6 CLIMATE IMPACTS ON WATER-RELATED ILLNESS

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Key Findings

Seasonal and Geographic Changes in Waterborne Illness Risk

Key Finding 1: Increases in water temperatures associated with climate change will alter the seasonal windows of growth and the geographic range of suitable habitat for freshwater toxin-producing harmful algae *[Very Likely, High Confidence]*, certain naturally occurring *Vibrio* bacteria *[Very Likely, Medium Confidence]*, and marine toxin-producing harmful algae *[Likely, Medium Confidence]*. These changes will increase the risk of exposure to waterborne pathogens and algal toxins that can cause a variety of illnesses *[Medium Confidence]*.

Runoff from Extreme Precipitation Increases Exposure Risk

Key Finding 2: Runoff from more frequent and intense extreme precipitation events will increasingly compromise recreational waters, shellfish harvesting waters, and sources of drinking water through increased introduction of pathogens and prevalence of toxic algal blooms *[High Confidence]*. As a result, the risk of human exposure to agents of water-related illness will increase *[Medium Confidence]*.

Water Infrastructure Failure

Key Finding 3: Increases in some extreme weather events and storm surges will increase the risk that infrastructure for drinking water, wastewater, and stormwater will fail due to either damage or exceedance of system capacity, especially in areas with aging infrastructure *[High Confidence]*. As a result, the risk of exposure to water-related pathogens, chemicals, and algal toxins will increase in recreational and shellfish harvesting waters and in drinking water where treatment barriers break down *[Medium Confidence]*.

6.1 Introduction

Across most of the United States, climate change is expected to affect fresh and marine water resources in ways that will increase people's exposure to water-related contaminants that cause illness. Water-related illnesses include waterborne diseases caused by pathogens, such as bacteria, viruses, and protozoa. Water-related illnesses are also caused by toxins produced by certain harmful algae and cyanobacteria (also known as blue-green algae) and by chemicals introduced into the environment by human activities. Exposure occurs through ingestion, inhalation, or direct contact with contaminated drinking or recreational water and through consumption of fish and shellfish.

Factors related to climate change—including temperature, precipitation and related runoff, hurricanes, and storm surge—affect the growth, survival, spread, and virulence or toxicity of agents (causes) of water-related illness. Heavy downpours are already on the rise and increases in the frequency and intensity of extreme precipitation events are projected for all U.S. regions.[1] Projections of temperature, precipitation, extreme events such as flooding and drought, and other climate factors vary by region of the United States, and thus the extent of climate health impacts will also vary by region.

Climate Change and Health—*Vibrio*

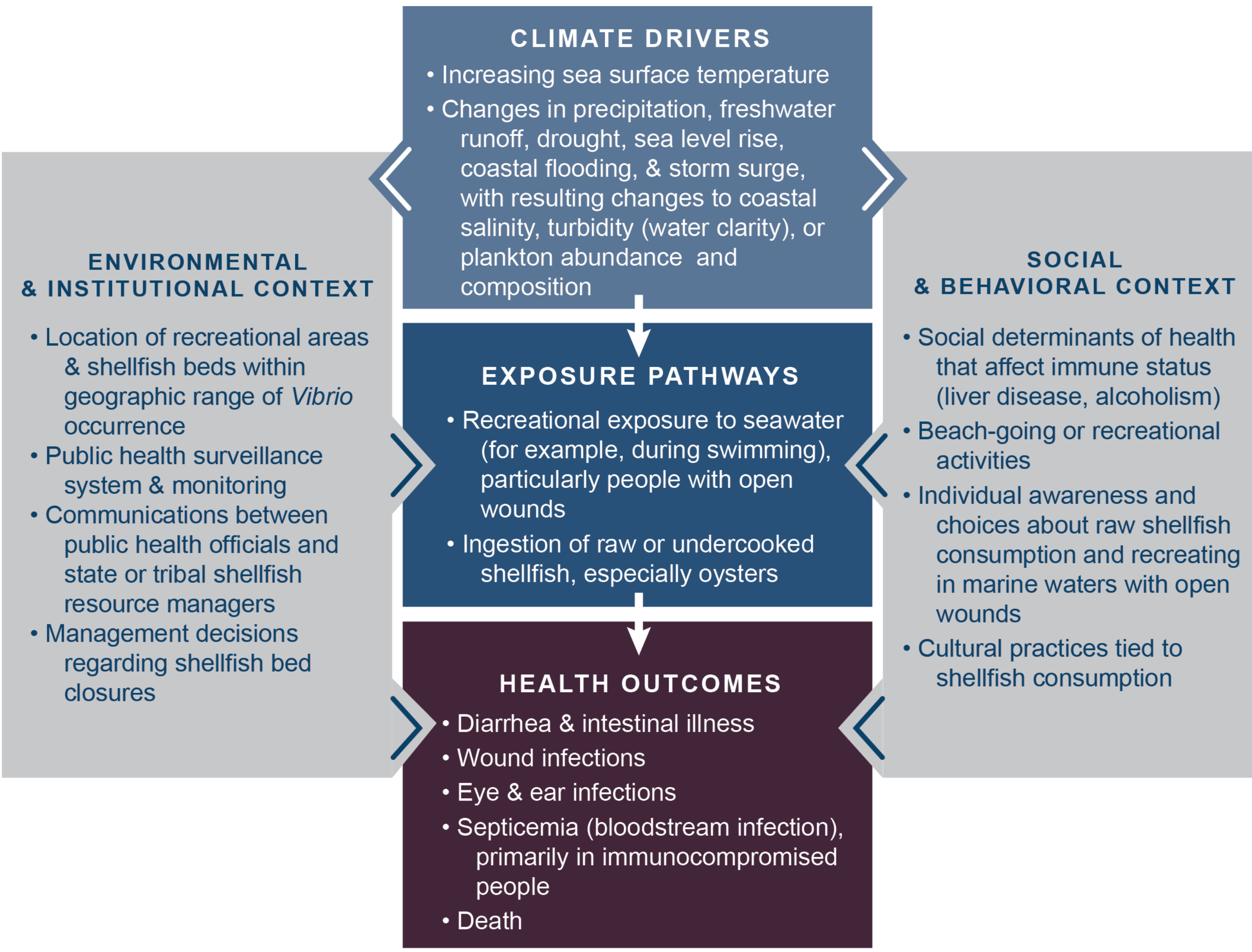

Figure 1: This conceptual diagram for an example of infection by *Vibrio* species (*V. vulnificus, V. parahaemolyticus,* or *V. alginolyticus*) illustrates the key pathways by which humans are exposed to health threats from climate drivers. These climate drivers create more favorable growing conditions for these naturally occurring pathogens in coastal environments through their effects on coastal salinity, turbidity (water clarity), or plankton abundance and composition. Longer seasons for growth and expanding geographic range of occurrence increase the risk of exposure to *Vibrio*, which can result in various potential health outcomes (center boxes). These exposure pathways exist within the context of other factors that positively or negatively influence health outcomes (gray side boxes). Key factors that influence vulnerability for individuals are shown in the right box and include social determinants of health and behavioral choices. Key factors that influence vulnerability at larger scales, such as natural and built environments, governance and management, and institutions, are shown in the left box. All of these influencing factors can affect an individual's or a community's vulnerability through changes in exposure, sensitivity, and adaptive capacity and may also be affected by climate change. See Ch. 1: Introduction for more information.

Waterborne pathogens are estimated to cause 8.5% to 12% of acute gastrointestinal illness cases in the United States, affecting between 12 million and 19 million people annually.[2, 3, 4] Eight pathogens, which are all affected to some degree by climate, account for approximately 97% of all suspected waterborne illnesses in the United States: the enteric viruses norovirus, rotavirus, and adenovirus; the bacteria *Campylobacter jejuni*, *E. coli* O157:H7, and *Salmonella enterica*; and the protozoa *Cryptosporidium* and *Giardia*.[5]

Specific health outcomes are determined by different exposure pathways and multiple other social and behavioral factors, some of which are also affected by climate (Figure 1). Most research to date has focused on understanding how climate drivers affect physical and ecological processes that act as key exposure pathways for pathogens and toxins, as shown by the arrow moving from the top to the middle box in Figure 1. There is currently less information and fewer methods with which to measure actual human exposure and incidence of illness based on those physical and ecological metrics (arrow moving from middle to bottom box in Figure 1). Thus, it is often not possible to quantitatively project future health outcomes from water-related illnesses under climate change (bottom box in Figure 1).

This chapter covers health risks associated with changes in natural marine, coastal, and freshwater systems and water infrastructure for drinking water, wastewater, and stormwater (*Legionella* in aerosolized water is covered in Ch. 3: Air Quality Impacts). This chapter also includes fish and shellfish illnesses associated with the waters in which they grow and which are affected by the same climate factors that affect drinking and recreational waters (impacts related to handling and post-harvest processing of seafood are covered in Ch. 7: Food Safety). The framing of this chapter addresses sources of contaminations, exposure pathways, and health outcomes when available. Based on the available data and research, many of the examples are regionally focused and make evident that the impact of climate change on water-related illness is inherently regional. Table 1 lists various health outcomes that can result from exposure to agents of water-related illness as well as key climate-related changes affecting their occurrence.

Whether or not illness results from exposure to contaminated water, fish, or shellfish is dependent on a complex set of factors, including human behavior and social determinants of health that may affect a person's exposure, sensitivity, and adaptive capacity (Figure 1; see also Ch. 1: Introduction and

Table 1. Climate Sensitive Agents of Water Related Illness

Pathogen or Toxin Producer	Exposure Pathway	Selected Health Outcomes & Symptoms	Major Climate Correlation or Driver (strongest driver(s) listed first)
Algae: Toxigenic marine species of *Alexandrium, Pseudo-nitzschia, Dinophysis, Gambierdiscus; Karenia brevis*	**Shellfish Fish Recreational waters (aerosolized toxins)**	Gastrointestinal and neurologic illness caused by shellfish poisoning (paralytic, amnesic, diarrhetic, neurotoxic) or fish poisoning (ciguatera). Asthma exacerbations, eye irritations caused by contact with aerosolized toxins (*K. brevis*).	Temperature (increased water temperature), ocean surface currents, ocean acidification, hurricanes (*Gambierdiscus* spp. and *K. brevis*)
Cyanobacteria (multiple freshwater species producing toxins including microcystin)	**Drinking water Recreational waters**	Liver and kidney damage, gastroenteritis (diarrhea and vomiting), neurological disorders, and respiratory arrest.	Temperature, precipitation patterns
Enteric bacteria & protozoan parasites: *Salmonella enterica; Campylobacter* species; Toxigenic *Escherichia coli; Cryptosporidium; Giardia*	**Drinking water Recreational waters Shellfish**	Enteric pathogens generally cause gastroenteritis. Some cases may be severe and may be associated with long-term and recurring effects.	Temperature (air and water; both increase and decrease), heavy precipitation, and flooding
Enteric viruses: enteroviruses; rotaviruses; noroviruses; hepatitis A and E	**Drinking water Recreational waters Shellfish**	Most cases result in gastrointestinal illness. Severe outcomes may include paralysis and infection of the heart or other organs.	Heavy precipitation, flooding, and temperature (air and water; both increase and decrease)
Leptospira and *Leptonema* bacteria	**Recreational waters**	Mild to severe flu-like illness (with or without fever) to severe cases of meningitis, kidney, and liver failure.	Flooding, temperature (increased water temperature), heavy precipitation
Vibrio bacteria species	**Recreational waters Shellfish**	Varies by species but include gastroenteritis (*V. parahaemolyticus*, *V. cholerae*), septicemia (bloodstream infection) through ingestion or wounds (*V. vulnificus*), skin, eye, and ear infections (*V. alginolyticus*).	Temperature (increased water temperature), sea level rise, precipitation patterns (as it affects coastal salinity)

Ch. 9: Populations of Concern). Water resource, public health, and environmental agencies in the United States provide many public health safeguards to reduce risk of exposure and illness even if water becomes contaminated. These include water quality monitoring, drinking water treatment standards and practices, beach closures, and issuing advisories for boiling drinking water and harvesting shellfish.

Many water-related illnesses are either undiagnosed or unreported, and therefore the total incidence of waterborne disease is underestimated (see Ch. 1: Introduction for discussion of public health surveillance data limitations related to “reportable” and “nationally notifiable” diseases).[6, 7] On average, illnesses from pathogens associated with water are thought to be underestimated by as much as 43-fold, and may be underestimated by up to 143 times for certain *Vibrio* species.[7]

6.2 Sources of Water-Related Contaminants

The primary sources of water contamination are human and animal waste and agricultural activities, including the use of fertilizers. Runoff and flooding resulting from expected increases in extreme precipitation, hurricane rainfall, and storm surge (see Ch. 4: Extreme Events) may increase risks of contamination. Contamination occurs when agents of water-related illness and nutrients, such as nitrogen and phosphorus, are carried from urban, residential, and agricultural areas into surface waters, groundwater, and coastal waters (Figure 2). The nutrient loading can promote growth of naturally occurring pathogens and algae. Human exposure occurs via contamination of drinking water sources (page 163), recreational waters (page 164), and fish and shellfish (page 165).

Water contamination by human waste is tied to failure of local urban or rural water infrastructure, including municipal wastewater, septic, and stormwater conveyance systems. Failure can occur either when rainfall and subsequent runoff overwhelm the capacity of these systems—causing, for example, sewer overflows, basement backups, or localized flooding—or when extreme events like flooding and storm surges damage water conveyance or treatment infrastructure and result in reduction or loss of performance and functionality. Many older cities in the Northeast and around the Great Lakes region of the United States have combined sewer systems (with stormwater and sewage sharing the same pipes), which are prone to discharging raw sewage directly into surface waters after moderate to heavy rainfall.[8] The amount of rain that causes combined sewer overflows is highly variable between cities because of differences in infrastructure capacity and design, and ranges from 5 mm (about 0.2 inches) to 2.5 cm (about 1 inch).[9, 10] Overall, combined sewer overflows are expected to increase,[11] but site-specific analysis is needed to predict the extent of these increases (see Case Study on page 164). Extreme precipitation events will exacerbate existing problems with inadequate, aging, or deteriorating wastewater infrastructure throughout the country.[12, 13] These problems include broken or leaking sewer pipes and failing septic systems that leach sewage into the ground. Runoff or contaminated groundwater discharge also carries pathogens and nutrients into surface water, including freshwater and marine coastal areas and beaches.[14, 15, 16, 17, 18, 19, 20, 21]

Water contamination from agricultural activities is related to the release of microbial pathogens or nutrients in livestock manure and inorganic fertilizers that can stimulate rapid and excessive growth or blooms of harmful algae. Agricultural land covers about 900 million acres across the United States,[22] comprising over 2 million farms, with livestock sectors concentrated in certain regions of the United States (Figure 3). Depending on the type and number of animals, a large livestock operation can produce between 2,800 and 1,600,000 tons of manure each year.[23, 24] With the projected increases in heavy precipitation for all U.S. regions,[1] agricultural sources of contamination can affect water quality across

Links between Climate Change, Water Quantity and Quality, and Human Exposure to Water-Related Illness.

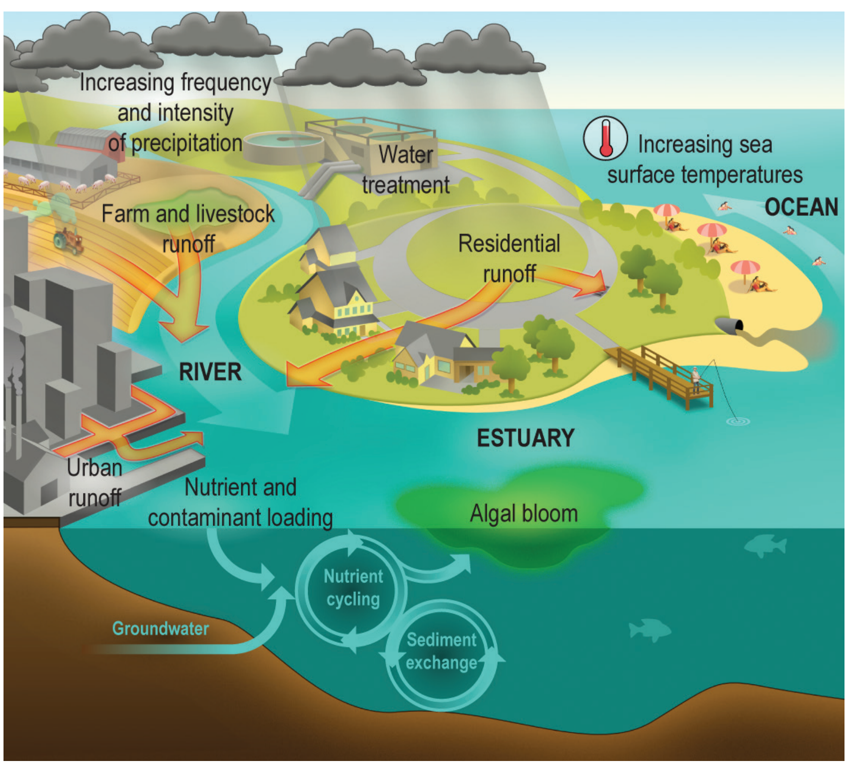

Figure 2: Precipitation and temperature changes affect fresh and marine water quantity and quality primarily through urban, rural, and agricultural runoff. This runoff in turn affects human exposure to water-related illnesses primarily through contamination of drinking water, recreational water, and fish and shellfish.

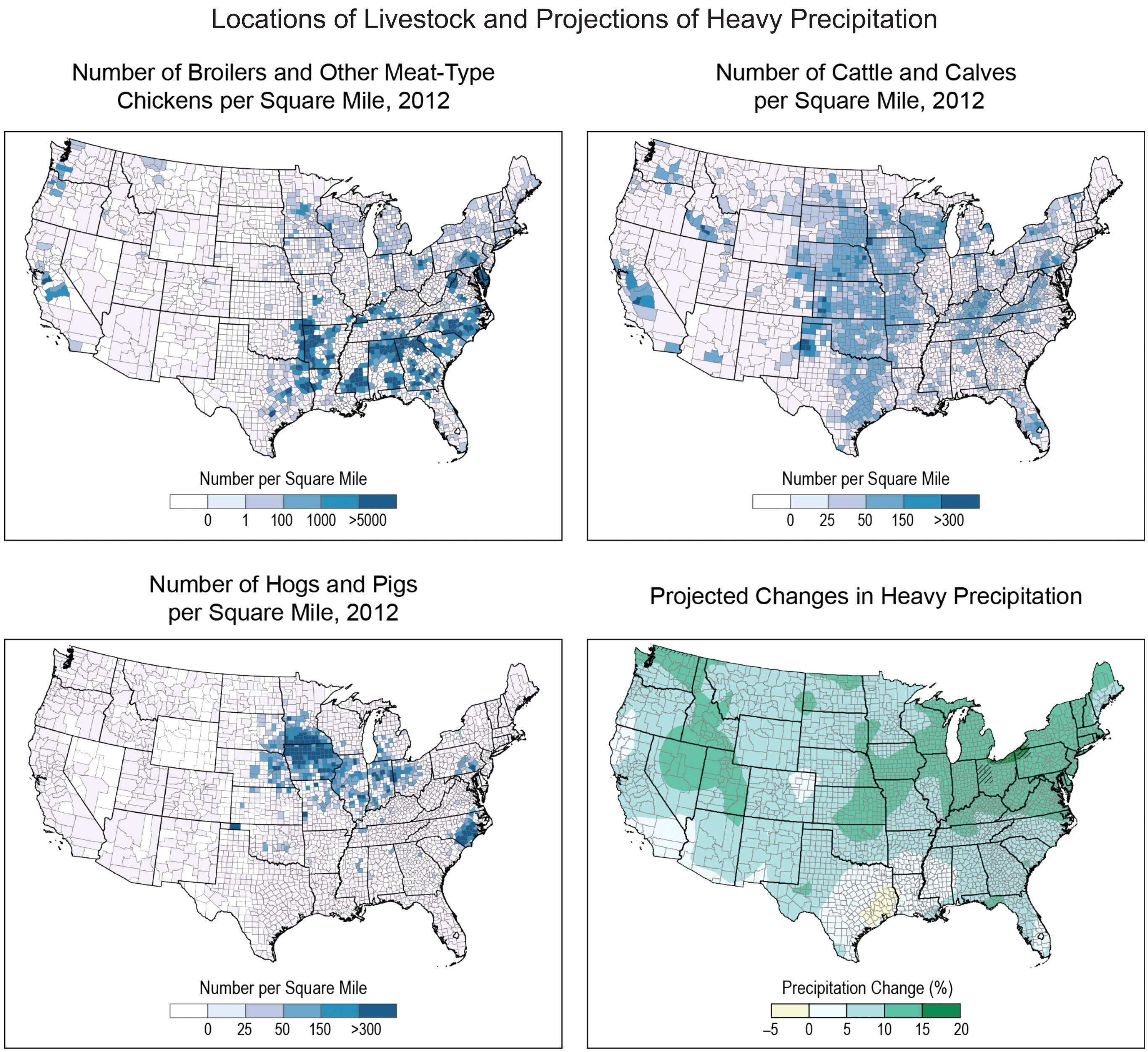

Figure 3: This figure compares the geographic distribution of chicken, cattle, and hog and pig densities to the projected change in annual maximum 5-day precipitation totals (2046–2065 compared to 1981–2000, multi-model average using RCP8.5) across the continental United States. Increasing frequency and intensity of precipitation and subsequent increases in runoff are key climate factors that increase the potential for pathogens associated with livestock waste to contaminate water bodies. (Figure sources: adapted from USDA 2014 and Sun et al. 2015).[26, 27]

the Nation. Runoff from lands where manure has been used as fertilizer or where flooding has caused wastewater lagoons to overflow can carry contamination agents directly from the land into water bodies.[23, 24, 25]

Management practices and technologies, such as better timing of manure application and improved animal feeds, help reduce or eliminate the risks of manure-borne contaminant transport to public water supplies and shellfish harvesting waters and reduce nutrients that stimulate harmful algal blooms.[23, 25, 28, 29] Drinking water treatment and monitoring practices also help to decrease or eliminate exposure to waterborne illness agents originating from agricultural environments.

Water contamination from wildlife (for example, rodents, birds, deer, and wild pigs) occurs via feces and urine of infected animals, which are reservoirs of enteric and other pathogens.[29, 30, 31] Warmer winters and earlier springs are expected to increase animal activity and alter the ecology and habitat of animals that may carry pathogens.[1] This may lengthen the exposure period for humans and expand the geographic ranges in which pathogens are transmitted.[1, 32]

6.3 Exposure Pathways and Health Risks

Humans are exposed to agents of water-related illness through several pathways, including drinking water (treated and untreated), recreational waters (freshwater, coastal, and marine), and fish and shellfish.

Drinking Water

Although the United States has one of the safest municipal drinking water supplies in the world, water-related outbreaks (more than one illness case linked to the same source) still occur.[33] Public drinking water systems provide treated water to approximately 90% of Americans at their places of residence, work, or schools.[34] However, about 15% of the population relies fully or in part on untreated private wells or other private sources for their drinking water.[35] These private sources are not regulated under the Safe Drinking Water Act.[36] The majority of drinking water outbreaks in the United States are associated with untreated or inadequately treated groundwater and distribution system deficiencies.[33, 37]

Pathogen and Algal Toxin Contamination

Between 1948 and 1994, 68% of waterborne disease outbreaks in the United States were preceded by extreme precipitation events,[38] and heavy rainfall and flooding continue to be cited as contributing factors in more recent outbreaks in multiple regions of the United States.[39] Extreme precipitation events have been statistically linked to increased levels of pathogens in treated drinking water supplies[40] and to an increased incidence of gastrointestinal illness in children.[21, 41] This established relationship suggests that extreme precipitation is a key climate factor for waterborne disease.[42, 43, 44, 45] The Milwaukee *Cryptosporidium* outbreak in 1993—the largest documented waterborne disease outbreak in U.S. history, causing an estimated 403,000 illnesses and more than 50 deaths[46]—was preceded by the heaviest rainfall event in 50 years in the adjacent watersheds.[10] Various treatment plant operational problems were also key contributing factors.[47] (See future projections in the Case Study on page 164). Observations in England and Wales also show waterborne disease outbreaks were preceded by weeks of low cumulative rainfall and then heavy precipitation events, suggesting that drought or periods of low rainfall may also be important climate-related factors.[48]

Small community or private groundwater wells or other drinking water systems where water is untreated or minimally treated are especially susceptible to contamination following extreme precipitation events.[49] For example, in May 2000, following heavy rains, livestock waste containing *E. coli* O157:H7 and *Campylobacter* was carried in runoff to a well that served as the primary drinking water source for the town of Walkerton, Ontario, Canada, resulting in 2,300 illnesses and 7 deaths.[43, 44, 50] High rainfall amounts were an important catalyst for the outbreak, although non-climate factors, such as well infrastructure, operational and maintenance problems, and lack of communication between public utilities staff and local health officials were also key factors.[44, 51]

Likewise, extreme precipitation events and subsequent increases in runoff are key climate factors that increase nutrient loading in drinking water sources, which in turn increases the likelihood of harmful cyanobacterial blooms that produce algal toxins.[52] The U.S. Environmental Protection Agency has established health advisories for two algal toxins (microcystins and cylindrospermopsin) in drinking water.[53] Lakes and reservoirs that serve as sources of drinking water for between 30 million and 48 million Americans may be periodically contaminated by algal toxins.[54] Certain drinking water treatment processes can remove cyanobacterial toxins; however, efficacy of the treatment processes may vary from 60% to 99.9%. Ineffective treatment could compromise water quality and may lead to severe treatment disruption or treatment plant shutdown.[53, 54, 55, 56] Such an event occurred in Toledo, Ohio, in August 2014, when nearly 500,000 residents of the state's fourth-largest city lost access to their drinking water after tests revealed the presence of toxins from a cyanobacterial bloom in Lake Erie near the water plant's intake.[57]

Extreme precipitation events have been statistically linked to increased levels of pathogens in treated drinking water supplies.

Water Supply

Climate-related hydrologic changes such as those related to flooding, drought, runoff, snowpack and snowmelt, and saltwater intrusion (the movement of ocean water into fresh groundwater) have implications for freshwater management and supply (see also Ch. 4: Extreme Events).[58] Adequate freshwater supply is essential to many aspects of public health, including provision of drinking water and proper sanitation and personal hygiene. For example, following floods or storms, short-term loss of access to potable water has been linked to increased incidence of illnesses including gastroenteritis and respiratory tract and skin infections.[59] Changes in precipitation and runoff, combined with changes in consumption and withdrawal, have reduced surface and groundwater supplies in many areas, primarily in the western United States.[58] These trends are expected to continue under future climate change, increasing the likelihood of water shortages for many uses.[58]

Future climate-related water shortages may result in more municipalities and individuals relying on alternative sources for drinking water, including reclaimed water and roof-harvested rainwater.[60, 61, 62, 63] Water reclamation refers to the treatment of stormwater, industrial wastewater, and municipal wastewater for beneficial reuse.[64] States like California, Arizona, New Mexico, Texas, and Florida are already implementing wastewater reclamation and reuse practices as a means of conserving and adding to freshwater supplies.[65] However, no federal regulations or criteria for public health protection have been developed or proposed specifically for potable water reuse in the United States.[66] Increasing household rainwater collection has also been seen in some areas of the country (primarily Arizona, Colorado, and Texas), although in some cases, exposure to untreated rainwater has been found to pose health risks from bacterial or protozoan pathogens, such as *Salmonella enterica* and *Giardia lamblia*.[67, 68, 69]

Projected Changes

Runoff from more frequent and intense extreme precipitation events will contribute to contamination of drinking water sources with pathogens and algal toxins and place additional stresses on the capacity of drinking water treatment facilities and distribution systems.[10, 52, 59, 70, 71, 72, 73] Contamination of drinking water sources may be exacerbated or insufficiently addressed by treatment processes at the treatment plant or by breaches in the distribution system, such as during water main breaks or low-pressure events.[13] Untreated groundwater drawn from municipal and private wells is of particular concern.

Climate change is not expected to substantially increase the risk of contracting illness from drinking water for those people who are served by treated drinking water systems, if appropriate treatment and distribution is maintained. However, projections of more frequent or severe extreme precipitation events, flooding, and storm surge suggest that drinking water infrastructure may be at greater risk of disruption or failure due to damage or exceedance of system capacity.[6, 58, 70, 74, 75] Aging drinking water infrastructure is one longstanding limitation in controlling waterborne disease, and may be especially susceptible to failure.[6, 13, 74] For example, there are more than 50,000 systems providing treated drinking water to communities in the United States, and most water distribution pipes in these systems are already failing or will reach their expected lifespan and require replacement within 30 years.[6] Breakdowns in drinking water treatment and distribution systems, compounded by aging infrastructure, could lead to more serious and frequent health consequences than those we experience now.

Case Study: Modeling Future Extreme Precipitation and Combined Sewer Overflows in Great Lakes Urban Coastal Areas

The Great Lakes contain 20% of the Earth's surface freshwater and provide drinking water to 40 million people. Milwaukee, WI, is typical of urban areas in the Great Lakes in that it has a combined sewer system that overflows during moderate or heavy rainfall. In 1994, unrelated to but shortly after the 1993 *Cryptosporidium* outbreak, the city completed a project to increase sewer capacity; reducing combined sewage overflows from 50 to 60 per year, to 2 to 3 per year.[10]

In order to assess how changing rainfall patterns might affect sewer capacity in the future, Milwaukee was one of the first cities to integrate regional climate projections into its detailed engineering models. Under a future climate scenario (for 2050) that had one of the largest projected increases in spring rain, a 37% increase in the number of combined sewage overflows in spring was projected, resulting in an overall 20% increase from the baseline in the volume of discharge each year.[76]

Recreational Waters

Humans are exposed to agents of water-related illness through recreation (such as swimming, fishing, and boating) in freshwater and marine or coastal waters. Exposure may occur directly (ingestion and contact with water) or incidentally (inhalation of aerosolized water droplets).

Pathogen and Algal Toxin Contamination

Enteric viruses, especially noroviruses, from human waste are a primary cause of gastrointestinal illness from exposure to contaminated recreational fresh and marine water (Table 1).[77] Although there are comparatively few reported illnesses and outbreaks of gastrointestinal illness from recreating in marine waters compared to freshwater, marine contamination still presents a significant health risk.[39, 78, 79, 80, 81] Illnesses from marine sources are less likely to be reported than those from freshwater beaches in part because the geographical residences of beachgoers are more widely distributed (for example, tourists may travel to marine beaches for vacation) and illnesses are less often attributed to marine exposure as a common source.[39, 77]

Key climate factors associated with risks of exposure to enteric pathogens in both freshwater and marine recreational waters include extreme precipitation events, flooding, and temperature. For example, *Salmonella* and *Campylobacter* concentrations in freshwater streams in the southeastern United States increase significantly in the summer months and following heavy rainfall.[82, 83, 84] In the Great Lakes—a freshwater system—changes in rainfall, higher lake temperatures, and low lake levels have been linked to increases in fecal bacteria levels.[10] The zoonotic bacteria *Leptospira* are introduced into water from the urine of animals,[85, 86] and increased illness rates in humans are linked to warm temperatures and flooding events.[87, 88, 89, 90, 91]

In marine waters, recreational exposure to naturally occurring bacterial pathogens (such as *Vibrio* species) may result in eye, ear, and wound infections, diarrheal illness, or death (Table 1).[92, 93, 94] Reported rates of illness for all *Vibrio* infections have tripled since 1996, with *V. alginolyticus* infections having increased by 40-fold.[92] *Vibrio* growth rates are highly responsive to rising sea surface temperatures, particularly in coastal waters, which generally have high levels of the dissolved organic carbon required for *Vibrio* growth. The distribution of species changes with salinity patterns related to sea level rise and to changes in delivery of freshwater to coastal waters, which is affected by flooding and drought. For instance, *V. parahaeomolyticus* and *V. alginolyticus* favor higher salinities while *V. vulnificus* favors more moderate salinities.[95, 96, 97, 98, 99, 100]

Harmful algal blooms caused by cyanobacteria were responsible for nearly half of all reported outbreaks in untreated recreational freshwater in 2009 and 2010, resulting in approximately 61 illnesses (health effects included dermatologic, gastrointestinal, respiratory, and neurologic symptoms), primarily reported in children/young adults age 1–19.[101] Cyanobacterial blooms are strongly influenced by rising temperatures, altered precipitation patterns, and changes in freshwater discharge or flushing rates of water bodies (Table 1).[102, 103, 104, 105, 106, 107, 108] Higher temperatures (77°F and greater) favor surface-bloom-forming cyanobacteria over less harmful types of algae.[109] In marine water, the toxins associated with harmful "red tide" blooms of *Karenia brevis* can aerosolize in water droplets through wind and wave action and cause acute respiratory illness and eye irritation in recreational beachgoers.[110, 111] People with preexisting respiratory diseases, specifically asthma, are at increased risk of illness.[112, 113] Prevailing winds and storms are important climate factors influencing the accumulation of *K. brevis* cells in the water.[78, 114] For example, in 1996, Tropical Storm Josephine transported a Florida panhandle bloom as far west as Louisiana,[115] the first documented occurrence of *K. brevis* in that state.

Projected Changes

Overall, climate change will contribute to contamination of recreational waters and increased exposure to agents of water-related illness.[10, 82, 116, 117, 118, 119, 120] Increases in flooding, coastal inundation, and nuisance flooding (linked to sea level rise and storm surge from changing patterns of coastal storms and hurricanes) will negatively affect coastal infrastructure and increase chances for pathogen contamination, especially in populated areas (see also Ch. 4: Extreme Events).[70, 121] In areas where increasing temperatures lengthen the seasons for recreational swimming and other water activities, exposure risks are expected to increase.[122, 123]

In areas where increasing temperatures lengthen recreational swimming seasons, exposure risks are expected to increase.

As average temperatures rise, the seasonal and geographic range of suitable habitat for cyanobacterial species is projected to expand.[124, 125, 126, 127, 128] For example, tropical and subtropical species like *Cylindrospermopsis raciborskii*, *Anabaena* spp., and *Aphanizomenon* spp. have already shown poleward expansion into mid-latitudes of Europe, North America, and South America.[107, 129, 130] Increasing variability in precipitation patterns and more frequent and intense extreme precipitation events (which will increase nutrient loading) will also affect cyanobacterial communities. If such events are followed by extended drought periods, the stagnant, low-flow conditions accompanying droughts will favor cyanobacterial dominance and bloom formation.[103, 131]

In recreational waters, projected increases in sea surface temperatures are expected to lengthen the seasonal window of growth and expand geographic range of *Vibrio* species,[96, 132] although the certainty of regional projections is affected by underlying model structure.[133] While the specific response of *Vibrio* and degree of growth may vary by species and locale, in general, longer seasons and expansion of *Vibrio* into areas where it had not previously been will increase the likelihood of exposure to *Vibrio* in recreational waters. Regional climate changes that affect coastal salinity (such as flooding, drought, and sea level rise) can also affect the population dynamics of these agents,[97, 99, 134] with implications for human exposure risk. Increases in hurricane intensity and rainfall are projected as the climate continues to warm (see Ch 4: Extreme Events). Such increases may redistribute toxic blooms of *K. brevis* ("red tide" blooms) into new geographic locations, which would change human exposure risk in newly affected areas.

Fish and Shellfish

Water-related contaminants as well as naturally occurring harmful bacteria and algae can be accumulated by fish or shellfish, providing a route of human exposure through consumption (see also Ch. 7: Food Safety).[135, 136, 137] Shellfish, including oysters, are often consumed raw or very lightly cooked, which increases the potential for ingestion of an infectious pathogen.[138]

Pathogens Associated with Fish and Shellfish

Enteric viruses (for example, noroviruses and hepatitis A virus) found in sewage are the primary causes of gastrointestinal illness due to shellfish consumption.[139, 140] Rainfall increases the load of contaminants associated with sewage delivered to shellfish harvesting waters and may also temporarily reduce salinity, which can increase persistence of many enteric bacteria and viruses.[141, 142, 143, 144] Many enteric viruses also exhibit seasonal patterns in infection rates and detection rates in the environment, which may be related to temperature.[145, 146, 147]

Among naturally occurring water-related pathogens, *Vibrio vulnificus* and *V. parahaemolyticus* are the species most often implicated in foodborne illness in the United States, accounting for more than 50% of reported shellfish-related illnesses annually.[140, 148, 149, 150, 151] Cases have increased significantly since 1996.[92, 148] Rising sea surface temperatures have contributed to an expanded geographic and seasonal range in outbreaks associated with shellfish.[96, 152, 153, 154, 155]

Precipitation is expected to be the primary climate driver affecting enteric pathogen loading to shellfish harvesting areas, although temperature also affects bioaccumulation rates of enteric viruses in shellfish. There are currently no national projections for the associated risk of illness from shellfish consumption. Many local and state agencies have developed plans for closing shellfish beds in the event of threshold-exceeding rain events that lead to loading of these contaminants and deterioration of water quality.[156]

Research Highlight: The Effect of Warming on Seasonal *Vibrio* Abundance and Distribution

Importance: *Vibrio* species are naturally occurring pathogens in coastal environments that cause illnesses ranging from gastroenteritis to septicemia (bloodstream infection) and death from both water contact and ingestion of raw or undercooked seafood, especially shellfish.[93] *Vibrio* are highly responsive to environmental conditions. For example, local nutrient availability can affect *Vibrio* abundance, though coastal waters generally have sufficient levels of the dissolved organic carbon required for *Vibrio* growth.[159]

Over longer timescales and larger geographic areas, key climate-related factors that increase *Vibrio* growth and abundance include rising sea surface temperatures and changes in precipitation, freshwater runoff, drought, sea level rise, coastal flooding, and storm surge, with resulting changes to coastal salinity patterns, turbidity (water clarity), and plankton abundance and composition (see Figure 1).[95, 96, 97, 98, 99, 100, 134, 160, 161, 162, 163]

Water temperature is a major contributor to *Vibrio* growth potential and, in turn, human exposure risk. The minimum water temperature threshold for the growth of most *Vibrio* species that cause illness in humans is 15°C (59°F), with growth rates increasing as temperature increases.[132, 152, 154, 157] Thus, it is projected that global ocean warming will increase risk of exposure by extending seasonal windows of growth and geographical range of occurrence.[132]

Projections of *Vibrio* Occurrence and Abundance in Chesapeake Bay

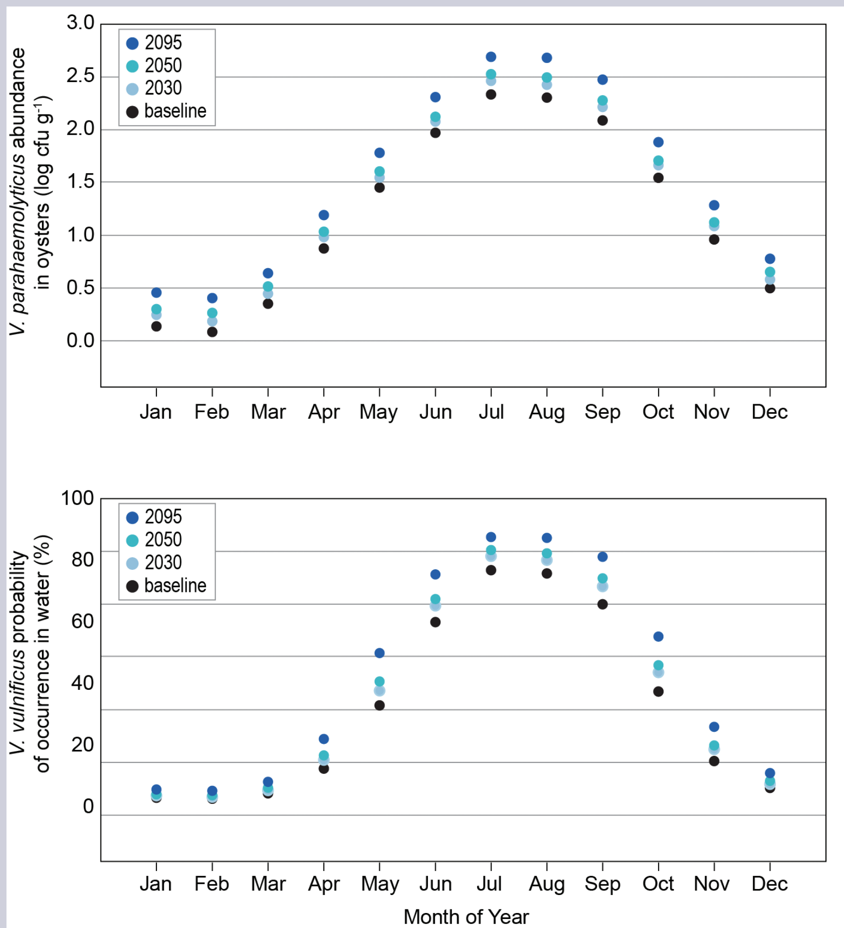

Figure 4: Seasonal and decadal projections of abundance *of V. parahaemolyticus* in oysters of Chesapeake Bay (top) and probability of occurrence of *V. vulnificus* in Chesapeake Bay surface waters (bottom). The circles show average values in the baseline period (1985–2000) and future years averaged by decadal period: 2030 (2025–2034), 2050 (2045–2054), and 2095 (2090–2099). (Figure source: adapted from Jacobs et al. 2015).[132]

Research Highlight: The Effect of Warming on Seasonal *Vibrio* Abundance and Distribution, continued

Objective: A quantitative projection of future shifts in *Vibrio* seasonal abundance and geographic range.

Method: Monthly average sea surface temperatures were projected for the 2030s, 2050s, and 2090s based on statistical downscaling of up to 21 global climate models for the Chesapeake Bay and Alaskan coastline. Previously published empirical models relating sea surface temperature and salinity to *Vibrio vulnificus* and *V. parahaemolyticus* were used to project probability of occurrence and abundance in Chesapeake Bay waters and oysters. Geographic information system (GIS) mapping of Alaskan coastal waters was used to project the distribution of monthly average water temperatures exceeding 15°C (59°F), considered to be the minimum temperature favorable for growth.[132]

Results and Conclusions: Modeling results find increases in abundance, geographical range, and seasonal extent of available habitat for *Vibrio*. In the Chesapeake Bay, the probability of occurrence of *V. vulnificus* is projected to increase by nearly 16% in the shoulder months of the growing season (May and September), with a similar increase in abundance of *V. parahaemolyticus* in oysters (Figure 4).

Analysis of temperature projections for Alaskan coastal waters based on an average of four climate models showed that habitat availability for *Vibrio* growth will increase to nearly 60% of the Alaskan shoreline in August by the 2090s (Figure 5).

Sources of uncertainty include different rates of warming associated with each model ensemble and other factors that affect growth and abundance, but all models used in this study project warming of coastal waters.

Changes in Suitable Coastal *Vibrio* Habitat in Alaska

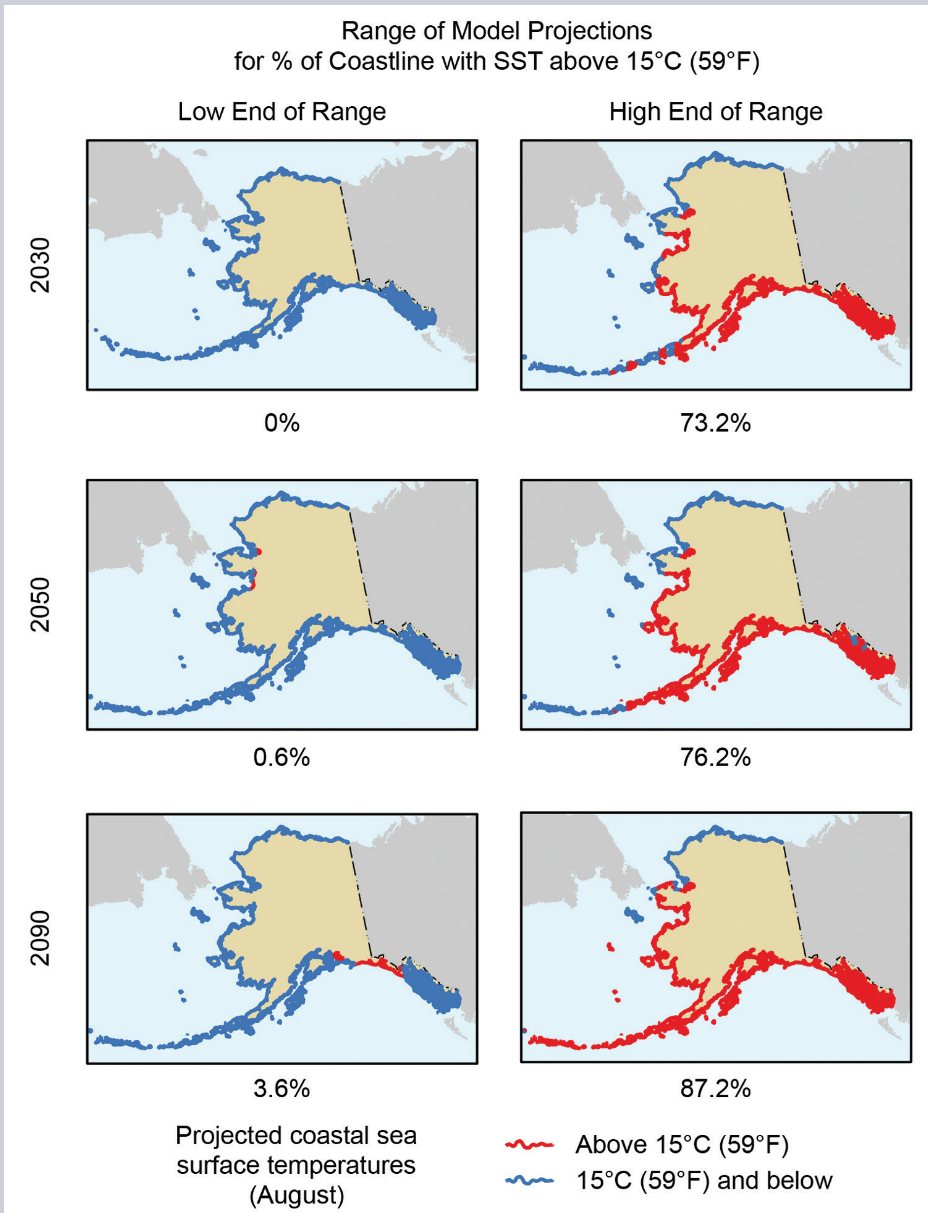

Figure 5: *Vibrio* growth increases in temperatures above 15°C (59°F). These maps show the low and high end of the ranges for projected area of Alaskan coastline with water temperature averages in August that are greater than this threshold. The projections were made for the following future time periods: 2030 (2026–2035), 2050 (2046–2055), and 2090 (2086–2095). On average, the models project that by 2090, nearly 60% of the Alaskan shoreline in August will become suitable *Vibrio* habitat. (Figure source: adapted from Jacobs et al. 2015)[132]

Increases in sea surface temperatures, changes in precipitation and freshwater delivery to coastal waters, and sea level rise will continue to affect *Vibrio* growth and are expected to increase human exposure risk.[96, 134, 152, 157] Regional models project increased abundance and extended seasonal windows of growth of *Vibrio* pathogens (see Research Highlight on page 166).[132] The magnitude of health impacts depends on the use of intervention strategies and on public and physician awareness.[158]

Harmful Algal Toxins

Harmful algal blooms (HABs) that contaminate seafood with toxins are becoming increasingly frequent and persistent in coastal marine waters, and some have expanded into new geographic locations.[164, 165, 166, 167, 168] Attribution of this trend has been complicated for some species, with evidence to suggest that human-induced changes (such as ballast water exchange, aquaculture, nutrient loading to coastal waters, and climate change) have contributed to this expansion.[167, 169]

Climate change, especially continued warming, will dramatically increase the burden of some marine HAB-related diseases in some parts of the United States

Among HABs associated with seafood, ciguatera fish poisoning (CFP) is most strongly influenced by climate.[170, 171, 172] CFP is caused by toxins produced by the benthic algae *Gambierdiscus* (Table 1) and is the most frequently reported fish poisoning in humans.[173] There is a well-established link between warm sea surface temperatures and increased occurrences of CFP,[170, 171, 172] and in some cases, increases have also been linked to El Niño–Southern Oscillation events.[174] The frequency of tropical cyclones in the United States has also been associated with CFP, but with an 18-month lag period associated with the time required for a new *Gambierdiscus* habitat to develop.[170, 171]

Paralytic shellfish poisoning (PSP) is the most globally widespread shellfish poisoning associated with algal toxins,[175] and records of PSP toxins in shellfish tissues (an indicator of toxin-producing species of *Alexandrium*) provide the longest time series in the United States for evaluating climate impacts. Warm phases of the naturally occurring climate pattern known as the Pacific Decadal Oscillation co-occur with increased PSP toxins in Puget Sound shellfish on decadal timescales.[176] Further, it is very likely that the 20th century warming trend also contributed to the observed increase in shellfish toxicity since the 1950s.[177, 178] Warm spring temperatures also contributed to a bloom of *Alexandrium* in a coastal New York estuary in 2008.[179] Decadal patterns in PSP toxins in Gulf of Maine shellfish show no clear relationships with long-term trends in climate,[180, 181, 182] but ocean–climate interactions and changing oceanographic conditions are important factors for understanding *Alexandrium* bloom dynamics in this region.[183]

There is less agreement on the extent of climate impacts on other marine HAB-related diseases in the United States. Increased abundances of *Pseudo-nitzschia* species, which can cause amnesic shellfish poisoning, have been attributed to nutrient enrichment in the Gulf of Mexico.[184] On the U.S. West Coast, increased abundances of at least some species of *Pseudo-nitzschia* occur during warm phases associated with El Niño events.[185] For *Dinophysis* species that can cause diarrhetic shellfish poisoning, data records are too short to evaluate potential relationships with climate in the United States,[164, 186] but studies in Sweden have found relationships with natural climate oscillations.[187]

The projected impacts of climate change on toxic marine harmful algae include geographic range changes in both warm- and cold-water species, changes in abundance and toxicity, and changes in the timing of the seasonal window of growth.[188, 189, 190, 191] These impacts will likely result from climate change related impacts on one or more of 1) water temperatures, 2) salinities, 3) enhanced surface stratification, 4) nutrient availability and supply to coastal waters (upwelling and freshwater runoff), and 5) altered winds and ocean currents.[188, 190, 191, 192, 193]

Limited understanding of the interactions among climate and non-climate stressors and, in some cases, limitations in the design of experiments for investigating decadal- or century-scale trends in phytoplankton communities, makes forecasting the direction and magnitude of change in toxic marine HABs challenging.[189, 191] Still, changes to the community composition of marine microalgae, including harmful species, will occur.[188, 194] Conditions for the growth of dinoflagellates—the algal group containing numerous toxic species—could potentially be increasingly favorable with climate change because these species possess certain physiological characteristics that allow them to take advantage of climatically-driven changes in the structure of the ocean (for example, stronger vertical stratification and reduced turbulence).[190, 193, 195, 196, 197]

Climate change, especially continued warming, will dramatically increase the burden of some marine HAB-related diseases in some parts of the United States, with strong implications for disease surveillance and public health preparedness. For example, the projected 4.5°F to 6.3°F increase in sea surface temperature in the Caribbean over the coming century is expected to increase the incidence of ciguatera fish poisoning by 200% to 400%.[171] In Puget Sound, warming is projected to increase the seasonal window of growth for *Alexandrium* by approximately 30 days by 2040, allowing blooms to begin earlier in the year and persist for longer.[177, 190, 198]

Research Highlight: Increased Risk of Ciguatera Fish Poisoning (CFP)

Importance: Ciguatera fish poisoning is caused by consumption of fish contaminated with toxins produced by dinoflagellates, such as those of the genus *Gambierdiscus*. There is a well-established link between warm sea surface temperatures and increased occurrence of CFP,[171] and thus concern that global ocean warming will affect the risk of illness.

Objective: A quantitative projection of future shifts in species of *Gambierdiscus*.

Method: Growth models developed for three Caribbean species of *Gambierdiscus* were run using 11 global climate model projections for specific buoy locations in the western Gulf of Mexico, Yucatan channel, and eastern Caribbean Sea through 2099. For further detail, see Kibler et al. 2015.[199]

Results and Conclusions: Modeling results suggest substantial changes in dominant species composition (Figure 6). Lower thermal tolerances of some species may result in geographic range shifts to more northern latitudes, particularly from the Yucatan and eastern Caribbean Sea. The projected shift in distribution is likely to mean that dominant CFP toxins enter the marine food web through different species, with increases of toxins in new areas where waters are warming and potential decreases in existing areas where waters are warming less rapidly.

Projected Changes in Caribbean *Gambierdiscus* Species

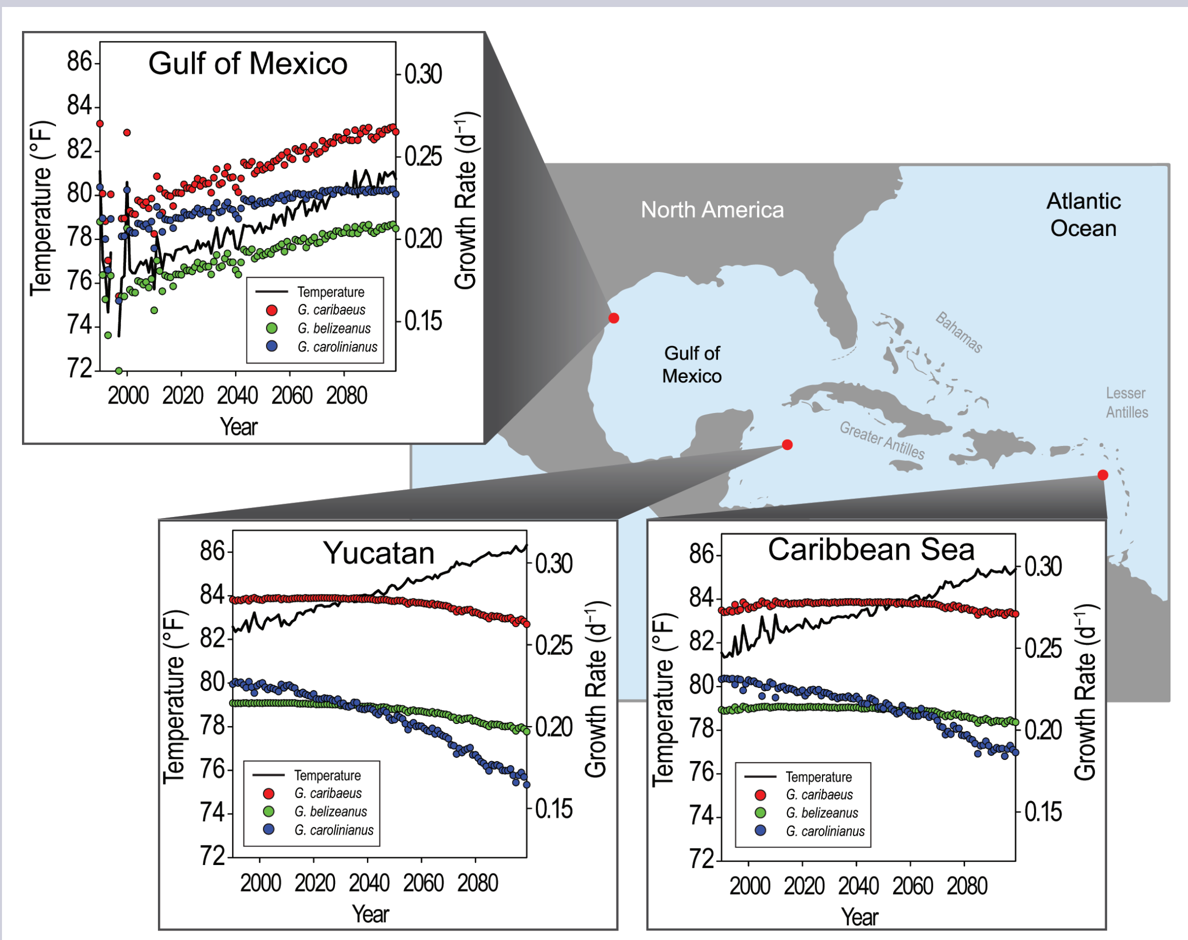

Figure 6: Water temperature data from 1990–2013 were collected or reconstructed for buoy sites in the western Gulf of Mexico, Yucatan channel, and eastern Caribbean Sea. These data were then used in calculations to project average annual water temperature and average growth rates for three Caribbean *Gambierdiscus* species (*G. caribaeus*, *G. belizeanus*, *G. carolinianus*) for the period 2014–2099. (Figure source: adapted from Kibler et al. 2015).[199]

Research Highlight: Expanded Seasonal Windows for Harmful Algal Blooms

Importance: When some harmful algae in the genus *Alexandrium* bloom, toxins that can accumulate in shellfish are produced. When these shellfish are consumed, gastrointestinal illness and neurological symptoms, known as paralytic shellfish poisoning (PSP), can occur. Death can result in extreme cases. Because growth of *Alexandrium* is regulated in part by water temperature, warm water conditions appropriate for bloom formation may expand seasonally, increasing the risk of illness.

Objective: A quantitative projection of future conditions appropriate for *Alexandrium* bloom formation in Puget Sound.

Method: Monthly average sea surface temperature was projected for Quartermaster Harbor, Puget Sound, for the 2030s, 2050s, and 2090s based on statistical downscaling of 21 global climate models. The projections were applied to previously published empirical models relating temperature and salinity to *Alexandrium* growth. For more detail, see Jacobs et al. 2015.[132]

Projections of Growth of *Alexandrium* in Puget Sound

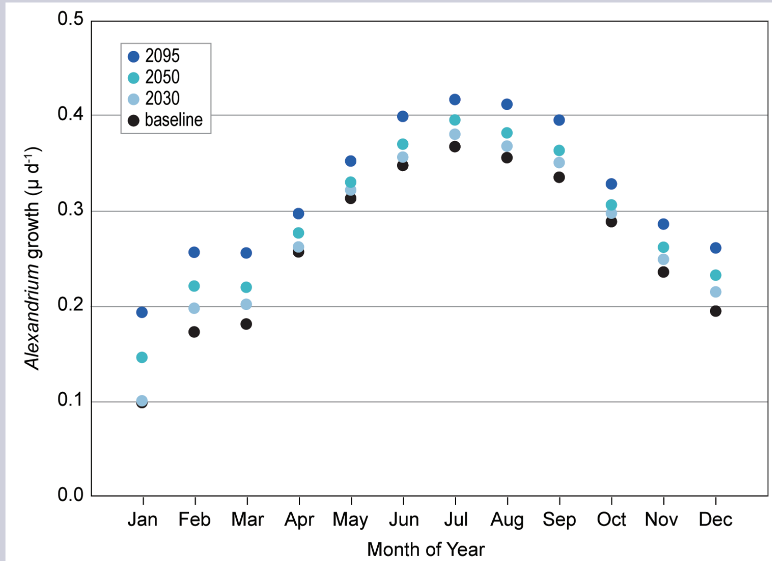

Figure 7: Seasonal and decadal projections of growth of *Alexandrium* in Puget Sound. The circles show average values in the baseline period (2006–2013) and future years averaged by decadal period: 2030 (2025–2035), 2050 (2045–2055), and 2095 (2090–2099). Growth rate values above 0.25μd^{-1} constitute a bloom of *Alexandrium* (Figure source: adapted from Jacobs et al. 2015)[132]

Results and Conclusions: Modeling results indicate that *Alexandrium* blooms could develop up to two months earlier in the year and persist for up to two months longer by 2100 compared to the present day (Figure 7). All model projections indicate that the bloom season will expand by at least one month on either side of the present-day bloom season by 2100. Therefore, it is likely that the risk of *Alexandrium* blooms that can contaminate shellfish with potent toxins will increase. This may increase the risk of human exposure to the toxins, which can cause paralytic shellfish poisoning. Sources of uncertainty include different rates of warming associated with each model ensemble and other factors that affect growth and abundance, but all models used project warming of coastal waters.

6.4 Populations of Concern

Climate change impacts on the drinking water exposure pathway (see page 163) will act as an additional stressor on top of existing exposure disparities in the United States. Lack of consistent access to potable drinking water and inequities in exposure to contaminated water disproportionately affects the following populations: tribes and Alaska Natives, especially those in remote reservations or villages; residents of low-income rural subdivisions known as colonias along the U.S.–Mexico border; migrant farm workers; the homeless; and low-income communities not served by public water utilities—which can be urban, suburban, or rural, and some of which are predominately Hispanic or Latino and Black or African American communities in certain regions of the country.[200, 201, 202, 203, 204, 205, 206, 207, 208] In general, the heightened vulnerability of these populations primarily results from unequal access to adequate water and sewer infrastructure, and various environmental, political, economic, and social factors jointly create these disparities.[201]

Children, older adults (primarily age 65 and older), pregnant women, and immunocompromised individuals have higher risk of gastrointestinal illness and severe health outcomes from contact with contaminated water.[4, 209, 210, 211, 212, 213] Pregnant women who develop severe gastrointestinal illness are at high risk for adverse pregnancy outcomes (pregnancy loss and preterm birth).[214] Because children swallow roughly twice as much water as adults while swimming, they have higher recreational exposure risk for both pathogens and freshwater HABs.[101, 120] Recent cryptosporidiosis and giardiasis cases have frequently been reported in children aged one to nine years, with onset of illness peaking during the summer months.[215] In addition, 40%

of swimming-related eye and ear infections from *Vibrio alginolyticus* during the period 1997–2006 were reported in children (median age of 15).[93]

Traditional tribal consumption of fish and shellfish in the Pacific Northwest and Alaska can be on average 3 to 10 times higher than that of average U.S. consumers, or even up to 20 times higher.[216] Climate change will contribute to increased seafood contamination by toxins and potentially by chemical contaminants (see "6.5 Emerging Issues" below), with potential health risks and cultural implications for tribal communities. Those who continue to consume traditional diets may face increased health risks from contamination.[217] Alternatively, replacing these traditional nutrition sources may involve consuming less nutritious processed foods and the loss of cultural practices tied to fish and shellfish harvest.[218, 219]

Water-related contamination of shellfish may reduce consumption and contribute to loss of tribal cultural practices tied to shellfish harvest.

6.5 Emerging Issues

A key emerging issue is the impact of climate on new and re-emerging pathogens. While cases of nearly-always-fatal primary amoebic meningoencephalitis due to the amoeba *Naegleria fowleri* and other related species remain relatively uncommon, a northward expansion of cases has been observed in the last five years.[220, 221] Evidence suggests that in addition to detection in source water (ground and surface waters), these amoebae may be harbored in biofilms associated with water distribution systems, where increased temperatures decrease efficacy of chlorine disinfection and support survival and potentially growth.[222, 223, 224]

Climate change may also alter the patterns or magnitude of chemical contamination of seafood, leading to altered effects on human health—most of which are chronic conditions. Rising temperatures and reduced ice cover are already linked to increasing burdens of mercury and organohalogens in arctic fish,[225] a sign of increasing contamination of the arctic food chain. Changes in hydrology resulting from climate change are expected to alter releases of chemical contaminants into the Nation's surface waters,[226] with as-yet-unknown effects on seafood contamination.

6.6 Research Needs

In addition to those identified in the emerging issues discussion above, the authors highlight the following potential areas for additional scientific and research activity on water-related illness, based on their review of the literature. Enhanced understanding of climate change impacts will be facilitated by improved public health surveillance for water-related infectious diseases and expanded monitoring and surveillance of surface and coastal water quality. In addition, improved understanding of how human behaviors affect the risk of waterborne diseases can facilitate the development of predictive models and effective adaptation measures. Predictive models can also help identify major areas of uncertainty and refine key research questions.

Future assessments can benefit from research activities that

- assess the interactions among climate drivers, ecosystem changes, water quality and infectious pathogens, including *Vibrio spp., N. fowlerii,* chemical contaminants, and harmful algal blooms;
- increase understanding of how marine and terrestrial wildlife, including waterfowl, contribute to the distribution of pathogens and transmission of infectious disease and assess the role of climate;
- explore how ocean acidification affects toxin production and distribution of marine HABs and pathogens;
- analyze the hydrologic (discharge, flow-residence time, and mixing) thresholds for predicting HAB occurrences; and
- increase understanding of how the impacts of climate change on drinking water infrastructure, including the need for development of new and emerging technologies for provision of drinking water, affect the risks of waterborne diseases.

Supporting Evidence

PROCESS FOR DEVELOPING CHAPTER

The chapter was developed through technical discussions of relevant evidence and expert deliberation by the report authors at several workshops, teleconferences, and email exchanges. Authors considered inputs and comments submitted by the public, the National Academies of Sciences, and Federal agencies. For additional information on the overall report process, see Appendices 2 and 3.

Many water-related illnesses are of critical importance globally, such as cholera and hepatitis E virus, and they affect U.S. interests abroad, but the focus of this chapter is to address climate impacts on water-related illnesses of primary importance to human health within the United States. In addition, although climate change has the potential to impact national as well as global seafood supplies, this chapter does not cover these types of impacts because the peer-reviewed literature is not yet robust enough to make connections to human health outcomes in the United States. Even with those constraints, the impacts of climate on water-related illness are regionally or locally specific and may include increased risks as well as benefits. For example, the projected geographic range shifts of some *Gambieridiscus* species to more northern latitudes may mean that dominant ciguatera fish poisoning toxins enter the marine food web through different species, with increases of toxins in new areas where waters are warming and potential decreases in areas such as the Yucatan and eastern Caribbean Sea.[199]

KEY FINDING TRACEABLE ACCOUNTS

Seasonal and Geographic Changes in Waterborne Illness Risk

Key Finding 1: Increases in water temperatures associated with climate change will alter the seasonal windows of growth and the geographic range of suitable habitat for freshwater toxin-producing harmful algae [*Very Likely, High Confidence*], certain naturally occurring *Vibrio* bacteria [*Very Likely, Medium Confidence*], and marine toxin-producing harmful algae [*Likely, Medium Confidence]*. These changes will increase the risk of exposure to waterborne pathogens and algal toxins that can cause a variety of illnesses [*Medium Confidence*].

Description of evidence base

Vibrio, a genus of naturally occurring waterborne pathogens, thrives in water temperatures above a 15°C/59°F threshold.[132, 152, 154, 157] Rising sea surface temperatures have contributed to an expanded geographic and seasonal range in outbreaks of human illness associated with *Vibrio* in shellfish.[96, 152, 153, 154, 155] In recreational waters, projected increases in sea surface temperatures are expected to lengthen the seasonal window of growth and expand geographic range of *Vibrio*.[96, 132] Like other heterotrophic bacteria, growth of *Vibrio* is ultimately limited by availability of carbon substrate, though the coastal areas where *Vibrio* exposure is most likely, either through recreation or consumption of shellfish, generally have sufficient dissolved organic carbon.[159] Reported rates of all *Vibrio* infections have tripled since 1996 in the United States, with *V. alginolyticus* infections having increased by 40-fold.[92] Increasing sea surface temperatures, changes in precipitation and freshwater delivery to coastal waters, and sea level rise will continue to affect *Vibrio* growth and are expected to increase human exposure.[96, 134, 152, 157]

Most harmful algae, including freshwater cyanobacteria that can contaminate drinking water and marine dinoflagellate species that can contaminate fish and shellfish with natural toxins, thrive during the warm summer season or when water temperatures are higher than usual. As the climate continues to warm, water temperatures will rise above thresholds that promote bloom development earlier in the spring and will persist longer into the fall and expand into higher latitudes. This will result in a longer seasonal window and expanded geographic range for human exposure into higher latitudes.[124, 125, 126, 127, 128, 188, 189, 190, 191, 192, 193] Climate change, especially continued warming, will increase the burden of some marine HAB-related diseases, particularly ciguatera fish poisoning, in some regions of the United States.

Major uncertainties

Uncertainty remains regarding the relative importance of additional factors that may also act on naturally occurring pathogens and harmful algae at local or regional levels to influence their growth, distribution, and toxicity. In many cases, it is uncertain how these multiple factors may interact with each other to influence the seasonal windows and geographic range for pathogens and harmful algae, especially in dynamic coastal marine environments. For example, changes in salinity, competition with other plankton, and presence of viruses or other organisms that consume plankton or bacteria can affect abundance.[162, 163] Changing distribution patterns for some marine species of harmful algae is not well understood and some regions may become too warm for certain species of harmful algae to grow, shifting (without changing in total size) or even shrinking their geographic range.

Additionally, there are limited studies on projections for changes in illness rates due to naturally occurring waterborne pathogens and harmful algae. Uncertainty remains regarding appropriate methods for projecting changes in illness rates, including how to integrate considerations of human behavior into modeling (current methods to assess exposure risk assume similar human behavior across time scales and geography). Methodological challenges are related to 1) underreporting and underdiagnosis of cases that affect the accuracy of baseline estimates of illness, 2) ability to project changes in strain virulence, 3) accounting for the effects of potential adaptation strategies/public health interventions (for example, public service announcements on how to avoid exposure), and 4) accounting for changes in public healthcare infrastructure and access that can reduce the risk of exposure or illness/death if exposed.

Assessment of confidence and likelihood based on evidence

Based on the evidence, there is **medium confidence** that, with changing climate, the annual seasonal and the geographic range for *Vibrio* and certain marine harmful algae will expand. The assessment of **medium confidence** is due to less certainty from modeling results regarding the magnitude of projected changes in abundance. The conclusions were deemed **very likely** to occur for *Vibrio* and **likely** for marine harmful algae based on good levels of agreement found in the published quantitative modeling projections for both *Vibrio* and marine harmful algae (*Alexandrium* and *Gambieridiscus*) cited above. This conclusion takes into consideration that for some marine algae (for example, *Gambieridiscus*), lower latitudes may become too warm and risk may decline in those areas as it increases at higher latitudes. For freshwater harmful algae, there is **high confidence** that annual season and geographic range will expand with changing climate, which will also prolong the time for exposure and the potential for public health impacts. Consistent and high-quality evidence from a limited number of laboratory studies, modeling efforts, field surveys, and comparisons of historic and contemporary conditions support this assessment. The conclusion was deemed **very likely** to occur for freshwater harmful algae with **high confidence** based on laboratory studies and field observations, as well as a greater fundamental understanding of inland hydrodynamics and bloom ecology as indicated in the literature cited in the chapter. There is **medium confidence** regarding increased risk to human health from a longer potential time for exposure to waterborne pathogens and algal toxins and potential exposure for a wider (or novel) population. This confidence level was chosen due to less certainty stemming from a relative lack of quantitative data and projections for future illness rates in the peer-reviewed literature.

Runoff from Extreme Precipitation Increases Exposure Risk

Key Finding 2: Runoff from more frequent and intense extreme precipitation events will increasingly compromise recreational waters, shellfish harvesting waters, and sources of drinking water through increased introduction of pathogens and prevalence of toxic algal blooms [*High Confidence*]. As a result, the risk of human exposure to agents of water-related illness will increase [*Medium Confidence*].

Description of evidence base

Extreme precipitation can mobilize pathogens, nutrients, and chemical contaminants from agricultural, wildlife, and urban sources. Waterborne illness and outbreaks from pathogens following heavy precipitation events have been well documented in multiple studies using both passive and active surveillance on a local and regional level.[38, 39, 40, 42, 43, 44, 45, 46, 47] Likewise, extreme precipitation events and subsequent increases in runoff are key climate factors that increase nutrient loading in freshwater and marine recreational waters, shellfish harvesting waters, and sources of drinking water, which in turn increases the likelihood of harmful cyanobacterial blooms that produce algal toxins.[56] The drinking water treatment process can remove cyanobacterial blooms; however, efficacy of the treatment processes may vary from 60% to 99.9%. Ineffective treatment could compromise water quality and may lead to severe treatment disruption or treatment plant shutdown.[53, 54, 55, 56] More frequent and intense extreme precipitation events are projected for many regions in the United States as climate changes. Consistent, high-quality evidence from multiple studies supports a finding that increased runoff and flooding events are expected to increase contamination of source waters (for drinking water supply) and surface waters used for recreation, which may increase people's exposure to pathogens and algal toxins that cause illness.[10, 52, 59, 70, 71, 72, 73, 76, 82, 116, 117, 118, 119, 120] Other factors may modify these risks, such as increased air or water temperatures, residence time in the environment, lower water levels, or dilution.

Major uncertainties

Changes in exposure and risk are attributable to many factors in addition to climate. While extreme precipitation and flooding events introduce contaminants and pathogens to water to varying degrees depending on the characteristics of each individual event, they may not always result in increases in exposure due to planning and adaptive actions. There are limited studies on actual projections for changes in illness rates due to increasing frequency or intensity of extreme precipitation events. Uncertainty remains regarding appropriate methods for projecting changes in illness rates, including how to integrate considerations of human behavior into modeling (current methods to assess exposure risk assume similar human behavior across time scales and geography). Methodological challenges are related to 1) baseline case reporting issues (underreporting and underdiagnosis), 2) accounting for the effects of potential adaptation strategies/public health interventions (for example, public service announcements about how to avoid exposure), and 3) accounting for changes in public healthcare infrastructure and access that can reduce the risk of exposure or of illness/death if exposed.

Assessment of confidence and likelihood based on evidence
Based on the evidence, there is **high confidence** that increasing frequency or intensity of extreme precipitation events will compromise recreational waters and sources of drinking water with pathogens, nutrients, and chemical contaminants from agricultural, wildlife, and urban sources.

There is consistent qualitative evidence that flooding associated with extreme precipitation events and storm surge results in loading of pathogens and nutrients to surface and groundwater (and drinking water distribution systems) through stormwater runoff and sewage overflows. However, other human and social factors modify risk, and there are no national-level studies upon which to draw conclusions regarding quantitative projections of increased exposure. Thus, the limited number of studies supports a **medium confidence** level that human exposure risk will increase due to changes in extreme events.

Water Infrastructure Failure

Key Finding 3: Increases in some extreme weather events and storm surges will increase the risk that infrastructure for drinking water, wastewater, and stormwater will fail due to either damage or exceedance of system capacity, especially in areas with aging infrastructure [*High Confidence*]. As a result, the risk of exposure to water-related pathogens, chemicals, and algal toxins will increase in recreational and shellfish harvesting waters and in drinking water where treatment barriers break down [*Medium Confidence*].

Description of evidence base
Water infrastructure in the United States is aging and may be inadequate or deteriorating. Combined sewers in many older cities were not designed to handle extreme precipitation events that are becoming more frequent with climate change. Multiple studies provide consistent, high-quality evidence that these systems are at risk of being overwhelmed during flood events or may be further damaged during other extreme weather events (e.g., storm surge), allowing contaminated surface water to run off into drinking water and recreational water sources.[10, 52, 59, 70, 76, 116] Drinking water source contamination may be exacerbated or insufficiently addressed by treatment processes at the plant or the distribution system. Drinking water treatment plants may be challenged by high pathogen loads and toxic cyanobacterial bloom events.[52, 55, 56] Multiple studies support a finding that climate change will place additional stresses on the capacity of drinking water treatment facilities and may increase the risk that water infrastructure, especially aging infrastructure, will fail through either damage or exceedance of system capacity.[6, 70, 74, 75]

Major uncertainties
The human health consequences of aging water infrastructure failure depend not only on the local and regional climate factors that contribute to damage or capacity challenges but also the nature of the system and the pressures on it, the population affected, and the timeliness and adequacy of the response—all of which are inherently local or regional factors. Due to the complicated local and regional specificity, there are no national projections of the human health impact of water infrastructure failure. Uncertainty remains regarding appropriate methods for projecting changes in illness rates, including how to integrate considerations of human behavior into modeling (current methods to assess exposure risk assume similar human behavior across time scales and geography). Methodological challenges are related to 1) baseline case reporting issues (underreporting and underdiagnosis), 2) accounting for the effects of potential adaptation strategies/public health interventions (for example, mitigating risk with improvements to current water and sewerage systems), and 3) accounting for changes in public healthcare infrastructure and access that can reduce the risk of exposure or of illness/death if exposed.

Assessment of confidence based on evidence
Based on the evidence found in the peer-reviewed literature, there is **high confidence** that the anticipated climate change related increases in some extreme weather events and in storm surge will increase the risk that water infrastructure for drinking water, wastewater, and stormwater will fail through either damage or exceedance of system capacity, with aging infrastructure being particularly vulnerable. Evidence shows contamination to or from these systems occurs with heavy precipitation and other extreme weather events. There is consistent qualitative evidence suggesting that projected climate change effects on extreme weather patterns—particularly extreme precipitation and storm surge—can adversely affect water infrastructure and lead to increased loading of pathogens, algal toxins, and contaminants. However, there are no national-level studies upon which to draw conclusions regarding quantitative projections of increased exposure. Thus, the limited number of studies supports a **medium confidence** level regarding risk of exposure.

DOCUMENTING UNCERTAINTY

This assessment relies on two metrics to communicate the degree of certainty in Key Findings. See Appendix 4: Documenting Uncertainty for more on assessments of likelihood and confidence.

Confidence Level
Very High
Strong evidence (established theory, multiple sources, consistent results, well documented and accepted methods, etc.), high consensus
High
Moderate evidence (several sources, some consistency, methods vary and/or documentation limited, etc.), medium consensus
Medium
Suggestive evidence (a few sources, limited consistency, models incomplete, methods emerging, etc.), competing schools of thought
Low
Inconclusive evidence (limited sources, extrapolations, inconsistent findings, poor documentation and/or methods not tested, etc.), disagreement or lack of opinions among experts

Likelihood
Very Likely
≥ 9 in 10
Likely
≥ 2 in 3
As Likely As Not
≈ 1 in 2
Unlikely
≤ 1 in 3
Very Unlikely
≤ 1 in 10

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Pg. 165–Family jumping in lake: © Juice Images/Corbis

Pg. 171–Razor clam dig: Courtesy of Vera Trainer/NOAA

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