Infectious diseases of severe weather-related and flood-related natural disasters

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Purpose of review
The present review will focus on some of the possible infectious disease consequences of disastrous natural phenomena and severe weather, with a particular emphasis on infections associated with floods and the destruction of infrastructure.

Recent findings
The risk of infectious diseases after weather or flood-related natural disasters is often specific to the event itself and is dependent on a number of factors, including the endemicity of specific pathogens in the affected region before the disaster, the type of disaster itself, the impact of the disaster on water and sanitation systems, the availability of shelter, the congregating of displaced persons, the functionality of the surviving public health infrastructure, the availability of healthcare services, and the rapidity, extent, and sustainability of the response after the disaster. Weather events and floods may also impact disease vectors and animal hosts in a complex system.

Summary
Weather or flood-related natural disasters may be associated with an increased risk of soft tissue, respiratory, diarrheal, and vector-borne infectious diseases among survivors and responders.

Keywords
cyclone, flood, hurricane, monsoon, tsunami, typhoon

Curr Opin Infect Dis 19:408–414.

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Current Opinion in Infectious Diseases 2006, 19:408–414

0951-7375

Introduction

Many infectious pathogens are susceptible to changes in environmental conditions, and climate affects the epidemiology of many infectious diseases [1]. Climate is distinguished from weather by a matter of timescale: weather reflects day-to-day changes; climate reflects patterns or changes over years or decades. Extreme weather events include high winds, periods of very high or low temperatures, and periods of very high or low rainfall. Such conditions may result in damage to infrastructure and ecological changes that may impact the risk of infection among humans and animals that live in the affected area [2]. Natural phenomena such as tsunamis after earthquakes can similarly result in flooding and destruction of critical infrastructure. Such events can increase the risk of soft tissue, respiratory, diarrheal, and vector-borne infectious diseases as a result of the direct inoculation of pathogenic organisms (tetanus, wound infections, aspiration pneumonia), the destruction of shelters and resultant crowding of surviving displaced individuals (influenza, measles, meningitis, tuberculosis), the elimination of potable water supplies (shigella, cholera), and altered vector breeding grounds or zoonotic reservoirs (malaria, dengue, arboviral encephalitis). Such natural disasters can also have long-term and secondary effects, such as those caused by the disruption of vaccine, maternal–child health, and tuberculosis public health programmes. This review will focus on some of the possible flood-associated infectious disease consequences of disastrous natural phenomena and severe weather.

Flooding after tropical cyclones, monsoons, and tsunamis

Floods may have direct effects on the infectious disease risk, and flooding is common after severe weather. Tropical cyclones are low-pressure weather systems that develop over warm ocean waters and are referred to as 'hurricanes' in the north Atlantic, 'typhoons' in the western Pacific, and 'cyclones' in the Indian ocean and Australasia [3••]. When these weather patterns move to land, they can result in storm surges (coastal flooding with wind-driven and tidal ocean water), heavy rainfall, flooding, and high winds.

A tsunami is a series of oceanic waves following an earthquake, and tsunamis may result in severe flooding across a long but often relatively thin (a few hundred meters to less than one or two miles) coastal area. The relative geographical thinness of the area of destruction, and the relative proximity of unaffected areas, may facilitate disaster response and facilitate the access of survivors to rescue shelters and potable water, perhaps mitigating the risk of infection compared with that which occurs after the passage of a cyclonic system that usually affects a broader geographical area within a given region.

Monsoon rains usually occur on a regular pattern, although the quantity of rainfall in a monsoon season may vary widely, and monsoons may result in severe and extensive flooding.

Immediate infectious disease effects

After a weather-related or flood-related disaster, an increased risk of infectious diseases among survivors and displaced persons is often an immediate concern [4••]. In complex emergencies, measles, diarrhea, acute respiratory infections and malaria can be responsible for large numbers of deaths [4••]. The degree to which such epidemics occur, however, is associated with the regional endemicity of specific diseases, the nature and scope of the disaster, the level of public health infrastructure in place both before and after the event, and the level and efficacy of disaster response. In resource-rich countries with adequate public health infrastructure, posthurricane and postflood infectious disease surveillance has only occasionally detected relatively small increases in life-threatening infectious diseases after natural disasters [3••,5–8]. In comparison, in resource-poor nations, larger outbreaks of infectious diseases, including cholera, typhoid, acute respiratory infections, and leptospirosis, after disasters are not infrequent [5,9–12].

Wound infections

Wound infections after natural disasters are common. Puncture wounds may result from wind-driven debris and missiles, and crush injuries may result from falling debris, trees, and buildings. Wounds may be contaminated with concrete, wood, metal, soil, and water. The destruction of the regional health infrastructure, the inability to wash wounds with clean water, and the inability to treat individuals with topical or systemic antimicrobial agents can all lead to severe wound infections, even if the initial trauma was relatively minor. Tetanus (*Clostridium tetani*) and gas gangrene (*Clostridium perfringens*) may complicate wounds contaminated with soil [13••]. The contamination of wounds with salt water or brackish water may predispose to wound infections caused by *Aeromonas* spp., non-cholera *Vibrio* spp., and rapid growing mycobacteria (such as *Mycobacterium marinum*) [14–16]. The contamination of wounds with fresh water or water–soil mixtures may predispose to wound infections caused by *Pseudomonas* spp., rapidly growing mycobacteria, and *Burkholderia pseudomallei* (melioidosis) [17–19,20•]. After natural disasters, scavenging animals are common, increasing the risk of human–animal violent contact. Dog, cat and other animal bites are associated with wound infections, and may involve infection with *Capnocytophaga canimorsus* and *Pasteurella multocida* organisms.

After the 2004 Indian Ocean tsunami, wound contamination involved a mixture of sea and fresh water as well as soil. Sewage, soil, and foreign materials were removed from wounds and found in sinuses and respiratory passages. Polymicrobial infection was common [20•,21•]. Infections included marine pathogens such as *Aeromonas* spp. and *Pseudomonas* spp., as well as enteric pathogens normally found in sewage. *Plesiomonas* spp., *Burkholderia* spp. and common skin flora such as *Staphylococcus aureus* and streptococci were also responsible for wound and systemic infections. Inoculation with typical soil pathogens resulted in cases of anaerobic infection, mucormycosis and melioidosis [22–25], and cases of disseminated *Scedosporium apiospermum* and *Mycobaceterium chelonae* were reported [20•].

In 2005, hurricane Katrina affected the Gulf Coast of the United States and 18 cases of *Vibrio* spp. wound infections were noted among individuals in the affected area. Most patients had associated co-morbidities that probably increased their risk of vibrio wound infection, and many had been wading in flood-waters. Vibrio wound infections may progress rapidly and five of the 18 patients with wound-associated vibrio infections died [26••].

Respiratory infections

Flooding after natural disasters may also result in episodes of near-drowning, immersion, and aspiration. Direct inoculation of the pulmonary system with marine and soil debris may cause serious respiratory and systemic infections [16,27–29]. Approximately 30% of displaced individuals seeking medical care in Sri Lanka after the 2004 tsunami disaster complained of respiratory problems, probably reflecting a combination of post-aspiration pneumonitis and true infection [30]. All 17 of one group of critically ill tourists airlifted from an affected area had polymicrobial pneumonia [21•]. Cases of severe sinusitis were reported with debris, sand, and foreign materials being removed from affected sinuses [31•]. Flood-related aspiration pneumonia is often polymicrobial, and may lead to pulmonary parenchymal necrosis, empyemas, and pulmonary abscesses and cavitation. Necrotic pulmonary abscesses may result in right-to-left vascular shunting and the metastatic spread of infection, particularly to the central nervous system [23,24,32••,33–36].

Leptospirosis

Humans usually acquire leptospirosis after exposure to fresh water contaminated with the urine of infected animals such as rats. Natural disasters may result in the scattering of garbage, debris, and food that may contribute to the amplification of rodent populations. Free-ranging animals may also contaminate flood-waters. Outbreaks of leptospirosis are well documented after flooding and cyclones [37–39], and during the monsoon season in the Philippines in 1999 a threefold increase in leptospirosis cases was reported in Manila, with most cases recorded in poor, low-lying areas [12].

Mold

If flooded areas remain submerged for long periods of time, extensive mold growth may result, leading to concerns for respiratory health. Airborne mold is associated with opportunistic infection in immunocompromised individuals and respiratory symptoms in normal hosts. Visible mold growth was found in 45% of homes inspected after hurricane Katrina, and although interpreting the significance of measures of airborne mold toxins is complex, indoor air levels were markedly elevated and usual indoor/outdoor ratios were reversed (indoor levels of mold toxin were higher than outdoor) [40,41•].

Damage to infrastructure

Damage to infrastructure may result in the congregating of survivors in overcrowded temporary shelters, as well as the destruction of water, sanitation, electrical, cooking and refrigeration systems. The destruction of roads and points of access may also impede disaster response efforts.

Overcrowding

Overcrowding is common if severe weather causes structural damage to dwellings, and victims or evacuees are housed in temporary shelters. Overcrowding is associated with a number of potential infectious diseases, including measles, meningitis, influenza, diarrheal illness, and tuberculosis. Death rates of over 60 times the normal have been documented among refugees and displaced individuals, with three-quarters of these deaths being attributable to communicable diseases [42].

Contaminated food and drinking water

The disruption of sewage systems and contamination of drinking water during floods may contribute to water and food-borne infectious diseases [9]. Drinking water systems may become contaminated during water surges [43–48], and the lack of facilities for personal hygiene, and the disruption of electrical, refrigeration and cooking systems, may all facilitate the transmission of food-borne illness. The disruption of access to potable water may be intermediate to long term: 6 months after the 2004 tsunami, only one in five individuals in an affected area of rural Indonesia had regained access to potable water [49]. Heavy rainfalls have also been associated with increases in measurable giardial oocysts and pathogenic viruses in water, as well as outbreaks of water-associated diseases such as cryptosporidiosis and *Escherichia coli* O157:H7 [50,51]. The contamination of water supplies may also result in non-intestinal infections. For example, an outbreak of acanthamoebic keratitis was associated with the contamination of household water after regional flooding in the United States [52].

Diarrheal illness

Diarrheal illness after disasters is common, even in resource-rich areas. After hurricane Katrina, outbreaks of gastroenteritis among approximately 1000 evacuees and relief workers in three facilities in Texas were reported to the US Centers for Disease Control and Prevention. Noroviruses spread easily from person to person, especially in overcrowded settings, and were confirmed in 50% of patients [26••]. Clusters of diarrheal disease were reported in evacuation centers in four states, and gastroenteritis was the most common acute disease complaint among evacuees in Memphis, Tennessee [53•]. Two cases of toxigenic *Vibrio cholerae* O1 infection were reported in a couple in Louisiana after hurricanes Katrina and Rita [54]; however, there was no epidemic and no evidence to suggest that there was an increased risk of cholera among residents of the Gulf Coast after the hurricanes. Non-toxigenic *V. cholerae* was also isolated from the stools of two individuals who presented with gastroenteritis [26••].

In contrast, two devastating monsoon-related floods in Bangladesh in 2004 resulted in very large outbreaks of diarrheal disease reaching epidemic proportions throughout the capital city of Dhaka. Over 17 000 patients were seen in one hospital during one of these flood periods. Cholera was the most common cause of admission, and enterotoxigenic *E. coli* was also an important cause of acute watery diarrhea, particularly in children less than 2 years of age [55•]. During monsoon flood-associated epidemics of diarrhea occurring in 1988, 1998 and 2004 in Dhaka, cholera was the most common cause of diarrhea, followed by rotavirus. Although absolute numbers of cases of diarrhea resulting from other causes such as enterotoxigenic *E. coli*, shigella and salmonella were detected, only cholera increased in incidence proportionally to non-flood periods [56,57]. In addition to flooding, extreme temperatures may also impact the risk of cholera. Warm sea-surface temperatures have been associated with an increased incidence of outbreaks of cholera [58–60], perhaps as a result of increased plankton bloom.

Heavy rain-associated floods have also been associated with outbreaks of hepatitis E in Khartoum, Sudan [11], and postflood increases in cryptosporidiosis, poliomyelitis, rotavirus, typhoid and paratyphoid have also been reported [61,62,63••,64].

Vector-borne diseases

Many vector-borne diseases of humans are transmitted by mosquitoes, and mosquito populations may markedly increase after flooding. Although modeling may be used to predict mosquito abundance after flooding [65], the predicted impact of severe weather or floods on vector-borne illness is less certain than that on enteric infections [66]. The effect of weather on insects and vector-borne diseases is complex; severe weather can either increase or decrease the transmission of vector-borne illness. Few studies have documented these phenomena in the short term, and even fewer in the long term [5,67]. Monsoon rains and floods have been associated with outbreaks of dengue fever in India [68–71]. In Thailand, dengue was a common cause of fever in children after heavy rain-associated flooding [72], and in Brazil, Indonesia and Venezuela rain, temperature, and relative humidity have been associated with patterns of dengue infection [73–75]. Heavy rains and flooding have also been associated with epidemics of St Louis encephalitis in Florida, believed to be associated with the feeding activities of the responsible vector (*Culex nigripalpus*) [76], and flooding has been associated with increases in other arboviral diseases and lymphatic filariasis around the world [77–79].

Increased numbers of cases of resistant malaria have also been noted after floods in Sudan [9,80], and an outbreak of more than 75 000 cases of *Plasmodium falciparum* occurred in Haiti after hurricane Flora in 1963 [81]. A four to fivefold increase in malaria incidence also occurred after a flood disaster in 2000 in Mozambique [82]. In Indonesia, however, after the 2004 tsunami, no appreciable increase in the number of malaria cases was evident. Such variance probably mirrors the complexity of a given situation, and partly reflects the prevalence of vector-borne diseases in the region before the disaster, the identity and ecology of the local vectors (some vectors prefer clean water, others prefer organically rich water; some prefer fresh water, others prefer water containing low amounts of salt), and the impact of control programmes or other interventions that minimize vector–human contact (for example, the use of larvacidal or insecticidal agents, access of survivors to nets or window screens, and access of survivors to shelters versus sleeping outdoors after a natural disaster).

Temperature itself may also affect the risk of vector-borne diseases. Outbreaks of St. Louis encephalitis have occurred after periods of hot weather when temperatures have been greater than 30°C for more than seven consecutive days [83], and temperature and rainfall may not only impact the distribution of vectors, but also the effectiveness with which the vector is able to transmit the pathogen [65,84–88].

Severe weather may affect not just vectors, but also animal reservoirs and intermediate hosts that can act as reservoirs or amplification hosts for vector-borne diseases (such animals may be increased or decreased after a natural disaster). Chagas' disease is a zoonosis caused by *Trypanasoma cruzi* and transmitted by triatomine bugs. In 2002, hurricane Isidore devastated the Yucatan peninsula of Mexico. During the 6 months after the hurricane, there was a marked increase in the domestic abundance of the vector in the affected area, with the maximal increase reflecting the path of the hurricane [89•]. Studies have also shown that rainfall, temperature, and humidity are important predictors of house infestation with bugs and of their infection by *T. cruzi* [90].

Long-term effects

Disasters may also have long-term impact, especially on the local public health system.

Tuberculosis treatment and continuity

The disruption to tuberculosis care is a major concern when weather or flood-related disasters interrupt infrastructure and when public health services are compromised. Resource-poor areas with high prevalence rates of tuberculosis may experience an increased incidence of cases of tuberculosis after a disaster, such as occurred in Bangladesh after a 1970 cyclone [5]. In countries where tuberculosis prevalence is low and resources are abundant, increases in the cases of tuberculosis after natural disasters are not as common. For example, all 130 individuals in Louisiana who were in a tuberculosis control programme at the time of hurricane Katrina were traced and restarted appropriately on therapy despite the fact that the state tuberculosis control programme had been forced to abandon its headquarters and the laboratory and medication depot were flooded [91].

Vaccine-preventable diseases

Overcrowding and an interruption in public health campaigns after natural disasters can impact the incidence of a number of vaccine-preventable illnesses, including measles, meningitis, and influenza. Measles case fatality rates in complex emergencies may be as high as 33%, compared with a mortality rate in stable populations of approximately 1% [92••]. Mass measles vaccination campaigns are recommended in settings of large groups of refugees, and such a campaign was carried out in Indonesia after the 2004 tsunami [49]. Disruption of the public health infrastructure may also impact the administration of standard childhood vaccines, and catch-up vaccine programmes should be instituted after recovery from the natural disaster.

Ecological impact

Increased populations of roaming and scavenging dogs, pets, and other animals may lead to an increased incidence of animal bites and the risk of rabies. Increased or decreased animal reservoirs and amplification hosts may also impact the risk of human infection. For example, the rodent population may increase explosively after natural disasters, possibly increasing the risk of rodent-associated infections, including rat-bite fever, leptospirosis, lymphochoriomeningitis virus, and hantavirus infection. Increased precipitation has also been associated with an increased incidence of human infections with *Yersinia pestis*, the agent of plague, and the number of days at certain temperatures has been associated with both increased numbers of cases (for a low temperature threshold) and decreased numbers of cases (for a high temperature threshold), probably a result of the effect of weather on population dynamics of the rodent hosts and flea vectors [93].

Conclusion

The risk of infectious diseases after weather or flood-related natural disasters is often specific to the event itself, and is dependent on a number of factors including the endemicity of specific pathogens in the affected region before the disaster, the type of disaster itself, the impact of the disaster on water and sanitation systems, the availability of shelter, the congregating of displaced individuals, the functionality of the surviving public health infrastructure, the availability of healthcare services, and the rapidity, extent, and sustainability of the response after the disaster. Weather events and floods may also impact disease vectors and animal hosts in a complex system. The numbers of resultant human infections may thus be increased or decreased. Considering the effects of short-term changes in weather, long-term climatic changes would be predicted to have a substantial impact on the risk of infectious diseases among humans.

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Additional references related to this topic can also be found in the Current World Literature section in this issue (p. 494).

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