. 2023). Improving treatment plants, including the biological processes within the plant, to deal with anticipated challenges, such as high biological oxygen demand of incoming waste streams, would maintain effluent water quality standards.

Most of the focus on the role of microbes in wastewater treatment has been at the treatment plant, yet there are tens of thousands of miles of pipes that contain an extremely high biomass (McLellan and Roguet 2019). Further, there may be an opportunity to harness the potential of microbes as the nature-based solution for enhancing pre-treatment of waste or reducing detrimental effects that cause pipe deterioration through the design or reengineering of systems. Current wastewater conveyance systems have selected for a uniform microbial population regardless of geographic location and time of year; however, the functional significance of many of the population is relatively unexplored (LaMartina et al. 2021). Impacts of sewer corrosion are well documented and are expected to increase with drought conditions that reduce flows (Li et al. 2023). Unraveling the role of specific microbes in both beneficial and detrimental effects on these systems can lead to more informed engineering strategies to maintain and improve sanitation.

Water Reuse Case Study

In Southern California, the water resource is a critical issue that hinders economic development due to its arid climate and high population (Vicuna et al. 2007). Over the years, overuse and contamination reduced availability of this resource, and traditional water sources can no longer sustain Southern California's water demands (Vasco et al. 2019). The change in water resources escalates competing demands among urban users, farmers and environmental groups in California. Southern California is a major producer of strawberries, citrus and many winter vegetables, and the sole avocado producer for the state, with more than 90% of U.S. domestic avocado production (Boxall et al. 2006). A water crisis threatens local agriculture and, consequently, food security and the financial well-being of farming communities.

Forced by the need to meet the water demand, Southern California has turned to municipal wastewater as a new source of water supply. Orange County, California, recycles 140 million gallons of municipal wastewater per day to recharge the local groundwater reservoir that is drawn for drinking water (Dadakis et al. 2011). Several large municipal water recycling programs to produce potable water are ongoing in Southern California to meet the demand of population growth and increasingly uncertain water resources in the region (Asano and Levine 1996). The trend of wastewater recycling and reuse is rapidly spreading in the U.S., with wastewater recycling for non-potable reuse replacing potable water for landscape irrigation, cooling, toilet flushing, etc. (Bracken 2012; Rezaei et al. 2019).

However, reuse of insufficiently treated human wastewater may carry a significant risk (Salgot et al. 2003; Chandrasekaran and Jiang 2018; Hong et al. 2018). Depending on the level of wastewater treatment, the effluent may contain unacceptable levels of pathogens, harmful chemicals and antibiotic-resistant bacteria. All of these contaminants render recycled wastewater unsafe, posing potential risk to human health. Among the array of health hazards of treated wastewater, microbial pathogens and contaminants of emerging concern (CECs) are the most important public health concern. CECs include pharmaceutical and personal care products, antibiotics and bacteria carrying antibiotic-resistant genes, all of which are ubiquitous in municipal wastewater effluent (Ternes et al. 2004; Kim et al. 2007; Daughton 2009; Sui et al. 2011). Wastewater treatment engineering practices need to incorporate an understanding of CECs and microbial removal efficiency.

Innovative investment in research on water, especially recycled wastewater, could provide an important alternative source of water and economic benefits for the community. Reclaimed municipal wastewater may prove to be a long-term component of regional water resources since wastewater quantity is reliable and increasing with population growth. However, research must be done to determine the fate and transport of microbial and chemical contaminants. Quantitative health risk assessments will also be needed for safe and efficient management of this alternative water resource.

Understanding waterborne disease prevalence and spread is critical for the health of humanity.

Scientific and Community Engagement

Interdisciplinary thinking creates powerful opportunities for insight, discovery and innovation, yet the research environment dissuades crossing disciplinary boundaries. Managing, evaluating and funding researchers who stay within familiar disciplinary tracks is frequently easier than understanding individual needs, impacts and discovery horizons of those who cross boundaries. Scientists do not always have a deep understanding of other fields, which makes it difficult for scientists to communicate or see connections with disparate fields. In addition, many of the challenges facing researchers who cross disciplines are not scientific but cultural. Going forward, the culture of science will have to focus on cross-disciplinary training, along with training in science communication, so scientists can effectively incorporate scientific, social, economic and physiological factors into their discussions of scientific results (Kappel and Holmen 2019).

Better understanding waterborne disease prevalence and spread is critical for the health of humanity, necessitating scientific and medical communities work together to lower barriers to transdisciplinary approaches. Additionally, community members and organizations need to be partners in the planning stages of any research or public health initiatives. Community insight will be pivotal to ensuring programs meet local needs and wants, which will bolster usage of programs by the community. This co-creation allows all impacted stakeholders to address hard, practical problems involving far more insight than from a single discipline.

The link between planetary sciences, public health and climate-impacted communities is increasingly important. However, large-agency science funding has limited interdisciplinary research, which enables relatively close disciplines to collaborate while creating gulfs between more distant ones. This kind of research, where the intersection of planetary science and biology can alleviate human suffering and illness, is not easy to fit into the scope of any single agency. However, appreciation of the nexus of climate science, planetary scale processes, microbiology and infection biology is a relevant necessity. Science interaction with cities, states, regions, nations and the world is moving faster and the associated work needs support. Small funding organizations, especially from non-government sectors globally, are often more agile and can effectively support projects focused on health, environment and civil society. In addition, professional societies and global partnerships offer unique opportunities for engagement and innovation for a healthier future.

Conclusions

Water is an essential resource of life, but this vital resource is under threat. Extreme weather events, pollution and microbial pathogens all jeopardize access to safe water. Fortunately, microbes and microbial data are the foundation on which to improve human health and well-being. Environmental intelligence that integrates environmental and public health data into infectious disease models will reduce waterborne disease and build public health resilience.

The participants of the colloquium outlined major opportunities for strengthening waterborne disease prevention systems.

- **Environmentally intelligent integrated data systems.** An extraordinary amount of environmental and weather data, Earth observations, public health information and waterborne pathogen monitoring exists. However, the data are not always integrated to provide a holistic view of the role and impact of weather on waterborne outbreaks. Data systems that harmonize diverse types of data to connect environmental data and weather events with infectious disease will be critical for real-time disease monitoring and proactive public health support. Harnessing AI and machine learning to assess emerging threats will prepare local communities better for outbreaks, such as have occurred in the aftermath of extreme weather events, to increase public health, safety and security.
- **Sustainable and economically resilient public health systems.** Integration of surveillance systems with modern water infrastructure and community monitoring allows improved water safety standards and sustainable economic benefit while reducing disease risk. Microbes can be harnessed to reengineer water systems to be more resilient to changing weather parameters. Implementation of the interventions will create stronger systems while reducing downstream costs and fostering sustainable development.
- **Global perspective with local solutions.** Since more than 4 billion people globally do not have access to safe drinking water, addressing this worldwide issue will require solutions that meet local needs. Scientists must engage with community members and organizations to understand the local issues and work across disciplines and sectors to co-develop collaborative solutions. Expanded science communication and cross-disciplinary training for scientists allows greater efficacy in assessing and communicating risk, key to addressing waterborne disease outbreaks.

To protect lives and reduce public health burdens, future efforts should focus on enhancing disease surveillance, strengthening water infrastructure and improving the assessment of current and future risks. Addressing these major challenges will require cross-disciplinary collaboration, community engagement and innovative monitoring and research programs. A global community of scientists, public health advocates, local leaders and philanthropists will constitute the foundation for a safer future by supporting societal health and well-being.

References

Akanda A, Jutla A, Gute D, Evans T, Islam S. 2012. Reinforcing cholera intervention through prediction-aided prevention. Bull World Health Org 90:243–244.

Anderson DM, Charles KK, Rees D. 2018. Public Health Efforts and the Decline in Urban Mortality. w25027. National Bureau of Economic Research, Cambridge, MA.

Aranguren-Gassis M, Kremer CT, Klausmeier CA, Litchman E. 2019. Nitrogen limitation inhibits marine diatom adaptation to high temperatures. Ecol Lett 22:1860–1869.

Asano T, Levine AD. 1996. Wastewater reclamation, recycling and reuse: past, present, and future. Water Sci Technol 33:1–14.

Barnes DS. 2002. Scents and sensibilities: disgust and the meanings of odors in late nineteenth-century Paris. Hist Reflect/Reflect Hist 28:21–49.

Beach B. 2022. Water infrastructure and health in U.S. cities. Reg Sci Urban Econ 94:103674.

Bell JE, Brown CL, Conlon K, Herring S, Kunkel KE, Lawrimore J, Luber G, Schreck C, Smith A, Uejio C. 2018. Changes in extreme events and the potential impacts on human health. J Air Waste Manag Assoc 68:265–287.

Benedict KM, Reses H, Vigar M, Roth DM, Roberts VA, Mattioli M, Cooley LA, Hilborn ED, Wade TJ, Fullerton KE, Yoder JS, Hill VR. 2017. Surveillance for waterborne disease outbreaks associated with drinking water — United States, 2013–2014. MMWR Morb Mortal Wkly Rep 66:1216–1221.

Berg N, Hall A. 2015. Increased interannual precipitation extremes over California under climate change. J Clim 28:6324–6334.

Bertuzzo E, Mari L. 2017. Hydrology, water resources and the epidemiology of water-related diseases. Adv Water Resour 108:329–331.

Bignami A. 1898. The inoculation theory of malarial infection: account of a successful experiment with mosquitoes. Lancet 152.3928:1541–1544.

Boretti A, Rosa L. 2019. Reassessing the projections of the World Water Development Report. npj Clean Water 2:15.

Boxall ABA, Johnson P, Smith EJ, Sinclair CJ, Stutt E, Levy LS. 2006. Uptake of veterinary medicines from soils into plants. J Agric Food Chem 54:2288–2297.

Bracken NS. 2012. Water reuse in the West: state programs and institutional issues. A report compiled by the Western States Water Council. Hastings W.-Nw. J. Envt'l L. & Pol'y 18:451.

Brumfield KD, Chen AJ, Gangwar M, Usmani M, Hasan NA, Jutla AS, Huq A, Colwell RR. 2023. Environmental factors influencing occurrence of Vibrio parahaemolyticus and Vibrio vulnificus. Appl Environ Microbiol 89:e00307–e00323.

Brumfield KD, Usmani M, Chen KM, Gangwar M, Jutla AS, Huq A, Colwell RR. 2021. Environmental parameters associated with incidence and transmission of pathogenic Vibrio spp. Environ Microbiol 23:7314–7340.

Cavicchioli R, Ripple WJ, Timmis KN, Azam F, Bakken LR, Baylis M, Behrenfeld MJ, Boetius A, Boyd PW, Classen AT, Crowther TW, Danovaro R, Foreman CM, Huisman J, Hutchins DA, Jansson JK, Karl DM, Koskella B, Welch DBM, Martiny JBH, Moran MA, Orphan VJ, Reay DS, Remais JV, Rich VI, Singh BK, Stein LY, Stewart FJ, Sullivan MB, van Oppen MJH, Weaver SC, Webb EA, Webster NS. 2019. Scientists' warning to humanity: microorganisms and climate change. Nat Rev Microbiol 17:569–586.

Chan SK, Bindlish R, O'Neill P, Jackson T, Njoku E, Dunbar S, Chaubell J, Piepmeier J, Yueh S, Entekhabi D, Colliander A, Chen F, Cosh MH, Caldwell T, Walker J, Berg A, McNairn H, Thibeault M, Martínez-Fernández J, Uldall F, Seyfried M, Bosch D, Starks P, Holifield Collins C, Prueger J, van der Velde R, Asanuma J, Palecki M, Small EE, Zreda M, Calvet J, Crow WT, Kerr Y. 2018. Development and assessment of the SMAP enhanced passive soil moisture product. Remote Sens Environ 204:931–941.

Chan SK, Bindlish R, O'Neill PE, Njoku E, Jackson T, Colliander A, Chen F, Burgin M, Dunbar S, Piepmeier J, Yueh S, Entekhabi D, Cosh MH, Caldwell T, Walker J, Wu X, Berg A, Rowlandson T, Pacheco A, McNairn H, Thibeault M, Martínez-Fernández J, González-Zamora Á, Seyfried M, Bosch D, Starks P, Goodrich D, Prueger J, Palecki M, Small EE, Zreda M, Calvet JC, Crow WT, Kerr Y. 2016. Assessment of the SMAP passive soil moisture product. IEEE Trans Geosci Remote Sens 54:4994–5007.

Chandrasekaran S, Jiang SC. 2018. A dynamic transport model for quantification of norovirus internalization in lettuce from irrigation water and associated health risk. Sci Total Environ 643:751–761.

Chorus I. 2021. Toxic cyanobacteria in water: a guide to their public health consequences, monitoring and management. Taylor & Francis, London.

Chua PLC, Ng CFS, Tobias A, Seposo XT, Hashizume M. 2022. Associations between ambient temperature and enteric infections by pathogen: a systematic review and meta-analysis. Lancet Planet Health 6:e202–e218.

Colliander A, Jackson TJ, Bindlish R, Chan S, Das N, Kim SB, Cosh MH, Dunbar RS, Dang L, Pashaian L, Asanuma J, Aida K, Berg A, Rowlandson T, Bosch D, Caldwell T, Caylor K, Goodrich D, al Jassar H, Lopez-Baeza E, Martínez-Fernández J, González-Zamora A, Livingston S, McNairn H, Pacheco A, Moghaddam M, Montzka C, Notarnicola C, Niedrist G, Pellarin T, Prueger J, Pulliainen J, Rautiainen K, Ramos J, Seyfried M, Starks P, Su Z, Zeng Y, van der Velde R, Thibeault M, Dorigo W, Vreugdenhil M, Walker JP, Wu X, Monerris A, O'Neill PE, Entekhabi D, Njoku EG, Yueh S. 2017. Validation of SMAP surface soil moisture products with core validation sites. Remote Sens Environ 191:215–231.

Collier S, Deng L, Adam E, Benedict K, Beshearse E, Blackstock A, Bruce B, Derado G, Edens C, Fullerton K, Gargano J, Geissler A, Hall A, Havelaar A, Hill V, Hoekstra R, Reddy S, Scallan E, Stokes E, Yoder J, Beach M. 2021. Estimate of burden and direct healthcare cost of infectious waterborne disease in the United States. Emerg Infect Dis 27:140.

Colwell RR, Huq A, Islam MS, Aziz KMA, Yunus M, Khan NH, Mahmud A, Sack RB, Nair GB, Chakraborty J, Sack DA, Russek-Cohen E. 2003. Reduction of cholera in Bangladeshi villages by simple filtration. Proc Natl Acad Sci 100:1051–1055.

Colwell RR, Kaper J, Joseph SW. 1977. Vibrio cholerae, Vibrio parahaemolyticus, and other Vibrios: occurrence and distribution in Chesapeake Bay. Science 198:394–396.

Colwell RR. 1996. Global climate and infectious disease: the cholera paradigm. Science 274:2025–2031.

Cutler D, Miller G. 2005. The role of public health improvements in health advances: the twentieth-century United States. Demography 42:1–22.

Dadakis J, Patel M, and Fitzsimmons S. 2012. Orange County's groundwater replenishment system: water quality monitoring and facility expansion in the face of changing regulations. Proc Water Environ Fed 2011: 1355–1366.

Daughton CG. 2009. Chemicals from the practice of healthcare: challenges and unknowns posed by residues in the environment. Environ Toxicol Chem 28:2490–2494.

DeFlorio-Barker S, Shrestha A, Dorevitch S. 2021. Estimate of Burden and Direct Healthcare Cost of Infectious Waterborne Disease in the United States. Emerging Infectious Disease journal 27:2241.

Dutkiewicz S, Scott JR, Follows MJ. 2013. Winners and losers: ecological and biogeochemical changes in a warming ocean. Global Biogeochem Cycles 27:463–477.

Ebi KL, Vanos J, Baldwin JW, Bell JE, Hondula DM, Errett NA, Hayes K, Reid CE, Saha S, Spector J, Berry P. 2021. Extreme weather and climate change: population health and health system implications. Annu Rev Public Health 42:293–315.

Escobar D, Ascencio K, Ortiz A, Palma A, Fontecha G. 2020. Distribution and phylogenetic diversity of Anopheles species in malaria endemic areas of Honduras in an elimination setting. Parasit Vectors 13:333.

Florida Department of Health. (2021). Waterborne Diseases.

Grassi B, Bignami A, Bastianelli G. Ulteriore ricerche sul ciclo dei parassiti malarici umani sul corpo del zanzarone. Atti Reale Accad Lincei 1899;8:21–28.

Greenwood EE, Lauber T, van den Hoogen J, Donmez A, Bain RES, Johnston R, Crowther TW, Julian TR. 2024. Mapping safe drinking water use in low- and middle-income countries. Science 385:784–790.

Hamilton DP, Wood SA, Dietrich DR, Puddick J. 2014. Chapter 15, Costs of harmful blooms of freshwater cyanobacteria, p. 245–256. In Sharma NK, Rai AK, Stal LJ (ed), Cyanobacteria, Wiley, New York.

Hamlington BD, Bellas-Manley A, Willis JK, Fournier S, Vinogradova N, Nerem RS, Piecuch CG, Thompson PR, Kopp R. 2024. The rate of global sea level rise doubled during the past three decades. Communications Earth & Environment 5:601.

Hong P-Y, Julian TR, Pype M-L, Jiang SC, Nelson KL, Graham D, Pruden A, Manaia CM. 2018. Reusing treated wastewater: consideration of the safety aspects associated with antibiotic-resistant bacteria and antibiotic resistance genes. Water 10.

Hou AY, Kakar RK, Neeck S, Azarbarzin AA, Kummerow CD, Kojima M, Oki R, Nakamura K, Iguchi T. 2014. The global precipitation measurement mission. Bull Am Meteorolog Soc 95:701–722.

Huffman G, Bolvin D, Braithwaite D, Hsu K, Joyce R, Kidd C, Nelkin E, Xie P. 2015. NASA Global Precipitation Measurement (GPM) Integrated Multi-satellitE Retrievals for GPM (IMERG). NASA report 16 November 2015, available at https://gpm.nasa.gov/sites/default/files/document_files/IMERG_ATBD_V4.5.pdf

Hughes J, Cowper-Heays K, Olesson E, Bell R, Stroombergen A. 2021. Impacts and implications of climate change on wastewater systems: a New Zealand perspective. Clim Risk Manag 31:100262.

Huisman J, Codd GA, Paerl HW, Ibelings BW, Verspagen JMH, Visser PM. 2018. Cyanobacterial blooms. Nat Rev Microbiol 16:471–483.

Hulton G, World Health Organization. 2012. Global costs and benefits of drinking-water supply and sanitation interventions to reach the MDG target and universal coverage. World Health Organization, Geneva.

Huq A, Small EB, West PA, Huq MI, Rahman R, Colwell RR. 1983. Ecological relationships between Vibrio cholerae and planktonic crustacean copepods. Appl Environ Microbiol 45:275–283.

Hutton G, Haller L, World Health Organization. 2004. Evaluation of the costs and benefits of water and sanitation improvements at the global level.

Jacobs JM, Rhodes M, Brown CW, Hood RR, Leight A, Long

W, Wood R. 2014. Modeling and forecasting the distribution of Vibrio vulnificus in Chesapeake Bay. J Appl Microbiol 117:1312–1327.

Jamal Y, Usmani M, Brumfield KD, Singh K, Huq A, Nguyen TH, Colwell R, Jutla A. 2024. Quantification of climate footprints of Vibrio vulnificus in coastal human communities of the United States Gulf Coast. GeoHealth 8:e2023GH001005.

Johnson S. 2006. The ghost map: the story of London's most terrifying epidemic and how it changed science, cities, and the modern world. Riverhead Books, New York.

Joseph SW, Colwell, Rita R, Kaper JB. 1982. Vibrio parahaemolyticus and related halophilic vibrios. Crit Rev Microbiol 10:77–124.

Jutla A, Aldaach H, Billian H, Akanda A, Huq A, Colwell R. 2015. Satellite based assessment of hydroclimatic conditions related to cholera in Zimbabwe. PLoS One 10:e0137828.

Jutla A, Usmani M, Brumfield KD Singh K, McBean F, Potter A, Gutierrez A, Gama S, Huq A, Colwell RR. 2023. Anticipatory decision-making for cholera in Malawi. mBio 14:e00529-23.

Kapetanović D, Katouli M, Lušić DV. 2024. Microbial communities in changing aquatic environments. Microorganisms 12:726.

Kappel K, Holmen SJ. 2019. Why science communication, and does it work? A taxonomy of science communication aims and a survey of the empirical evidence. Front Commun 4:1–12.

Khan R, Anwar R, Akanda S, McDonald MD, Huq A, Jutla A, Colwell R. 2017. Assessment of risk of cholera in Haiti following Hurricane Matthew. Am J Trop Med Hyg 97:896–903.

Khan R, Nguyen TH, Shisler J, Lin L-S, Jutla A, Colwell R. 2018. Evaluation of risk of cholera after a natural disaster: lessons learned from the 2015 Nepal earthquake. J Water Resour Plan Manag 144:04018044.

Kim SD, Cho J, Kim IS, Vanderford BJ, Snyder SA. 2007. Occurrence and removal of pharmaceuticals and endocrine disruptors in South Korean surface, drinking, and waste waters. Water Res 41:1013–1021.

Kirchhoff CJ, Watson PL. 2019. Are Wastewater Systems Adapting to Climate Change? JAWRA Journal of the American Water Resources Association 55:869–880.

LaKind JS, Overpeck J, Breysse PN, Backer L, Richardson SD, Sobus J, Sapkota A, Upperman CR, Jiang C, Beard CB, Brunkard JM, Bell JE, Harris R, Chretien J-P, Peltier RE, Chew GL, Blount BC. 2016. Exposure science in an age of rapidly changing climate: challenges and opportunities. J Expo Sci Environ Epidemiol 26:529–538.

LaMartina EL, Mohaimani AA, Newton RJ. 2021. Urban wastewater bacterial communities assemble into seasonal steady states. Microbiome 9:116.

Laveran A. 1881. Un nouveau parasite trouvé dans le sang de malades atteints de fièvre palustre. Origine parasitaire des accidents de l'impaludisme. Bull Mém Soc Méd Hôpitaux Paris 17:158–164.

Le Roux F, Blokesch M. 2018. Eco-evolutionary dynamics linked to horizontal gene transfer in vibrios. Annu Rev Microbiol. Annu Rev 72:89–110.

Lenski RE. 2017. Experimental evolution and the dynamics of adaptation and genome evolution in microbial populations. ISME J 11:2181–2194.

Levin BR, Bergstrom CT. 2000. Bacteria are different: observations, interpretations, speculations, and opinions about the mechanisms of adaptive evolution in prokaryotes. Proc Natl Acad Sci 97:6981–6985.

Levy K, Smith SM, Carlton EJ. 2018. Climate change impacts on waterborne diseases: moving toward designing interventions. Curr Environ Health Rep 5:272–282.

Levy K, Woster AP, Goldstein RS, Carlton EJ. 2016. 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.

Levy S. ECDC vibrio map viewer: tracking the whereabouts of pathogenic species. Environ Health Perspect 126:034003.

Li J, Li X, Liu H, Gao L, Wang W, Wang Z, Zhou T, Wang Q. 2023. Climate change impacts on wastewater infrastructure: a systematic review and typological adaptation strategy. Water Res 242:120282.

Liang SY, Messenger N. 2018. Infectious diseases after hydrologic disasters. Emerg Med Clin N Am 36:835–851.

Litchman E, Edwards KF, Klausmeier CA. 2015. Microbial resource utilization traits and trade-offs: implications for community structure, functioning, and biogeochemical impacts at present and in the future. Front Microbiol 6:254.

Litchman E. 2023. Understanding and predicting harmful algal blooms in a changing climate: a trait-based framework. Limnol Oceanogr Lett 8:229–246.

Liu Q, Du M, Wang Y, Deng J, Yan W, Qin C, Liu M, Liu J. 2024. Global, regional and national trends and impacts of natural floods, 1990–2022. Bull World Health Organ 102:410–420.

Lynch V, Shaman J. 2023. Waterborne infectious diseases associated with exposure to tropical cyclonic storms, United States, 1996–2018. Emerg Infect Dis J 29:1548.

Mala-Jetmarova H, Barton A, Bagirov A. 2014. A history of water distribution systems and their optimisation. Water Supply 15:224–235.

Marchiafava E, Celli A. 1885. Nouve richerche sulla infezione malarica. Arch Sci Med Torino 9:311–340.

Mathivanan K, Chandirika JU, Vinothkanna A, Yin H, Liu X, Meng D. 2021. Bacterial adaptive strategies to cope with metal toxicity in the contaminated environment – a review.

Ecotoxicol Environ Saf 226:112863.

McLellan SL, Roguet A. 2019. The unexpected habitat in sewer pipes for the propagation of microbial communities and their imprint on urban waters. Curr Opin Biotechnol 57:34–41.

McNairn H, Jackson TJ, Wiseman G, Bélair S, Berg A, Bullock P, Colliander A, Cosh MH, Kim S-B, Magagi R, Moghaddam M, Njoku EG, Adams JR, Homayouni S, Ojo, ER, Rowlandson TL, Shang J, Goïta K, Hosseini M. 2015. The soil moisture active passive validation experiment 2012 (SMAPVEX12): prelaunch calibration and validation of the SMAP soil moisture algorithms. IEEE Trans Geosci Remote Sens 53:2784–2801.

Motesaddi S, Mohseni-Bandpei A, Nasseri M, Rafiee M, Hashempour Y. 2025. Climate change impact on water treatment plants: analysis of chlorophyll-a levels and process performance. Environmental Science and Pollution Research 32:2055–2068.

O'Donnell DR, Hamman CR, Johnson EC, Kremer CT, Klausmeier CA, Litchman E. 2018. Rapid thermal adaptation in a marine diatom reveals constraints and trade-offs. Glob Change Biol 24:4554–4565.

Olds HT, Corsi SR, Dila DK, Halmo KM, Bootsma MJ, McLellan SL. 2018. High levels of sewage contamination released from urban areas after storm events: a quantitative survey with sewage specific bacterial indicators. PLoS Med 15:e1002614.

Panhwar A, Muhammad A, Abro R, Kandhro A, Khaskheli AR, Gishkori K, Jalbani N, Qaisar S. 2022. Chapter 11, Global water mapping, requirements, and concerns over water quality shortages. In Dincer S, Merci�mek Takci HA, Sumengen Ozdenefe M, Uslu FM, Yiğittekin ES (ed), Water Quality: New Perspectives. IntechOpen, Rijeka.

Patz JA, Vavrus SJ, Uejio CK, McLellan SL. 2008. Climate change and waterborne disease risk in the great lakes region of the U.S. Am J Prev Med 35:451–458.

Paz S. 2024. Climate change: a driver of increasing vector-borne disease transmission in non-endemic areas. PLoS Med 21:e1004382.

Peer K, Hubbard B, Monti M, Vander Kelen P, Werner AK. 2024. The private well water climate impact index: characterization of community-level climate-related hazards and vulnerability in the continental United States. Sci Total Environ 957:177409.

Philippot L, Griffiths BS, Langenheder S. 2021. Microbial community resilience across ecosystems and multiple disturbances. Microbiol Mol Biol Rev 85:10.1128/mmbr.00026-20.

Phillips MA, Burrows JN, Manyando C, van Huijsduijnen RH, Van Voorhis WC, Wells TNC. 2017. Malaria. Nat Rev Dis Prim 3:17050.

Progress on household drinking water, sanitation and hygiene 2000-2017. Special focus on inequalities. New York: United Nations Children's Fund (UNICEF) and World Health Organization, 2019.

Rezaei N, Diaz-Elsayed N, Mohebbi S, Xie X, Zhang Q. 2019. A multi-criteria sustainability assessment of water reuse applications: a case study in Lakeland, Florida. Environ Sci Water Res Technol 5:102–118.

Salgot M, Vergés C, Angelakis AN. 2003. Risk assessment in wastewater recycling and reuse. Water Supply 3:301–309.

Scheuerl T, Hopkins M, Nowell RW, Rivett DW, Barraclough TG, Bell T. 2020. Bacterial adaptation is constrained in complex communities. Nat Commun 11:754.

Schmidt ML, Biddanda BA, Weinke AD, Chiang E, Januska F, Props R, Denef VJ. 2020. Microhabitats are associated with diversity–productivity relationships in freshwater bacterial communities. FEMS Microbiol Ecol 96:fiaa029.

Seidel L, Ketzer M, Broman E, Shahabi-Ghahfarokhi S, Rahmati-Abkenar M, Turner S, Ståhle M, Bergström K, Manoharan L, Ali A, Forsman A, Hylander S, Dopson M. 2022. Weakened resilience of benthic microbial communities in the face of climate change. ISME Commun 2:21.

Seymour JR, McLellan SL. 2025. Climate change will amplify the impacts of harmful microorganisms in aquatic ecosystems. Nat Microbiol 10:615–626.

Shaman J, Day J. 2005. Achieving operational hydrologic monitoring of mosquitoborne disease. Emerg Infect Dis J 11:1343–1350.

Shaman J, Stieglitz M, Stark C, Le Blancq S, Cane M. 2002. Using a dynamic hydrology model to predict mosquito abundances in flood and swamp water. Emerg Infect Dis J 8:6–13.

Smith AB. 2020. U.S. Billion-dollar weather and climate disasters, 1980 - present (NCEI Accession 0209268). NOAA National Centers for Environmental Information.

Smith DFQ, Casadevall A. 2022. Disaster microbiology—a new field of study. mBio 13:e01680-22.

Sui Q, Huang J, Deng S, Chen W, Yu G. 2011. Seasonal variation in the occurrence and removal of pharmaceuticals and personal care products in different biological wastewater treatment processes. Environ Sci Technol 45:3341–3348.

Tarr JA, McCurley J, McMichael FC, Yosie T. 1984. Water and wastes: a retrospective assessment of wastewater technology in the United States, 1800–1932. Tech Cult 25:226–263.

Teittinen A, Soininen J, Virta L. 2022. Studying biodiversity–ecosystem function relationships in experimental microcosms among islands. Ecology 103:e3664.

Ternes T, Josse A, Siegrist H. 2004. Peer reviewed: scrutinizing pharmaceuticals and personal care products in wastewater treatment. Environ Sci Technol 38:392A–399A.

Thomas MK, Kremer CT, Litchman E. 2016. Environment and evolutionary history determine the global biogeography of phytoplankton temperature traits. Glob Ecol Biogeogr 25:75–86.

Toubiana M, Salles C, Tournoud M-G, Licznar-Fajardo P, Zorgniotti I, Trémélo M-L, Jumas-Bilak E, Robert S, Monfort 2021. Monitoring urban beach quality on a summer day: determination of the origin of fecal indicator bacteria and antimicrobial resistance at Prophète Beach, Marseille (France). Front Microbiol 12:710346.

Usmani M, Brumfield KD, Magers BM, Chaves-Gonzalez J, Ticehurst H, Barciela R, McBean F, Colwell RR, Jutla A. 2023. Combating cholera by building predictive capabilities for pathogenic Vibrio cholerae in Yemen. Sci Rep 13:2255.

Usmani M, Brumfield KD, Magers BM, Huq A, Barciela R, Nguyen TH, Colwell RR, Jutla A. 2022. Predictive intelligence for cholera in Ukraine? GeoHealth 6:e2022GH000681.

Vangay P, Burgin J, Johnston A, Beck KL, Berrios DC, Blumberg K, Canon S, Chain P, Chandonia J-M, Christianson D, Costes SV, Damerow J, Duncan WD, Dundore-Arias JP, Fagnan K, Galazka JM, Gibbons SM, Hays D, Hervey J, Hu B, Hurwitz BL, Jaiswal P, Joachimiak MP, Kinkel L, Ladau J, Martin SL, McCue LA, Miller K, Mouncey N, Mungall C, Pafilis E, Reddy TBK, Richardson L, Roux S, Schriml LM, Shaffer JP, Sundaramurthi JC, Thompson LR, Timme RE, Zheng J, Wood-Charlson EM, Eloe-Fadrosh EA. 2021. Microbiome metadata standards: report of the national microbiome data collaborative's workshop and follow-on activities. mSystems 6:10.1128/msystems.01194-20.

Vasco DW, Farr TG, Jeanne P, Doughty C, Nico P. 2019. Satellite-based monitoring of groundwater depletion in California's Central Valley. Sci Rep 9:16053.

Vicuna S, Maurer EP, Joyce B, Dracup JA, Purkey D. 2007. The sensitivity of California water resources to climate change scenarios. J Am Water Resour Assoc 43:482–498.

World Bank Group. 2017. Reducing Inequalities in Water Supply, Sanitation, and Hygiene in the Era of the Sustainable Development Goals: Synthesis Report of the WASH Poverty Diagnostic Initiative. © World Bank. http://hdl.handle.net/10986/27831

World Health Organization. 2021. Global technical strategy for malaria 2016–2030, 2021 update. World Health Organization. https://www.who.int/publications/i/item/9789240031357

World Health Organization. 2023. World malaria report 2023. World Health Organization. https://www.who.int/teams/global-malaria-programme/reports/world-malaria-report-2023

Wright KR, Witt GD, Zegarra AV. 1997. Hydrogeology and paleohydrology of ancient Machu Picchu. Groundwater 35:660–666.

Yang K, LeJeune J, Alsdorf D, Lu B, Shum CK, Liang S. 2012. Global distribution of outbreaks of water-associated infectious diseases. PLoS Negl Trop Dis 6:e1483.

Zouboulis A, Tolkou A. 2015. Effect of Climate Change in Wastewater Treatment Plants: Reviewing the Problems and Solutions, p. 197–220. In Shrestha, S, Anal, AK, Salam, PA, van der Valk, M (eds.), Managing Water Resources under Climate Uncertainty: Examples from Asia, Europe, Latin America, and Australia. Springer International Publishing, Cham.

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This report is based on the deliberations of experts who gathered to discuss a series of questions developed by the steering committee. All participants had the opportunity to provide feedback, and every effort has been made to ensure that the information is accurate and complete. The contents reflect the views of the participants and are not intended to reflect official positions of the Academy or of American Society for Microbiology.

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