Climate Variability and Change in the United States: Potential Impacts on Water- and Foodborne Diseases Caused by Microbiologic Agents

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Exposure to waterborne and foodborne pathogens can occur via drinking water (associated with fecal contamination), seafood (due to natural microbial hazards, toxins, or wastewater disposal) or fresh produce (irrigated or processed with contaminated water). Weather influences the transport and dissemination of these microbial agents via rainfall and runoff and the survival and/or growth through such factors as temperature. Federal and state laws and regulatory programs protect much of the U.S. population from waterborne disease; however, if climate variability increases, current and future deficiencies in areas such as watershed protection, infrastructure, and storm drainage systems will probably increase the risk of contamination events. Knowledge about transport processes and the fate of microbial pollutants associated with rainfall and snowmelt is key to predicting risks from a change in weather variability. Although recent studies identified links between climate variability and occurrence of microbial agents in water, the relationships need further quantification in the context of other stresses. In the marine environment as well, there are few studies that adequately address the potential health effects of climate variability in combination with other stresses such as overfishing, introduced species, and rise in sea level. Advances in monitoring are necessary to enhance early-warning and prevention capabilities. Application of existing technologies, such as molecular fingerprinting to track contaminant sources or satellite remote sensing to detect coastal algal blooms, could be expanded. This assessment recommends incorporating a range of future scenarios of improvement plans for current deficiencies in the public health infrastructure to achieve more realistic risk assessments. *Key words:* cholera, climate change, climate variability, cryptosporidiosis, *E. coli,* foodborne diseases, global warming, shellfish poisoning, waterborne diseases. — *Environ Health Perspect* 109(suppl 2):211–221 (2001).
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This article addresses three overlapping environmental health-related areas affected by weather and climatic factors: *a*) waterborne diseases, including fresh water for drinking and recreational waters; *b*) foodborne diseases linked to water contamination; and *c*) marine or coastal issues, including harmful algal blooms (HABs) and ecologic disruption. An example of the interrelatedness among these divisions is toxic algae bioaccumulation in shellfish, which is both a foodborne and coastal problem.

Waterborne diseases are caused by pathogens spread through contaminated drinking water or recreational water. A waterborne disease outbreak occurs when two or more persons experience similar illness after consumption or use of a common water source proven using epidemiologic methodologies (*1*). Weather conditions influence water quality and quantity through various processes (e.g., source water and watershed contamination) (Figure 1).

Incidence of Waterborne Disease in the United States

In the United States more than 200 million people have direct access to disinfected public water supply systems, yet as many as 9 million cases of waterborne disease are estimated to occur each year (*2*). Quantifying the present threat of waterborne disease in the United States is made difficult by the fact that many cases of waterborne disease, typically, gastrointestinal illness, go unreported; the symptoms usually do not last long and are self-limiting in healthy people. There may be other suspected causes of the illnesses, such as foodborne exposures and person-to-person infection (*3*). However, gastrointestinal illness can be chronic and even fatal in infants, the elderly, pregnant women, and people with immune systems severely weakened by acquired immune deficiency syndrome (AIDS), chemotherapy, transplants, chronic illness such as diabetes, or preinfection by another agent such as measles virus, or other causes. Furthermore, waterborne pathogens can cause extended illnesses, such as hepatitis, that last several months even in healthy people. Waterborne pathogens cause or are associated with other serious conditions including hepatic, lymphatic, neurologic, and endocrinologic diseases (*4*), and possibly increased risk of some cancers (e.g., due to *Helicobacter*). Concern about disease transmission has been heightened with the emergence or reemergence of new pathogens (e.g., *Escherichia coli* O157:H7 and *Cryptosporidium*), antibiotic-resistant strains, and a larger susceptible population (more elderly persons, AIDS patients, and patients undergoing immune-suppressant medical treatments) (*5*).

Source Contamination and Exposure Pathways

There are many routes of exposure, as well as individual or population susceptibility, to waterborne pathogens, with water quality, availability, sanitation, and hygiene all playing a role. Human exposure pathways include ingestion, inhalation, and dermal absorption of microbial organisms or algal toxins. For example, people can ingest these microbial agents by drinking contaminated water, or by eating seafood from contaminated waters, or by eating fresh produce irrigated or processed with contaminated water (*6*). They also may be exposed by contact with contaminated water through commerce (e.g., fishing) or recreation (e.g., swimming) (*4*).

Water quality depends partly on land use and how water resources are managed and protected. Both freshwater bodies and coastal waters can be directly or indirectly affected by point and non-point contamination (industrial, urban, and agricultural operations). Storm water drainage can carry animal and human waste and untreated sewage (*1*). Ecologic stresses may also affect wildlife habitats and the abundance and distribution of

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natural microbial hazards in marine systems, which in turn may affect human health (*7–10*). Such stressors include overfishing, bottom trawling, introduced species, altered freshwater discharges, increased nutrients, increased ultraviolet radiation, and climate variability.

A constant issue in water quality is the management and disposal of sewage and other wastes. Waste is discharged into freshwater and saltwater bodies, injected into underground wells, dumped on or buried in land, and disposed to the subsurface, where it can leach into groundwater or migrate to surface waters. Municipal sewage treatment plants, combined sewer overflows (CSOs), urban runoff, sewage spills, discharges from septic tanks, boating wastes, and urban and agricultural storm water runoff are sources of microorganisms in water systems (*11*). An example of poor sewage disposal practices, the use of combined sewer systems, is highlighted in the next section. Extreme precipitation and high water tables decrease the efficiency of onsite sewage disposal and may increase the likelihood of microorganisms in water systems. Another possible factor is urban or agricultural development; increased urbanization has and will continue to alter watersheds and freshwater flows. This may result in contamination from both point sources (e.g., factory and sewage treatment discharge pipes) and nonpoint sources (e.g., microbe-contaminated runoff from farmlands).

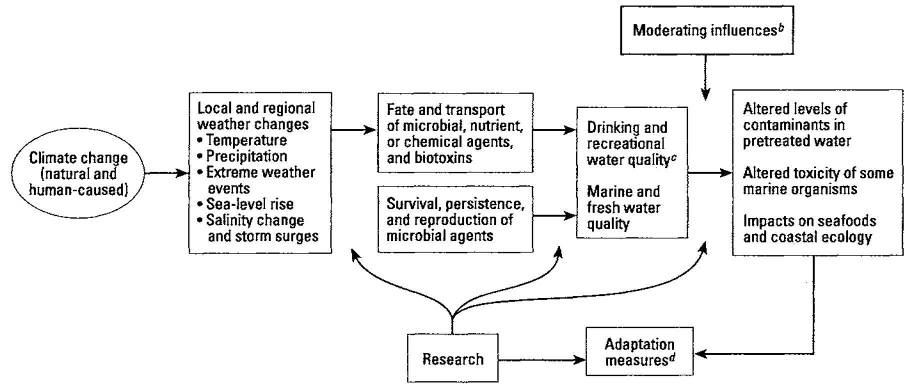

Figure 1. Potential waterborne and foodborne[a] diseases. [a]Foodborne diseases primarily related to marine or freshwater contamination. [b]Moderating influences include nonclimate factors that effect climate-related health outcomes, such as state of coastal wetlands, land use, and water treatment facilities. [c]Finished drinking water must meet higher regulatory standards than recreational water or water used for irrigation. [d]Adaptation measures include actions to reduce risks of water contamination, such as watershed management, improved water treatment engineering, and enhanced surveillance of waterborne disease outbreaks.

Table 1. Health risks associated with selected waterborne pathogens.[a]

Health risks	Type of pathogen	Found in sewage	Waterborne transmission	Foodborne transmission
Acute peritonitis	*Anisakis simplex*	–	+ (recreational)	+
Arthritis	*Giardia, Salmonella, Campylobacter*	+	+	+
Aseptic meningitis	Echoviruses, Coxsackie viruses	+	+	+
Cancer, peptic ulcer	*Helicobacter pylori*	+/– (presumed, in feces)	+/– (preliminary in groundwater)	+
Cholera	*V. cholerae*	–	+	+
Diarrhea and gastroenteritis[b]	Many enteric viruses	+	+	+
	Norwalk virus	+	+	+
	Giardia, Cryptosporidium	+	+	–
	Salmonella, E. coli 0157[c]	+	+	+
	Shigella species, *Salmonella*	+	+	+
	Calciviruses	+	+	+
	Rotaviruses (infantile gastroenteritis viruses)	+	+	+
	Astroviruses, enteroviruses	–	–	–
Granuloma	*Mycobacterium marinum*	–	+	–
Heart disease	Coxsackie B virus	+	+	+
Insulin-dependent diabetes	Coxsackie B virus (*159*)	+	+	+
Kidney failure	*E. coli* O157:H7	+	+	+
	Microsporidia	+	+	+/–
	Cyclospora	+	+	+
	V. vulnificus	–	–	+
Liver failure	Hepatitis A virus	+	+	+
	Hepatitis E virus	–	+	–
Wound infection	*V. alginolyticus*	–	+	–
Wound infection, gastroenteritis	*V. parahaemolyticus*	–	+	+

+, refers to being associated with; –, not associated; +/–, possible or suspected linkage.
[a]Adapted from the National Research Council (*160*) and Howard et al. (*161*). [b]Over 100 microorganisms are associated with diarrhea. They include viruses such as rotavirus, a major cause of diarrhea and dehydration in infants. [c]*S. typhimurium* DT104, which has recently emerged, carries with it two antibiotic resistance markers.

Waterborne Diseases

Drinking Water

Outbreaks of disease due to drinking water source contamination occur when a number of events happen simultaneously. There must be contamination of the source water, transport of the contaminant to the water intake or well of the drinking water system, insufficient treatment to reduce the level of contamination, and exposure to the contaminant.

There may also be recontamination of finished water in the public or homeowner's distribution system (*12*). About 10–15 infectious disease outbreaks attributable to drinking water are reported annually in the United States (*1,12*). Many more go unreported. Illnesses such as gastroenteritis are not specific to water (may be foodborne) and most cases are not serious enough to warrant medical visits (*13*). The contaminant source is often not identified. "With current surveillance programs, even an outbreak resulting in many medically attended illnesses in a large city could be unrecognized" (*6*).

Notwithstanding the current lack of understanding of the full extent of the problem of contaminated drinking water, it is believed to be a serious and growing concern. More than 100 types of pathogenic bacteria, viruses, and protozoa can be found in contaminated water (*14–16*). Many of these have been implicated in a variety of illnesses via waterborne and foodborne transmission (Table 1). From 1971 to 1996 there were 674 outbreaks in the United States, including chemical outbreaks (approximating 25–26 outbreaks/year). In the last few years there have been 10–12 per year (*17*). For 1993–1994, an estimated 405,366 people became ill in the United States from consuming contaminated drinking water (*18*), most of these arising from the 1993 Milwaukee, Wisconsin, outbreak described below.

A large number of drinking water outbreaks have been related to protozoan parasites. The largest drinking water outbreak ever documented occurred in Milwaukee in 1993 and was caused by ***Cryptosporidium parvum***. This outbreak resulted in an estimated 403,000 cases of intestinal illness and

54 deaths among immunocompromised individuals (*19*). *Cryptosporidium,* a protozoan that completes its life cycle within the intestine of mammals, is shed in high numbers in the form of infectious oocysts dispersed in feces. The Milwaukee water supply, which is treated by filtration and disinfection (chlorination), comes from Lake Michigan. However, because of a preceding period of heavy rainfall and runoff, there was a decrease in raw water quality along with a diminished effectiveness of the system's coagulation–filtration process, which in turn led to increased turbidity of the treated water and inadequate removal of the oocysts (*20,21*). Other waterborne cryptosporidiosis outbreaks have been reported worldwide, and rainfall has been mentioned as playing a role in a number of them (*22–24*).

C. parvum is a common cause of diarrhea in AIDS patients in both the developed and developing worlds, with reported prevalence rates of 3.6% in the United States to about 50% in Africa (*24*). One year after the Milwaukee episode, a cluster of cryptosporidiosis cases and deaths among AIDS patients in Las Vegas (Clark County), Nevada, alerted health officials to another waterborne outbreak (*25*). The Nevada outbreak was associated with water from Lake Mead that was both filtered and chlorinated. Researchers in Brazil reported that *Cryptosporidium* was the most common cause of diarrhea in AIDS patients, and disease incidence showed a distinct seasonality, suggesting an association with rainfall (*26*).

Reporting of cryptosporidiosis cases to the Centers for Disease Control and Prevention (CDC) began in 1995 with 2,972 cases reported from 27 states. In 1997, 2,566 cases were reported from 45 states. These numbers probably underreport the national incidence of cryptosporidiosis, and laboratories do not routinely test for *C. parvum* infection (*27*).

Giardia lamblia is the second most common pathogenic parasite in the United States and the most common identifiable etiologic agent of waterborne outbreaks (*1*). Like *Cryptosporidium,* the protozoan produces a cyst that is shed in the feces of humans and animals. Rainfall has been implicated in a waterborne outbreak of giardiasis (*28*).

Both *C. parvum* oocysts and *G. lamblia* cysts are commonly found in raw surface water surface. One study reported positive contamination in 87 and 81%, respectively, of 66 water plants in 14 states in the United States (*29*). That same study showed that 39% of filtered drinking water samples from these treatment plants contained *C. parvum* (27%) or *G. lamblia* (17%), although 78% of the plants met the turbidity requirements of the then-applicable Surface Water Treatment Rule (*30*). A subsequent study in 1995 still found 13% of finished treated water to be contaminated with *Cryptosporidium* oocysts (*31*). Correlations between increased rainfall and increased *Cryptosporidium* oocyst and *Giardia* cyst concentrations in river water have been reported (*32*).

Among the other water-related diseases, Legionnaire disease is a respiratory illness transmitted solely by water. The bacterium *Legionella* grows in natural waters, pipes, distribution systems, and water- and air conditioning systems and is inhaled through contaminated aerosols produced from showers, humidifiers, and cooling towers. Water temperature among other factors (e.g., nutrients, association with free-living amoebas, such as *Acanthamoeba*) are known to influence the potential for *Legionella* to colonize water systems (*33,34*).

Untreated Sewage Disposal: The Story of Combined Sewer Overflows

Contamination of the marine and freshwater environment may be caused by human waste disposal through raw waste or septic tanks, inadequately disinfected sewage effluents, outfalls, and storm water. One critical, continuing threat to water quality and public health is the use by many communities of combined sewer systems. These systems are vestiges of early sanitation efforts in this country designed to carry both storm water and sanitary wastewater through the same pipe to a sewage treatment plant. During periods of rainfall or snow melt, the volume of water in the system can exceed the capacity of the sewer system or treatment plant; in such a situation, the system is designed to overflow and discharge the excess wastewater directly into surface water bodies. Because such CSOs contain untreated human and industrial waste, they can carry solids, oxygen-demanding substances, ammonia, other potential toxics, and pathogenic microorganisms associated with human disease and fecal pollution to the receiving waters, precipitating beach closings, shellfishing restrictions, and other water body impairments (*35,36*). The U.S. EPA estimates that CSOs and other wet weather pollution sources such as storm water runoff cause about half of the estuary contamination nationwide (*35*).

There are currently 950 communities in the United States that have combined sewer systems, primarily in the Northeast and Great Lakes regions. Most serve small communities (less than 10,000 people); exceptions include New York, Philadelphia, and Atlanta. The U.S. EPA issued a CSO Control Policy in 1994 (*37*) intended to control CSOs through the national wastewater discharge permitting system, and it has issued a series of implementing guidelines to municipalities. The goal of the CSO Control Policy was to reduce the number of overflows by about 85%, reduce loadings of suspended solids from 3.7 billion pounds to 1.29 billion pounds per year, and reduce discharge of oxygen-demanding pollutants from 1,150 million pounds to 650 million pounds per year (*35*). These controls may or may not affect microbial contaminants. The U.S. EPA reported in May 1998 that after 4 years just over half of the communities (52%) with CSOs had implemented the nine minimum technology-based controls intended to reduce the number and impact of CSOs (*35,37*). Another 25% that had not implemented the controls were under an enforceable requirement to do so in the future (*35,37*).

Recreation-Related Waterborne Diseases

Another direct exposure pathway to waterborne pathogens (bacteria, parasites, and viruses) and toxins is through recreational activities such as swimming, fishing, or boating in contaminated waters (*38–40*). The presence of microbial contaminants in freshwater bodies and marine waters has been associated with eye, ear, nose, skin, respiratory, gastrointestinal (including gastroenteritis and hepatitis), and other infections (*37,41–44*).

Contamination of recreational waters can result from numerous sources, including urban and nonurban runoff, industrial pollution, storm waters, human and animal wastes, and indigenous sources such as red tides. During 1996 nearly 3,700 beach closings and advisories were issued at U.S. ocean, bay, and Great Lakes beaches (*45*). The detection of excessive concentrations of bacteria caused 83% of the closings. Haile et al. (*46*) found increased illness due to swimming in contaminated ocean water in relationship to the proximity of storm drains to the beach.

In freshwaters, besides fecal-associated microorganisms, free-living parasites are of a concern to swimmers. *Naegleria fowleri* causes primary amoebic meningoencephalitis, generally in children or young adults, and is acquired through the parasite entering the nasal passages. Although the disease has a low frequency, it has a very high fatality ratio. Water temperature is a significant factor in the occurrence and distribution of this organism (*47–50*). *Acanthamoeba* has been associated with keratitis (*51*), shows marked seasonality [peaking in June and November (*52*)], and may be affected by climate conditions.

The strongest evidence linking infectious diseases to fecally contaminated marine water activities comes from prospective epidemiologic studies (*44*). For example, Cabelli et al., in a prospective cohort study (*52*), reported a linear relationship between the incidence of gastroenteritis among swimmers and counts of marine enterococci and *E. coli.* They found that the frequency of gastrointestinal symptoms was inversely related to the distance from known municipal wastewater sources.

Marine *Vibrio* bacteria, one of which can cause cholera (see discussion of foodborne diseases below), can also cause swimming-related illnesses (*53,54*). *Vibrio cholerae* non-O1 (*55*) has caused cystitis in swimmers in the Chesapeake Bay, Virginia (*56*). Cases of central nervous system disease, wound infections, and osteomyelitis have resulted from wounds exposed to *V. alginolyticus* in saltwater (*57–59*), and leg gangrene and sepsis have been attributed to *V. parahaemolyticus* exposure in New England coastal waters (*60*). *V. vulnificus* (*61,62*) has caused endometritis (*63*), serious wound infections, and fatal septicemia.

Marine-related disease is not always communicable. Swimmer's itch is a dermatitis acquired worldwide from the cercaria of *Microbilharzia variglandis* and other free-swimming avian schistosomes or flukes (*64*). Outbreaks of swimmer's itch have been reported in Delaware and Connecticut (*65*). "Seabather's eruption," or "sea lice," is a self-limited dermatitis caused by *Linuche unguiculata* (jellyfish) and *Edwardsiella lineata* (sea anemone) larvae trapped under bathing suits (*66*). Outbreaks have been reported in the Caribbean; Florida; and Long Island, New York (*67–70*).

Foodborne Diseases

In the United States foodborne diseases are estimated to cause 76 million cases of illness, with 325,000 hospitalizations and 5,000 deaths per year (*71*). Foodborne diseases may be one of the most significant contemporary public health problems, not only because of the large number of cases reported and the associated economic costs (*72*), but also because many of the causative organisms are newly recognized. For example, CDC believes that a new bacterial pathogen, *E. coli* O157:H7, was responsible for outbreaks of gastroenteritis associated with ingestion of undercooked ground beef since the 1980s (*73,74*). Other foodborne pathogens also include *Listeria monocytogenes*, which can cause meningitis, and *Campylobacter*, which causes diarrhea. Other factors in the emerging number of threats to food safety in the United States include *a*) the growing susceptible population, including the elderly and immunocompromised (AIDS, transplant and cancer patients, and other debilitating conditions such as diabetes); *b*) the lowering of international trade barriers, which has resulted in increased importation of food from global markets; *c*) changing food-processing technology; *d*) developing national and international food safety policy; and *e*) changing food consumption patterns (i.e., more fresh fruits and vegetables). The National Food Safety Initiative was established in 1997 to deal with these issues, and in 1998 the President's Council on Food Safety was formed as an advisory group to further develop a comprehensive strategic plan for federal food safety initiatives.

Foodborne Diseases Related to Water Contamination

The water–food connection is apparent, as microbial agents in water (e.g., viruses, bacteria, and protozoa) can contaminate food. For example, there have been instances of fresh fruits and vegetables contaminated via irrigation waters (*75*). Fish and shellfish from contaminated waters have also been major sources of foodborne diseases in the United States (*76,77*). Seafood illnesses from biotoxins in marine environments are discussed below in the subsection on coastal water issues. To date, no study has adequately estimated the proportion of foodborne diseases associated with contaminated water. The group of foodborne diseases associated with contaminated water is a subset of all foodborne diseases reported in the United States. Other foodborne diseases are not discussed in this report except for a brief mention above.

Shellfish-associated outbreaks of gastroenteritis have involved a variety of bacterial pathogens, both fecal associated and naturally occurring, including *Salmonella typhi*, *Campylobacter* spp., *Vibrio* spp., *V. cholerae*, *V. vulnificus*, and *V. parahaemolyticus* (Table 2). *V. cholerae*, responsible for outbreaks of cholera around the world, has been found in plankton and fish in ponds and coastal waters of pandemic areas (*78*). However, the local environment interacts with microbial spread in multiple and complex ways. *V. vulnificus* is a naturally occurring estuarine bacterium that causes a high percentage of mortality associated with contaminated shellfish consumption (*61,79*).

Many studies have linked foodborne disease with consumption of raw or partially cooked shellfish that contained viruses from human sewage (*80–82*). These viruses are abundant in marine systems (*15,40,83–85*). Some viruses survive longer in sea water than do bacteria (*83,86*) and are more likely than bacteria to survive sewage treatment processes (*14*). Indeed, viruses are found in concentrations ranging from hundreds to thousands (as high as 3,000/L) in sewage and storm waters that may impact estuaries (*45*). Seyfried et al. (*87*) found that after sewage treatment, 40% of chlorinated effluent samples contained viruses; enteroviruses were detected in over 40% of recreational waters deemed safe by fecal coliform standards. Because viruses are heat resistant, outbreaks have occurred from the consumption of baked, broiled, steamed, or fried shellfish (*77*). In the United States, hepatitis A was the predominant seafood-related disease reported in the 1960s. Today, acute gastroenteritis is most prevalent (*80*), frequently caused by small round-structured viruses (calciviruses) such as Norwalk and Norwalklike viruses (*80,88*). Documented outbreaks of seafood-related diseases due to gastrointestinal enteroviruses and other viral species are outlined in Table 2.

Table 2. Foodborne outbreaks associated with fish and shellfish.

Reference(s)	Findings
Blake, 1983 (*162*)	Repeated incidents of high levels of *V. vulnificus* that occurred off the coast of Apalachicola, Florida, which produces 15% of the nation's supply of oysters, resulted in closures that cost the seafood industry $9 million per year.
CDC, 1993 (*163*); Heidelberg, 1997 (*164*)	*V. vulnificus* found in oysters from the Gulf of Mexico and the Chesapeake Bay was associated with illness and death in persons with preexisting liver disease.
CDC, 1998 (*165*)	In the summer of 1997 an outbreak of *V. parahaemolyticus* infections in the western United States was associated with consumption of raw oysters. As a result, oyster beds in Washington State were closed by public health officials.
ProMED, 1998 (*166*)	In 1998 there were numerous reports of oysters from Galveston, Texas, and the U.S. Northwest coast contaminated with *V. parahaemolyticus*.
CDC, 1999 (*167*)	In the summer of 1998 an outbreak of *V. parahaemolyticus* was traced to consumption of raw oysters and clams from Long Island Sound.
CDC, 1993 (*168*)	Norwalklike viruses contaminated oyster beds in several areas along the Gulf of Mexico, leading to outbreaks of gastroenteritis and to recalls of shellfish.
MacKenzie, 1988 (*169*); Todd, 1993 (*170*)	Several deaths and symptoms of amnesia were associated with consumption of mussels contaminated with domoic acid (a biotoxin originating from diatoms; *Pseudonitzschia* spp.) in the Canadian maritime region.
Steidinger, 1993 (*99*); Landsberg and Shumway, 1998 (*110*)	Ingestion or inhalation of brevetoxins from *G. breve*) contributed to mass mortalities of mammals and to reported human illness in Florida.
Price et al., 1991 (*171*)	Ingestion of shellfish contaminated with *Alexandrium* spp. dinoflagellates was associated with symptoms of numbness and tingling of the face and other body parts.
DeSylva, 1994 (*172*)	Benthic *Gambierdiscus, Prorocentrum, Ostreopsis,* and *Coolia* spp., toxic dinoflagellates, were associated with ciguatera fish poisoning (CFP) in the Florida Keys. CFP is due to bioaccumulation of toxins from consumption of top-predator reef fish species, such as barracuda.

The increase in foodborne disease associated with produce is a growing concern. Vegetables and fruits eaten raw, some imported from other countries and others grown within the United States, have caused outbreaks of illness. Perhaps most dramatic were the cases of cyclosporiasis (*89*). *Cyclospora* is a protozoan species implicated as an etiologic agent of prolonged watery diarrhea, fatigue, and anorexia in humans (*90*). In 1996 1,465 cases of cyclosporiasis were reported in 20 states in the United States (*91*). In 1997, several outbreaks of cyclosporiasis associated with fresh produce, including raspberries, lettuce, and basil, occurred in the United States (*73*). The largest of these outbreaks, associated with consumption of fresh raspberries, involved 41 clusters with a total of 762 cases (a fourth of which were laboratory confirmed) reported by 13 states, the District of Columbia, and a Canadian province (*27*). Cryptosporidiosis outbreaks have been associated with apple cider and green onions (*92,93*). Foodborne outbreaks traced to fresh produce and their contamination sources are outlined in Tables 3 and 4.

Coastal Water Issues

Consumption of fish and shellfish contaminated with biologic toxins (biotoxins) is associated with a number of diarrheal and paralytic human diseases (*94–98*). The most common are microalgal toxins from HABs. In general, algal blooms result from the rapid reproduction and localized dominance of phytoplankton. Marine and estuarine HABs can cause shellfish and tropical fish poisoning, wildlife disease and mortality, and disease in humans who ingest contaminated seafoods (*99–101*). Ciguatoxin (from a few reef fish species), scombrotoxin (from tuna, mackerel, bluefish, and a few other species), and raw mollusc consumption represent more than 90% of outbreaks and 75% of individual cases of seafoodborne illnesses reported to the CDC from 1978 to 1987 (*43*).

Several toxic dinoflagellates (e.g., *Alexandrium, Gymnodinium, Pyrodinium, Dinophysis, Prorocentrum* spp.), diatoms (e.g., *Pseudonitzschia* spp.), and cyanobacteria (e.g., *Anabaena* spp.) are associated with human shellfish poisonings (*99,102,103*). Outbreaks have clustered in the Northeast, Florida, and the Gulf States and resulted in beach and shellfish bed closings. In addition, there are reports of introduction of harmful algal species via ballast water or aquaculture into areas favorable for their proliferation (*104,105*). Several reported outbreaks of human poisonings associated with seafood ingestion are outlined in Table 2. An additional potential public health threat is respiratory irritation from aerosolized inhalation of toxic sea spray in the vicinity of a bloom (*106,107*). A possible new health risk currently under study is possible estuary-associated syndrome, comprising a range of neurologic symptoms, including memory loss, from exposure to coastal waters harboring the *Pfiesteria piscicida* dinoflagellate (*108*). A variety of freshwater and estuarine animals are at risk for disease from HABs (*109,110*). In addition, cattle, other livestock, and wildlife are at risk from toxic cyanobacterial blooms in freshwater systems (*111*). Contamination of beaches and shellfish beds and its effects on marine wildlife and other animals can have wide-ranging and negative economic impacts on seafood industries, recreation, tourism, and the livelihoods of communities. Although this report does not address food supply or livelihood issues, they are important issues for water resource management.

Environmental Influence on Cholera Transmission

The recent history of cholera highlights the influence of environmental change on disease transmission. *V. cholerae* O1 biotype El Tor, the agent of the seventh pandemic of cholera, was responsible for the explosive outbreak in Latin America beginning in January 1991 (*78*). It is unclear how *V. cholerae* was introduced, but migration of the disease across the continent over the subsequent 18 months clearly followed continental waterways. *V. cholerae* has been found in the plankton and fish in ponds and coastal waters of Latin America.

Laboratory and field studies identified a viable, but nonculturable, quiescent form of *V. cholerae* that can be associated with a wide range of surface marine life, including plankton (*112–114*). When conditions are conducive to phyto- and zooplankton blooms (e.g., sufficient nitrogen and phosphorus and favorable water temperature), *V. cholerae* can revert to an infectious state (*112,115*). Prolonged survival of *V. cholerae* is associated with the presence of cyanobacteria, silicated diatoms and drifting dinoflagellates, seaweed, macroalgae, and zooplankton. Algal-derived surface films and slimes can enhance growth of the bacteria by creating turbulence-free microenvironments (*116*). Up to 1 million bacteria have been detected on the egg sacs of zooplankton copepods (*117*).

Seasonal warming of sea-surface temperatures enhances plankton blooms of copepods (*78*) that serve as reservoirs for *V. cholerae.* These blooms have been followed by a lagged increase in cholera cases that generally occur in the wake of El Niño events affecting the Bay of Bengal, according to a study using satellite remote sensing to measure sea-surface temperature and height (*118*). This relationship with El Niño has been observed in Bangladesh over an 18-year period (*119*). Similar linkage between elevated temperature and detection of *V. cholerae* in the environment have been documented in Peru as well (*120*).

Role of Climate

Key climatic variables, particularly precipitation and temperature, have a relationship to drinking-waterborne disease, foodborne disease, and coastal water quality issues. Much of the data and evidence are preliminary; however the emerging implications demonstrate

Table 3. Foodborne outbreaks traced to fresh produce, 1990–1996.[a]

Year	Pathogen	Food	Reported cases (no.)	States (no.)	Location
1990	*S.* Chester	Cantaloupe	245	30	Central America
1990	*S.* Javiana	Tomatoes	174	4	United States
1990	Hepatitis A	Strawberries	18	2	United States
1991	*S.* Poona	Cantaloupe	> 400	23	United States/Central America
1993	*E. coli* O157:H7	Apple cider	23	1	United States
1993	*S.* Montevideo	Tomatoes	84	3	United States
1994	*Shigella flexneri*	Scallions	74	2	Central America
1995	*S.* Stanley	Alfalfa sprouts	242	17	Source not known
1995	*S.* Harford	Orange juice	63	21	United States
1995	*E. coli* O157:H7	Leaf lettuce	70	1	United States
1996	*E. coli* O157:H7	Leaf lettuce	49	2	United States
1996	*Cyclospora*	Raspberries	978	20	Central America
1996	*E. coli* O157:H7	Apple juice	71	3	United States

[a]Data from Tauxe (*75*), CDC (*92,93*), and Millard et al. (*173*).

Table 4. Produce-processing events and potential contamination sources.[a]

Event	Potential contamination sources
Production and harvest	
Growing, picking, bundling	Irrigation water, manure, lack of field sanitation
Initial processing	
Washing, waxing, sorting, boxing	Washwater, handling
Distribution	
Trucking	Ice, dirty trucks
Final processing	
Slicing, squeezing, shredding, peeling	Washwater, handling, cross-contamination

[a]Data from Tauxe (*75*).

Table 5. Examples of some waterborne and foodborne agents and the climate connection.

Pathogen groups	Pathogenic agent	Foodborne agents	Waterborne agents	Indirect weather effect	Direct weather effect
Viruses	Enteric viruses (e.g., hepatitis A virus, Coxsackie B virus)	Shellfish	Groundwater	Storms can increase transport from fecal and wastewater sources	Survival increases at reduced temperatures and sunlight (ultraviolet)[a]
Bacteria; cyanobacteria; dinoflagellates	*Vibrio* (e.g., *V. vulnificus*, *V. parahaemolyticus*, *V. cholerae* non-01; *Anabaena* spp., *Gymnodinium*, *Pseudonitzschia* spp.)	Shellfish	Recreational, wound infections	Enhanced zooplankton blooms	Salinity and temperature associated with growth in marine environment
Protozoa	Enteric protozoa (e.g., *Cyclospora*, *Cryptosporidium*)	Fruits and vegetables	Recreational and drinking water	Storms can increase transport from fecal and wastewater sources	Temperature associated with maturation and infectivity of *Cyclospora*

[a]Also applies to bacteria and protozoa.

Table 6. Studies examining the role of weather in waterborne diseases.

Waterborne health risk	Location (reference)	Findings
Drinking water contamination	Milwaukee (*20*); Oxford/ Swinden, UK (*174*)	Cryptosporidium outbreak; associated with a rainfall event
	Delaware River (*32*)	*Cryptosporidium* and *Giardia* concentrations in river; positively correlated with rainfall
	Red Lodge, Montana (*28*)	Two outbreaks of waterborne giardiasis; associated with heavy precipitation runoff
	Peru (*121,123*); Nepal (*175*)	*Cyclospora* infections in children; associated with increasing ambient temperatures
		Above-average temperatures in Peru during the 1997/1998 El Niño were associated with a significant increase in the number of hospital admissions of children with severe diarrhea in Lima, Peru. During the El Niño period, admissions increased by 8% for every 1°C rise in ambient temperature.
Coastal-related diseases	Florida (*130*)	*V. vulnificus* reached a high concentration in conditions of low salinity associated with increased freshwater flow to estuaries. In addition, human enterovirus was detected in a significantly greater than normal percentage of water samples during heavy rainfall events associated with El Niño between December 1997 and February 1998.

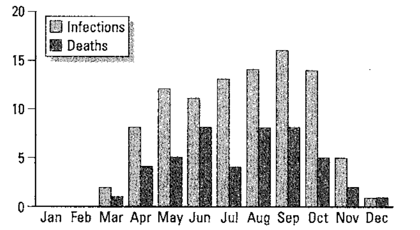

Figure 2. Seasonality of shellfish poisoning in Florida, 1981–1994. Monthly distribution of oyster-associated *V. vulnificus* illness (or shellfish poisoning) and deaths occurring in Florida from 1981 to 1994. Over the 14-year period higher numbers of cases occurred during summer. Monitoring in Florida shows a statistically significant association between concentrations of this pathogen in estuaries and temperature and salinity, the latter being affected by rainfall and runoff. Adapted from Lipp and Rose (*77*).

that these relationships can be further studied and elucidated, given an adequate research agenda. Direct and indirect effects of weather factors on enteric viruses, *Vibrio* species, and enteric protozoa are outlined in Table 5. Studies examining the interactions of weather with waterborne diseases are summarized in Table 6.

International studies on cholera and other diarrheal diseases shed some light on the seasonal influence of climate on waterborne diseases. In addition, above-average temperatures in Peru during the 1997/1998 El Niño were associated with a doubling in the number of children admitted to the hospital with diarrhea (*121*). Spore maturation of *C. cayetanensis* quickens as temperatures warm (*90,122*), and in Peru the incidence of cyclosporosis peaks during the warmer summer months (*123*) (Table 6).

Drinking Water

Data on drinking water outbreaks in the United States from 1948 to 1994 from all infectious agents demonstrated a distinct seasonality, a spatial clustering in key watersheds, and a statistical association with extreme precipitation (*124,125*), thus suggesting that in certain watersheds, by virtue of the land use, fecal contaminants from both human sewage and animal wastes are transported into waterways and drinking water supplies by precipitation events (*124*).

As previously mentioned, many anecdotal reports suggest rainfall as a contributing factor to waterborne outbreaks and the association of rainfall with contamination of river water supplies (*24,32*). In September 1999 the largest reported waterborne associated outbreak of *E. coli* O157:H7 occurred at a fairground in the State of New York and was linked to contaminated well water (*126*). Heavy rains following a period of drought coincided with this major outbreak event (*127*). The likelihood of this type of problem occurring may be increased under conditions of high soil saturation, which enhances rapid transport of microbial organisms (*128*).

Foodborne Diseases

Seafood. Changing weather parameters have been associated with the contamination of coastal waters and shellfish-related diseases. *Vibrio* spp., as well as the diseases they cause, are strongly associated with weather factors, particularly temperature (*129*), which dictate their seasonality and geographic distribution (Figure 2) (*77*). In temperate estuaries *V. vulnificus* is rarely recovered during winter months. In more subtropical regions (to temperatures of 17°C), this pathogen is found throughout the year (*130*). As *V. vulnificus* thrives under moderate salinity conditions, this factor is also responsible for much of the seasonal and geographic distribution of the organism. In southwest Florida *V. vulnificus* reached its highest concentrations at salinities below 15 practical salinity units (psu). Correlations between salinity and bacterial concentrations were significantly positive below 15 psu and significantly negative above 15 psu (*130*).

Runoff from rainfall is also a key factor in contamination of coastal waters and shellfish harvesting areas. A recent year-long microbiologic survey of a southwest Florida estuary (Charlotte Harbor) showed that the concentrations of fecal indicator organisms during winter of the high-precipitation El Niño of 1997/1998 were manyfold greater than were the concentrations found throughout the rest of the year (*131*). During the same period, infectious enteroviruses were detected at 75% of the sites sampled, whereas in previous months no viruses were found. Viruses were detected in open shellfish harvesting areas during this increase in rainfall. Antecedent rainfall predicted the presence of enteroviruses 1 week later. Likewise, fecal indicators were significantly correlated with rainfall.

Produce. Another example of how weather can influence foodborne diseases is the transmission of *C. cayetanensis*, a protozoan associated with diarrheal disease (*90*). Human fecal wastes are the source of oocysts. The oocysts are immature when excreted, then mature in the outside environment through a process known as sporulation. This process is dependent on warm temperatures (*122,132*). Outbreaks in the United States associated with imported produce occurred in the late spring or early summer (*89,91*). In Peru, for example, the incidence of cyclosporosis shows marked seasonality, peaking in the summer (*123*). In addition, during the strong El Niño of 1997/1998, hospital admissions in Lima, Peru for all causes of childhood diarrhea increased 2-fold; temperatures were 5°C above normal for Lima at the time (*121*).

Coastal Impacts

HABs occur in association with local factors such as effluents and land use changes and are triggered by changes in ocean temperatures, upwelling, and weather patterns (*133*). Reports of HABs, red tides involving dinoflagellates as well as other harmful algal blooms have increased globally in the past several decades (*105,134*). Of the approximate 5,000 identified marine microalgae, the number known to be toxic or harmful has increased over the past several years from about 20 to 86 species (*100*). Some of this increase may be attributed to the expanded study of benthic (bottom-dwelling) microalgae and to previously described species not known to be toxic (*110*). HABs are influenced by weather and marine ecology. HABs can be both the consequence of human disturbance (e.g., blooms stemming from CSOs and nutrient runoff) and part of the natural processes of the marine ecosystem.

Extreme weather events can also lead to waterborne disease outbreaks and marine-related diseases. Heavy rains and flooding flush microorganisms, nutrients (sparking HABs) and toxic chemicals into watersheds and coastal zones. On the other hand, droughts can diminish water flow, thereby concentrating organisms and chemicals, and may reduce water for basic hygiene.

Adaptation

Protection of Drinking Water

The nation's drinking water comes from ground and surface water. Surface waters include lakes, rivers, and reservoirs. Just over half the U.S. population depends on groundwater from wells for drinking water, including 23 million people who obtain their water from private wells (*135*). Drinking water quality is protected by federally established minimum standards passed under the federal Safe Drinking Water Act (*136*), first enacted in 1974. There are legally enforceable National Primary Drinking Water Regulations (*135*) (primary standards) or maximum contaminant levels (MCLs) (*137*), for more than 80 contaminants; the list includes inorganic chemicals, organic chemicals, radionuclides, and microorganisms. States are responsible for enforcement, although the federal government maintains an oversight role. These rules apply to 55,000 community water systems that are public (*138*) systems serving people year-round.

Primary treatment of water to reduce microbial contamination involves the addition of a disinfectant such as chlorine. Despite federal regulations and treatment technologies, MCL violations and violations of specific treatment standards are reported (*135*). In addition, some households, especially in rural areas, rely on untreated water such as water from shallow wells for part or all of their residential needs. It is now known that certain emerging pathogens can pass through existing filtration and disinfection systems, among them *Cryptosporidium*. Water chlorination, a widely used method of disinfection, is not as efficient as ozone for inactivating the *Cryptosporidium* oocysts (*24*).

The Safe Drinking Water Act (*136*) was substantially amended in 1996 to include new provisions for source and groundwater protection and improved enforcement and oversight of water suppliers (*139*). In 1998 the federal government began implementing a Clean Water Action Plan, a primary focus of which is watershed protection. Implemented by the U.S. EPA, the U.S. Department of Agriculture, and state, tribal, and local governments, the Action Plan involves preparation of unified watershed assessments, development of strategies for watershed restoration and pollution prevention, and provision of small federal grants to local organizations interested in watershed protection (*4*).

Protection against Marine-Related Human Disease

The most obvious protections against marine-related human disease outbreaks include avoidance (e.g., beach closings) (*140*); adequate sewage/sanitation systems; safe food preparation (cooking of shellfish), storage infrastructures, and monitoring (e.g., red tides, *Vibrio* spp., and algal toxins). However the restoration of ecosystems, particularly protection of wetlands, may also influence the occurrence and distribution of hazardous microbial blooms, as coastal wetlands filter nutrients, microorganisms, and chemicals, and buffer coasts from storm surges. Currently, in most states fecal coliform monitoring determines when beaches and shellfish beds are closed. Several states, realizing that fecal coliform is an ineffective measure of risk, implement *Enterococci* monitoring for marine waters. For freshwater beaches *E. coli* monitoring is recommended (*45,141,142*). In some states, such as California, a virus standard has even been discussed.

Hazards associated with the consumption of biotoxins in seafood can be categorized into three areas: product safety, food hygiene, and institutional and business compliance (*43*). Procedures to help protect humans from marine-associated risks include closing of shellfish beds and fishing areas, and better education and training of health-management and food-handling personnel on the proper use and storage of food. Extra label and handling guides for selected foods are under consideration (*143*). Streamlined enforcement efforts are being developed to ensure compliance with new food safety regulations and new regulatory control procedures, such as Hazard Analysis and Critical Control Points (HACCP) of the U.S. Food and Drug Administration (U.S. FDA) (*144*).

Recommended public health measures for preventing water- and foodborne diseases include waste treatment, watershed protection, remediation, improved water treatment technology, public education, early diagnosis, and appropriate drug prophylaxis and immunization when available. Measures to protect against potential harmful health effects from aerosolized biotoxins include public warnings proscribing outdoor activity in areas with significant fish kills. The feasibility of enacting such public health measures is dependent upon the adequacy of financial resources and the level of socioeconomic development.

Current Surveillance System

As discussed below in the section addressing knowledge gaps, surveillance is one area where improvements are greatly needed. Further documentation on the state of public health surveillance for infectious diseases has been reviewed elsewhere (*145–147*).

Knowledge Gaps and Research Needs

Improved Drinking Water Monitoring and Treatment

One of the disadvantages of the current system is that the outbreaks are detected after the fact—after the contamination event and after individuals have become ill. The disease surveillance system is incapable of detecting outbreaks when diagnosed cases are not reported to the health department, such as when mild symptoms are attributed to other causes or when health problems are not medically treated. In addition, delays exist in detecting outbreaks because of the time required for laboratory testing and reporting of findings. Ultimately, better assessment of water quality and risk to the drinking water system from the watershed to the tap will allow for better prevention and controls to limit the impact of contamination events. Event monitoring, as well as development and implementation of better monitoring tools for waterborne microorganisms, is imperative. These need to be tied to watershed descriptors and hydrologic models for the development of water quality models for key pathogens.

Improved Wastewater Management

Wastewater management can also be improved. Whereas most large urban centers have well-developed systems to transport, treat, and discharge wastewaters, these systems are aging and becoming overburdened by increasing population. A recent Water Environment Research Foundation survey showed that both combined sewer systems and separate sanitary sewers report an average flow of 173 gallons per capita per day (gpcd), well above the U.S. EPA maximum flow guidance of 100 gpcd (*34*). Wastewater facilities with separate sanitary sewers report that their sewers are approximately 34 years old and experience 44 collapses per year, or 1 per 24 miles of sewer. Weather perturbations such as increased precipitation can increase the load to combined sewer systems and sanitary sewers through increased inflow and infiltration. To effectively treat wastewater under these conditions, facilities must increase their capacity and storage and improve their process control.

Non-point sources such as septic tanks are a big concern for high-tourist areas and coastal communities. The change in management of wastes in these areas will be expensive and need to be fully examined. Assessment of the impacts of subsurface disposal on groundwater and surface microbial water quality is needed for appropriate decisions to be made, particularly in light of the possible change in the rainy season and storms that could impact the contamination of surface and groundwaters.

Watershed Protection

Watershed protection will continue to be an extremely important factor influencing water quality. Watershed water quality directly impacts source water and finished water quality as well as recreational sites and coastal waters. Better farming practices (to capture and treat agricultural wastes) and surrounding vegetation buffers, along with improved city disposal systems to capture and treat wastes, would reduce the runoff of nutrients, toxic chemicals, trace elements, and microorganisms flowing into reservoirs, groundwater, lakes, rivers, estuaries, and coastal zones. For urban watersheds, more than 60% of the annual load of contaminant is transported during storm events (*148*). Reducing these effluents would also improve the overall health of marine ecosystems and could protect against HABs. Monitoring tied to hydrologic quantity and quality models could improve assessment and changes needed in watersheds to protect water quality for downstream users and ecosystems.

Prevention of Foodborne Diseases

Many factors contribute to foodborne disease outbreaks associated with contaminated water, including meteorologic conditions, unsanitary handling of food, and contamination of water supplies with sewage and other pollution sources. Improvements in protection of water resources, drinking water treatment, and wastewater management will continue to be important in disease prevention. Citizen education campaigns about the recognition, prevention, and treatment of seafood-related disease and food-handling practices will be helpful. With more imported produce entering the U.S. market, improved surveillance systems and adaptive measures such as irradiation may become necessary.

Improved protection against HABs: understanding ecologic degradation. The potential health effects of HABs are not fully understood (*149*). Understanding the long-term impacts of sublethal, chronic effects will require field studies, time-series monitoring, and modeling (*110*). The long-term effects of toxins bioaccumulated within food chain predators and in people who consume seafood also need further study. HABs can affect the health of sea mammals, shore lands, fish, and humans, thus potentially altering food sources and nutrition. Better understanding of these ecosystem–health interactions is necessary. Finally, many stresses and perturbations may affect near-coastal areas in unknown ways. Such disturbances may be cumulative and additive. Systems experiencing multiple stresses show reduced ability to resist and rebound in the face of additional stresses (*150*). Many studies have shown that the cumulative effect of multiple stresses acting in concert over time serves to undermine the stability of species interactions and complex food webs (*151*).

Disease Surveillance

Waterborne and foodborne diseases often go undetected and/or unreported, and there is a great need for improving epidemiologic surveillance. Timely, accurate reports of human water-related and marine-related morbidity and mortality are needed to further develop comprehensive assessments with the U.S. FDA and CDC in cooperation with the Food and Agriculture Organization of the United Nations and the World Health Organization. In the United States, the Council of State and Territorial Epidemiologists and the National Association of City and County Health Officials, groups central to monitoring and surveillance, have not yet received standardized, uniform criteria for reporting water-related and marine-related human disease information. A newly developed reporting system, PulseNet National Computer Network to Combat Food-borne Illness (*152*) prompted by *E. coli* O157:H7-contaminated food outbreaks, offers great promise, but has not yet been extended to include the full spectrum of diseases (virus, protozoan, and marine-related infections, and toxin-related illnesses). Another national communication system, FoodNet: Food-borne Disease Active Surveillance Network (*153*), was set up in 1995 by the CDC, the U.S. Department of Agriculture, and several state health departments, and will add to a better understanding and response to the spread of marine pathogens within the food transportation system.

Currently, uniform standards are lacking for interpreting and analyzing the data collected by various institutions. For example, Florida both collects and releases detailed information on clusters and cases of foodborne illness. Massachusetts, on the other hand, collects less-detailed data and releases only aggregate data by county and year. It should be noted that *Vibrio* infections were recently made reportable in several southern states, and programs such as the Gulf of Mexico Network (*154*) are improving intra- and interstate recognition of the importance of waterborne diseases (*155*). Development of uniform standards for health effects databases remains a future goal.

With international travel, the global food market, and increased shipping throughout the world, worldwide impacts may be seen in the future, even if only one section of the hemisphere is effected climatically. Disease surveillance, proper case management, environmental monitoring, and international communication systems are key for curbing the spread of contamination and/or outbreaks. International regulations on the safety of imported produce and seafood will curb foodborne disease outbreaks. Expanding current controls on ballast water and transport of exotics may help prevent the spread of harmful algal species and the distribution of disease-causing agents (*104*).

Early-warning systems. Ultimately, if key climatic or environmental factors or rapid monitoring tools could be developed and linked to the potential for health impacts, early-warning systems could be coupled to such surveillance efforts to optimize intervention measures. Advanced early-warning systems can be used to generate public health advisories and generate preventive public health measures, including boil water orders, shellfish bed closings, and temporary bans on seafood consumption. One example is warning for HABs based on remotely sensed data with targeted sea sampling. Imagery from the Advanced Very High Resolution Radiometer satellite is used to detect suspected blooms of toxic dinoflagellates (*156*). When signatures of blooms are visualized by remote sensing, ships are sent out to sample the water. The use of a newer Sea Wide Field Sensor (SeaWiFS) satellite ocean color imagery provides more accurate detection of algal blooms and an opportunity to improve warnings for HABs.

Development of health early-warning systems for watersheds and coastal regions will require cooperation among health monitoring and resource agencies, both national and international. Monitoring of the marine environment from space and in coastal zones must be complemented by surveillance of seafood safety and national health statistics. For example, a potential disease database could be developed from monitoring of pharmaceutical sales and nurse or physician visitation records (*157,158*).

Future Climate and Health Assessments

A high priority for future assessments of climate change and waterborne diseases is more studies of the basic relationships among temperature, sea-level rise, other climatic factors, and the ecology of disease agents. Such studies need to consider potentially increased variability of precipitation affecting runoff. Downscaled analysis from general circulation models to obtain more site-specific relevant projections also is important.

Coordinated monitoring of physical, chemical, and biologic parameters is needed to continue to build databases and to develop models integrating environmental and social conditions, consequences, and costs. Integrating models of causal factors with models of ecologic dynamics also is needed. Collaborative, multidisciplinary approaches, involving health and veterinary professionals, biologists, ecologists, physical scientists, database specialists, modelers, and economists, are needed to carry out integrated assessments. Interagency agreements will be needed to coordinate and support this initiative. Testing models and hypotheses based upon observed temporal and spatial co-occurrences may help focus research policies. It is essential to better delineate, in time and location, the occurrence of disease and to maintain standardized health databases.

Waterborne diseases remain a major public health problem in the United States. Due to the sensitivity of many waterborne diseases to changes in weather factors (or parameters), improved surveillance, watershed/source water protection, and educational programs are needed to understand and prevent disease outbreaks.

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137. Primary standards protect the public health; secondary standards address public welfare by protecting against drinking water that looks or tastes bad.
138. "Public" water systems serve piped water or water delivered by "constructed conveyances" to at least 25 people in their homes or 15 service connections at least 60 days per year; other systems are considered private. Some public systems, for example, in schools, factories, or campgrounds, have their own water supply. Both community and noncommunity systems are regulated under the Safe Drinking Water Act; private or individual systems are not.
139. The new law required the U.S. EPA to publish (within 18 months and then every 5 years thereafter) a list of contaminants not currently subject to any proposed or final national primary drinking water regulation and that are known or anticipated to occur in public water systems. Several microbial contaminants are on the list, including cyanobacteria, calciviruses, echoviruses, *Helicobacter pylori*, and *Microsporidia*. The final Interim Enhanced Surface Water Treatment Rule of the U.S. EPA, which became effective February 16, 1999, is intended to improve control of microbial pathogens including, in particular, *Cryptosporidium*, and to address risks posed by disinfection byproducts. The new rule set an MCL goal of zero for *Cryptosporidium* and imposed measures to improve filtration in an effort to reduce the likelihood of endemic illness from *Cryptosporidium*. The 1996 amendments to the Safe Drinking Water Act also required the U.S. EPA to develop rules to address the potential risks posed by disinfectants themselves; that rule was issued in December 1998.
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