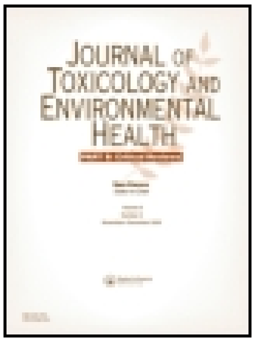

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Journal of Toxicology and Environmental Health, Part B
Critical Reviews

ISSN: 1093-7404 (Print) 1521-6950 (Online) Journal homepage: https://www.tandfonline.com/loi/uteb20

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To cite this article: Timothy B. Erickson, Julia Brooks, Eric J. Nilles, Phuong N. Pham & Patrick Vinck (2019): Environmental health effects attributed to toxic and infectious agents following hurricanes, cyclones, flash floods and major hydrometeorological events, Journal of Toxicology and Environmental Health, Part B, DOI: 10.1080/10937404.2019.1654422

To link to this article: https://doi.org/10.1080/10937404.2019.1654422

Published online: 22 Aug 2019.

JOURNAL OF TOXICOLOGY AND ENVIRONMENTAL HEALTH, PART B
https://doi.org/10.1080/10937404.2019.1654422

Environmental health effects attributed to toxic and infectious agents following hurricanes, cyclones, flash floods and major hydrometeorological events

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ABSTRACT

Extreme hydrometeorological events such as hurricanes and cyclones are increasing in frequency and intensity due to climate change and often associated with flash floods in coastal, urbanized and industrial areas. Preparedness and response measures need to concentrate on toxicological and infectious hazards, the potential impact on environmental health, and threat to human lives. The recognition of the danger of flood water after hurricanes is critical. Effective health management needs to consider the likelihood and specific risks of toxic agents present in waters contaminated by chemical spills, bio-toxins, waste, sewage, and water-borne pathogens. Despite significant progress in the ability to rapidly detect and test water for a wide range of chemicals and pathogens, there has been a lack of implementation to adapt toxicity measurements in the context of flash and hurricane-induced flooding. The aim of this review was to highlight the need to collect and analyze data on toxicity of flood waters to understand the risks and prepare vulnerable communities and first responders. It is proposed that new and routinely used technologies be employed during disaster response to rapidly assess toxicity and infectious disease threats, and subsequently take necessary remedial actions.

KEYWORDS

Toxicology; environmental health; hurricanes; cyclones; climate change

Introduction

Three powerful and devastating hurricanes from the 2017 Atlantic hurricane season (Harvey, Irma, and Maria) resulted in hundreds of human fatalities and displacement of thousands of individuals. Morbidity and mortality surveillance was critical to the emergency disaster response because it provided government and public health officials the information needed to assess damage and guide necessary evacuations (Issa et al. 2018). During the 2018 hurricane season, two other significant hurricanes reached the United States' coasts. Hurricane Florence ravaged the Carolina shoreline with structural damage and massive flooding resulting in displaced populations and environmental destruction. Hurricane Michael hit the Florida Panhandle as a Category 4 hurricane and became one of the strongest to make landfall in the United States since Hurricane Katrina in 2004. More frequent and more powerful hurricanes, cyclones, flash floods, rising sea levels, and changing precipitation patterns may all exert adverse effects upon water quality, availability of drinking water, as well as restoration and protection of watersheds, wetlands, shorelines and aquatic ecosystems (U.S. EPA 2014). In 2019, flash flooding in the Indonesian province of Papua killed one hundred people near the provincial capital of Jaypura. Cyclones Idai and Kenneth resulted in the death of one thousand individuals across Mozambique, Malawi and Zimbabwe and more than 100,000 homes were damaged or destroyed, along with at least 1 million acres of crops (Reid 2019). Most recently, Cyclone Fani, the strongest cyclone to hit the Indian subcontinent in 20 years, struck the east coast of India and Bangladesh killing hundreds and resulting in mass evacuation of 1.2 million people (Al Jazeera News Agencies 2019).

World-wide, floods are among the most significant natural disasters in terms of the number of subjects affected (Issa et al. 2018). Of note, flash floods resulted in the highest average mortality per event (Lowe, Ebi, and Forsberg 2013). Flooding events account for approximately 40% of natural disasters globally and is responsible for approximately half of all deaths (Bich et al. 2011). The greatest potential flood hazard is in the

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Asian continent, representing nearly 90% of all flood-related deaths world-wide. Over the past two decades, nearly 500 million individuals annually have been directly exposed to floods. The health consequences of floods have been described in relation to time as follows: (1) immediate adverse health effects of flooding include drowning, traumatic injury, outbreaks of gastroenteritis, and respiratory infections (2) mid-term effects of flooding include wound infections, environmental poisonings, communicable diseases, and starvation while (3) long-term consequences include chronic disease states, physical disability, mental health issues, post-traumatic stress disorders, and malnutrition. The long-term effects of flooding on mental health may exert a more significant impact than other illnesses since psychological problems may continue indefinitely (Bich et al. 2011). Limited systematic research on the health outcomes of flooding exists in the literature (Du et al. 2010; Ohl and Tapsel 2000). In addition, these burdens are not distributed equally, but typically fall heaviest on disadvantaged communities. It is evident that more investigations highlighting active surveillances of these environmental toxicities, infectious pathogens, and human health disparities due to extreme hydrometeorological events such as hurricanes, cyclones and flash floods are needed.

In heavily populated and industrial regions, flood waters may be contaminated with chemical spills, heavy metals, bio-toxins, invasive species, waste, sewage, and debris. These environmental and infectious hazards might initiate consequent adverse chronic health risks that are largely underreported and inadequately monitored in the emergency response and recovery stages after a hurricane or other water-borne disasters. The risk posed by toxic substances present in water is rarely considered in hurricane risk analysis and immediate response. This is despite the fact that recent cost-effective mobile technologies have become available for monitoring, rapid testing, and measurement of toxicity, as well as for detecting the presence of infectious pathogens (Eskenazi et al. 2014).

Environmental health and infectious pathogens

Excessive or heavy rainfall events mobilize pathogens in the environment and increase runoff of water from fields, flowing into rivers, lakes, marine harbors and wells (CCDR 2000; Tinker et al. 2008). Heavy rainfall might also lead to changes in the direction of flow of water through channels. During periods of heavy rainfall, water treatment plants might be overwhelmed, resulting in overflow and cross-contamination between sewage and drinking-water pipes, particularly when water collecting systems are not modernized (Semenza and Nichols 2007). Extreme precipitation events may also enhance the risk of stagnant flooding in many areas, increasing human exposure to waterborne pathogens (Cann et al. 2012; Fewtell et al. 2011).

A range of factors elevate the risk of infectious disease transmission following hurricanes and other natural flooding events including contamination of drinking water, poor sanitation, displaced and overcrowded populations, and increased exposure to disease vectors (Karanis, Kourenti, and Smith 2007).

Outbreaks caused by the contamination of community water systems have the potential to produce extensive diseases, particularly where the public health infrastructure is less resilient. (Karanis, Kourenti, and Smith 2007). Flooding may contaminate water sources with pathogenic *Escherichia coli* or Shigella which produce vomiting, diarrhea, gastrointestinal bleeding, dehydration, and febrile illness (Firger 2017). *Vibrio vulnificus* a bacterium found in salt and brackish water leads to rapidly progressive and life-threatening cellulitis and sepsis (Firger 2017).

Flooding and heavy rainfall have been associated with numerous global outbreaks of leptospirosis (Lau et al. 2010).With climate change, extreme weather events such as cyclones and floods are expected to occur with increasing frequency and greater intensity and consequently resulting in an upsurge in the incidence of leptospirosis outbreaks (Lau et al. 2010). Flooding and exposure to water or mud contaminated with leptospira spirochetes, usually from urine and feces of infected rodents, may also be transmitted by other wild and domestic species such as horses, cattle, dogs and pigs (Socolovschi et al. 2011). Leptospirosis is known to produce systemic illnesses such as renal and hepatic failure, pulmonary hemorrhage and meningitis (Haake and Levett 2015). In a review of the health impacts of floods and storms, Saulnier, Brolin Ribacke, and von Schreeb (2017) found heightened risk of wounds, soft tissue infections and gastrointestinal (GIT) diseases. After flooding, specific GIT infections such as leptospirosis typically rise – mostly within 4–6 weeks of the disaster (Saulnier, Brolin Ribacke, and von Schreeb 2017). Aldermana, Turnera, and Shilu-Tongab (2012) reported that in some settings, mortality rates may increase by up to 50% in the first year after a flood primarily due to infectious outbreaks such as hepatitis, GIT diseases and leptospirosis. An outbreak attributed to systemic infections initiated by leptospirosis recently resulted in 26 fatalities over a 6-month period following Hurricane Maria in Puerto Rico (Cook 2018a).

Skin and soft tissue infections induced by *Streptococcus, Staphylococcus sp*, and methicillin-resistant *Staphylococcus aureus* (MRSA) occur frequently after floods (Bandion, Hang, and Norton 2015; Cook 2018b; Tabuchi and Kaplan 2017). Other infectious illnesses, particularly in tropical low-middle income countries, include typhoid, melioidosis, schistosomiasis, viral hepatitis, and arsenicosis (Davies et al. 2014). Typhoid fever related to severe floods was more commonly reported in low and middle-income countries, especially in Asia and Africa (Ahern et al. 2005; Aldermana, Turnera, and Shilu-Tongab 2012). Melioidosis is a serious and potentially fatal infection caused by *Burkholderia pseudomallei*, which is found in water and soil and is endemic in Southeast Asia and Northern Australia (Dance 2000). The intensity of precipitation is a predictor of melioidosis hospitalizations for pneumonia and septic shock. Schistosomiasis, a leading source globally of hematuria, is spread by contact with water containing parasites from snails (McCreesh and Booth 2013). Flooding in Asia is thought to enhance the risk of schistosomiasis outbreaks by spreading snails to previously unaffected areas (MeCreesh and Booth 2013). Outbreaks of arsenicosis are also related to drinking ground and well water contaminated with environmental arsenic (Davies et al. 2014).

Heavy rains and flooding, particularly in urban and tropical regions (Tissera et al. 2016), elevate mosquito populations including *Aedes* species, which transmit Chikungunya, yellow fever and dengue (Singh et al. 2017). Dengue is now endemic to most tropical areas of the world (Musso and Gubler 2016). In Latin America and the Caribbean, over 1.5 million cases were recently reported from 36 countries and territories. The burden of disease from dengue in this region is comparable to the burden of malaria and hepatitis B. Local climate change and the El Niño–Southern Oscillation (ENSO) are also drivers of the inter-annual variability in dengue fever transmission. ENSO influences the inter-annual variability in weather patterns and elevates the likelihood of regional extreme hydrometeorological events, such as hurricanes, cyclones and flash floods (Stewart-Ibarra and Lowe 2013).

Another related threat is Zika virus, a mosquito-borne virus in the genus *Flavivirus* of the *Flaviviridae* family that is transmitted by *Aedes aegypti* and *Ae. albopictus* mosquitoes, with the potential for rapid spread (Kraemer et al. 2019). Zika is a single-stranded RNA virus that is closely related to dengue virus, yellow fever virus, and West Nile virus (Kraemer et al. 2019). Predisposing factors such as climate change, globalization, population rise, and increased urbanization have contributed to the spread of these viruses, posing pandemic threats (Boyer et al. 2018; Kraemer et al. 2019).

Overcrowding, which is common in emergency evacuation shelters, also facilitates the transmission of human-to-human pathogens, including influenza and other respiratory viruses such as Legionella (Firger 2017; Walker 2018) Some hurricane-related infections resolve with supportive care alone, but others, particularly bacterial infections, require appropriate antibiotic therapy (Kouadio et al. 2012). Tetanus prophylaxis vaccination is critical against *Clostridial* infections from lacerations and wounds contaminated with flood water and debris (IDSA 2018). Table 1 summarizes infectious agents and pathogens potentially encountered with flood water exposure.

Flooding, tropical conditions, and the lack of adequate shelter in the aftermath of hurricanes may increase human encounters with venomous animals including snakes seeking higher ground, as well as stinging Hymenoptera (bees, wasps, and

Table 1. Infectious hazards from major hydrometeorological events.

Gastrointestinal infections
Vibrio cholerae (cholera)
Escherichia coli
Shigella sonnei (shigellosis)
Vibrio vulnificus
Salmonella typhi (typhoid)
Hepatitis A virus
Dermal infections
Streptococcus pyogenes
Methicillin-resistant *Staphylococcus aureus* (MRSA)
Clostridial tetanii (tetanus)
Pulmonary Infections
Legionella pneumophilia
Streptococcus pneumoniae
Influenza virus
Cryptococcus neoformans, C. gatti
Disseminated infections
Leptospirosis *Leptospira interrogans*
Brucellosis *Brucella melitensis, B. abortus, B. suis*, and *B. canis*.
Melioidosis *Burkholderia pseudomallei*
Schistosomiasis *Schistosoma haematobium, S. japonicum*, and *S. mansoni.*
Rabies rhabdovirus *Lyssavirus sp.*
Mosquito-borne infections (*Aedes, Anopheles, spp*)
Dengue fever
Zika virus
Chikungunya
Yellow fever
West Nile virus
Malaria (*Plasmodium falciparum, P. vivax)*

fire ants). In addition, stray dogs, cats and wild animals such as raccoons and bats may harbor rhabdoviruses enhancing the chance of rabies transmission to humans when bitten (Kerber 2005; Zurko 2017).

Floodwaters also impact indoor environments and make homes and dwellings more susceptible to mold, particularly in humid conditions as noted with the hurricanes in Texas and Florida (Bloom et al. 2009; He et al. 2014; Johanning et al. 2014; Rando, Kwon, and LeFante 2014) Rapidly multiplying mold spores carry public health risks, especially for patients with existing mold allergies, asthma, and chronic obstructive pulmonary disease (COPD) (Grimsley et al. 2012) Efforts need to be made to limit contact with flood water due to these risks, including potentially elevated levels of contamination associated with raw sewage and other hazardous substances. This includes breathing water vapors or mists from the contaminated water, particularly when pumped or sprayed. Table 2 summarizes the Environmental Protection

Table 2. EPA & Department of Health and Human Services guidelines if contact with flood waters.

Wash hands before drinking and eating
Wash frequently using disinfecting soap
Limit direct contact with contaminated flood water
Cover lacerations or open wounds and limit exposure
Keep vaccinations current
Remove standing water as quickly as possible.
Remove wet materials and discard those that cannot be thoroughly cleaned and dried. Materials that have been wet for longer than 48 hours need to be discarded since may harbor mold growth.
Heavily contaminated flood waters resulting from hurricanes may contain micro-organisms and other contaminants that can penetrate deep into soaked, porous materials and are later released into air or water. The growth of micro-organisms will continue whenever materials is wet and humidity is high.
If there is no standing water in the building and it is safe to use electricity, circulating fans can accelerate the disinfection and cleaning process.

Agency (EPA) recommendations for contact with flood waters. Specifically, when removing flooded materials, exposure reduction to airborne mold spores by wearing gloves, goggles, and dust particle masks are advised.

Environmental toxicity

Chemical leaks and spills in drinking and flood water are known to pose serious risks to environmental and human health (Ritter et al. 2002). As seen in the aftermath of hurricanes, toxic chemicals and environmental contaminants create unique hazards to those evacuating from or returning to disaster-affected areas, especially vulnerable populations who have limited options other than to remain or return to their places of dwelling. Flood waters might be contaminated with chemicals, heavy metals, bio-toxins, invasive species, waste, sewage, and debris.

The heightened risks of environmental hazards from natural disasters like flooding produced by Hurricane Harvey in Texas are well-described in the lay press yet under-reported in the scientific literature during the emergency response and recovery periods. Over 40 industrial sites leaked hazardous pollutants into flood water attributed to Hurricane Harvey (Griggs et al. 2017). Airborne emissions of toxic gases such as methane and sulfur dioxide were also released into the environment. Other industrial chemicals such as benzene and butadiene, which are known to elevate cancer risk with acute or chronic exposures, pose additional threats. Benzene levels were measured 6-fold higher than the normal permissible environmental limits following Hurricane Harvey (Song, Shaw, and Collier 2017). This hurricane produced additional flooding or damage to at least 14 Superfund toxic waste sites in and around the Houston metropolitan area contaminated with dioxins, lead, arsenic, and mercury, as well as other industrial hydrocarbon compounds (Figure 1)

Hurricane Florence left behind stagnant flood waters which saturated hog farms which subsequently leaked manure, nitrates, and fertilizers (Figures 2 and 3).Carolina coal mining regions contaminated surrounding soil, waterways, fish, and wildlife with coal ash, an industrial waste created by coal-burning power plants that contain toxic heavy metals such as arsenic, lead, and mercury (Christensen, Moshtaghian, and Goldschmidt 2018; Formuzis 2018). When these elements are released, these substances can not only result in long-term environmental contamination, but also carry produce additional human health risks such as neurotoxic and hematological abnormalities (Pierre-Louis, Popovich, and Tabuchi 2018).

Flooding from more intense and frequent hurricanes might push toxins from other Superfund sites into underground fresh drinking water sources in aging aquifers such as the one in Miami-Dade County Florida (Flavelle 2018; U.S. Environmental Protection Agency 2014). Annual hurricanes and increased flooding events may dislodge toxic chemicals that remain near these and other industrial sites, resulting in cross contamination. These toxic materials include arsenic, cyanide, mercury, nickel, lead, cadmium, chromium, chloroform, and hydrocarbons. Table 3 summarizes potential toxic agents and materials from flood waters.

Many natural gas and other fuel lines were disrupted during Hurricanes Harvey and Katrina, and highly explosive vapors were present in buildings (EPA 2005). During Hurricanes Katrina, Ike and Sandy increased exposure to gasoline products were widely reported. (Cox, Amundson, and Brackin 2008; Forrester 2013; Kim et al. 2013). In addition, methane and other explosive gases may accumulate from decaying materials (EPA 2005). These buildings need to be evacuated and monitored during the aftermath of hurricane and flooding events. Flood victims need to be instructed not

Figure 1. Flood waters from Hurricane Harvey surrounding damaged oil refinery storage tanks in a Texas City.

"Flood waters caused by Tropical Storm Harvey encompass the Motiva Enterprises LLC in Port Arthur, Texas, U.S. August 31, 2017. REUTERS/Adrees Latif. Used with permission.

Figure 2. Satellite imagery of North Carolina coastline after Hurricane Florence hit the coastline in September 2018. Note toxic waste run-off into waterways from near-by swine farms.

Source: Environmental Working Group. Credit: Alex Formuzis alex@ewg.org Copyright Environmental Working Group, www.ewg.org. Reproduced with permission.

Table 3. Toxic hazards from major hydrometeorological events.

Toxic gases
Combustible gases
Carbon monoxide
Sulfur dioxide
Hydrogen sulfide
Cyanide
Hydrocarbons
Aliphatic (methane, butane, butadiene, propane)
Aromatic (benzene, toluene, xylene)
Heavy metals
Lead (Pb)
Arsenic (As)
Mercury (Hg)
Cadmium (Cd)
Polychlorinated chemicals
Polychlorinated dibenzo-*p*-dioxins (dioxins)
Polychlorinated biphenyls (PCBs)
Pentachlorophenol (PCP)
Fertilizers
Ammonium phosphates
Nitrates
Pesticides
Insecticides (organophosphates, carbamates, pyrethroids)
Herbicides (glycosates)
Rodenticides (zinc and aluminum phosphides, brodifacoum)
Caustics agents
Acids (sulfuric acid, hydrochloric acid, hydrofluoric acid)
Alkali (sodium hydroxide, potassium hydroxide)
Pulmonary carcinogens
Asbestosis
Natural venoms
Hymenoptera (bees, wasps, ants)
Venomous snakes: Families Elapidae (cobras, kraits, coral snakes) and Viperidae, subfamily Crotalidae (pit vipers) includes rattlesnakes (Crotalus, Sistrurus), cottonmouths and copperheads (Agkistrodon)

to return to homes or occupational sites until deemed safe by local public health and Hazardous Materials (HazMat) authorities.

Another toxic threat is exposure to carbon monoxide (CO) gas produced when fuels are burned for heating and power sources in disaster areas (Cox, Amundson, and Brackin 2008; Forrester 2013). CO exposures following weather-related disasters are a significant public health concern, and the use of fuel-burning equipment is a common source of storm-related morbidity and mortality (CDC 2009).

After the 2005 Florida hurricanes caused widespread power outages, increasing generator use directly resulted in a surge in CO poisonings (Becker et al. 2012; CDC. Centers for Disease Control and Prevention 2006; Pierre-Louis, Popovich, and Tabuchi 2018). Of the 126 CO poisonings documented during this time-period, 75% were related to generator use, and 40% of these generators although placed outside, but in close proximity to an open window or entry way

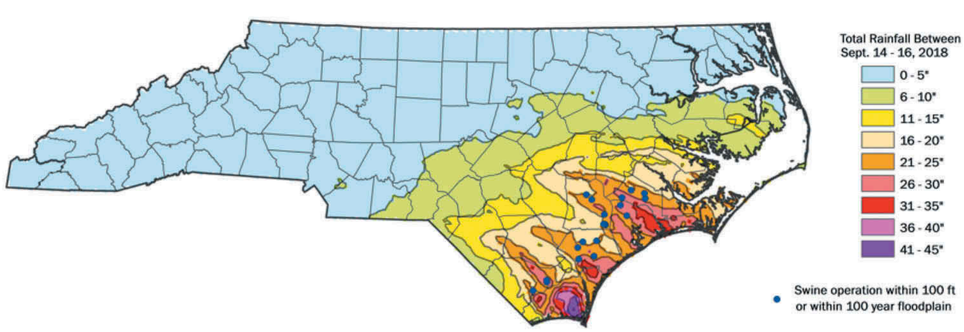

Figure 3. Hurricane Florence induced rainfall totals in North Carolina between Sept 14–18, 2018. Note swine farm operations were located within 100ft of the floodplain.

Source: The Environmental Working Group (EWG), from **National Weather Service** data.

(Becker et al. 2012; Pierre-Louis, Popovich, and Tabuchi 2018). In 2012, Hurricane Sandy made the US east coast landfall and devastated New York City's metropolitan area, resulting in widespread damage to homes and the utility infrastructure. One week later, snow and freezing temperatures from a nor'easter storm delayed utility restoration and resulted in an elevated number of CO poisoning cases called into the regional poison control center, the majority from the employment of generators and indoor charcoal grills utilized as make-shift heating sources (Chen et al. 2013). As such, it is important that fuel-burning devices including gasoline-powered generators, camp stoves and lanterns, or charcoal grills not be used in enclosed homes or confined spaces such as garages, basements or attics. Vents and chimneys need to be checked to ensure that storm debris does not block the exhaust from water heaters and gas furnaces. Symptomatic patients with neurological symptoms need to be evacuated from the site of exposure and transported to the closest hospital on high flow oxygen therapy. If suffering profound toxicity, the patient may necessitate transfer to a medical facility with hyperbaric oxygen (HBO) therapy capabilities. HBO units are however, less accessible in rural and sparsely populated areas because these expensive chambers are typically housed in large urban medical centers. Recently, the Food and Drug Administration (FDA) approved a Clear Mat device which may be utilized in standard emergency departments. The device works by accelerating the elimination of CO from the poisoned victim by delivering both 100% oxygen, as well as a mixture of oxygen and carbon dioxide enabling the patient to increase their respiratory drive thus accelerating the rate at which CO is eliminated from the body, allowing oxygen-rich blood to reattach to hemoglobin molecules (FDA U.S. Food and Drug 2019).

The EPA also urges the public to be on the alert for leaking containers and reactive household chemicals, caustics, hydrocarbons, and pesticides after hydrometeorological-induced flooding. Table 4 summarizes necessary precautions to prevent injury or further environmental damage. Hurricanes and other disasters produce structural damage and are also likely to dislodge hazardous building materials such as lead (Pb) or asbestos, which pose serious health hazards to returning residents as well as rescue and recovery crews involved with demolition, clean-up, and reconstruction. Many homes built in the United Sates before 1978 contain Pb-based paint, and the removal of materials containing Pb paint may result in elevated concentrations of contaminated dust in the air. Acute and chronic Pb poisoning produces a range of adverse health effects including anemia and profound neurocognitive disorders, particularly in young children (Mayans 2019). Buildings constructed before 1970 are more likely to contain hazardous materials such as asbestos, which may be inhaled, resulting in adverse health effects such as pneumococcus. Longer-term airborne asbestos exposure might potentially induce lung cancer and mesothelioma (Lemen 2016; Soeberg, Leigh, and van Zandwijk 2016). Asbestos containing materials include boiler/pipe insulation, fireproofing materials, floor tiles, roofing shingles, lab tabletops, and acoustic tiles found in classrooms and auditoria.

Table 4. EPA precautions to prevent injury or further damage from spilled chemicals and containers.

Keep children and pets away from leaking or spilled chemicals.
Do not combine chemicals from leaking or damaged containers since this may potentiate explosions
Do not dump chemicals down drains, storm sewers or toilets.
Do not attempt to burn household chemicals.
Mark and set aside chemical containers until they can be properly disposed of by HazMat experts.
Leave damaged or unlabeled chemical containers undisturbed whenever possible.

Environmental infectious pathogen monitoring

Monitoring of environmental indicators related to excessive water accumulation may help assess the risk associated with water-borne diseases. Remote sensing might also contribute to early warning for diseases with environmental drivers, such as flooding and cholera (Ledien et al. 2017).

Cholera was one of the first diseases for which the use of remote slow-cost sensing significantly improved disease epidemiological analysis and capacity to anticipate outbreaks (Lobitz et al. 2000). In recent years, cholera has become endemic in different regions of the world and incidence is increased in flash flood disasters. Traditional culture and microscopic methods are considered the standard for the diagnosis of *Vibrio cholerae*. However, these methods require days-to-weeks for confirmation. Therefore, more sensitive and rapid analyzes of *V. cholerae* are needed. Mehrabadi et al. (2012) demonstrated that a polymerase chain reaction (PCR)-based method rapidly detected cholera in a cost effective and accurate manner. This multiplex method also distinguishes *V. cholerae* bacteria from other Vibrio species and bacteria. This test provides a sensitive tool for quickly detecting the presence of toxigenic and pathogenic *V. cholerae* (Mehrabadi et al. 2012). These assays and sensors could be deployed in lab settings which are in proximity to contaminated water sites.

Contamination of surface and drinking water due to the presence of *Escherichia coli* bacteria is another major cause of water-borne disease outbreak in flash flood environments. Newly developed thermally reduced graphene oxide-based field effect transistors provide real-time detection of E. coli bacteria (Thakur et al. 2018). The biosensor exhibits reliable selectivity and rapid detection for E. coli sensing in river water. This low-cost sensor may also be mass produced for detection of other water-borne pathogens (Thakur et al. 2018).

Adaptable and reliable methods decrease the costs of diagnosis and treatment of the major water-borne bacterial pathogens including *E. coli, Shigella sp, Salmonella sp, Brucella sp, Legionella pneumophilia and Vibrio cholera*. A DNA microarray chip for a rapid detection and accurate identification of these bacterial agents was developed by Ranibar et al. (2017). The DNA microarray chip is capable of simultaneously testing and identifying all of these bacterial agents (Ranibar et al. 2017). Microarray technology is a low cost, reliable and accessible technique that can be rapidly deployed in a natural disaster setting. This "lab on chip" technique is applicable for several thousand specimens at once with a significantly shorter turnaround time other lab assays. It is useful for detecting and identifying infectious agents and even antibiotic resistant strains with high accuracy and sensitivity.

International lab guidelines are needed, including preparation protocols with affordable analyses to address the spread of mosquito-borne diseases (Charrel et al. 2016). The marked increase in mosquito-borne outbreaks such as dengue hemorrhagic fever and Zika virus exacerbated by flooding require improved surveillance and better control of these diseases (Tissera et al. 2016). Assays such as reverse transcription-PCR and enzyme-linked immunosorbent assay were developed for Zika diagnosis and other related flaviviruses Singh et al. 2017). These assays may be performed using urine and blood, during early stages of infection. Newer and faster biosensors were also developed and are currently being validated for commercialization (Singh et al. 2017).

Monitoring environmental toxins

In stream and river water, contaminants usually occur in conjunction with floods, attributed to surface run-off and drainage following from large precipitation and extreme events such as hurricanes and cyclones. There are monitoring devices now available that measure herbicide and pesticide concentrations during flash flood events by applying intensive sampling programs as opposed to spot sampling in estimating time-weighted average concentrations and total loads of herbicides (Kennedy et al. 2012; Novic et al. 2017; Peterson et al. 2012). Rapid point-of- care assays capable of detecting clinically relevant organophosphate (OP) nerve agent toxicity following low-level exposure are now available (Wei, Yen, and Cheng 2018). These tests utilize a peripheral finger stick blood sample. While acute nerve agent exposure might be lethal, lower-level chronic OP exposures produce vague signs and symptoms. A rapid detection test for will assist in identifying contaminated patients earlier in the clinical course and trigger an appropriate response (VanDine et al. 2013). An additional acetylcholinesterase (AChE) test-mate field kit is available for rapid detection acute OP poisoning. This portable field kit is designed for detecting OP exposure that measures red blood cell AChE and plasma cholinesterase in less than 5 min (Rajapakse et al. 2011)

Low-cost and simple methods to test water supplies onsite might protect vulnerable communities from the impact of contaminants in drinking water. A biodegradable paper microbial fuel cell with carbon-based electrodes was developed as a sensor for bioactive compounds in water (Chouler et al. 2018). This sensor can test water in the field, is environmentally safe, easy-to-operate, rapid, and affordable.

Because of potential risks to the environment and human health arising from heavy-metal pollution in water, graphene-based water sensors are being developed for real-time detection of heavy-metal ions (Chang et al. 2014). These portable microsystems are ideal for environmental monitoring of contaminated drinking water. An ultrasensitive pulse-driven capacitance-based Pb ion sensor utilizing a graphene oxide to recognize heavy metal ions in water may be implemented in flash-flood environments (Maity et al. 2017). Another field-effective transistor device-based graphene oxide sensor was developed to specifically detect toxic elemental Pb ions in aqueous environments. With a rapid response time and low detection limit, these sensors also differentiate Pb from other metal ions (Zhou et al. 2014). In terms of human monitoring of elemental Pb levels after flash flooding, there currently exists a relatively non-invasive, low-cost fingertip capillary test that might easily be implemented in the field. Those victims with resultant Pb levels due to concern for toxicity development may then be removed from the source of exposure and referred for more accurate blood analysis and treatment (Green et al. 2017; Roberts et al. 2013).

As previously described, non-fire-related CO toxicity from generators has been among the leading causes of unintentional poisoning during flash-flood events (Lane et al. 2013; Lowe, Ebi, and Forsberg 2013). Real-time epidemiologic surveillance tools may be useful in estimating the prevalence of CO exposure, assisting public health efforts to prevent these poisoning outbreaks during and after disasters. The benefit of using low cost CO detectors in dwellings and buildings to prevent exposure far exceeds the cost of installation (Ran, Nurmagambetov, and Sircar 2018). Public health programs need to implement installation of CO detectors in homes and buildings not only prone to fires, but flash flooding and hydrometeorological events.

A noninvasive pulse CO-oximetry might also be useful as a first-line screening test enabling rapid detection and management of CO-poisoned patients in hurricane or flash-flooding environments. The pulse CO-oximeter is a cost-effective lightweight device allowing noninvasive measurement of carboxyhemoglobin. Patients with elevated levels might thus be evacuated from the source of exposure and treated with oxygen therapy. These pulse-ox CO detectors are not a substitute for standard blood COHb measurements. However, noninvasive pulse CO-oximetry may be a useful screening test in the field enabling rapid detection and evacuation of CO-poisoned patients to nearby medical care facilities and emergency departments for more definitive evaluation and treatment (Sebbnae et al. 2013).

A multi-gas sensor system was recently designed that employs a single broadband light source that detects CO, carbon dioxide, and methane. The sensor has potential applications in various fields requiring detection of these toxic gases in coal mines and might be extended to environments affected by flash floods and major structural damage (Dong et al. 2017). In certain types of fire, volatile organic compounds (VOC) appear prior to smoke particles. Therefore, systems based upon chemical sensing provide faster alarm responses than conventional smoke-based fire detectors. Since most casualties in fires are produced from exposures to toxic substances rather than actual traumatic burns, these multi-variant gas sensors provide an additional level of safety to victims of hydrometeorological events with concomitant structural building damage (Fonollosa, Solorzano, and Marco 2018).

Environmental satellite surveillance monitoring

After the launch of land satellites in the 1970's and development of earth observation systems in the 1980's, several environmental indicators produced from satellite images were employed for health studies, especially for surveillance of vector-borne diseases that have potential environmental health ramifications. Remotely-sensed data might be utilized to map different factors such as coastline destruction, deforestation, inland flooding, or population shifts, and is useful in early warning systems for major natural disaster threats mandating rapid evacuation (Ledien et al. 2017).

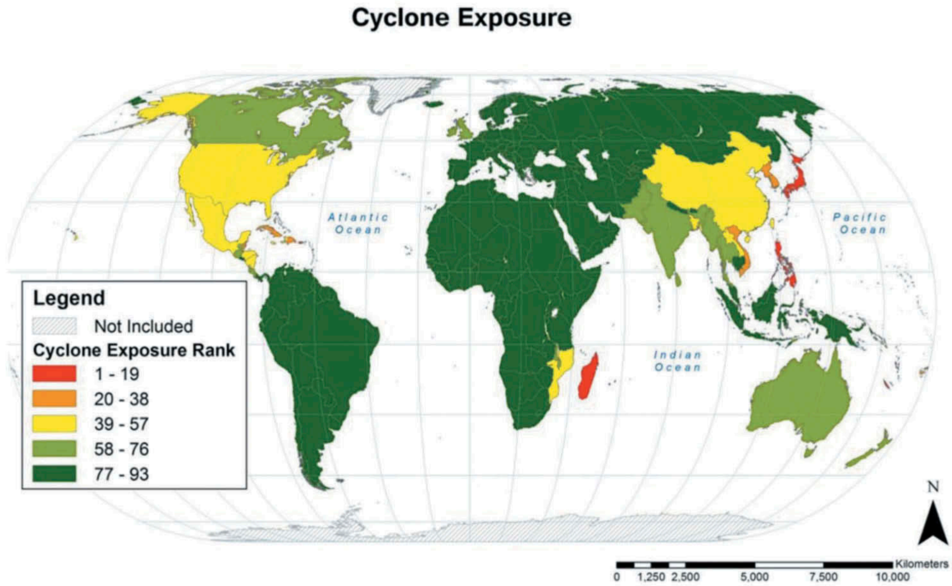

Figure 4. Rankings of country-level population cyclone exposure expressed as quintiles.
Christenson E., M. Elliot, O. Banerjee, L. Hamrick, and J. Bartram. 2014. A Method for Global Assessment of Urban and Rural Population Exposure to Cyclones, Droughts, and Floods. *Int. J. Environ. Res. Public Health. 11*(2), 2169–2192.

Satellite imagery with accurate topographical detail may also document real-time toxic spills in post-hurricane settings as noted with Hurricane Harvey (Figure 1) and Hurricane Florence (Figures 2 and 3) (Thomas 2017). These images are frequently updated and used to evaluate the need for evacuation, clean-up efforts, and ongoing environmental exposure during and after hurricane and flash flood events.

Assessing social vulnerabilities to environmental health threats

Improving risk analysis and preparedness for sources of environmental hazards and enhancing the use of rapid testing for toxins and infectious pathogens might be insufficient if it is not accompanied by reducing social vulnerability to natural disasters and flooding in the aftermath. Prolonged flooding events produce serious health problems for local inhabitants, particularly elderly and disabled individuals residing in poor conditions with limited food supplies, contaminated water sources, and poor sanitation. Epidemic diseases such as dengue fever, leptospirosis, and cholera are more common in these groups of individuals (Bich et al. 2011; Du et al. 2010; Ohl and Tapsel 2000).

According to one study, during flash floods, females and children appear to be at greater risk of psychological and physical health effects, while young males are at greater risk of injuries (Lowe, Ebi, and Forsberg 2013). Post-flood, geriatric patients and males are at increased risk of adverse physical health effects, while females appear at greater risk of psychological health effects (2013). Other risk factors include greater flood depth, traumatic injuries, pre-existing illnesses, medication shortages, and low education or socio-economic status (Lowe, Ebi, and Forsberg 2013).

Densely populated areas with mixed residential, commercial, and industrial facilities along coastal waterfronts are more commonplace in areas known for hurricanes and storm surges. The risk of chemical contamination from accidental industrial releases is elevated following a devastating hurricane or flash flood. Industrial waterfront communities, which frequently represent more vulnerable populations, may be exposed to numerous environmental toxins particularly when located in close proximity to residential neighborhoods, schools, and playgrounds (Madrigano et al. 2018).

Globally, coastal populations are the most vulnerable (Guglielmi 2018), especially in low-middle income countries (Figure 4) where hurricanes, cyclones and typhoons may produce substantial morbidity and increased mortality rates (Christenson et al. 2014; Stover and Vinck 2008) A recent survey indicating that the number of excess deaths related to Hurricane Maria in the Caribbean was more than 70-fold higher than the official estimate; with one third of the deaths attributed to delayed or interrupted health care (Kishore et al. 2018). One study reviewing major hurricane events found that lower per capita GDP and higher wind speeds were associated with greater mortality rates in hurricane-prone countries (Dresser et al. 2016). Excessive fatality rates occurred when powerful storms struck these low resource nations.

Predictions of increasing storm amplitude over time suggest greater disparity between death rates with poorer nations (Dresser et al. 2016). These vulnerable communities often do not have the financial or health infrastructure to evacuate or monitor infectious or toxicological outbreaks resulting from hurricane or long-standing flood damage (Donner and Lavariega-Monforti 2018; Vinck et al. 2009). Hurricanes and cyclones with flash floods will continue and exert greater effects on human health, mortality rates and environmental impact due to climate extremes. Environmental science predicts that hurricanes might increase in frequency and strength during the coming decades. Impacts will continue to arise due to elevated precipitation intensity and the fact more individuals are residing in coastal regions (Lowe, Ebi, and Forsberg 2013).

Slower hurricanes that stagnate over land lead to more land rainfall and more flooding (Kosslin 2018), as seen with Hurricane Florence in 2018. These events represent a risk to public health in low and upper incomed countries, but also impact poorer countries disproportionately, compounding pre-existing health disparities (Cann et al. 2012).

Conclusions

Hydrometeorological events such as hurricanes, cyclones and typhoons produce structural damage, traumatic injuries, and create flash flood waters that might be mixed with chemical spills, heavy metals, bio-toxins, invasive species, sewage, and debris that contaminate fresh water supplies. These environmental and infectious hazards might result in immediate and long-term adverse health risks in susceptible populations that are underreported and poorly monitored in emergency response and recovery stages. Moreover, these burdens are not distributed equally, but typically fall heaviest on already disadvantaged countries. Systematic research such as active surveillances of these environmental toxicities, infectious diseases, and human health disparities due to natural disasters, are needed. Unlike other natural disasters, hurricanes and cyclones often provide several days for active preparation and evacuation. In addition, regions more susceptible to these seasonal events are known. This advance knowledge provides valuable opportunities to develop protocol that permit effective evacuation and preparedness.

There is an urgent need to collect, analyze, and monitor toxic chemicals and infectious pathogens in contaminated environments following hurricanes and flash floods. There currently exist technologies that might be used during disaster response to rapidly assess toxicities, infection threats, and take remedial actions. These innovations might help document risks and may be employed to better prepare and protect vulnerable communities during and after these major hydrometeorological events.

Author contributions

TBE: Provided original concept, writing, literature review, toxicology expertize, and final edits
JB: Provided editing, manuscript organization, literature review, and grammatical changes
EN: Provided editing and infectious disease expertize
PNP: Provided editing, figures analysis, and overall review of manuscript
VP: Provided senior authorship oversight, editing, and disaster response expertize

Consent

All above named coauthors consent to publication.

Disclosure

The authors declare no competing financial interests.

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