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REVIEWS

Climate Change and Cholera: A Review Exploring the Association Between Storm Severity and Global Human *Vibrio spp.* Incidence.

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Current global meteorological evidence suggests that climate change is a direct contributor to the increased severity of weather events, such as hurricanes and typhoons, putting billions of people at increased risk of physical harm, property damage, and destructive flooding. When flood water becomes stagnant, communities are more susceptible to a multitude of infectious diseases, ranging from mosquito-borne parasites to bacterial infections. In the case of *Vibrio spp.*, a bacterial pathogen class with an infamous history of waterborne illness, recent data has demonstrated the ability for salt water, fresh water, and brackish water replication, creating ideal conditions for spread after a tropical cyclone. *Vibrio spp.* infections, specifically species *V. vulnificus*, *V. parahaemolyticus*, and *V. cholerae*, have shown significant upticks in the number of global cases, with some species increasing in incidence by more than 8-fold in the last 40 years. These outbreaks are contained mainly in areas susceptible to large-scale storm events and primarily occur during or immediately following the conclusion of local storm seasons, suggesting a potential correlation between the presence of tropical weather events and increases in the number of human *Vibrio* infections. In this review, we present a compilation of sources from tropical cyclone-susceptible areas, including the Americas, Asia, Africa, and Oceania, containing evidence demonstrating that recent outbreaks of *Vibrio spp.* are correlated with an increase in the severity of storms. Many of the included studies used modeling to forecast future trends of vibriosis and, therefore, directly link the effects of climate change with detrimental impacts to human global health.

Introduction

Tropical cyclones are low-pressure storm systems that form over tropical or subtropical waters and keep organized circulation over a given area, primarily in warm, humid climate conditions.[1] This class of storms encompasses hurricanes, primarily in the Western hemisphere, including regions of the Caribbean, Gulf of Mexico, and the Western United States; typhoons, localized to Southern and Southeast Asia; and cyclones, which affect Southern Africa and regions of Oceania.[2] Recent meteorological data have shown there is a direct correlation between increasing global temperatures because of climate change and the strengthening of tropical cyclones. Since 1980, the proportion of hurricanes that has met or exceeded a category 3 distinction, in which storms induce considerable damage and devastation to communities through injury, property damage, and flooding, has more than doubled.[3]

In addition to strengthening tropical cyclones, climate change has a profound impact on the spread of infectious disease and the origination of pandemics. The bacterial family *Vibrionaceae,* specifically the genus *Vibrio*, is one such pathogen class that is of rising concern to epidemiologists, as the recent incidence of *Vibrio spp.* infections has significantly increased. In the Eastern United States, the incidence of *V. vulnificus* infection, one of the most pathogenic forms of *Vibrio spp.*, has increased more than 8-fold from 1988 to 2018, with case numbers projected to double by 2100.[4] In the 15 years from 2008 to 2023, *V. vulnificus* infections in Florida nearly tripled, increasing from 16 cases with 6 fatalities to 46 cases with 11 fatalities, with health authorities noting an additional increase in cases attributed to Hurricane Ian in 2022.[5] This trend is similar in other common *Vibrio* species, such as *V. parahaemolyticus* and *V. cholerae,* the incidence of the latter in 2021 was the highest recorded rate globally in more than a decade.[6] Vibriosis, the general condition describing infection with *Vibrio* species, is commonly acquired through consuming seafood or water contaminated with the pathogen or exposing an open wound to brackish or saltwater containing *Vibrio spp.* When caused by consuming contaminated products, this condition is characterized by general gastrointestinal distress, including vomiting, diarrhea, and the presence of fever.[7] When introduced through an open wound, vibriosis manifests as a localized infection surrounding the injury, often with the infected area experiencing discharge, redness, and swelling.[8] Each of these infection routes has the potential for systemic spread and life-threatening complications if proper medical intervention is not pursued, with global estimates for the fatality rate of *V. vulnificus* at 1 in 5 and for *V. cholerae* at 1 in 4.[6,9] Because vibriosis is mainly spread through contact with contaminated water, *Vibrio* outbreaks are more likely to occur during storm seasons when communities face severe flooding and precipitation.[10] Given the environmental connection between tropical cyclones and the incidence of vibriosis, this review details recent studies that addressed the potential correlation between warmer global temperature as a result of climate change and increased human *Vibrio* disease incidence, while looking ahead towards mitigation strategies to face new global challenges. Increased incidence of vibriosis has already begun to have deleterious effects on the tourism and seafood industries, as well as public health and coastal recreational activities. While previous literature has described the impact of vibriosis on specific states, nations, or continental regions or focused largely on one storm incident, this review takes a global perspective on increasing *Vibrio* caseloads to establish trends and analyze prediction models based on data from severe weather events and natural disasters spanning several decades.

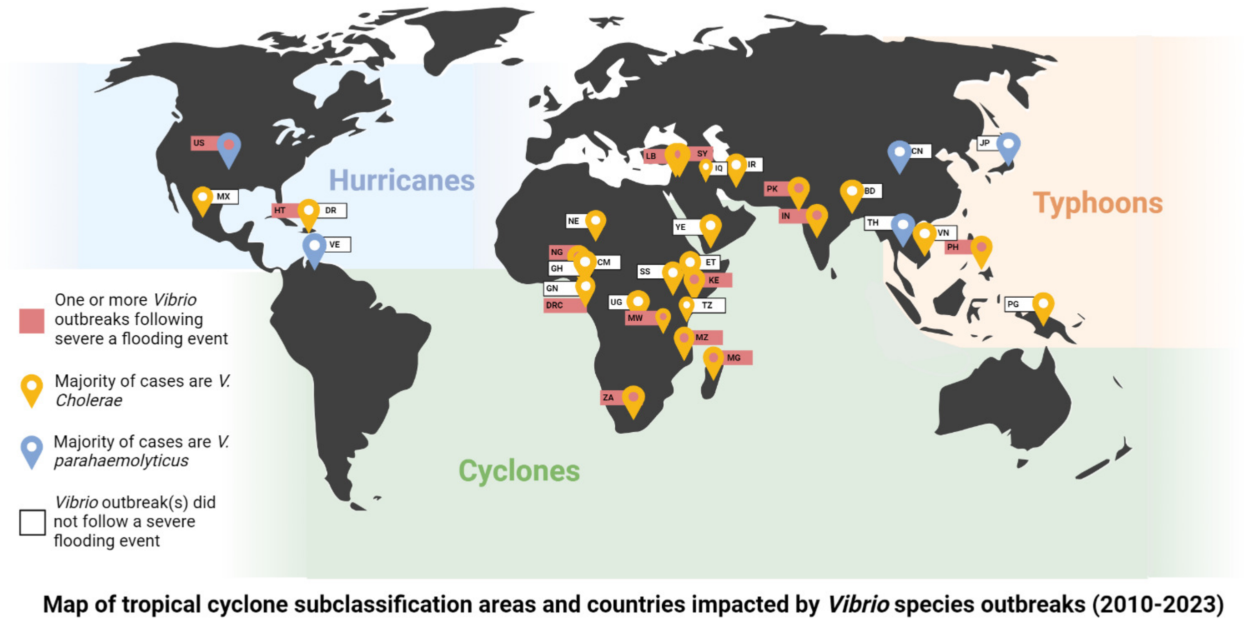


Figure 1. Map of Tropical Cyclone Subclassification Areas and Countries Impacted by *Vibrio* Species Outbreaks (2010-2023)

The map shows the global distribution of *Vibrio* species outbreaks separated by species and uses red labeling to indicate countries that have experienced outbreaks directly correlating with ≥1 multiple flooding events. For countries that had multiple outbreaks of different *Vibrio* species, the species with the highest incidence was chosen for the map marker color. Because *V. vulnificus* did not have the highest incidence in any country, it is excluded from the map. Underreporting is a global issue with diarrheal illnesses, particularly that of cholera, so it is possible that smaller outbreaks or outbreaks in areas with low epidemiological surveillance could have been excluded. Countries are indicated by 2-letter country codes (i.e. Cameroon (CM), China (CN), Democratic Republic of the Congo (DRC), Dominican Republic (DR), Ethiopia (ET), Ghana (GH), Guinea (GN), Haiti (HT), India (IN), Iran (IR), Iraq (IQ), Japan (JP), Kenya (KE), Lebanon (LB), Madagascar (MG), Malawi (MW), Mexico (MX), Mozambique (MZ), Niger (NE), Nigeria (NG), Pakistan (PK), Papua New Guinea (PG), Philippines (PH), South Sudan (SS), Syria (SY), Tanzania (TZ), Thailand (TH), Uganda (UG), United States (US), Venezuela (VE), Vietnam (VN), Yemen (YE), and Zambia (ZA)).[11-23] Created with BioRender.

Global Trends in Human *Vibrio* Incidence During Storm Seasons

Vibriosis infections are hypothesized to occur from a combination of both meteorological and environmental conditions that increase the potential for exposure between humans and *Vibrio spp.* pathogens. The occurrence of tropical cyclones is one such factor that can drastically increase the likelihood of human interaction with *Vibrio* bacteria. As flood water accumulates in densely populated areas, especially those without reliable storm infrastructure, the risk of waterborne human exposure to *Vibrio spp.* increases.[6] Recent data showed that most *Vibrio* species, such as *V. parahaemolyticus*, rely heavily on salt for replication, thriving especially in warm seawater; however, the species *V. cholerae* does not have the same requirement for salinity and is more commonly found in fresh water, increasing the likelihood of infection when individuals do not have access to clean water.[24] Other *Vibrio* species, such as *V. vulnificus*, have been shown to have specific salinity limits, favoring environmental conditions of 20 to 25 parts per thousand, which is in the salinity range of brackish water.[24] Given that environmental disasters can involve each of these three types of water, establishing the differences in optimal growth conditions is important in understanding why specific types of severe weather events may correlate with different *Vibrio* species outbreaks, given the geographic availability of salt or fresh water and the infrastructure used to support communities after water-involved storms. Global health trends generally show a positive correlation between tropical cyclone occurrence and vibriosis incidence. Consequently, an understanding of the unique challenges faced by different geographic regions, as well as historical endemic and outbreak incidence of *Vibrio spp.*, is imperative in aiding in the establishment of predictive models that can forecast vibriosis outbreaks in the future.

Americas

Of the geographic regions analyzed in this review, the Americas, specifically North America, supply the most comprehensive epidemiologic studies investigating the correlation between tropical cyclones and vibriosis incidence. Prior to 1990, studies examining the prevalence of *Vibrio* species on coastal beaches in California revealed higher occurrences of pathogenic *Vibrio* during the wet season, particularly of subspecies of *V. cholerae*.[25] In an assessment of coastal regions of California, it was found that wet season *Vibrios* generally are more diverse within coastline samples, with the water temperature and salinity being primary contributors to this phenomenon.[25] Because beaches attract more tourists during warmer seasons, increases to the diversity and quantity of pathogenic *Vibrio* species result in an increased risk for exposure of these pathogens to human hosts. In the early 2000s, the correlation between *Vibrio* and storms, particularly North American hurricanes, became a burgeoning field as multiple category 5 hurricanes correlated with a rise in severe vibriosis infections. Most notably, Hurricane Katrina was directly attributed to 22 cases (5 of which were fatal) of post-hurricane *Vibrio* infection, characterized by the development of *Vibrio* infection, from August 29 to September 11, 2005, in Louisiana and Mississippi.[26] Of the infected individuals, 18 experienced wound-borne illness, while only 4 developed vibriosis because of ingestion or other exposure; all 5 fatalities resulted from wound-borne illness.[26] This incident involved 3 primary species of *Vibrio*, with *V. parahaemolyticus* and *V. vulnificus* causing wound-borne infection and *V. cholerae* causing other nonwound-borne infections.[26] In the present decade, hurricanes Ian (2022) and Idalia (2023) both correlated with a rise in vibriosis infections in eastern coastal communities, with *V. vulnificus* being the primary species of concern.[27] However, datasets are still being collected to determine the impact of these recent weather events on the observed outbreaks. Together, these incidents serve as further evidence supporting the potential correlation of tropical storms and increased *Vibrio* incidence.

Africa

Vibrio species, primarily *V. cholerae,* are historically endemic to many regions of Africa, with Mozambique, Malawi, and other neighboring countries facing severe outbreaks in the last 2 years.[6] During the seventh cholera pandemic in the 1970s, *V. cholerae* serotype O1 biotype 7PET spread to Africa via intercontinental travel from Asia, where the outbreak began.[28,29] Since this introduction, cholera has remained endemic to Africa, fueled by infrastructural deficits, inaccessibility to clean water, and tropical storms. In 1985, refugee camps in Sudan experienced severe cholera outbreaks, with 1175 documented cases and 51 recorded deaths.[30] While the primary cause was attributed to the migration of refugees, flash flooding from storms was noted as a contributor to the severity of the outbreak.[30] It has been observed that directly following the rainy cyclone season, there is an uptick in vibriosis cases, exacerbated by droughts due to poor access to water, the marginalization of communities, and the increase of individuals living in urban settings.[17] While *V. vulnificus* cases are primarily attributed to increased exposure to brackish water from flooding, increased severity in droughts in combination with other public health emergencies in recent years have impacted individuals' ability to access health care and clean sources of drinking water, contributing to an increase in cases. The early 2000s provide an example of these combined causes; 924 suspected cholera cases and 95 reported deaths in Uganda were documented following severe wind and rain caused by the El Niño climate pattern in 2002-2003.[31] In the present decade, tropical storms have contributed greatly to the formation of localized outbreaks throughout Africa, most recently seen following Tropical Storm Ana (2022) and Tropical Cyclone Gombe (2022), which resulted in record cholera cases in Malawi.[32]

Asia/Oceania

The high rates of natural disasters in the Asian and Pacific regions are a key factor when examining regional *Vibrio spp.* infections. As of 2021, Asia reported more natural disasters than any other world region, representing 40% of total global incidents, with many storm incidents occurring in the warm, late summer period.[33] A study conducted in South Korea observed that species *V. cholerae* and *V. vulnificus* were only observed in tidal and mud water collected during the summer months, while species such as *V. parahaemolyticus* were found year-round, demonstrating warm-season specificity of select *Vibrio* species, coinciding with typical severe storm seasons.[34] Precipitation levels have also been shown to coincide with *Vibrio* outbreaks. In Japan between 1975 and 2005, there were an average of 6 infections per year, yet in 2001, a notably rainy year, there were 20 recorded cases, demonstrating a possible correlation between the increase in flooding and human vibriosis cases.[35] In a study of *Vibrio spp.* conducted in Australia in 2021, pathogenic *Vibrio* species were not only significantly more common during wet seasons associated with increased rainfall, but were also more diverse, mirroring trends observed in North America.[36] While many notable vibriosis outbreaks occur following unnamed localized flooding events resulting from expected rainfall patterns, there are recorded cases of increased vibriosis incidence following specific weather events. In May 2007, Bangladesh reported significant increases in illnesses involving *Vibrios* following a cyclone and monsoon, with a mudslide worsening pathogen spread and increasing the potential for human-pathogen contact.[37] In the present decade, studies investigating the effects of tropical storms on clam populations in Vietnam suggested that changes to water quality induced by cyclones and storms resulted in large fluctuations of clam-endemic *Vibrio* species, which may translate to a later increase of human cases upon consumption of contaminated seafood.[38] As floodwaters from tropical storms move inland, they result in changed salinity, pH, and nitrate levels that can result in optimal conditions for *Vibrio* species to grow, altering the water quality towards more favorable environmental conditions for pathogenic *Vibrio*.[38] Across these diverse continents, documented trends show that storms and flooding fuel vibriosis incidence.

Global Predictions for Human *Vibrio* Incidence

Climate change predictions are reliant on integrated biotic and abiotic factors within environments, as well as social determinants and lifestyle choices of humans. Models capturing such complexities and intricacies are known as shared socioeconomic pathways (SSPs). Essentially, SSPs are robust anthropogenic narratives that chronicle factors such as socioeconomic status, urbanization, population, access to technology, gross domestic product, geographic location, and reliance on fossil fuels, and other human-involved factors. Each individual SSP varies based on differences in the factors mentioned above and clarified in Figure 2.

In addition to their other applications, these narratives can serve as the basis for predicting global *Vibrio* incidence. The repertoire of SSPs forecasting multiple climate change outcomes also functions as a prognosticative tool for modeling outbreaks of bacteria within the *Vibrio* genus. Ultimately, these *Vibrio* models are a great resource for informing future public health measures and forecasting future affected regions.

North America

Future *V. vulnificus* cases in North, Central, and South America will burgeon at an alarming rate. For example, Archer et al modeled several SSPs of *V. vulnificus* outbreaks on the east coast of the United States, 2 of which were particularly important and had a central focus on the intersection of *Vibrio* and the environment, as the authors noted: “We focus on scenarios SSP1-2.6 which is set against the SSP1 narrative of ‘sustainability’ and is a low emissions scenario, and SSP3-7.0, which is set against the SSP3

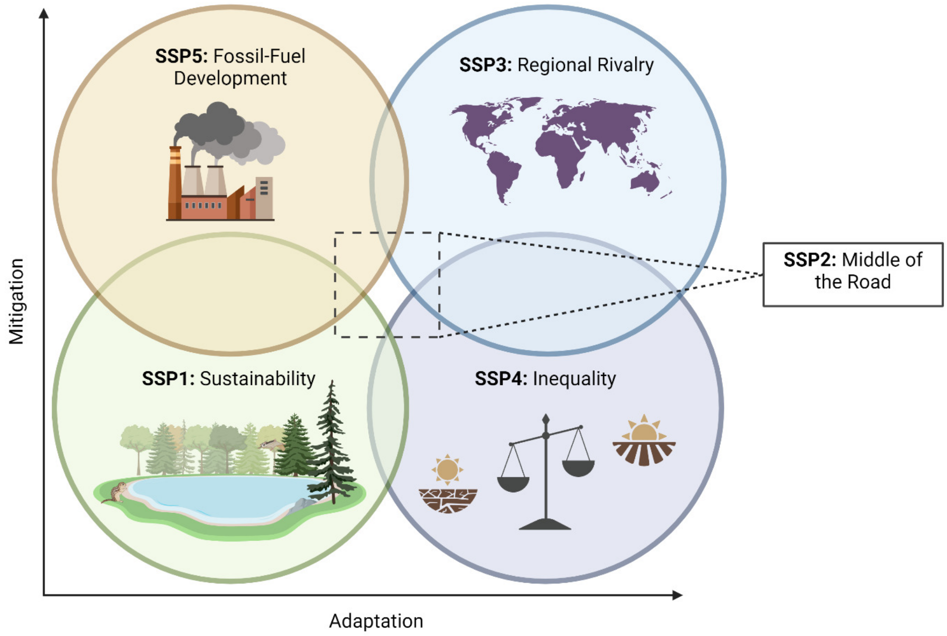


Figure 2. Example Schematic of How to Interpret a Socioeconomic Pathway (SSP) Figure.

This schematic representation shows how to read and analyze a typical SSP figure, aiding in the interpretation of the SSPs related to *Vibrio* incidence. Created with BioRender.

socioeconomic backdrop of 'regional rivalry,' where resurgent nationalism and regional conflicts shift focus away from climate mitigation leading to medium-to-high emissions. These are referred to hereafter as SSP126 and SSP370."[4]

As seen in Figure 3, SSP 1-2.6 demonstrates that the average incidence distribution of *V. vulnificus* will extend into the Mid-Atlantic region as far north as the New Jersey and New York City metropolitan area between 2081 and 2100.[4] States in the New England region are relatively untouched. This model portrays incidence of *V. vulnificus* with the assumption that emissions levels have been reduced from present-day levels and a reversion of unsustainable habits has contributed to more stable climate patterns. In contrast, the SSP 3-7.0 projection highlights an even more striking increase in cases along New England coastal states, extending up to New Hampshire and just barely into Maine. The dramatic incidence of *V. vulnificus* along the eastern seaboard in SSP 3-7.0 considers a moderate to excessive emissions level, which, in turn, would exacerbate climate change.[4] Naturally, the accelerated climate change would significantly alter aquatic environments, contributing to the striking incidence of bacteria along the coast.

Further examining the Chesapeake Bay watershed, there has been extensive environmental monitoring and modeling of *V. vulnificus* outbreaks in Chesapeake Bay by the National Oceanic and Atmospheric Administration's

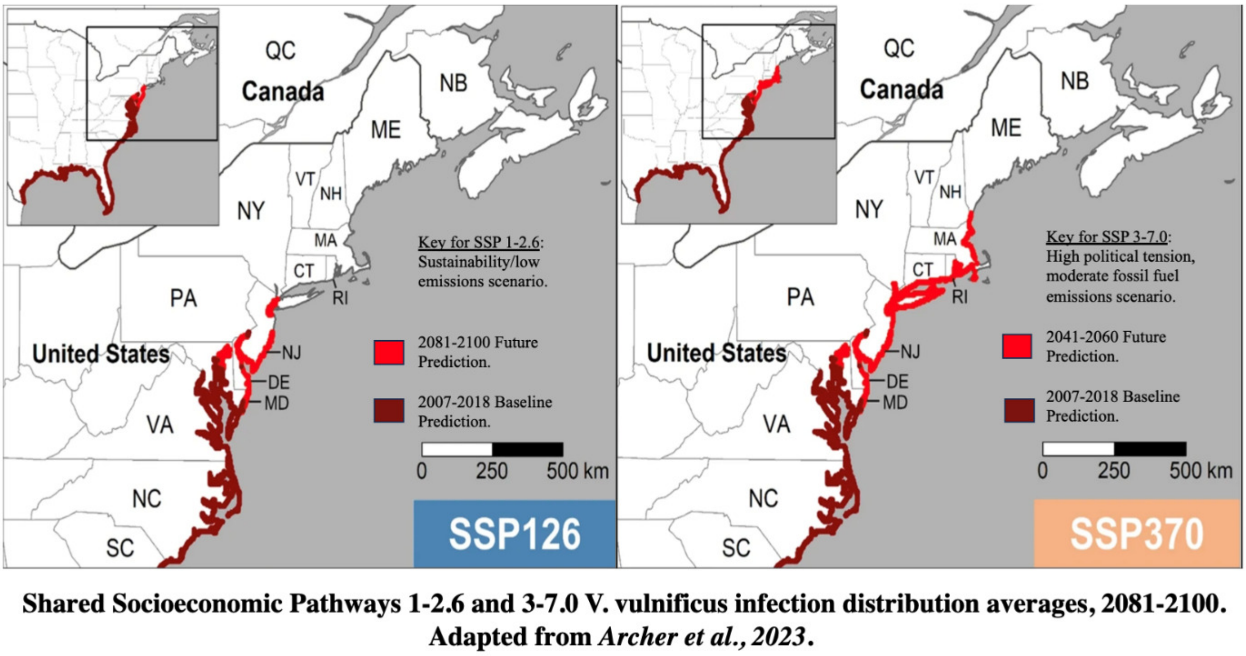


Figure 3. Earlier and Future Average Incidence of *Vibrio vulnificus* Cases Contextualized in 2 Shared Socioeconomic Pathways (SSPs).

Adapted from Archer et al.[4] Results and data unchanged.

National Centers for Coastal Ocean Science.[39] Interestingly, the data suggest that the prevalence of *V. vulnificus* may correlate with seasonality and densely populated areas.

As seen in Figure 4, bacterial concentrations peak in the summer until early fall, indicated by the green-yellow shading, and subsequently wane in the winter and spring. The September 1, 2023, snapshot from Figure 4 has been recapitulated in Figure 5 to present the proximate cities to each individual river listed.[39]

Figure 5 demonstrates that there was a higher probability of *V. vulnificus* bacteria in rivers proximate to densely populated cities. The cities and their corresponding nearby rivers of particular importance include the Potomac River, serving the Washington, DC, metropolitan area, encompassing parts of Maryland and Virginia and all of DC; additionally, the Patapsco River supplying Baltimore, Maryland. The Chesapeake Bay includes several more rivers beyond what is represented in the image, as it extends between parts of New York and terminates in coastal southeastern Virginia near Virginia Beach, where it flows into the Atlantic Ocean. To clarify, there are many complex factors at play contributing to the increased probability of *V. vulnificus* in Chesapeake Bay within the summer and fall months, such as temperature, salinity levels, dissolved oxygen, sedimentation, increased outdoor recreational activity, and more. Nonetheless, it is interesting to

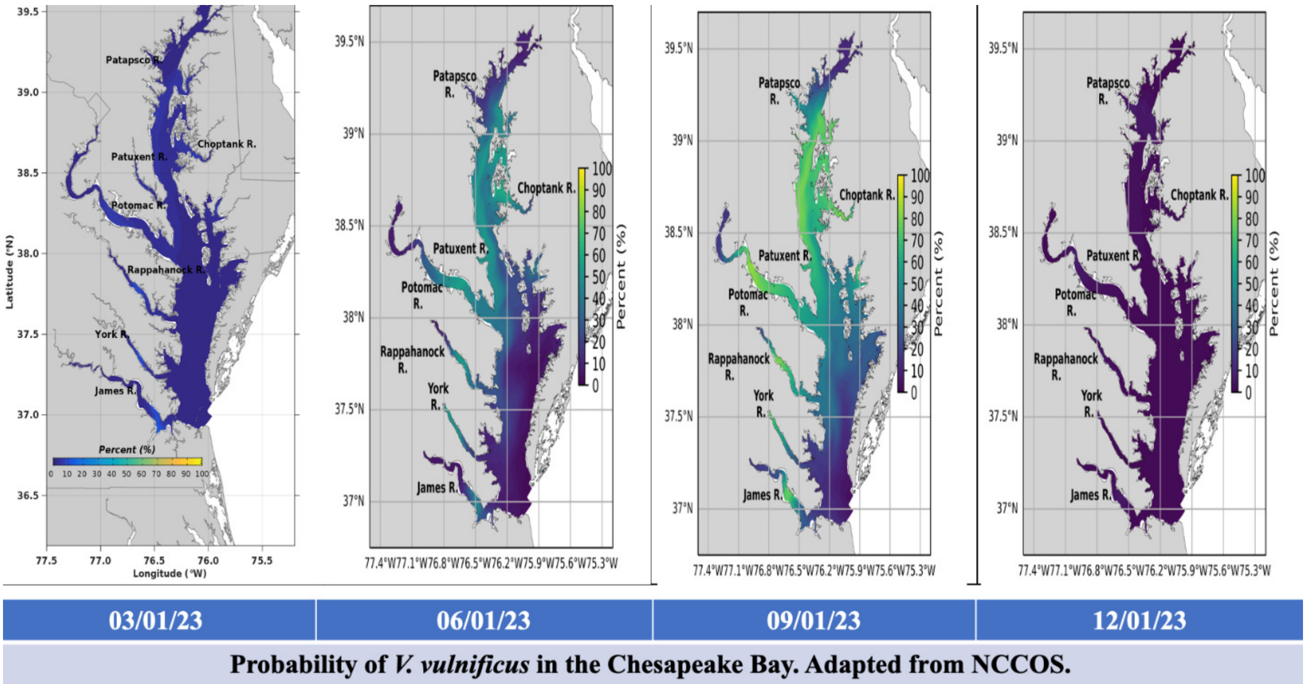
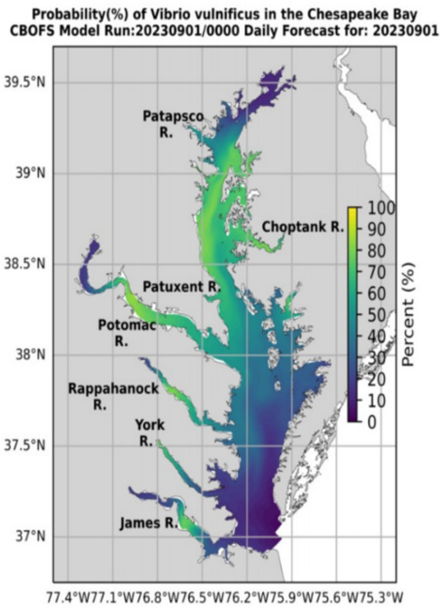


Figure 4. Probability of *Vibrio vulnificus* in the Chesapeake Bay.

Adapted from the National Oceanic and Atmospheric Association's National Centers for Coastal Ocean Science - source #360. Results and data unchanged.



River	Proximate City/Cities
Patapsco	Baltimore, MD
Choptank	Easton, MD Cambridge, MD
Patuxtent	Upper Marlboro, MD
Potomac	Washington, D.C. metro area (MD, DC, VA)
Rappahanock	Fredericksburg, VA
York	Williamsburg, VA Yorktown, VA
James	Richmond, VA

09/01/2023

Probability of *V. vulnificus* in the Chesapeake Bay Surrounding Urban Areas. Adapted from NCCOS.

Figure 5. Probability of *Vibrio vulnificus* in the Chesapeake Bay Surrounding Urban Areas.

Recapitulates Figure 3 with a table presenting cities that are proximate to the adjacent river within the Chesapeake Bay watershed. Adapted from the National Oceanic and Atmospheric Association's National Centers for Coastal Ocean Science - source #360. Results and data unchanged.

use these data from an extensively monitored area, suggesting a possible relationship between seasonality and urbanization, as the basis for regional predictions.

Another insightful predictive modeling tool includes comparing rates of *Vibrio* cases both before and after hurricane seasons. This is especially useful because climate change consequences include more extreme weather events, such as hurricanes, floods, cyclones. *V. vulnificus* was show to be the most common bacteria to be found in Gulf Coast states at 39% after Hurricane Katrina in 2005 compared with its *Vibrio spp.* counterparts.[40] Data on *Vibrio* following Hurricane Idalia have not been gathered yet, but previous trends indicate that there will be a subsequent increase in *Vibrio* outbreaks.

South America

Overall, modeling projections for Central and South America are more difficult because there is less clinical and epidemiological data available compared with the United States. Nonetheless, predictions surrounding gastrointestinal vibriosis cases are fueled by the recent discovery of *Vibrios* in local seafood; *V. parahaemolyticus* has been documented as the primary agent in raw oysters in northwestern Mexico, linked with vibriosis incidence.[41] However, the potential for *V. cholerae, V. vulnificus*, and other *Vibrio spp.* cases to increase is likely because several bacteria within the genus grow together. This is a particularly relevant aspect to creating models because bacteria such as *Vibrio* do not live in complete isolation of one another, nor in isolation of other species. For instance, "*V. cholerae* and *V. vulnificus* were found mainly with *V. parahaemolyticus* [in oyster samples]."[39] Fortunately, strict laws concerning *Vibrio* in seafood from South America have significantly decreased caseloads, with very few reported cases in the present or previous decade.[42] While *V. parahaemolyticus* has been found in environmental samples from nearly all coastal areas of the continent, ranging from Colombia to Argentina, *V. vulnificus* is limited in its geographical extent, represented by minimal isolated cases largely on the Atlantic seaboard.[42] An important abiotic factor may account for the distinction of *Vibrio* cases between the northern and southern hemispheres: "...salinity in South America is found to be, in general, higher than 25‰, which could explain the lower prevalence of *V. vulnificus* compared to the United States."[42] Ultimately, gaining further insight into why *V. parahaemolyticus* predominates in contaminating seafood vs *V. vulnificus* in South America can boost accuracy and precision in predicting outcomes.

Africa

Social determinants of health are an important aspect when modeling *V. vulnificus* cases in Africa, particularly within the sub-Saharan region. This vast region of Africa encompasses ecosystems such as tropical and subtropical grasslands and savannas.[43] Rainfall is sparse in such environments, so most residents rely on natural rivers, streams, and lakes for water. In some cases, a minority of people use potable water, but current meteorological projections estimate that 4 of 5 African countries will have severe water stress, caused by water mismanagement, by 2030.[44] In conjunction with accelerated changes to climate, these circumstances could heighten the probability of waterborne diseases, namely from the *Vibrio* genus. At this time, ample data on *Vibrio* outbreaks are lacking in the sub-Saharan region and overall, for the continent, resulting in a lack of *Vibrio* incidence projection models similar to those created for North America. However, the following report detailing the inadequate water treatment infrastructure in South Africa may elucidate such risks.

In 2021, a team of microbiologists and environmentalists investigated several wastewater treatment plants across South Africa. The team concluded "six medically important *Vibrio* species were detected in the water samples, indicating that the methods employed were efficient in revealing that [wastewater treatment plants] are potential reservoirs of *Vibrio* pathogens, which could pose a substantial public health risk if the receiving water is used for domestic purposes."[45] Thus, if water management infrastructure does not drastically improve in the near future, *Vibrio* infections are likely to worsen as clean water access continues to decrease.

In summation, due to the increased incidence of severe storm events, coupled with a lack of reliable access to clean water, particularly after devastating storm effects, these factors increase the likelihood of human contact with *Vibrio* species. Furthermore, growing political tensions, worsening water infrastructure, and increasing African storm severity show the high possibility of increasing vibriosis over time.

Asia/Oceania

The aquaculture enterprise is a particularly relevant factor when analyzing *Vibrio spp.* outbreaks in this region because it is a vital means of harvesting seafood, and it is a substantial economic industry. A 2021 article in *Nature* demonstrated the tremendous scope of this enterprise, as well as the driving market forces behind it: "Asia remains the largest aquaculture producer, accounting for 92% of the live-weight volume of animals and seaweeds in 2017...A key characteristic of freshwater aquaculture growth during the past 20 years has been the proliferation of value chains in and across countries located in South and Southeast Asia, for example, in Andra Pradesh, India, Bangladesh, Myanmar, Thailand, and Vietnam. China remains the single largest producer of freshwater fish—for export and domestic consumption—accounting for 56% of the global output in 2017. The expansion of freshwater aquaculture in Asia (93% of global production) has been driven mainly by urban demand and the decline in wild inland fisheries that previously supported rural livelihoods and food security."[46] Likewise, seafood production in Australia and Tanzania is a substantial economic enterprise, as "the export value of fisheries and aquaculture products is forecast to rise in 2023-24, by 7% to $1.47 billion."[47] Despite the impressive technological advances and flourishing business within the Asian and Oceanian aquaculture industries, the complex issue of antibiotic resistance remains. *Vibrio* species are ubiquitous in all coastal areas around the world, therefore, it is no surprise that there have been documented cases of antibiotic-resistant *Vibrio* in multiple parts of the Asian continent, broadly ranging from East Asia, Southeast Asia, and Oceania.[48] Globalization may have contributed to the proliferation of the vast aquaculture sector; however, it may have also perpetuated certain downfalls: "With the rapid development of Asian fish culture in recent decades, the cases of *Vibrio* infection through aquatic products at home and abroad, causing human disease or huge economic losses, are also increasing year by year."[49] As a result of the increasing prevalence of antibiotic-resistant *Vibrio*, efforts are ongoing to produce biologics and therapeutics administered to fish both before and after exposure. These factors are critical in the future establishment of *Vibrio* models that account for these complex social and environmental factors.

Europe

Historically, Europe has been relatively untouched by *Vibrio* species; however, this may change in the near future. According to Baker-Austin et al, there is a broad array of social and environmental factors contributing to a possible uptick in European cases: "a myriad of epidemiological factors may greatly increase the incidence as well as clinical burden of these pathogens—including increasing global consumption and trade of seafood produce coupled to an increase in the number of susceptible individuals consuming seafood produce."[50]

More specifically, the Food and Agriculture Organization has projected that the "total consumption of aquatic food is expected to increase in all continents by 2030 in comparison with 2020, with higher growth rates projected in Africa and Oceania (26 percent in both regions), the Americas (17 percent), Asia (15 percent) and Europe (6 percent)."[51] In 2022, the European Environment Agency raised concerns with food quality and increases to foodborne illnesses as a result of climate change, specifically citing increases in *Vibrio spp.* found in seafood caught in the Baltic Sea as a pathogen of concern.[52] While historically unscathed, increasing globalization and trade involving contaminated food products could bring this pathogen class to Europe in the future, creating a need for preventive strategies.

Current Mitigation Strategies for *Vibrio* Storm-Induced Outbreaks

The World Health Organization (WHO) has implemented many strategies to combat the increasing prevalence of *Vibrio* outbreaks globally. As presented in the WHO 2023 Multi-country Cholera Situation Report, cholera incidence has been steadily rising, with cholera outbreaks identified across many parts of the world. This includes 15 separate countries in Africa, 1 in Central America, 4 in the Middle East, and 4 in Asia with the highest concentration of cases occurring in Africa and South Asia.[18] The WHO emphasizes the importance of improving public health surveillance systems globally through international coordination between countries resulting in the creation of standardized data and metadata sets to improve global cholera reporting practices. By improving these reporting systems, epidemiologists will be able to better track both outbreak prevalence and location for increased preparedness and for creation of future mitigation and response methods. In addition to the public health surveillance system, the WHO continues to manufacture and disperse cholera vaccinations in the wake of an outbreak. In 2023 alone, 9.8 million doses of the cholera vaccine have been shipped to countries who have been most affected by cholera outbreaks, with vaccination efforts expected to reach 25.5 million doses by the end of the year.[18] Unfortunately, the stockpile capabilities are not currently large enough for a preventative campaign, so it is used as a 1 dose reactive measure in locations experiencing an outbreak.

The WHO has also implemented two vibriosis preventative strategies: Infection Prevention and Control (IPC) and Water, Sanitation, and Hygiene (WASH). The IPC strategy is tasked with three primary goals: infection prevention in and out of the hospital setting, the establishment of IPC programs around the globe, and creating health measures that are holistic, treating factors such as water quality and antimicrobial resistance as key players in the fight against global infections.[53] WASH focuses specifically on the impact of water on global health, and prioritizes clean drinking water, hygiene, and sanitation in infection prevention; this program specifically places emphasis on diseases that have the potential to result in diarrheal deaths, such as those caused by *V. cholerae.*[54] These strategies are beneficial in that they reduce the likelihood that an individual will come into contact with *Vibrio spp.* by establishing better hygiene practices and improving water quality in the affected communities. Additionally, they teach practices that can be done by these communities long term such as proper personal protective equipment in hospitals and hand washing techniques to reduce disease spread in households. The WHO aims to decentralize treatment options and improve community access through these strategies. Collaboration to develop standard procedures and protocols for infection control of health care providers, and risk communication to the communities through webinars are methods taken to strengthen prevention and response.

Wastewater treatment plants have been a vital development in reducing the prevalence of waterborne diseases in modern times, and are an essential service provided by governments. Unfortunately, the biggest setback experienced with these services is a lack of financial resources. This results in outdated and deteriorating wastewater treatment plants that are unable to adequately clean the water of all contaminants before it is released back into the environment. The 2008-2009 Cholera outbreak in Zimbabwe is a prime example of this, which occurred in the midst of an economic crisis after the subsequent breakdown of their water treatment plant and lack of purification chemicals in the capital city.[54] This situation caused an emergency to be declared by the Ministry of Health with goals to improve their systems and improve education in communities, yet even over 10 years later cholera persists in the region. In a study conducted by two individuals from the University of Zimbabwe, the utilization of bioremediation, or "the use of living organisms, like microbes and bacteria, in the removal of contaminants, pollutants, and toxins from soil, water, and other environments" serves as a promising new technique to reduce levels of *V. cholerae* in wastewater. Using *Chlorella vulgaris,* a type of algae, they were able to fully eliminate the presence of *V. cholerae* on laboratory plates after 21 days; they have further prepared a prototype on how this can be adapted to the country's sewage treatment plants.[55] The benefit of a bioremediation strategy is that in countries where they do not have the access or economy to support the implementation of a new wastewater treatment system or keep up with maintenance, this provides a lower cost alternative with environmental benefits and has the potential to be applied to other harmful water borne bacteria.[56]

In addition to the strategies aimed at controlling *Vibrio* outbreaks directly, mitigation strategies targeted at climate change are also critical in lessening vibriosis incidence. Green Infrastructure Strategies, which are architectural designs that take into account the natural environment, could be used as one effective mechanism by which to control flood water; bioretention is one such solution in which floodwater is directed into a filtered storage mechanism before releasing the water contents below ground, reducing the likelihood of runoff contaminants.[57] As previously mentioned, these runoff contaminants can include substances such as nitrates, which can alter the water quality and create optimal replication conditions for *Vibrio* species. Bioretention also encourages floodwater to seep into the ground instead of remaining above stagnant, reducing the likelihood of human contact with contaminated water.[57] Initiatives such as bioretention are examples of climate change mitigation strategies that have the potential to have beneficial effects not only on the environment, but also on public health.

Conclusions

The observed connections between tropical cyclones, climate change, and infectious *Vibrio spp.* outbreaks prove a broader need for effective mitigation strategies to combat a set of growing global issues surrounding changing environmental conditions and the infectious diseases they enable. *Vibrio* bacteria have far-reaching consequences because they pose threats to the hospitality, tourism, and food industries, as well as seafood production, health care, and coastal recreational activities. The data presented in this review address the concerning trends of global *Vibrio spp.* infection, showing drastic increases of potentially fatal forms of vibriosis on nearly every populated continent.[6] This review also shows the need for mitigation strategies that are multifaceted, addressing the connections between infrastructural deficits, government and organizational inconsistencies, and the looming threat of further climate change, bringing stronger and more damaging storm systems to vibriosis-prone areas. With the occurrence of severe storms increasing, and increasing incidence of vibriosis outbreaks, effective climate change mitigation efforts are critical to global health. As the global incidence of *Vibrio spp.* infections rises, it is imperative that urban and rural areas receive the required resources and educational material to make informed decisions about the safety of their communities, and that global nongovernmental organizations are still aware of the increased likelihood of future outbreaks.

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REFERENCES

1. National Oceanic and Atmospheric Association. Tropical cyclone introduction. Accessed November 19, 2023. https://www.noaa.gov/jetstream/tropical/tropical-cyclone-introduction

2. SciJinks. How does a Hurricane form? National Oceanic and Atmospheric Association. Accessed November 19, 2023. https://scijinks.gov/hurricane/

3. Ocko I, Sun T. How climate change makes hurricanes more destructive. Environmental Defense Fund. Accessed November 19, 2023. https://www.edf.org/climate/how-climate-change-makes-hurricanes-more-destructive

4. Archer EJ, Baker-Austin C, Osborn TJ, et al. Climate warming and increasing Vibrio vulnificus infections in North America. Scientific Reports. Accessed November 19, 2023. https://www.nature.com/articles/s41598-023-28247-2

5. Florida Department of Health. Diseases and conditions: Vibrio vulnificus. Accessed November 19, 2023. https://www.floridahealth.gov/diseases-and-conditions/vibrio-infections/vibrio-vulnificus/index.html

6. World Health Organization. Disease outbreak news: cholera – global situation. Accessed November 19, 2023. https://www.who.int/emergencies/disease-outbreak-news/item/2023-DON437

7. Centers for Disease Control and Prevention. Symptoms: Vibrio species causing vibriosis. Accessed November 19, 2023. https://www.cdc.gov/vibrio/symptoms.html

8. Centers for Disease Control and Prevention. Vibrio vulnificus and wounds. Accessed November 19, 2023. https://www.cdc.gov/vibrio/wounds.html

9. Centers for Disease Control and Prevention. Oysters and vibriosis. Accessed November 19, 2023. https://www.cdc.gov/foodsafety/communication/oysters-and-vibriosis.html

10. Centers for Disease Control and Prevention. Severe Vibrio vulnificus infections in the United States associated with warming coastal waters. Accessed November 19, 2023. https://emergency.cdc.gov/han/2023/han00497.asp

11. Heng SP, Letchumanan V, Deng CY, et al. Vibrio vulnificus: An Environmental and Clinical Burden. *Front Microbiol*. 2017;8:997. Accessed April 18, 2024. https://www.frontiersin.org/journals/microbiology/articles/10.3389/fmicb.2017.00997/full

12. Oishi H, Ura Y, Mitsumizo S, Nakashima M. A collective review of Vibrio vulnificus infection in Japan. *kansenshogakuzasshi*. 2006;80(6):680-689. doi:10.11150/kansenshogakuzasshi1970.80.680

13. Esteves K, Hervio-Heath D, Mosser T, et al. Rapid proliferation of Vibrio parahaemolyticus, Vibrio vulnificus, and Vibrio cholerae during freshwater flash floods in French Mediterranean coastal lagoons. *Appl Environ Microbiol*. 2015;81(21):7600-7609. doi:10.1128/aem.01848-15

14. Bhuyan S, Vairale M, Arya N, et al. Molecular epidemiology of Vibrio cholerae associated with flood in Brahmaputra River valley, Assam, India. *Infection, Genetics and Evolution*. Accessed April 18, 2024. https://www.sciencedirect.com/science/article/pii/S1567134815300599

15. Blanca Begert G. As climate change leads to more and wetter storms, cholera cases are on the rise. PBS. Published 2023. Accessed April 18, 2024. https://www.pbs.org/newshour/health/as-climate-change-leads-to-more-and-wetter-storms-cholera-cases-are-on-the-rise

16. United Nations News. Global cholera surge likely accelerated by climate change, warns WHO. UN News. Published 2022. Accessed April 18, 2024. https://news.un.org/en/story/2022/12/1131787

17. World Health Organization. Disease Outbreak News; Cholera- Global situation. Published 2022. Accessed April 18, 2024. https://www.who.int/emergencies/disease-outbreak-news/item/2022-DON426

18. World Health Organization. Multi-country outbreak of cholera; external situation report #2. WHO. Published May 11, 2023. Accessed April 18, 2024. https://www.who.int/docs/default-source/coronaviruse/situation-reports/20230504_multi-country_outbreak_cholera_sitrep-2.pdf?sfvrsn=3a08f0fd_3

19. Hoefler F, Pouget-Abadie X, Roncato-Saberan M, et al. Clinical and epidemiological characteristics and therapeutic management of patients with Vibrio infections, Bay of Biscay, France, 2001-2019. *Emerging Infectious Diseases*. Published online 2022. Accessed April 18, 2024. https://wwwnc.cdc.gov/eid/article/28/12/22-0748_article

20. Loo K, Law J, Tan L, et al. The burden of Vibrio sp. Infections: A Scoping Review. *Progress in Microbes and Molecular Biology*. Published online 2023. Accessed April 18, 2024. https://hh-publisher.com/ojs321/index.php/pmmb/article/view/835/431

21. Raszl SM, Froelich BA, Vieira CRW, Blackwood AD, Noble RT. *Vibrio parahaemolyticus* and *Vibrio vulnificus* in South America: water, seafood and human infections. *J Appl Microbiol*. 2016;121(5):1201-1222. doi:10.1111/jam.13246

22. Domman D, Quilici ML, Dorman MJ, et al. Integrated view of *Vibrio cholerae* in the Americas. *Science*. 2017;358(6364):789-793. doi:10.1126/science.aao2136

23. United Nations Economic Commission for Europe. Shared Socioeconomic Pathways (SSPs). The United Nations. Published 2024. Accessed April 18, 2024. https://unece.org/fileadmin/DAM/energy/se/pdfs/CSE/PATHWAYS/2019/ws_Consult_14_15.May.2019/supp_doc/SSP2_Overview.pdf

24. Randa MA, Polz MF, Lim E. Effects of temperature and salinity on Vibrio vulnificus population dynamics as assessed by quantitative PCR. *Applied and Environmental Microbiology*. Published online 2004. Accessed November 19, 2023. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC520858/

25. Kenyon JE, Piexoto DR, Austin B, Gillies DC. Seasonal variations of Vibrio cholerae (non-O1) isolated from California coastal waters. *Appl Environ Microbiol*. 1984;47(6):1243-1245. doi:10.1128/aem.47.6.1243-1245.1984

26. Bopp C, Mintz E, Sobel J. Vibrio illnesses after Hurricane Katrina—multiple states, August-September 2005. Centers for Disease Control and Prevention. Published 2005. Accessed November 19, 2023. https://www.cdc.gov/mmwr/preview/mmwrhtml/mm54d914a1.htm

27. Study GD. Hurricane Ian unleashed flesh-eating bacteria into Florida waters. Health News Florida. Published 2023. Accessed November 19, 2023. https://health.wusf.usf.edu/health-news-florida/2023-10-31/study-hurricane-ian-unleashed-flesh-eating-bacteria-into-florida-waters

28. Smith AM, Sekwadi P, Erasmus LK, et al. Imported Cholera Cases, South Africa, 2023. *Emerg Infect Dis*. 2023;29(8). doi:10.3201/eid2908.230750

29. Mutreja A, Kim DW, Thomson NR, et. al. Evidence for several waves of global transmission in the seventh cholera pandemic. Nature. Published 2011. Accessed November 19, 2023. https://www.nature.com/articles/nature10392

30. Mulholland K. Cholera in Sudan: an account of an epidemic in a refugee camp in eastern Sudan, May–June 1985. *Disasters*. 1985;9(4):247-258. doi:10.1111/j.1467-7717.1985.tb00947.x

31. Alajo SO, Nakavuma J, Erume J. Cholera in endemic districts in Uganda during El Niño rains: 2002-2003. *African Health Sciences*. Published online 2006. Accessed November 19, 2023. https://www.ajol.info/index.php/ahs/article/view/6932

32. Miggo M, Harawa G, Kangwerema A, et al. Fight against cholera outbreak, efforts and challenges in Malawi. *Health Science Reports*. 2023;6(10). doi:10.1002/hsr2.1594

33. Asian Disaster Reduction Center. Natural Disaster Databook 2021: An Analytical Overview [dataset]. Published online 2021. Accessed November 19, 2023. https://www.adrc.asia/publications/databook/ORG/databook_2021/pdf/DataBook2021.pdf

34. Di DYW, Lee A, Jang J, Han D, Hur HG. Season-specific occurrence of potentially pathogenic Vibrio spp. on the southern coast of South Korea. *Appl Environ Microbiol*. 2017;83(3). doi:10.1128/aem.02680-16

35. Oishi H, Ura Y, Mitsumizo S, Nakashima M. A collective review of Vibrio vulnificus infection in Japan. *Kansenshogaku Zasshi*. 2006;80(6):680-689. doi:10.11150/kansenshogakuzasshi1970.80.680

36. Padovan A, Siboni N, Kaestli M, King WL, Seymour JR, Gibb K. Occurrence and dynamics of potentially pathogenic vibrios in the wet-dry tropics of northern Australia. *Marine Environmental Research*. 2021;169:105405. doi:10.1016/j.marenvres.2021.105405

37. Lara RJ, Neogi SB, Islam MS, Mahmud ZH, Yamasaki S, Nair GB. Influence of catastrophic climatic events and human waste on Vibrio distribution in the Karnaphuli Estuary, Bangladesh. *EcoHealth*. 2009;6(2):279-286. doi:10.1007/s10393-009-0257-6

38. Pham Thai G, Dang Thi L, Vu Thi Kieu L, et al. Potential risks of climate change and tropical storms on ecosystem and clams culture activities in Giao Thuy, Nam Dinh, Vietnam. *Human and Ecological Risk Assessment: An International Journal*. 2023;29(3-4):836-858. doi:10.1080/10807039.2023.2194998

39. Ellett A, Jacobs J. NOAA forecast predicts occurrence of pathogenic Vibrio bacteria in Chesapeake Bay in 2022. National Centers for Coastal Ocean Science. Published 2022. Accessed December 1, 2023. https://coastalscience.noaa.gov/news/noaa-forecast-predicts-occurrence-of-pathogenic-vibrio-bacteria-in-chesapeake-bay-in-2022/

40. Centers for Disease Control and Prevention. Summary of human Vibrio isolates reported to CDC, 2005. Published 2005. Accessed December 1, 2023. https://www.cdc.gov/nationalsurveillance/pdfs/vibrio2005.pdf

41. Villicaña C, Amarillas L, Soto-Castro L, Gómez-Gil B, Lizárraga-Partida ML, León-Félix J. Occurrence and abundance of pathogenic Vibrio species in raw oysters at retail seafood markets in northwestern Mexico. *J Food Prot*. 2019;82(12):2094-2099. doi:10.4315/0362-028x.jfp-19-237

42. Raszl SM, Froelich BA, Vieira CRW, Blackwood AD, Noble RT. *Vibrio parahaemolyticus*and*Vibrio vulnificus*in South America: water, seafood and human infections. *J Appl Microbiol*. 2016;121(5):1201-1222. doi:10.1111/jam.13246

43. Wilson JW, Primack RB. *Conservation Biology in Sub-Saharan Africa*. Open Book Publishers; 2019. doi:10.11647/obp.0177

44. Nullis C. State of climate in Africa highlights water stress and hazards. World Meteorological Organization. Published 2022. Accessed December 1, 2023. https://wmo.int/news/media-centre/state-of-climate-africa-highlights-water-stress-and-hazards

45. Osunla AC, Abioye OE, Okoh AI. Distribution and public health significance of Vibrio pathogens recovered from selected treated effluents in the Eastern Cape Province, South Africa. *Water*. 2021;13(7):932. doi:10.3390/w13070932

46. Naylor RL, Hardy RW, Buschmann AH, et al. A 20-year retrospective review of global aquaculture. Nature. Published 2021. Accessed March 26, 2024. https://www.nature.com/articles/s41586-021-03308-6

47. Australian Government Department of Agriculture, Fisheries, and Forestry. Australian fisheries and aquaculture Outlook 2023. Accessed March 26, 2024. https://www.agriculture.gov.au/abares/research-topics/fisheries/fisheries-economics/fisheries-forecasts#references

48. Elmahdi S, DaSilva LV, Parveen S. Antibiotic resistance of Vibrio parahaemolyticus and Vibrio vulnificus in various countries: a review. *Food Microbiol*. 2016;57:128-134. doi:10.1016/j.fm.2016.02.008

49. Xu K, Wang Y, Yang W, Cai H, Zhang Y, Huang L. Strategies for prevention and control of vibriosis in Asian fish culture. *Vaccines (Basel)*. Published online 2022. Accessed March 26, 2024. https://pubmed.ncbi.nlm.nih.gov/36679943/

50. Baker-Austin C, Stockley L, Rangdale R, Martinez-Urtaza J. Environmental occurrence and clinical impact of Vibrio vulnificus and Vibrio parahaemolyticus: a European perspective. *Environ Microbiol Rep*. Published online 2010. Accessed March 26, 2024. https://pubmed.ncbi.nlm.nih.gov/23765993/

51. Food and Agriculture Organization of the United Nations. The state of world fisheries and aquaculture 2022: fisheries and aquaculture projections. Published 2022. Accessed April 18, 2024. https://www.fao.org/3/cc0461en/online/sofia/2022/fisheries-and-aquaculture-projections.html

52. Henderson B. European Risk of Foodborne Illness from Vibrio Rising Due to Climate Change. Food Safety Magazine. Accessed April 18, 2024. https://www.food-safety.com/articles/8131-european-risk-of-foodborne-illness-from-vibrio-rising-due-to-climate-change

53. World Health Organization. Health topics: water, sanitation, and hygiene (WASH). Published 2023. Accessed March 26, 2024. https://www.who.int/health-topics/water-sanitation-and-hygiene-wash#tab=tab_1

54. Chirisa I, Nyamadzawo L, Bandauko E, Mutsindikwa N. The 2008/2009 cholera outbreak in Harare, Zimbabwe: case of failure in urban environmental health and planning. *Reviews on Environmental Health*. 2015;30(2). doi:10.1515/reveh-2014-0075

55. Rukawo H, Mukaro JP. Elimination of Vibrio cholerae from raw sewage using Chlorella vulgaris: a case of Chegutu waste reticulation, Zimbabwe. *European Journal of Environment and Public Health*. Published online 2022. Accessed April 18, 2024. https://www.ejeph.com/download/elimination-of-vibrio-cholerae-from-raw-sewage-using-chlorella-vulgaris-a-case-of-chegutu-waste-11724.pdf

56. Mitchell C. What is bioremediation, and how does it work (with examples)? Investopedia. Published 2022. Accessed March 26, 2024. https://www.investopedia.com/terms/b/bioremediation.asp

57. Environmental Resilience Institute. Adaptation Strategies for Flooding. Indiana University. Published 2024. Accessed March 26, 2024. https://eri.iu.edu/erit/strategies/flooding.html