
Climate Change and Waterborne Disease Risk in the Great Lakes Region of the U.S.

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Abstract: Extremes of the hydrologic cycle will accompany global warming, causing precipitation intensity to increase, particularly in middle and high latitudes. During the twentieth century, the frequency of major storms has already increased, and the total precipitation increase over this time period has primarily come from the greater number of heavy events. The Great Lakes region is projected to experience a rise these extreme precipitation events.

For southern Wisconsin, the precipitation rate of the 10 wettest days was simulated using a suite of seven global climate models from the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report. For each ranking, the precipitation rate of these very heavy events increases in the future. Overall, the models project that extreme precipitation events will become 10% to 40% stronger in southern Wisconsin, resulting in greater potential for flooding, and for the waterborne diseases that often accompany high discharge into Lake Michigan.

Using 6.4 cm (2.5 in) of daily precipitation as the threshold for initiating combined sewer overflow into Lake Michigan, the frequency of these events is expected to rise by 50% to 120% by the end of this century. The combination of future thermal and hydrologic changes may affect the usability of recreational beaches. Chicago beach closures are dependent on the magnitude of recent precipitation (within the past 24 hours), lake temperature, and lake stage. Projected increases in heavy rainfall, warmer lake waters, and lowered lake levels would all be expected to contribute to beach contamination in the future.

The Great Lakes serve as a drinking water source for more than 40 million people. Ongoing studies and past events illustrate a strong connection between rain events and the amount of pollutants entering the Great Lakes. Extreme precipitation under global warming projections may overwhelm the combined sewer systems and lead to overflow events that can threaten both human health and recreation in the region.

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Background

Climate Change and Hydrologic Extremes

Global climate change is expected to cause warming temperatures, sea-level rise, and a change in frequency of extremes of the hydrologic cycle (more floods and droughts). This study focuses on the health implications of heavy precipitation, with an in-depth look at related health risks in the U.S. Such heavy precipitation events often result in substantial societal impacts, including an increased risk of waterborne disease outbreaks. Heavy precipitation

can lead to stormwater discharge of contaminants into water bodies if the volume exceeds the containment capacity. The seasonal contamination of surface water in early spring in North America and Europe may explain some of the seasonality in sporadic cases of many types of waterborne diseases. According to the North American chapter of the most recent IPCC report,¹ heavy precipitation events are expected to increase under climate change scenarios (Figure 1).

Rainfall Projections for the Great Lakes Region

For the Great Lakes region of the U.S., contamination events typically occur when daily rainfall levels exceed a threshold of about 5–6 cm (2–2.5 in).^{2,3} Given that rainfall extremes are expressions of climate, there is heightened concern as to how this type of event might change in a warmer future climate.

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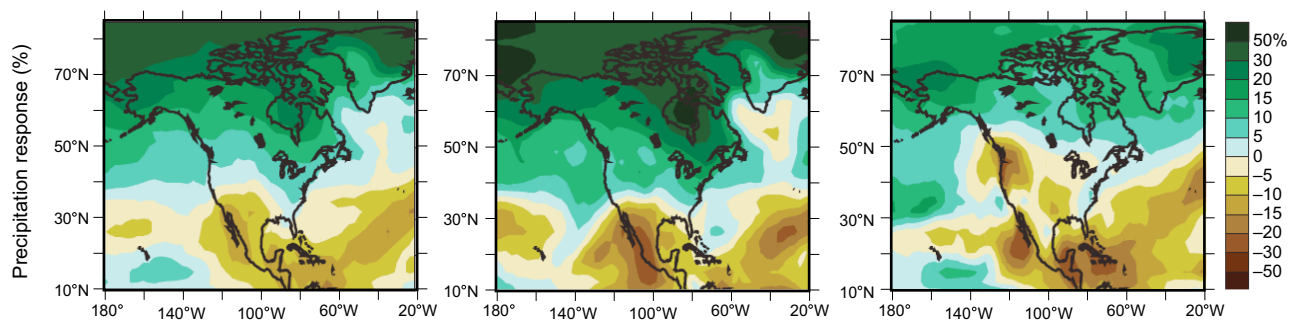


Figure 1. Projected changes in total precipitation from the late twentieth to the late twenty-first centuries, based on middle-of-the-road increases in greenhouse gases: annual (left), winter (center), and summer (right). Source: IPCC, 2007¹

Meteorologic theory indicates that the intensity of a precipitation event is regulated primarily by the local amount of moisture in the atmosphere during a storm and that the moisture-holding capacity of the atmosphere increases exponentially with temperature.⁴ Consequently, expectations are high that more intense precipitation will accompany global warming. This possibility is supported by many modeling studies that have simulated the climatic response to increasing concentrations of greenhouse gases.^{5–8} Precipitation intensity (total precipitation divided by the number of wet days) is projected to increase almost everywhere, particularly in middle and high latitudes where average precipitation is also expected to increase.⁹ Most of the Great Lakes region is projected to experience a rise in both average and extreme precipitation events.^{1,10}

These anticipated future changes are consistent with recent trends over the U.S., including the Great Lakes area. Major storms have been occurring with greater frequency during the twentieth century, and the total precipitation increase over this period has resulted disproportionately from the increase in heavy events.^{11–13} This trend has been accentuated by the increase in heavy events toward the end of the century, the time of most pronounced global warming.^{14,15}

These large-scale findings were tailored to the Wisconsin–Chicago region, where we are conducting research on the health impacts of extreme events. In one example, the recent and future simulated precipitation rate of the 10 wettest days were computed for the Madison WI area from seven global climate models (GCMs) used in the UN Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report¹ (Figure 2). For each ranking (tenth wettest day to the wettest day), the precipitation rate of these very heavy events increases in the future, and the enhancements are most pronounced for the most extreme events (wettest and second wettest days). Overall, the models project that these extremely heavy precipitation events will become 10% to 40% stronger in southern Wisconsin, resulting in greater potential for flooding and for the waterborne diseases that often accompany high discharge into Lake Michigan.³

A somewhat different approach was used to estimate future changes in extreme precipitation over Chicago. For this application, the GCM output from two representative models, the geophysical fluid dynamics laboratory (GFDL) model and the parallel climate model (PCM) was statistically downscaled to provide higher-resolution information. Statistical downscaling uses historical observational data to tailor projections from a global model to a local scale. A statistical relationship is first established between a location’s measured precipitation and the corresponding climate model output during a prior time interval, typically around 30 years. This historical relationship—between climate model output at the relatively coarse scale of the GCM and the daily precipitation values recorded on the local scale—is then used to downscale future model projections to the same local scale. This method assumes that

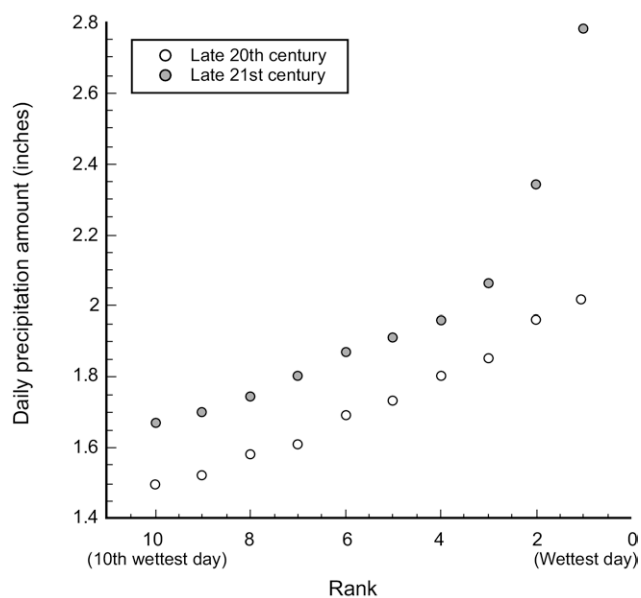


Figure 2. GCM-simulated precipitation amounts in southern Wisconsin for the 10 wettest days in the late twentieth and late twenty-first centuries (10 days total for each century), based on middle-of-the-road projected increases in greenhouse gases. GCM, global climate model

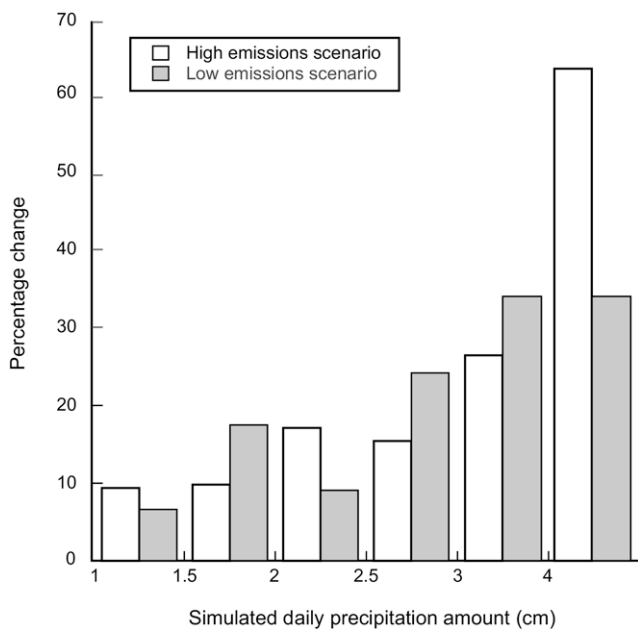


Figure 3. Projected change in the frequency of heavy precipitation in Chicago by the late twenty-first century, based on downscaled climate model output for high-end and low-end greenhouse gas emissions scenarios from two global climate models used in the Chicago Climate Impact Assessment. Source: Hayhoe and Wuebbles²

the relationships between large- and small-scale processes remain the same over time.

The change was analyzed in the frequency of heavy daily precipitation events, ranging from 1 to 5 cm (0.4–2.0 in), between the late twentieth and late twenty-first centuries (Figure 3). Although the precise changes are dependent on the assumed greenhouse gas emissions scenario, the results clearly indicate more frequent extreme events, ranging from $\leq 10\%$ increases for 1–1.5 cm (0.4–0.6 in) events to $>60\%$ for the heaviest storms (≥ 4 cm [≥ 1.6 in]) in the high-emissions scenario. Using 6.35 cm (2.5 in) of daily precipitation as the threshold for initiating combined sewer overflow into Lake Michigan,² the frequency of these events is expected to rise by 50%–120% by the end of this century. This translates into an expected occurrence of about one event every other year in the recent past to approximately one event every year (low-emissions scenario) to 1.2 events every year (high-emissions scenario) by the end of this century.²

The expected changes in the hydrologic cycle, including increases in extreme precipitation events, should have a direct bearing on waterborne diseases in the Great Lakes. For example, the 1993 *Cryptosporidium* outbreak in Milwaukee was preceded by the heaviest rainfall in 50 years in the associated watersheds.¹⁶ Summertime bacteria concentrations in an inland lake in Wisconsin (Lake Geneva) exhibit positive, significant correlations not only with mean summertime rainfall but also with the duration between rainfall events, a

variable that is expected to increase in the future.¹⁷ The combination of future thermal and hydrologic changes may affect the usability of recreational beaches. Chicago beach closures are dependent on the magnitude of recent precipitation (within the past 24 hours), lake temperature, and lake stage (i.e., height of the water surface above an established level).¹⁸ Projected increases in heavy rainfall, warmer lake waters, and lowered lake levels¹⁹ would all be expected to enhance beach contamination in the future. Although more extreme rainfalls would seem to contradict the projection of lower lake levels, the latter expectation stems from a large anticipated increase in evaporation at the lake surface (which can offset the precipitation gain) and a higher proportion of future precipitation falling as heavy events, even if the total precipitation amount does not rise.

Vulnerability Factors

Even today, many of our community water systems can be overburdened by extreme rainfall events. Heavy rainfall or snow melt can exceed the capacity of the sewer system or treatment plant, which are designed to discharge the excess wastewater directly into surface water bodies.^{20,21} In urban watersheds, more than 60% of the annual loads of all contaminants are transported during storm events.²² In general, turbidity increases during storm events, and studies have recently shown a correlation between increases in turbidity and illness in communities.^{23,24} Also, higher winter temperatures could further enhance flooding from the contribution of snow melt.

Combined Sewage Overflows and Aging Water Infrastructure

Older cities around the nation have combined sewer systems, which are designed to capture both sanitary sewage and stormwater and convey these flows to a wastewater treatment plant. Large rain events can overwhelm these systems, causing untreated sewage mixed with stormwater to be released directly into receiving waters. The U.S. Environmental Protection Agency (EPA) has estimated that 770 communities release more than 3.2 trillion liters (850 billion gallons) of combined sewage to the nation's waterways annually.²⁵ As infrastructure improvements to sewer system capacity are made, the number of combined sewer overflows can be decreased. For example, the construction of an inline storage system in Milwaukee reduced the number of combined sewer overflows from 40–60 per year to 0–4 per year (with the average approximating 1.5 per year over the past 10 years). However, it remains difficult to capture the most extreme events. Changing weather patterns that bring

more extreme storms to some regions may outpace the infrastructure improvements.

Case Study

Climate and water quality in Milwaukee. The urban environment presents unique risks of water contamination. Runoff from impervious surfaces contains metals, pesticides, pathogens, and fecal indicator bacteria. It has been linked to adverse public health effects.^{26–28} In most municipal areas, urban stormwater is conveyed in separated sewer systems and discharged directly into receiving waters. Aging infrastructure may cause sanitary sewage to infiltrate into stormwater pipes, where it is essentially discharged with no treatment. Beaches are often located in urbanized areas and highly susceptible to stormwater impacts.^{29–31} Accelerating development of urban coastal areas and changing storm patterns may synergistically increase the amounts of urban stormwater released into coastal systems.

The Milwaukee River Basin consists of 1440 km² (556 miles²) of rural, agricultural, suburban, and urban land use. The basin's watersheds drain to three major rivers that converge in downtown Milwaukee and discharge through a 140 m (0.09 mile) channel leading to Lake Michigan. Following storm events, the fecal indicator bacteria *Escherichia coli* can be detected in the channel at levels as high as 2000–7000 colony forming units (CFU)/100 ml. These levels are 10 times higher than the EPA-recommended limit for recreational waters.³² The presence of *E. coli* demonstrates that fecal pollution is present; however, given the complexity of this system, the bacteria may come from agricultural runoff, urban stormwater, or sanitary sewage. Human viruses have been detected at this same site following storm events with no reported sewage overflows, providing evidence that sanitary sewage may be continually released into the basins tributaries. Storm events of >3 inches of rainfall within 24 hours may overwhelm the combined sewer systems and lead to an overflow. In this case, the levels of *E. coli* detected in the channel leading to Lake Michigan can be up to 10 times higher (e.g., 20,000–50,000 CFU/100 ml) than when there are no sewage overflows.³ These events generally occur less than three times per year, and do not occur at all in dry years (Figure 4).

Milwaukee is not unique in terms of its impact on the lake; many cities around the Great Lakes are situated near major rivers that come from a complex mixture of watershed sources. The Great Lakes, which serve as a drinking water source for more than 40 million people, are particularly susceptible to fecal pollution and can become reservoirs for waterborne diseases. Ongoing studies and past events illustrate a strong connection between rain events and the amount of pollutants entering the Great Lakes. The 1993 *Cryptosporidium* outbreak in Milwaukee, which sickened more than

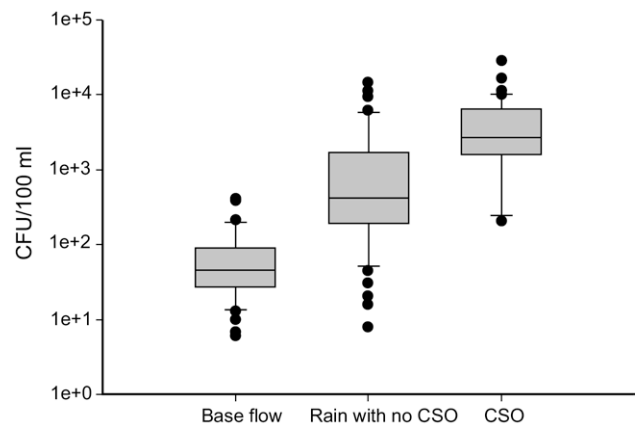


Figure 4. Levels of *E. coli* in the Milwaukee estuary, which discharges to Lake Michigan, 2001–2007, during base flow ($n=46$); following rain events with no CSO ($n=70$); and following CSO events ($n=54$). Boxes indicate 75% of values, with median values drawn in each. Whiskers are 95% of values and outliers are shown as closed circles. There were significant differences in *E. coli* levels following rainfall and CSOs compared to base flow ($p \leq 0.05$). CFU, colony forming units; CSO, combined sewer overflow

400,000 people, coincided with record high flows in the Milwaukee River, a reflection of the amount of rainfall in the watershed.¹⁶

Land-Use Patterns

Land cover conversion to impervious surfaces (such as roadways and parking lots) increases both the volume and velocity of stormwater runoff, while also reducing groundwater infiltration.³³ The percentage of impervious surface within a watershed, for example, explains most of the variability for indicator bacteria across watersheds.³⁴ Bacteria levels also tend to be elevated in agricultural catchments with higher levels of grazing cattle and sheep.³⁵ Zoning and development policies can be a strong influence on the amount of impervious surface within each municipality.³⁶

Pathways of Human Exposure Drinking Water

Waterborne disease outbreaks stemming from drinking water source contamination require a combination of determining factors. The requirements include: 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.

Recontamination of treated water may also occur at the public or homeowner's distribution system level.³⁷

Waterborne disease outbreaks from all causes in the U.S. are distinctly seasonal, clustered in key watersheds, and associated with heavy precipitation.¹⁶ In Walkerton, Ontario, in May 2000, heavy precipitation com-

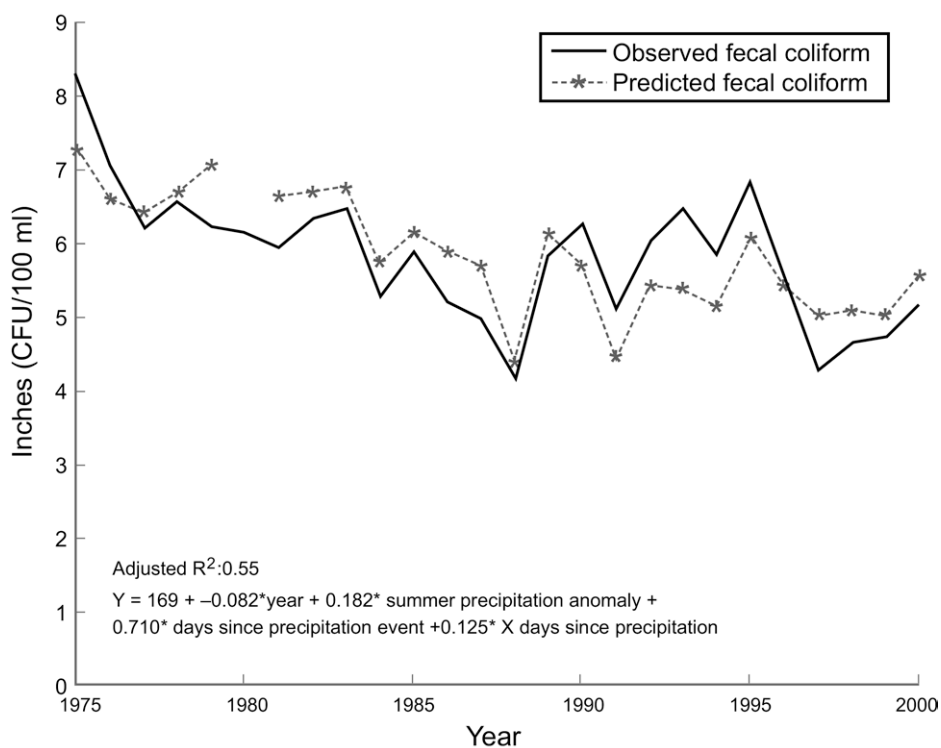


Figure 5. Relationship between rainfall and beach contamination, Lake Geneva, Wisconsin CFU, colony-forming units

bined with failing infrastructure contaminated drinking water with *E. coli* 0157:H7 and *Campylobacter jejuni*, resulting in an estimated 2300 illnesses and seven deaths.³⁸

Recreational Water and Stormwater Issues

Heavy runoff after severe rainfall can also contaminate recreational waters and increase the risk of human illness³⁹ through higher bacterial counts. This association is strongest at beaches closest to rivers.⁴⁰ Ear, nose, and throat; respiratory; and gastrointestinal illnesses are commonly associated with recreational swimming in fresh and oceanic waters. Less abundant and potentially more severe waterborne diseases such as hepatitis, giardiasis, cryptosporidiosis, and toxic algal blooms pose serious health threats to vulnerable human populations and local wildlife. Swimmers have an elevated risk of contracting gastrointestinal illnesses versus non-swimmers, and this risk generally increases with prolonged exposure.⁴¹ Frequent water users, such as lifeguards or recreational enthusiasts, are at risk for waterborne disease, and young children, the elderly, pregnant women, and the immunocompromised have the greatest risk of suffering serious complications.^{41,42} Macrodemographic trends toward an older and more immunocompromised U.S. population suggest that vulnerability to waterborne pathogens will continue to increase.

Precipitation events and subsequent runoff may flush pathogens and indicator bacteria directly into water bodies and overwhelm or decrease the efficiency of the sewage disposal infrastructure. Although pathogens tend to co-occur with indicator bacteria, indicators are prone to false positive readings. Indicator bacteria may survive in soil sediments or beach sand, become re-suspended during a precipitation event, and found estimates of waterborne disease risk.^{30,43,44} The periodicity and amplitude of contamination events are likely affected by processes that re-suspend or transport pathogens.^{45,46} Indicator bacteria are influenced by precipitation events up to a week prior to sample collection although recent precipitation (0–3 days) tends to exhibit the strongest relationships with their numbers.¹⁶ Interval time between rainfall events can increase pollutant accumulation and subsequent loading into water bodies.^{18,47} A disproportionately large pollutant mass similarly may be transported with the first precipitation event following the dry season in mid-latitude locations.^{48,49} Figure 5 shows an example of rainfall and contamination levels for Lake Geneva WI. Unseasonably high precipitation typically increases indicator bacteria loading into water bodies.⁵⁰ Earth system processes like the El Niño Southern Oscillation (ENSO) strongly influence interannual precipitation and therefore must be taken into account, especially for contamination events between September and March.^{50–52}

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Resulting Waterborne Illnesses

Agents of disease. More than 100 different types of pathogenic bacteria, viruses, and protozoa can be found in contaminated water.^{53–55} Many of these have been implicated in a variety of illnesses transmitted by food or water.

Waterborne and foodborne diseases continue to cause significant morbidity in the U.S. In 2002, there were 1330 water-related disease outbreaks,⁵⁶ 34 from recreational water and 30 from drinking water.^{57,58} In recreational water, bacteria accounted for 32% of outbreaks, parasites (primarily *Cryptosporidium*) for 24%, and viruses for 10%.⁵⁷ Bacteria were the most com-

monly identified agent in drinking water (29%, primarily *Campylobacter*) followed by parasites and viruses (each 5%).⁵⁸ Gastroenteritis continues to be the primary disease associated with food and water exposure. In 2003 and 2004, gastroenteritis was noted in 48% and 68% of reported recreational and drinking water outbreaks, respectively.^{57,58}

Surveillance

Variability of indicator bacteria is controlled by the physical dynamics of each water body, and quality can be inferred from water's chemical and biologic qualities. Prevailing wind direction, toward or away from the beach, modulates biophysical environment and indicator bacteria relationships in large water bodies.⁴⁶ Tidal cycles in large water bodies enhance indicator bacteria exchange from subsurface and soil reservoirs.^{59,60} Elevated nitrate, ammonium, and caffeine in water quality measurements suggest recent cross-contamination with sewage-like materials.^{61,62} Recent advances in molecular detection techniques have developed alternative indicators that are human-specific (e.g., demonstrating sewage inputs) such as human-specific *Bacteroides* spp., *Methanobrevibacter smithii*, and the surface protein gene present in enterococcus (*esp*).^{63–65} Precipitation and subsequent runoff events increase nutrient loading into water bodies, potentially enhancing floral productivity and water chlorophyll levels.⁴⁶ Indicator bacteria survival is inversely related to water salinity and survival exponentially decreases with the duration and magnitude of solar radiation exposure.⁶⁶ Surface water runoff also disturbs and re-suspends sediments, increases water turbidity, decreases solar radiation, and proportionally increases indicator bacteria loading into water bodies.⁴⁶

Conclusion and Recommendations

A broad range of improvements can be made toward attaining safe water quality in the U.S. These include such activities as data collection/surveillance, infrastructure improvements, land use planning, education, and research. Ultimately, better assessment of water quality and risk to the drinking water system from the watershed to the tap, as well as recreational water exposures, will allow for better prevention and controls to limit the impact of contamination events.

Data Collection

Based on the current state of surveillance, better indicators of fecal pollution are required. Public health officials and water managers need especially to be informed about the source of contamination, which could be from farm runoff, stormwater, or sanitary sewage.⁶⁷ Progress has been made in the field of microbial source tracking in terms of identifying

source-specific alternative indicators, and molecular approaches offer a broader range of target organisms because they are not dependent on culture (for reviews, see Santo Domingo et al.⁶⁸ and Savichtcheva and Okabe⁶⁹). These have been used successfully in field studies.^{70–72} However, widespread implementation will require extensive validation (including geographic differences), further assay development to reduce cost and complexity of new assay procedures, and standardization for use in public health laboratories.

One of the disadvantages of the current system is that the outbreaks are detected after the fact—that is, 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 health departments, such as when mild symptoms are attributed to other causes or when health problems cannot be treated medically. In addition, delays exist in detecting outbreaks because of the time necessary for laboratory testing and reporting of findings. Predictive forecasts of swimming-related health risk currently support beach management decisions at some U.S. coastal oceanic and Great Lakes beaches.^{46,73,74} Near-term forecast models require knowledge of the relationships between beach-specific environments and swimming health risks, collected and refined over multiple years of observations. Forecast models tend to have high sensitivity but relatively lower specificity and are therefore prone to false positive predictions of unsafe swimming conditions. Future research should investigate the extent to which dynamic environmental conditions can augment alternative human-specific pathogen indicators.

Infrastructure Improvements

This article has given specific examples of shortcomings in our current water systems. Upgrading sewage/stormwater infrastructure will obviously decrease the incidence of waterborne pathogen pollution.^{59,75} For example, $\leq 20\%$ of childhood bacterial or viral diarrheal illnesses can be attributed to the density of holding tanks and other septic tanks.⁷⁶ Improperly managed holding septic tanks discharge untreated sewage and contaminate surface water. Improving infrastructure may further reduce risks of contamination from extreme weather events.

Land use/watershed protection. Watershed protection will continue to be an extremely important factor influencing water quality.⁶⁷ Watershed water quality has a direct impact on source water and processed water quality as well as on 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 micro-

organisms flowing into reservoirs, groundwater, lakes, rivers, estuaries, and coastal zones.

Education and research. According to Rose and others,⁶⁷ coordinated monitoring of physical, chemical, and biologic parameters should go toward building databases and integrated models that include environmental, ecologic, and social conditions, consequences, and costs. Collaborative, multidisciplinary training and research—involving health and veterinary professionals, biologists, ecologists, physical scientists, database specialists, modelers, and economists—is required to carry out comprehensive assessments and management plans. Interagency agreements will be needed to coordinate and support this initiative. Testing models and hypotheses based on 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 U.S. and around the world. Enhanced understanding of the weather-sensitivity of many waterborne diseases is necessary along with improved surveillance, watershed/source water protection, and educational programs to improve the safety of our water. Scenarios of future global warming accompanied by climatic extremes only increase the importance of these improvements.

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