



University of Pennsylvania
ScholarlyCommons

Master of Science in Applied Geosciences
Project Designs

Department of Earth and Environmental
Science

5-2020

RISK ASSESSMENT OF CONTAMINANT MIGRATION ON ENVIRONMENT AND COASTAL COMMUNITIES DUE TO HURRICANES – A REVIEW

Meighan Long

Follow this and additional works at: https://repository.upenn.edu/msag_projects

 Part of the [Earth Sciences Commons](#)

This paper is posted at ScholarlyCommons. https://repository.upenn.edu/msag_projects/8
For more information, please contact repository@pobox.upenn.edu.

RISK ASSESSMENT OF CONTAMINANT MIGRATION ON ENVIRONMENT AND COASTAL COMMUNITIES DUE TO HURRICANES – A REVIEW

Abstract

Studies specifically focusing on effects of contamination migration to the environment and human health pertaining to hurricane activity are minimal, yet necessary to understand risk and mitigate future impacts of these devastating storms. A hurricane's speed and direction are heavily dependent on the intricate interaction between the atmosphere and ocean, including the presence or absence of additional weather patterns. The complexity of these conditions makes it very difficult to predict the impacts of such a storm, including threat to human health by exposure to contaminants, damage to structures and facilities housing hazardous substances, and contamination dispersion from a facility into the environment and surrounding communities. Since the intensity of hurricane events has been increasing globally, many efforts have been made to predict these natural storms. 1 Evaluations of the consequences that storms pose on impacted coastal communities and environments once they pass must not be neglected. A limited number of previous studies have discussed the destructive influences natural disasters have on technological industries, known as "na-tech" events. However, the majority of those studies are conducted with a wide lens, considering all the possibilities of natural disasters together and overlooking non-industrial cases. This project will review available data to analyze risk posed on environments and communities specifically from hurricane impacts. Thorough examination of public records will be conducted for industrial and non-industrial facilities that handle hazardous substances and contamination, such as chlorinated solvents, heavy metals, and organic compounds. The goal is to more accurately assess how communities and their surrounding environments will be affected by hurricane-induced contaminant releases in order to support future preparation, mitigation, and response efforts.

Disciplines

Earth Sciences | Physical Sciences and Mathematics

RISK ASSESSMENT OF CONTAMINANT MIGRATION ON ENVIRONMENT AND COASTAL COMMUNITIES DUE TO HURRICANES – A REVIEW

Meighan Long

Master of Science in Applied Geosciences - Environmental Geology
University of Pennsylvania

Spring 2020

Primary Reader: John A. Miller, P.E. CFM, CSM, Federal Emergency Management Agency
Secondary Reader: Mitch Cron, Earth & Environmental Science, University of Pennsylvania

ABSTRACT

RISK ASSESSMENT OF CONTAMINANT MIGRATION ON ENVIRONMENT AND COASTAL COMMUNITIES DUE TO HURRICANES – A REVIEW

Meighan Long

John Miller

Studies specifically focusing on effects of contamination migration to the environment and human health pertaining to hurricane activity are minimal, yet necessary to understand risk and mitigate future impacts of these devastating storms. A hurricane's speed and direction are heavily dependent on the intricate interaction between the atmosphere and ocean, including the presence or absence of additional weather patterns. The complexity of these conditions makes it very difficult to predict the impacts of such a storm, including threat to human health by exposure to contaminants, damage to structures and facilities housing hazardous substances, and contamination dispersion from a facility into the environment and surrounding communities. Since the intensity of hurricane events has been increasing globally, many efforts have been made to predict these natural storms.¹ Evaluations of the consequences that storms pose on impacted coastal communities and environments once they pass must not be neglected. A limited number of previous studies have discussed the destructive influences natural disasters have on technological industries, known as "na-tech" events. However, the majority of those studies are conducted with a wide lens, considering all the possibilities of natural disasters together and overlooking non-industrial cases. This project will review available data to analyze risk posed on environments and communities specifically from hurricane impacts. Thorough examination of public records will be conducted for industrial and non-industrial facilities that handle hazardous substances and contamination, such as chlorinated solvents, heavy metals, and organic compounds. The goal is to more accurately assess how communities and their surrounding environments will be affected by hurricane-induced contaminant releases in order to support future preparation, mitigation, and response efforts.

Introduction

In 2017, Hurricane Harvey set a United States record for most rainfall from a single storm dropping over 60 inches of rain in certain locations and leaving 125 billion dollars of damage.² This project will examine impacts on both environmental contamination and human health by reviewing available academic journals and news reports of industrial and non-industrial facilities that handle hazardous substances and contamination in coastal communities vulnerable to hurricane events. Hurricanes are one of many natural disasters that affect modern day societies along the coastlines and inland. Meteorologists know hurricanes as mesoscale cyclones which typically range from a few to several hundred kilometers, containing powerful winds, large energy, and thunderstorms.³ The public knows hurricanes as massive storms that bring large bands of rain, extreme flooding, and gale force winds. Not only is it important to observe immediate hydrological and atmospheric effects hurricanes pose on society, but also the local environmental and adverse health impacts that follow these catastrophic events. Long-term impacts of these storms rarely get attention because most media coverage is focused on immediate effects and emergency recovery efforts. By looking at the available environmental and human health records associated with these natural disasters, assessment of the effects of contamination in the environment and coastal communities may assist in understanding risk and mitigating future impacts.

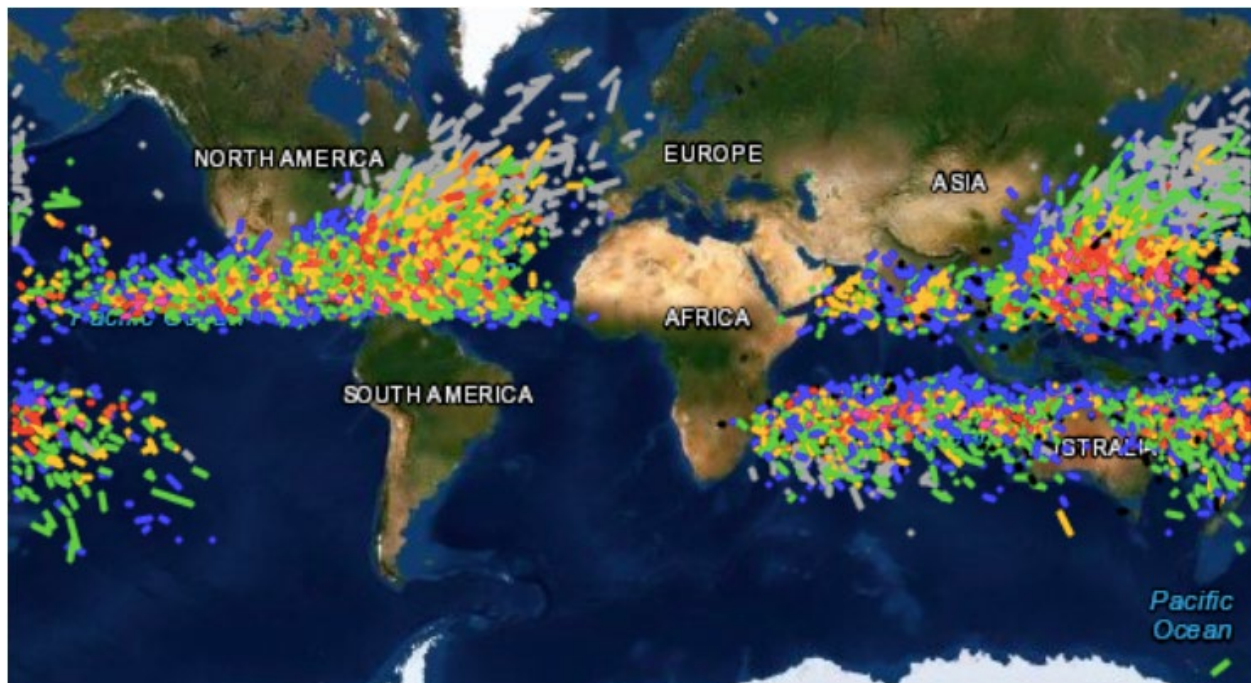
“The biggest lesson [from working on environmental projects following Hurricane Sandy] is disasters are local and response is different and dependent on where you are.”⁴

- Tim Reilly, United States Geological Survey (USGS)

Hurricanes and Trajectories

A hurricane is defined by the National Oceanic and Atmospheric Administration (NOAA) as “a tropical cyclone in which the maximum sustained surface wind is 64 knot (74 mph) or more. The term hurricane is used for Northern Hemisphere tropical cyclones east of the International Dateline to the Greenwich Meridian. The term typhoon is used for Pacific tropical cyclones north

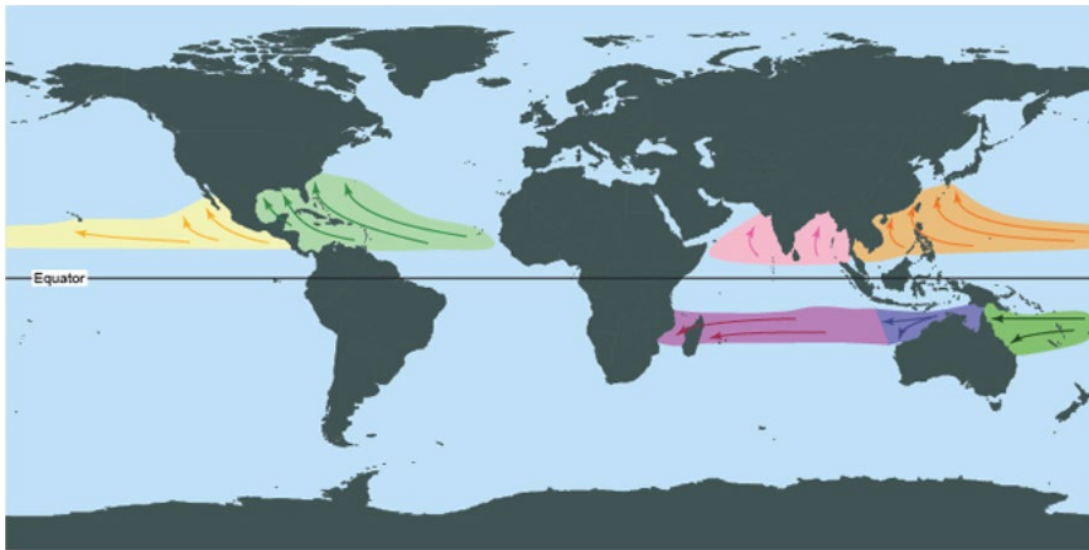
of the Equator west of the International Dateline”.⁵ The Saffir-Simpson Scale provides hurricane categorization from 1-5, primarily based on wind speed. The higher the category, the greater the hurricane’s potential for damage. Although the current classification system is based on wind speed, other factors contribute to a hurricane’s strength and potential for damage. A hurricane’s fuel comes from the warm moist air that forms over the oceans. As the warm air rises, areas of low-pressure form, creating a system of rotating cloud bands.⁶ Warm sea surface temperatures, lowering air pressures, amount of time for storm formation over the ocean, and sustaining winds are all factors that contribute to the storm’s intensity. These factors are not necessarily reflective of the devastating nature of the event. Other factors such as rainfall, storm surge, flooding, lightning, and the ability to produce tornadoes can contribute greatly to the impacts. Since hurricanes form over the ocean, coastal communities and coastal environments are the most vulnerable to their devastating impacts. Figure 1 depicts historical Category 1 through Category 5 hurricane trajectories for the entire period of record, over 150 years in some locations.



(Figure 1. Global Scale Tropical Cyclones Category 1-5 Trajectories From 1851 to 2019⁷)

Averaging each of the individual trajectories over the years is a climatological method that scientists use to predict places at most risk to hurricanes. Seven tropical cyclone basins, regions where storms occur the most, have been found. These basins are the Atlantic basin (North

Atlantic Ocean, Gulf of Mexico, and Caribbean Sea), Northeast Pacific basin (Mexico to the dateline), Northwest Pacific basin (from dateline to Asia including the South China Sea), North Indian basin (Bay of Bengal and Arabian Sea), Southwest Indian basin (Africa to Longitude 100 East of Greenwich), Southeast Indian/Australian basin (Longitude 100 East to Longitude 142 East of Greenwich), and the Australian/Southwest Pacific basin (Longitude 142 East to about Longitude 120 West of Greenwich) which are shown in Figure 2. Researchers studying climatological trends have suggested that active hurricane seasons differ for each basin, but all are on annual schedules. For the Atlantic basin, the official hurricane season is every year from the month of June through the end of November.⁸

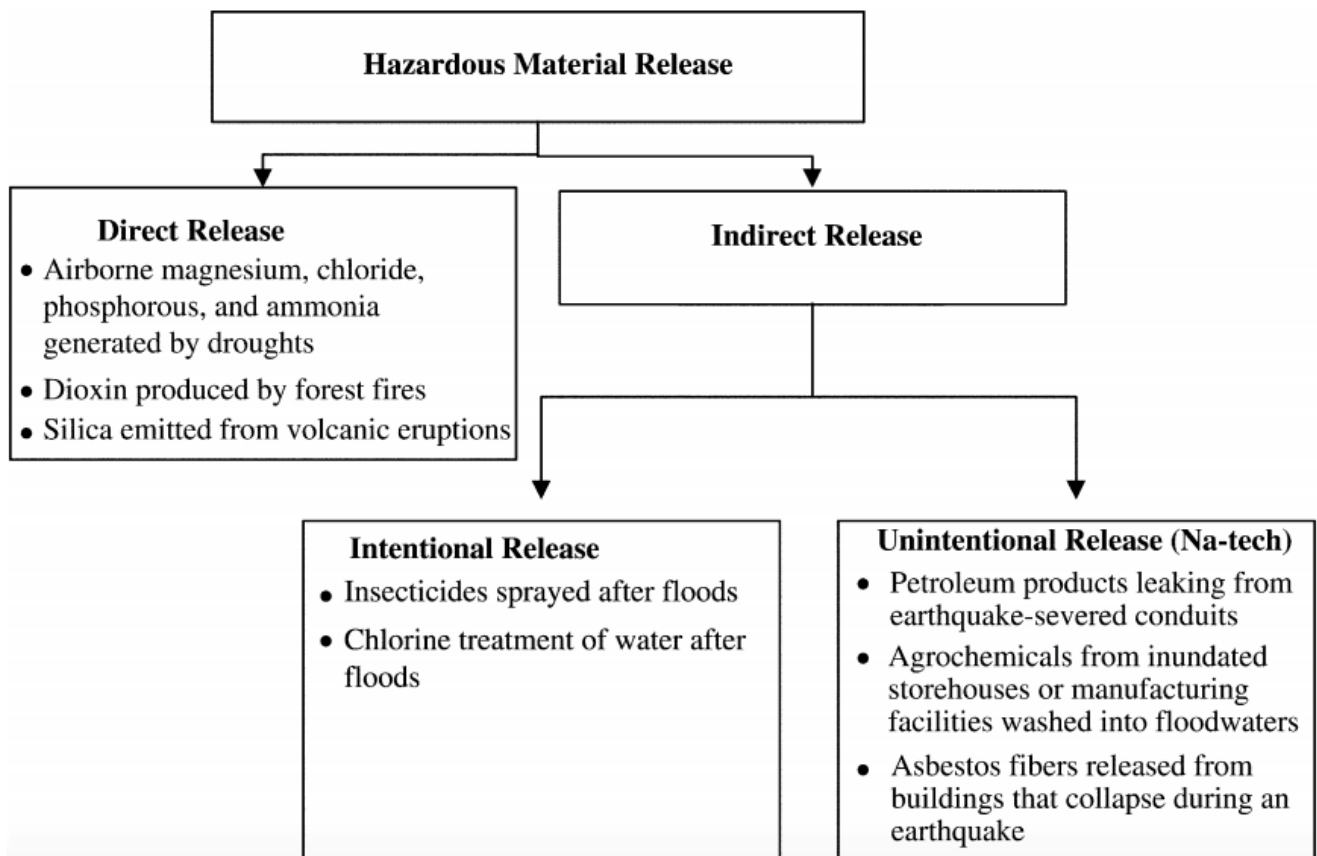


(Figure 2. Seven Tropical Cyclone Basins⁹)

Defining a Release

For the purpose of this paper, a release will follow the Environmental Protection Agency's (EPA) definition of release: "Any spilling, leaking, pumping, pouring, emitting, emptying, discharging, injecting, escaping, leaching, dumping, or disposing into the environment of a hazardous or toxic chemical or extremely hazardous substance".¹⁰ Releases can be categorized as direct and indirect and further subcategorized as intentional and unintentional, shown in Figure 3. A direct release of a hazardous substance has few, if any, mitigating actions that can be done for prevention, and are consistent with natural events. Indirect releases occur when

technologic circumstances in combination with a natural event result in a discharge into the environment. Unintentional releases are not planned and have no constructive purpose whereas intentional releases are made to stop other, more serious, threats. In efforts to stop vector borne diseases, an intentional release of potentially hazardous chemicals may occur. Chemical controls in the form of pesticides are considered the most effective way to prevent vector borne disease from spreading after flooding. The Center for Disease Control and Prevention (CDC) reported a method of mosquito management, a large issue in flood prone areas, that can reduce the risk of mosquito borne outbreaks following a flood event. The CDC advises that pesticides must be applied away from people to reduce negative exposure risks.¹¹ This form of mosquito management describes how an intentional release of pesticides may occur as a response to mitigate vector borne threats from hurricane flooding but still may have environmental and human health implications.



(Figure 3. Classification of Hazardous Material Releases Associated with Natural Disasters¹²)

Common Forms of Release

“Potential routes of [contaminant] exposure comes from debris associated with the event itself.”¹³

- Tim Reilly, USGS

In 2019, the EPA held a press release pertaining to waste mitigation due to the hurricane season. This news release from the Office of Land and Emergency Management emphasized the importance of “mitigating hazardous waste and securing potential harmful debris before the storms strike”.¹⁴ Assessments of hurricane responses from 2017 and 2018 to Hurricanes Harvey, Irma, Maria, and Florence, showed a large amount of waste was observed during the disaster recovery process. Some of the waste from these events included 470,100 containers (drums, oil containers, propane tanks, etc.) and 2,700 vessels containing sewage water waste, pathogens, and nutrients.¹⁵ The most common forms of contaminant releases are those of the petroleum, chemical, and biological nature from industrial plants, Superfund sites, and sites with waste-management land uses.

Types of Contaminants

There are thousands of contaminants that may be released during a hurricane event, but most are characterized into broad groups based on chemical structure, use in society, physical trait, and organic matter. Common groups of these contaminants and hazardous substances include heavy metals, chlorinated solvents, polycyclic aromatic hydrocarbons (PAHs), polychlorinated biphenyls (PCBs), and microbial. The historic nature of societies to settle around or along the waterbodies enabled coastal regions to become economical hubs of industry. Large industrial activities coupled with ability to create and globally distribute new chemicals and products contribute to the ubiquity of these contaminants and hazardous substances in society, affected communities, and the environment.

Heavy metals are naturally occurring and pose serious threat to human health and the environment due to their various industrial, domestic, agricultural, medical, and technological

uses. “The high degree of toxicity implicates arsenic, cadmium, chromium, lead, and mercury to rank among the priority metals that are of public health significance. These metallic elements are considered systemic toxicants that are known to induce multiple organ damage, even at lower levels of exposure. They are also classified as human carcinogens (known or probable) according to the EPA, and the International Agency for Research on Cancer”.¹⁶

Chlorinated solvents such as dichloromethane, tetrachloroethene, trichloroethane, trichloroethene, perchloroethane, and vinyl chloride are commonly used in the manufacturing industry to degrease fats, oils, waxes, and resins.¹⁷ The density of these compounds is greater than water, so they tend to sink to the bottom of groundwater systems which results in complex plume patterns and persistence in the environment. The tendency for these substances to sink to the bottom of groundwater systems make them difficult to detect and remediate once they are released. Chlorinated solvents are hazardous and are known to be carcinogenic to humans.

PAHs are a group of chemicals that occur naturally in coal, crude oil, and gasoline. They are also produced from the burning of wood, oil, gas, coal, garbage, and tobacco products. Naphthalene is a PAH that is commercially produced in the United States for other chemicals. These compounds may volatilize and can bind to or from small particles in the air. Specific mixtures of PAHs are known carcinogens.¹⁸

PCBs belong to a broad family of man-made organic chemicals known as chlorinated hydrocarbons. These chemicals were used for heat transfer and hydraulic equipment, as plasticizers in paints, plastics and rubber products, and in pigments, dyes and carbonless copy paper. PCBs were domestically manufactured from 1929 until manufacturing was banned in 1979. Even with discontinued use, PCBs are still present in the environment today because of their persistence and inability to quickly breakdown. They have no known taste or smell, and range in consistency from an oil to a waxy solid and range in toxicity. Due to their non-flammability, chemical stability, high boiling point and electrical insulating properties, PCBs were used in hundreds of industrial and commercial applications. PCBs are suspected carcinogens.¹⁹

Contaminants with microbial characteristics include viruses, bacteria, and pathogens. Flooding from hurricanes can disrupt water purification systems and sewage treatment systems, causing the overflow of toxic waste sites and discharge of chemicals previously safely contained.

“Floodwater often contains infectious organisms, including intestinal bacteria such as E. coli, Salmonella, and Shigella; Hepatitis A Virus; and agents of typhoid, paratyphoid and tetanus”.²⁰

Although, most of the time, flooding is not the mechanism that causes serious exposure health effects, it does pose a risk for first responders, residents, and others who come in contact with the contaminated flood water.

A United States Geological Survey (USGS) investigation report stated that many human-made organic contaminants bind to sediments and such sediments can accumulate in places over time. Hydrophobic constituents are those that prefer to bind to sediments instead of staying in the water column. PCBs, PAHs, chlorinated solvents, and some heavy metals are considered hydrophobic and are commonly detected in soil samples taken near industrial sites.²¹ Other contaminants prefer to stay in the water column and some even volatilize into the air, creating a potential risk for inhalation and ingestion of these toxic compounds.

Previous Studies of Contamination on Subsurface Strata

“The goal is to look at long-lived effects.”²²

- Tim Reilly, USGS

Testing for contaminants in sediments before and directly after a hurricane has been sparsely conducted throughout the country. These tests are used to draw comparisons between the environmental conditions before and after a storm event.²³ However, there is a lack of long-term data to draw conclusive answers from these comparisons. Another common concern is attributing shifting contamination concentrations solely to the hurricane event.²⁴ Flooding is arguably the most destructive impact of a hurricane; therefore, cases where environmental conditions pre- and post-flood are available are ideal to study.

“Places where there’s a local issue and local phenomena are well sampled,
but other places are not.”²⁵

- Tim Reilly, USGS

After Hurricane Sandy hit the eastern coast of the United States, several studies on contamination transport followed. A distribution assessment of contaminants in tidal creek sediments following Hurricane Sandy suggested that new contamination in the New Jersey Meadowlands could stem from legacy sediments from industrial pollution from the 1960s, instead of flooding from Sandy.²⁶ This study concluded that massive export of contaminants due to the sea surge was not apparent.²⁷ However, this study neglected to mention the resuspension of legacy sediments, a byproduct of erosion caused by landscape disturbance from human activity, due to flooding. Although Hurricane Sandy did not serve as the initial source of these contaminants, it should be considered as a secondary source for its role in potentially resurfacing the sediments and creating likely exposure to the environment and surrounding communities. A different study conducted on Fire Island, New York, following Hurricane Sandy focused on the relationship between wastewater treatment facilities and groundwater contamination. Groundwater samples were collected in 2011, before Hurricane Sandy, and in 2013, after Hurricane Sandy in three locations on Fire Island, New York. In two of these locations, concentrations of detected contaminants were higher in the post-storm samples. This suggested an increase in contaminants following hurricanes due to flooding and proximity to industry, wastewater facilities, and Superfund sites.²⁸ The authors mentioned that factors other than inundation of the area have potential to play a role in increasing contamination exposure. Future studies on the effects of inundation can improve understanding of the fate and transport of contaminants of concern, which is necessary to defining and predicting resiliency in coastal settings.²⁹ A third study conducted in New York following Hurricane Sandy found an increase of contaminant concentrations in soils at various locations downstream of an EPA Superfund site. Sixty-three soil samples were collected by “community scientists recruited by social media” and compared to “background” soil samples provided by the National Cooperative Soil Characterization Database. Although the detected contaminants could not be a proven result of Hurricane Sandy, evidence of changes in contamination concentrations across sampling locations suggest that flooding could have enabled the migration of contaminants.³⁰

A few studies have shown how organisms in the impact zone respond to severe storm events. One assessment following Hurricane Katrina and Hurricane Rita in 2005 used oyster tissue data from the Mussel Watch Program, a long-term government monitoring program, to assess the ecological damage of the hurricanes. The Mussel Watch Program was formed in 1986 by NOAA in response to concerns over environmental water quality. The mission is to continuously monitor chemical and biological contaminants through the use of biological indicators. Metal concentrations in the oyster tissue were found to be higher after the hurricanes and organic matter concentrations were lower after the hurricanes. No United States Food and Drug Administration action levels were exceeded in any samples collected, which suggested that contamination, although noteworthy, was not extreme.³¹ Another study on the impact of Hurricane Sandy on the Hudson-Raritan estuary explored interactions between long-term environmental degradation, climatic stresses, and human behavioral responses three years prior and three years following the hurricane event.³² This study found that the degree of impact on an estuary depends not only on storm severity, but also on the availability of watershed biodiversity, land use, and habitat heterogeneity. Results indicated that water clarity and nutrients returned to pre-storm conditions in about a year but shifts in the biological community persisted for multiple years.³³

Tim Reilly, Deputy Programs Coordinator with the Environmental Health Mission Area for the United States Geological Survey (USGS), led projects that focused on potential long-term contaminant threats resulting from compromised infrastructure, beach erosion, and sediment distribution in the coastal environments of New Jersey and New York in the aftermath of Hurricane Sandy. A timely study preceding Hurricane Sandy was funded by the State of New Jersey and focused on sediment toxicity in the Barnegat Bay, which fortunately provided local baseline comparison data for the hurricane aftermath study.³⁴ The study, which was funded by a supplemental appropriation to the USGS, following Hurricane Sandy mobilized researchers to use sediment and organism samples in conjunction with data from other programs, such as NOAA's Mussel Watch Program, for analysis. Most concentrations of persistent organic pollutants including PCBs, PAH, and pesticides in sampled fish and mussels were the same or lower after Hurricane Sandy, but trace elements in sediment samples taken from Barnegat Bay increased by two orders of magnitude, tripling the number of sites exceeding sediment quality

guidance levels. Results suggest that Hurricane Sandy played a fundamental role in mobilizing contaminants which greatly changed contaminant concentrations in the environment.³⁵ A second round of funding supported the development of the Sediment-bound Contaminant Resiliency and Response Strategy (SCoRR), a baseline data acquisition network. This network overlays a series of datasets from a geospatial perspective (e.g. historical hurricane tracks) and locations of concerns from government agencies and environmental organizations (e.g. EPA Toxic Substances Inventory sites) to identify potential hazard sources and risk-assess areas of concern. Currently SCoRR only covers the eastern seaboard of the United States and is dormant due to lack of funding and resources. The mission of SCoRR is to eventually reach a national scale to identify risk upon locations of interests from the suite of natural hazards.

Previous Studies on Natural and Technologic (Na-tech) Hazardous Material Releases from Natural Disasters

Natural hazard triggered technological (na-tech) accidents are frequent in the wake of natural disasters, and they “have repeatedly had significant and long-term social, environmental, and economic impacts”.³⁶ Iconic storm-triggered na-tech events were recorded when Hurricane Katrina and Rita hit Texas, Mississippi, and Louisiana in 2005. The combination of the two storms caused damage to onshore and offshore oil and gas infrastructure and triggered a number of hydrocarbon spills, resulting in environmental emergencies and great economic losses. During Hurricane Harvey, the US Coast Guard National Response Center filed 96 reports of spills of hazardous chemicals, crude oil, and fossil fuels which contaminated the Gulf Coast, while 46 facilities in 13 counties reported airborne emissions totaling 4.6 million pounds.³⁷

In May 2006, an EPA report discussed hazardous material releases and debris management following Hurricane Katrina, a Category 5 hurricane that hit the Gulf Coast in September 2005. Mass destruction was left in Hurricane Katrina’s wake in the states of Louisiana, Mississippi, and Alabama. The storm created an estimated 86 million cubic yards of debris, caused the spill of over 7 million gallons of oil, and passed over 400 industrial facilities that store or manage hazardous materials resulting in approximately 850 impacted underground storage tank facilities and over 300,000 discarded “white goods” (appliances, such as air conditioners and refrigerators,

which may contain harmful substances such as Freon).³⁸ The report states that millions of hazardous products such as bleach, cleaners, oils, fuels, pesticides, herbicides, paint, and batteries were scattered into the environment due to the flooding and storm surge.

Few researchers have focused on studying the hazardous materials that are unintentionally released as the result of a technological malfunction caused by a natural event. These events are referred to as natural technological or “na-tech” events, and usually involves a petroleum, chemical, or manufacturing industry that handles hazardous substances during operational processes. Thorough analysis of available historic disaster related hazardous material releases may assist in identifying threats and improvements for mitigation and prevention efforts.³⁹ Hazardous materials, pollution, and contaminants released during natural disasters (earthquakes, eruptions, landslides, hurricanes, tornadoes, etc.) threaten human health by increasing the likelihood that individuals will be exposed to those toxic substances. Secondary hazards such as fires, explosions, and falling debris may also result from na-tech events, causing residents in surrounding communities and workers of the facility to be at most risk for immediate impacts. “These releases may be small: paints, solvents, insecticides, and other household toxins stored in homes and washed away by flood waters or large such as: oil leaking from severed pipelines. Large-scale releases may pose serious risk for communities as water, soil, and air are potential media that may be impacted. These threats could translate into acute or chronic exposures and adverse health outcomes for communities surrounding the impacted area”.⁴⁰ In the United States, “regulations such as the Clean Water Act, Clean Air Act, Oil Pollution Act, and Comprehensive Environmental Response and Compensation Liability Act, can be adjusted to address specific hazmat threats posed by natural disasters”.⁴¹ Since many industrial facilities handle hazardous substances, cooperation among government, private industry, and academic communities is required in order to more accurately assess the risk of disaster-related releases and to promote appropriate technology to mitigate and prevent future environmental and public health issues.

Physical Mechanisms of Release

Toxic chemicals, heavy metals, and other contaminants are commonly found in the natural environment and innocuously locked in sub-surface strata or properly managed in containments

such as landfills and waste lagoons. A hurricane's potential to cause physical damage poses risk to change the innocuous nature of these contaminants and hazardous materials. Physical mechanisms such as erosion, scour, and overtopping could play a role in the fate and transport of contaminants by displacing them into the environment and surrounding communities.

Erosion refers to a general lowering of the ground surface over a wide area and can be “gradual, occurring over a long period of time (many years); more rapid, occurring over a relatively short period of time (weeks or months); or episodic, occurring during a single coastal storm event over a short period of time (hours or days)”.⁴² Erosion is more likely to affect areas that are closer to the shoreline or in specific geologic features such as karst topography. The loosening and suspense of soils which can be done by floodwaters or waves is called scour.⁴³ The effects of scour increase with increasing flow velocity, turbulence, and soil erodibility. Erosion and scour can cause foundations to fail resulting in the collapse or movement of structures storing contamination. More importantly, short-period, long-period, and episodic scour of the sediments can ultimately impact the mobilization of contamination to surrounding areas, increasing the potential of exposure to human health and the environment. As the landscape changes, it's important to track the changes of what substances are transitory and what substances are being deposited.

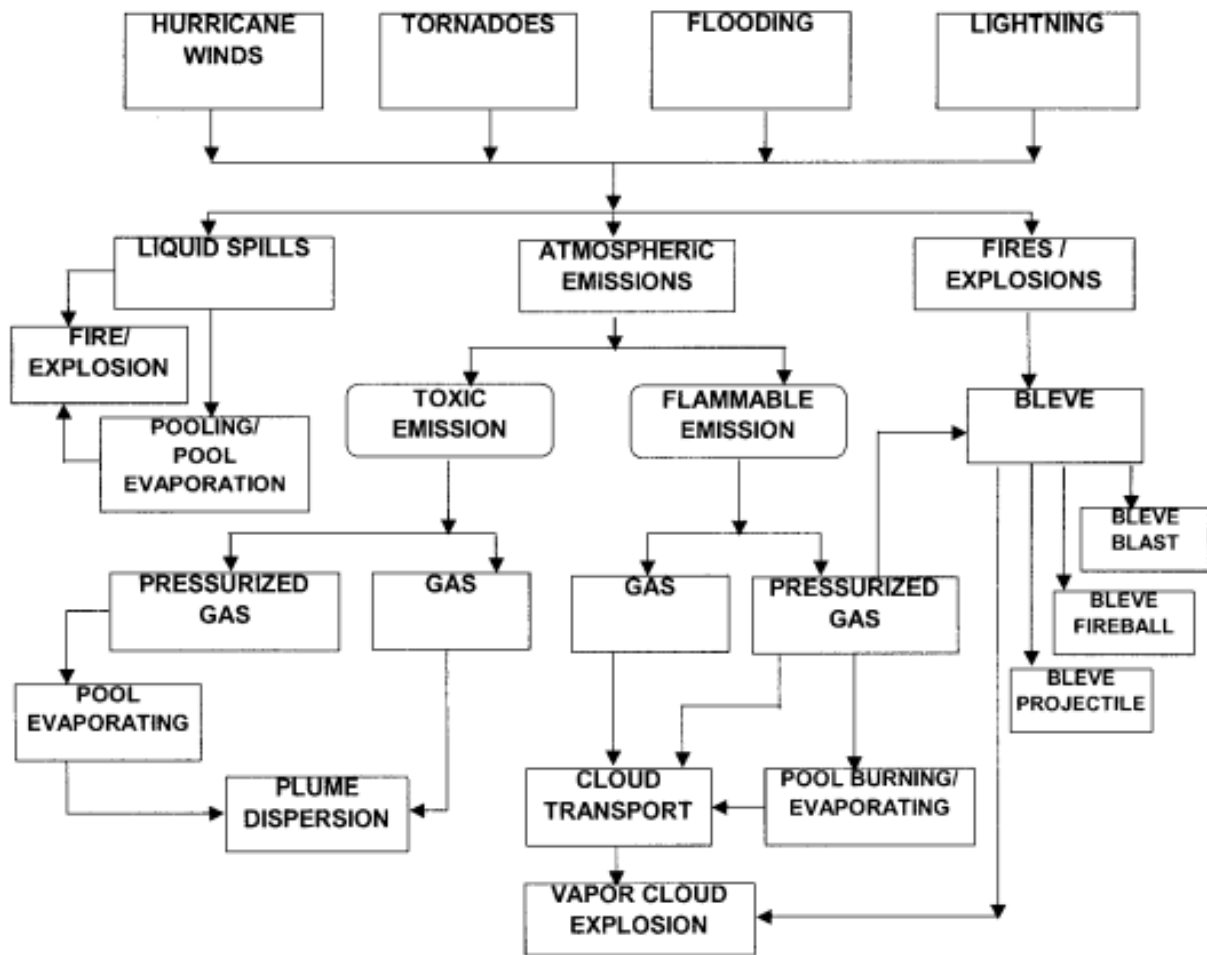
Overtopping or overflowing usually impacts waste pits and lagoons which are commonly used in agriculture and industrial processes. It generally occurs when containers holding contamination become inundated by floodwaters, releasing the contents into the environment. In 2016, Hurricane Matthew impacted North Carolina, a state which manages tons of hog waste largely due to heavy investments in the pork industry. The North Carolina Department of Environmental Quality (NCDEQ) stated the floodwaters from the hurricane overflowed at least 14 swine-waste lagoons, sparking fears that untreated animal waste contaminated local water supplies and spread disease.⁴⁴ The NCDEQ acknowledged the importance of confirming lagoons are “structurally sound” and testing floodwaters to ensure the “environment is protected”, especially in cases of an emergency, like a hurricane.⁴⁵ It's important to note, extensive disease outbreaks from waterborne pathogens have more potential to contaminate community water systems in locations where the public health and environmental infrastructure is less resilient.⁴⁶

There are many factors that determine the fate and transport of substances such as chemical composition, ability to sorb, and transport media. The thousands of hazardous substances and contaminants of concern have their own preferences to air, water, or soil based on their chemical composition. Depending on the environmental media, the exposure pathway to a receptor may vary. For example, a resident may inhale a contaminant through the air or ingest a hazardous substance through drinking water. Erosion, scour, and overtopping are few examples of release mechanisms which enable these contaminants to spread into the environment. A contaminant may resuspend and mobilize in soil due to erosion and scour or sorb to materials due to transport from overtopping. The fate of the contaminants depends on the combination of release mechanisms and contaminant properties. Conceptual site models, commonly used during environmental response processes, can help determine sources, release mechanisms, impacted media, exposure pathways, and receptors of these substances.

When designing a building, facility, or structure, it's important to account for release mechanisms. In 2009 a FEMA document stated, "definitive guidance for estimating coastal erosion and scour is not present in building codes and standards".⁴⁷ Designing facilities to withstand the powerful nature of a storm should be prioritized, especially in coastal locations identified as having a high-risk vulnerability. Proper management of facilities that handle or produce hazardous substances and contamination is necessary to reduce threats of releasing contaminants into the environment. A method that farmers currently use to prepare for the effects of a hurricane is to decrease the amount of waste in a lagoon. Although this method has helped in some cases, it is not a catch-all to prevent the spread of disease and contamination. To prevent exposure to harmful substances, it's crucial to examine existing controls and consider improving management of structures, facilities, and storage containers to mitigate risk of a release into the environment.

Threat to Human Health and Environment

Cruz et al. identified four hurricane threats from examining hurricane-induced hazardous material release scenarios in a petroleum refinery. These threats are high winds, tornadoes, flooding, and lightning, all of which, have potential to put human and environmental health in imminent risk. Each one can damage facilities and rupture equipment resulting in the release of stored chemicals and possibility of secondary disasters. Figure 3 depicts the impacts of these storms and the secondary events that may be triggered as a result are key factors in risk assessment.⁴⁸ Flooding is generally perceived as the most daunting hurricane threat. Flooding resulting from the heavy rain associated with a hurricane or the storm surge generated by hurricane winds can release chemicals from soils, residences, industrial-waste sites or other sources to create toxic runoff from those inundated areas.

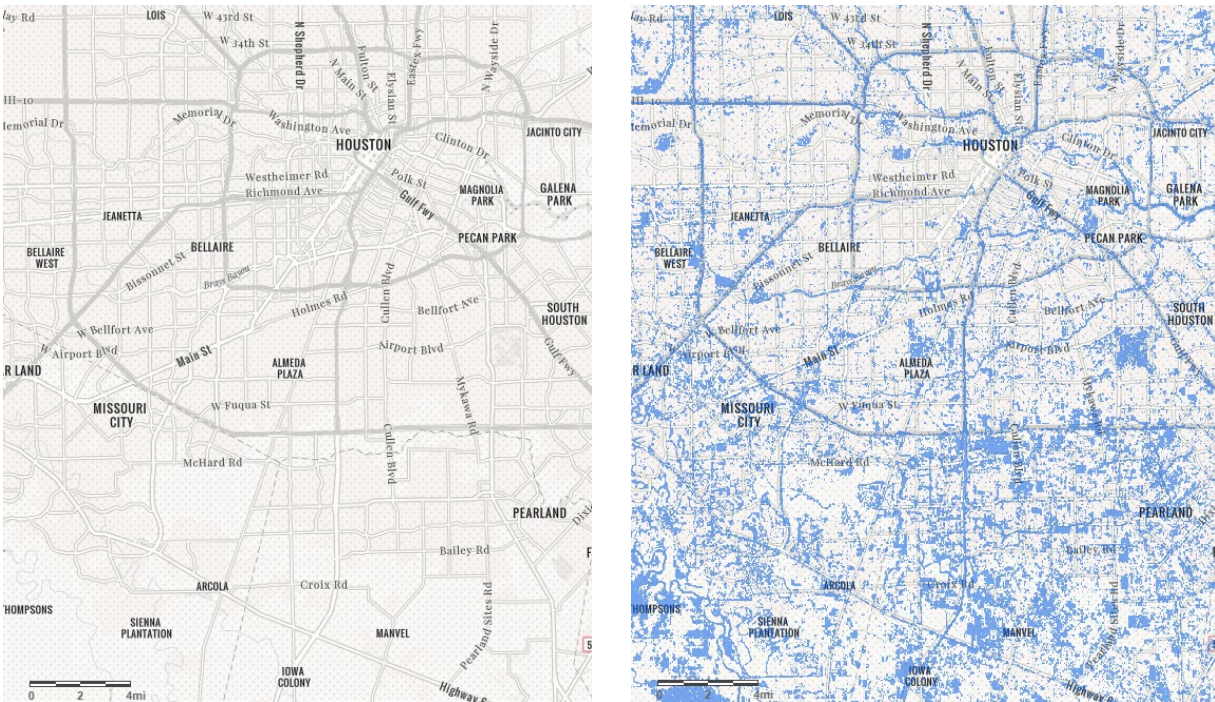


(Figure 4. Potential Hazardous Substance Releases from a Facility Due to High Winds, Tornadoes, Flooding, and Lightning⁴⁹)

In the aftermath of Hurricane Maria in 2017, a study was conducted by Dr. Kumar, a professor of environmental health at the University of Miami, with a focus on the spread of PCBs in Puerto Rico. He found that levels had tripled since Maria in Guánica, a bayside town with historically high concentrations of PCBs.⁵⁰ Dr. Kumar is also conducting study expected to finish by April 2020. This study is examining impacts of Hurricane Maria on PCB redistribution in Puerto Rico and assessing changes in community exposure through inhalation and consumption exposure pathways.⁵¹ Gina McCarthy, who ran the EPA during the Obama administration and directed the Center for Climate, Health and the Global Environment at Harvard University, told the New York Times, these toxic substances displaced during disasters “are much more long-lasting and ubiquitous than I think people realize...and we clearly haven’t caught up in terms of our laws and regulations, and the process of disaster response”.⁵²

“The goal is to look at long-lived effects.”⁵³

- Tim Reilly, USGS



(Figure 5. Estimation of Flooding Around Houston, Texas after Hurricane Harvey⁵⁴)

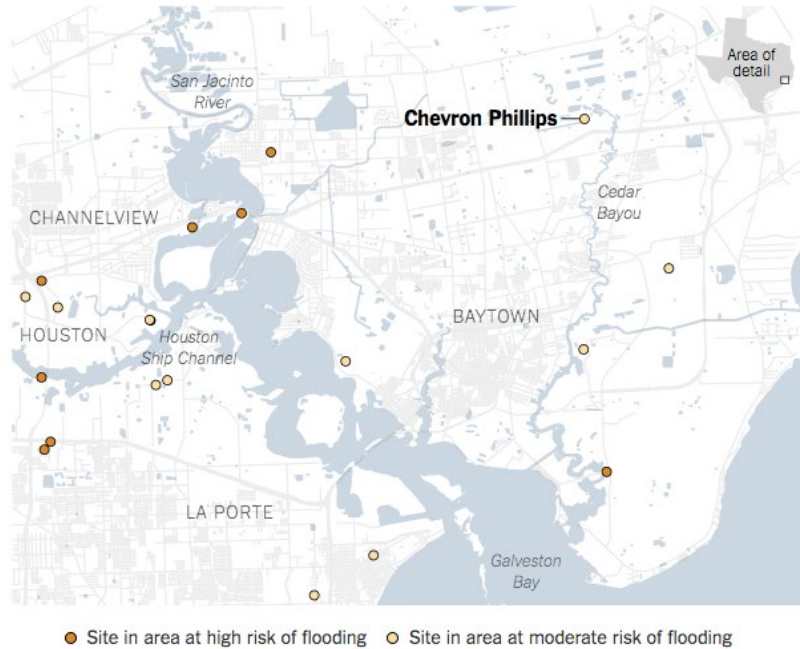
A team from Baylor College of Medicine distributed health questionnaires to Houston residents after Hurricane Harvey. Researchers took nasal swabs, spit and saliva tests, and fecal samples to see what toxins were in people’s bodies. Silicon wristbands which measured what chemicals the residents were exposed to were distributed and worn continuously by residents for seven days. Early results showed a range of health reactions, including sinus problems, skin irritation, and respiratory ailments.⁵⁵ The next step was to use spatial analysis to determine which participants were close to which chemical facilities and what contaminants were present in their bodies and homes, to try to link specific toxins to specific health effects. According to an article written in the Texas Medical Center, the “wristbands measured for more than 1,500 different chemicals”.⁵⁶ The Researchers focused on pesticides, pharmaceutical chemicals, industrial chemicals, polychlorinated biphenyls (PCBs), endocrine disruptors, dioxins and furans, polycyclic aromatic hydrocarbons (PAHs), flame retardants, and personal care products.⁵⁷ After analyzing the data from the 208 participants, researchers found an average of 26 chemicals on each wristband and detected 183 chemicals out of the 1,500 for which they were tested.⁵⁸ This study is in review and findings by the research team will be published in the near future.



(Photo 1. Satellite Images of Otey, Texas from Before and After Hurricane Harvey in 2017⁵⁹)

Cases at Industrial Facilities (Na-tech Cases)

As discussed before, materials handled, stored, and managed, at industrial facilities constitute a major possible source of contamination during natural disasters. Hurricane Harvey caused damage to a Chevron Phillips chemical plant in Baytown, Texas that released 34,000 pounds of sodium hydroxide and 300 pounds of benzene through a damaged valve.⁶⁰ Both sodium hydroxide and benzene are considered to be highly toxic compounds. David Gray, a representative from the EPA based in Dallas said that after the flood, employees pumped contaminated water into 80 steel tanks, but most of the product was “lost in the floodwater”.⁶¹ This chemical plant has been determined, by the government, to be in a “moderate-risk flood zone”, defined as having 0.2 percent chance of flooding in any year. This spill after Hurricane Harvey was the third incident within three years that the Chevron Phillips facility blamed heavy downpours for chemical leaks.⁶² The site has also been in the process of adding a new \$6 billion ethane processor, one of the biggest investments in the petrochemicals industry, to the location. Hurricane Harvey was the catalyst for the release of contamination and hazardous pollutants into flood waters for over 40 industrial sites.⁶³ Water bodies are not the only impacted environmental media following these events. Airborne emissions of toxic gases used in industrial processes, such as methane and sulfur dioxide have also been known to be released into the environment and inhaled. Air levels of benzene, a known carcinogen, were measured 6-fold higher than the normal permissible environmental limits following the events of Hurricane Harvey.⁶⁴



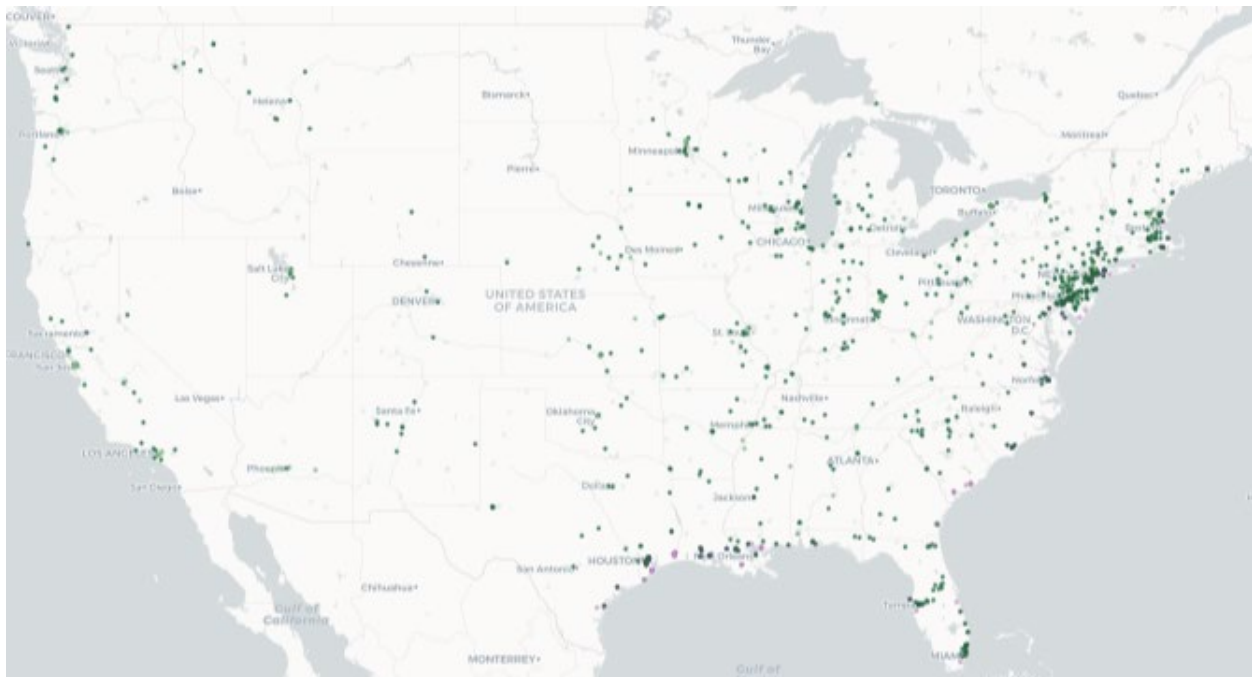
(Figure 6. Chevron Phillips Site⁶⁵)

In 2012, Tropical Storm Debby brought torrential rain to White Springs, Florida and impacted a chemical plant that produced phosphates used in fertilizer. Flooding cut off the power supply to the facility pumping system, which caused a chemical mixture to spill into a retention pond. This chemical mix eventually overflowed into a creek that feeds into the Suwannee River. “In large quantities into the environment, phosphates and phosphoric acid can cause uncontrolled algae and duckweed growth, causing oxygen levels in lakes and rivers to drop precipitously”.⁶⁶ The phosphates plant is in an high-risk flood zone area, determined by the government as having a one percent chance of flooding in any given year. For this particular event, the plant prepared for the storm by lowering water levels in the retention ponds, but Mike Williams, a spokesman for the company that operates the phosphates plant said, “every now and then there will be something that’s more than we planned for”.⁶⁷

Superfund Site Impacts from Hurricanes

In very simplistic terms, Superfund is the principal federal program for addressing sites containing hazardous substances. Superfund sites that warrant further investigation generally end

up on the National Priorities List (NPL), where they undergo remedial actions to address severe contamination. In October 2019, the United States Government Accountability Office (GAO) released a report reviewing issues related to the impacts of climate change on nonfederal NPL sites. GAO specifically examined “(1) what available federal data suggest about the number of...sites that are located in areas that may be impacted by selected climate change effects and (2) the extent to which EPA has managed risks to human health and the environment from the potential impacts of climate change effects”.⁶⁸ Findings based on available federal data from the EPA, Federal Emergency Management Agency (FEMA), NOAA, and U.S. Forest Service, suggest that about 60 percent of all nonfederal NPL sites are located in areas that may be impacted by potential climate change effects (hurricanes, flooding, storm surge, wild fires, sea level rise, etc.)



(Figure 7. Contiguous USA Superfund Sites at Risk Due to Flooding and Storm Surge⁶⁹)

The 2017 hurricane season provided the EPA an opportunity to collect data relating to the resiliency of Superfund remedies to extreme weather conditions from Hurricane Harvey, Irma, and Maria. The data, although not comprehensive, provided general observations and insight regarding design measures that may help remedies remain protective during extreme wind and flooding. Out of the 252 impacted sites considered, 16 of them “reported damage and damage reports were for auxiliary systems such as fencing”.⁷⁰ Many of these sites were impacted by

devastating hurricane-force winds and destructive flooding, but the report states that only minor damage was observed. The analysis completed for this study concluded that resiliency measures are being implemented and are effective. “Engineered caps...with drainage and erosion control components helped alleviate flooding and protected floodwater from contacting contaminated material when inundation did occur”.⁷¹ Automated controls to shut off industrial systems and notify operators prevented tank overflows and provided information on the systems when sites were not accessible. Although engineering and institutional designs implemented on some sites seemed to be working, other sites experienced unique challenges which provided information that may assist in developing future remedies. “The design of [a] temporary armored cap at San Jacinto River Waste Pits in Texas was not able to withstand the experienced flooding and scouring that resulted from Hurricane Harvey...it provides some information on the types of caps or site conditions that may be particularly susceptible during extreme weather events”.⁷²

Following Hurricane Harvey, a separate report published in the Journal of Toxicology and Environmental Health found flooding and damage impacts to at least 14 Superfund toxic waste sites in and around the Houston area that contained dioxins, lead, arsenic, mercury, and hydrocarbon compounds.⁷³ With increasing hurricane intensity, toxins from Superfund sites may redistribute into drinking water sources, aging infrastructure, and surrounding sediments. The findings of the EPA’s 2017 hurricane season report do not represent a true assessment. The EPA’s report was not comprehensive and did not intend to capture every incident in which a remedy was impacted. “The report centers on impacts on the resilience of existing remedies and does not focus on non-remedy related impacts from the severe weather events at Superfund...sites”.⁷⁴ This study was also conducted by the EPA under the Trump administration, an administration known for relatively lenient environmental decisions and financial cutbacks of environmental government agencies which resulted in distrust amongst many environmental communities. The report was conducted through a “desktop analysis”, gathering information from existing sources, such as the Superfund Enterprise Management System, media, site reports, and contacting remedial project managers. Only considering a portion of impacted sites does not present conclusive and transparent findings. Although the report is successful in studying some remedial measures’ ability to withstand storm intensities, critical information is missing. The results were also based on self-reporting from various regions affected by damage,

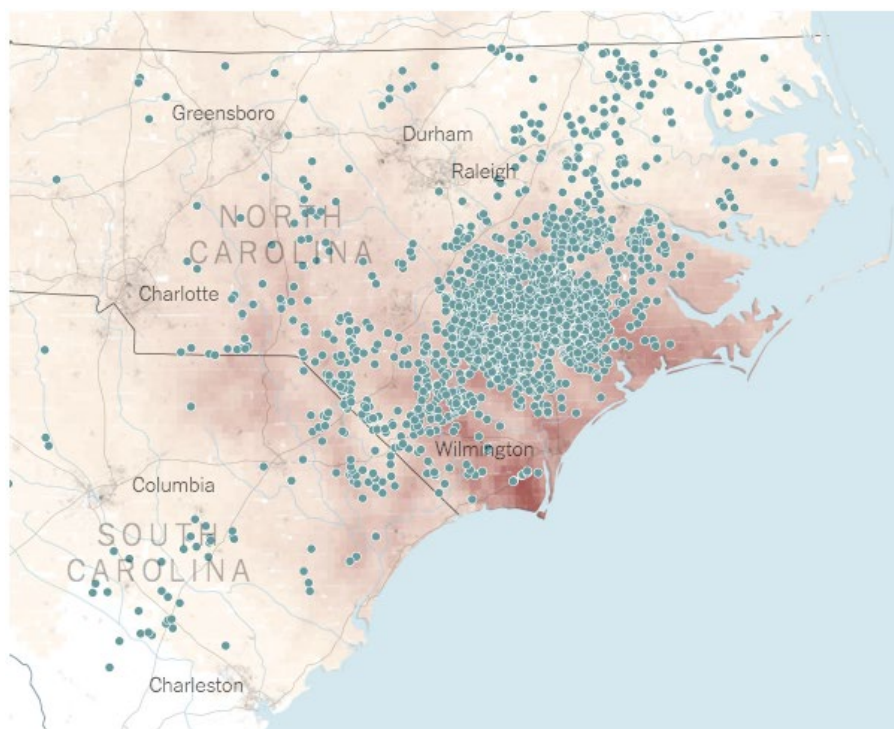
without stating confirmation from local and state agencies and other organizations. Contamination transport at these Superfund sites were not included in this report and are important for the mission of the EPA to protect human health, welfare, and the environment. The findings seem to imply a “no issue” conclusion by focusing on a select number of cases and neglecting field-work sampling. Considering facility history, Superfund site characteristics, and hurricane induced damage to these facilities, findings may be expected to be much more alarming. The study methods and conclusions of this report suggest insufficient effort was made to truly assess the damage to facilities, which seems to contradict and downplay the EPA’s mission.

Previously, EPA assessed 18 Superfund NPL sites in the affected areas of Louisiana and Mississippi after Hurricane Katrina hit the Gulf Coast in August 2005. Sediment, surface water, and groundwater samples were collected from September to October 2005 through coordination between federal and state agencies. Conclusions regarding the potential impacts of the hurricane on the sites were based on comparisons of post-hurricane data to past sample data collected during routine monitoring activities. Overall, EPA concluded that 15 of the 18 sites were not impacted.⁷⁵ All three remaining sites were in Louisiana. Two of these sites, Delatte Metals and PAB Oil, showed higher concentrations of metals in groundwater samples taken post-hurricane than from the pre-hurricane samples. At the time of the report the third site, Agriculture Street Landfill in Orleans Parish, was pending further sampling of flood deposited sediments that exceeded the Louisiana Department of Environmental Quality criteria.⁷⁶ This report followed a format that provided more transparent information to the public, including collaborative efforts from state and local agencies, environmental sampling, and implications of environmental contamination.

Toxic Sites and Hurricanes

North Carolina, a state heavily invested in the pork industry, has 9.7 million pigs that produce almost 10 billion gallons of manure annually.⁷⁷ Following Hurricane Florence, the NCDEQ reported that “five lagoons experienced structural damage and 32 had seen some form of overflow”.⁷⁸ A study by Duke University’s Environmental Health Scholars Program released

after Hurricane Florence in 2018 found higher adult death rates, infant mortality, emergency room visits, and hospital admission for people living around the largest farms, which have about 560 hogs per square mile.⁷⁹ The study's lead author, Julia Kravchenko, M.D., used national data to compare rates of illness in ZIP codes around the large farms to ZIP codes in communities that lack those operations nearby. They found that people living near large hog operations in North Carolina had 50 percent higher death rates from anemia and about a third higher from kidney disease than in communities with no hog farms. Both anemia and kidney disease can be a sign of exposure to toxins.⁸⁰ This study was released before Hurricane Florence made landfall, suggesting that living in close proximity to pig farms implicitly threatens health. Considering research that suggests contamination mobilizes to surrounding communities from waste pits due to hurricanes, the impacts from these animal farms may only be exacerbated.



(Figure 8. Flooding from Hurricane Florence Overlain by Pig Farms in North Carolina⁸¹)

A review of health impacts of floods and storms that was published in the *Journal of Toxicology and Environmental Health* found a heightened risk of wounds, soft tissue infections, and gastrointestinal diseases in communities following hurricanes. Cases of leptospirosis, a disease caused from being exposed to urine and feces of infected animals, typically rise within 4-6 weeks

after the disaster.⁸² 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, gastrointestinal diseases, and leptospirosis”.⁸³ These outbreaks are attributed to various release mechanisms, some of which were discussed previously in this paper.

Coal ash, a coal combustion residual, is produced primarily from the burning of coal in coal-fired power plants. Since coal ash contains heavy metals like mercury, cadmium, and arsenic, proper management is necessary to prevent pollution of surface water, groundwater, sediments, and the air. Breaches in a lake caused coal ash to enter Cape Fear from the L.V. Sutton power plant in Wilmington, North Carolina. Duke Energy, the company that owns the Sutton plant, said water tests conducted by the company showed “little to no impact to river quality”.⁸⁴ A separate and larger release was reported in Eden, Rockingham County, NC from a coal ash facility owned and operated by Duke Energy. Testing conducted on the Eden site by the EPA concluded that “no human health screening levels exceeded in the surface water or sediment samples for contaminants associated with coal ash”.⁸⁵ Subsequently, energy companies, such as Duke Energy, will maintain their stance that the storage of coal ash in earthen pits mixed with water, is safe.

The information provided by the EPA on this coal ash release focuses mostly on the potential impacts to human health and aquatic life, including instructions to avoid direct contact with coal ash due to its harmful potential. EPA stated that sediment samples and water samples were analyzed for this conclusion but did not provide specifications for the methods or locations of sample testing. Ongoing activities of Duke Energy with oversight by the EPA include installation of filters, monitoring, and sampling downstream, and focus mostly on releases from the facility instead of resuspension of existing contamination. In 2015, a court case between Duke Energy and the EPA resulted in Duke Energy pleading guilty and being sentenced to pay \$102 million for 9 criminal violations of the Clean Water Act.⁸⁶ The violations included unlawfully failing to maintain equipment at the Dan River and Cape Fear facilities and unlawfully discharging coal ash and/or coal ash wastewater from impoundments at multiple facilities.⁸⁷ Concerns for surrounding communities that have potential to be affected by these Duke Energy facilities surface from these cases since it displayed how industries are not properly managing their waste.

Contamination of waters by Duke Energy's negligence suggest that contamination of the environment from big industrial facilities is apparent and some studies suggest it can be intensified by hurricanes.

In 2005, Hurricane Katrina damaged over 100,000 homes and deposited significant amounts of sediment throughout New Orleans, Louisiana.⁸⁸ Two years after the storm, researchers from Tulane University School of Public Health and Tropical Medicine assessed the distribution of contaminants in residential soil and dust samples, focusing on lead exposure. These samples were compared to soil samples collected in 2000, five years before Hurricane Katrina. 109 households were randomly selected around the New Orleans area and results showed that 61% had at least one lead measurement above the federal standard.⁸⁹ Following Hurricane Katrina, the EPA worked closely with NOAA, USGS, and other state agencies to create a water monitoring plan. EPA and the Louisiana Department of Environmental Quality collaborated and collected over 631 environmental samples taken from various sample sites such as rivers and lakes. Results shows that the detected levels of lead exceeded the EPA drinking water standards, and in some samples several other chemicals, such as arsenic and petroleum products, were found.⁹⁰ Sediment samples revealed high levels of bacteria and a variety of chemicals such as petroleum-based products. In the Gulf Coast, an area known for petroleum refineries, a total of 1 million gallons of spilled oil was estimated.⁹¹ These results not only suggest the migration of contamination due to hurricane events, but also the risk of exposure to higher levels of contamination compared to pre-storm conditions.

Further Research

As hurricanes become more common, it is important to emphasize their tangible threat of long-term impacts and potential to adversely affect health. "Many disaster-related hazardous material releases never receive attention, in part, because public authorities, the media and the public generally overlook...releases in the rush to address and recover from immediate disaster threats".⁹² Limited resources for research funding and the incentive for responsible parties to subdue publicity for the sake of good public relations contribute to the lack of documentation and underreporting of hurricane-related releases. As a consequence, the magnitude of the risk

upon coastal communities and the environment due to hurricanes has probably been underestimated.

The finite studies that relate hurricane influence on environmental and community impacts have found an increase of contamination, not necessarily exclusive to hurricane events, but possibly other factors as well. This suggests that continued monitoring of the sediment profiles in hurricane-prone areas should be conducted so that further examination and analysis can be completed. The degree of impact depends on a variety of factors, including population size, density of industrial facilities, disaster preparedness, and chemical composition of the substance. The current amount of data available is a concern. Further monitoring and reporting efforts of these environmental conditions is needed because recent scientific studies have been relatively short and underfunded.

“Being asked a sediment toxicity question and having no data to compare current samples is a challenge. At that point you’re comparing apples to bobby pins.”⁹³

- Tim Reilly (USGS)

Most baseline data are from government Superfund sites, but there are many contaminated sites that do not fall under government jurisdiction and should be frequently sampled to contribute to a baseline program. Creating a standardized program that provides a baseline database for contaminant concentrations in water, air, and soil samples in and around hurricane-prone communities would be extremely beneficial to future research. Some existing studies used proxies such as fish and mussels in lieu of soil, air, and water contamination concentration data for comparison, resulting in qualitative data, instead of direct evaluations. National collaboration between environmental organizations, government, and communities to create a standard comparison database would provide a wide sample area and reliable information. A good start would be the USGS SCoRR program which provides an existing scientific framework and initial database. Funding for this program would ideally be specified to cover costs for sample collection, lab analysis, and community outreach and training. A program such as this one would enable future research to be more feasible and quantitative. As the intensity of other natural

disasters increase, this program would be implemented and applicable in environmental assessments other than hurricane disasters.

“Funding efforts are needed to build a baseline of datasets. There aren’t a lot of national scale contamination databases.”⁹⁴

- Tim Reilly (USGS)

“There currently exist technologies that might be used during disaster response to rapidly assess toxicities, identify infection threats, and take remedial actions”.⁹⁵ The necessity for more research is recommended in the limited, but invaluable, academic journals’ conclusions and common in the questions and concerns of community interviews. The public wants to know what contamination they’re being exposed to and how they’re being exposed. It is the duty of the scientific community and federal, state, and local governments to investigate these situations and answer these questions in a communicative, reliable, and transparent manner.

Conclusion

This review of academic journals, local/national news, and government reports has put forth the argument that collaboration across various disciplines, agencies, demographics, and borders is necessary to evaluate and find solutions to the lack of data. Future research with an interdisciplinary focus spanning environmental, social, and health issues is needed. Programs, not only for disaster recovery efforts, but for long-term impact studies need to be implemented to validate laboratory samples of environmental media on a national level to determine baseline contamination. Risk classification systems for facilities should consider more factors such as climatological data and meteorological models to truly assess the vulnerability of a location to a disaster related incident. This is especially true for sites that handle and manage hazardous wastes and other contaminants such as waste pits, Superfund sites, and industrial facilities. It is time to reevaluate the laws and regulations for building codes, zoning permits, and high-risk/low-risk criteria to reflect the current climate conditions. Industrial facilities continue to expand onto floodplains and other locations vulnerable to natural disasters, without being transparent of the details on how these facilities will be protected or designed to withstand future hurricanes. Implementation of these plans should incorporate community involvement, allowing

for the people residing in vulnerable properties to participate and know the what risk they are potentially exposed to.

The lack of current scientific evidence presents a void in an important environmental and human health topic. Limited amounts of available reports provide a starting insight to causes and potential mitigation methods, but questionable efforts and nontransparent reporting requires additional information to enhance these strategies. A combined effort from a regional or local assessment and future studies can provide law makers, emergency response personnel, and facility management personnel the most accurate vulnerability data upon which to base prevention and mitigation measures. Requiring transparency of these reports will increase education, awareness, and involvement for future disasters. Providing accurate and relevant disaster information through scientific studies can raise understanding in order to increase preparedness levels and mitigate damage. These efforts may assist in stopping future impacts and ensuring effective responses from government, private, and communal entities.

“Disasters are not a surprise. They happen all the time. The best we can do [as scientists studying contamination] is on the preparation side by saying, ‘This is what we know about this location already.’”⁹⁶

- Tim Reilly (USGS)

Acknowledgements

I wish to express my gratitude to readers John Miller, P.E. CFM, CSM, of the Federal Emergency Management Agency, and Mitch Cron, professor of the University of Pennsylvania, for invaluable involvement in the creation and completion of this paper. This paper benefitted from an interview with Timothy Reilly, Deputy Programs Coordinator at the Environmental Health Mission Area for the United States Geological Survey. Special thanks to Christopher Lomiguen for assistance with design, Jeffrey Tan, Tiffany Linh, and Farah Huynh for valuable input.

Endnotes

-
- ¹ National Weather Service, "Tropical Cyclone Formation Basins," <https://www.weather.gov/jetstream/tc> (accessed February, 2020).
- ² John D. Murphy, August/September 2017 Hurricane Harvey Service Assessment,[2018]).
- ³ American Meteorological Society, "Glossary of Meteorology," <http://glossary.ametsoc.org/wiki/Mesoscale> (accessed February, 2020).
- ⁴ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ⁵ American Meteorological Society, "Glossary of Meteorology," <http://glossary.ametsoc.org/wiki/Mesoscale> (accessed February, 2020).
- ⁶ National Aeronautics and Space Administration, "How do Hurricanes Form?" <https://spaceplace.nasa.gov/hurricanes/en/> (accessed February, 2020).
- ⁷ National Oceanic and Atmospheric Administration, "Historical Hurricane Tracks," <https://coast.noaa.gov/hurricanes/> (accessed February, 2020).
- ⁸ NOAA Hurricane Research Division, "Frequently Asked Questions," <https://www.aoml.noaa.gov/hrd/tcfaq/F1.html> (accessed February, 2020).
- ⁹ National Weather Service, "Tropical Cyclone Formation Basins," <https://www.weather.gov/jetstream/tc> (accessed February, 2020).
- ¹⁰ Environmental Protection Agency, "EPA Terminology Services," https://iaspub.epa.gov/sor_internet/registry/termreg/searchandretrieve/termsandacronyms/search.do (accessed February, 2020).
- ¹¹ Christine Jackson et al., Evidence on the use of Integrated Mosquito Management to Reduce the Risk of West Nile Outbreak After a Flooding Event Centers for Disease Control and Prevention.
- ¹² Stacy Young, Lina Balluz and Josephine Malilay, "Natural and Technologic Hazardous Material Releases during and After Natural Disasters: A Review," *Science of the Total Environment* 322, no. 1 (2004), 3-20. doi:10.1016/S0048-9697(03)00446-7. [http://dx.doi.org/10.1016/S0048-9697\(03\)00446-7](http://dx.doi.org/10.1016/S0048-9697(03)00446-7).
- ¹³ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ¹⁴ Environmental Protection Agency, EPA Prepares the Public for the 2019 Hurricane Season by Focusing on Waste Mitigation Environmental Protection Agency,[2019]).
- ¹⁵ Ibid
- ¹⁶ Paul B. Tchounwou et al., "Heavy Metals Toxicity and the Environment," *Exs* 101 (Jan 1, 2012), 133-164. doi:10.1007/978-3-7643-8340-4_6. <https://www.ncbi.nlm.nih.gov/pmc/articles/PMC4144270/>.
- ¹⁷ United States Geological Survey, "Chlorinated Solvents Contamination," https://toxics.usgs.gov/investigations/chlorinated_solvents.html (accessed February, 2020).
- ¹⁸ Ibid
- ¹⁹ Environmental Protection Agency, "Polychlorinated Biphenyls (PCBs)," <https://www.epa.gov/pcbs/learn-about-polychlorinated-biphenyls-pcbs#release> (accessed February, 2020).
- ²⁰ Occupational Safety & Health Administration, "Fact Sheets on Natural Disaster Recovery ," <https://www.osha.gov/OshDoc/floodCleanup.html> (accessed February, 2020).
- ²¹ Jennifer T. Wilson and United States Geological Survey, Assessment of Selected Contaminants in Streambed- and Suspended-Sediment Samples Collected in Bexar County, Texas, 2007-09 (Reston, VA: U.S. Dept. of the Interior, U.S. Geological Survey, 2011).
- ²² Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ²³ Francisco Artigas et al., "Baseline and Distribution of Organic Pollutants and Heavy Metals in Tidal Creek Sediments After Hurricane Sandy in the Meadowlands of New Jersey," *Environmental Earth Sciences* 76, no. 7 (April 8, 2017), 1-15. doi:10.1007/s12665-017-6604-y. <https://search.proquest.com/docview/1885415060>.
- ²⁴ Irene J. Fisher et al., "The Impact of Onsite Wastewater Disposal Systems on Groundwater in Areas Inundated by Hurricane Sandy in New York and New Jersey," *Marine Pollution Bulletin* 107, no. 2 (Jun 30, 2016), 509-517. doi:10.1016/j.marpolbul.2016.04.038. <https://www.sciencedirect.com/science/article/pii/S0025326X16302387>.
- ²⁵ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ²⁶ Artigas et al., "Baseline and Distribution of Organic Pollutants and Heavy Metals in Tidal Creek Sediments After Hurricane Sandy in the Meadowlands of New Jersey," *Environmental Earth Sciences* 76, no. 7 (Apr, 2017), 1-15. doi:10.1007/s12665-017-6604-y. <https://search.proquest.com/docview/1885415060>.
- ²⁷ Ibid.

-
- ²⁸ Fisher et al., "The Impact of Onsite Wastewater Disposal Systems on Groundwater in Areas Inundated by Hurricane Sandy in New York and New Jersey," *Marine Pollution Bulletin* 107, no. 2 (Jun 30, 2016), 509-517. doi:10.1016/j.marpolbul.2016.04.038. <https://www.sciencedirect.com/science/article/pii/S0025326X16302387>.
- ²⁹ Ibid.
- ³⁰ Amy Mandigo et al., "Chemical Contamination of Soils in the New York City Area Following Hurricane Sandy," *Environmental Geochemistry and Health* 38, no. 5 (October, 2016), 1115-1124. doi:10.1007/s10653-015-9776-y. <https://www.ncbi.nlm.nih.gov/pubmed/26486130>.
- ³¹ W. Johnson et al., "Chemical Contamination Assessment of Gulf of Mexico Oysters in Response to Hurricanes Katrina and Rita," *Environmental Monitoring and Assessment* 150, no. 1 (Mar, 2009), 211-225. doi:10.1007/s10661-008-0676-9. <https://www.ncbi.nlm.nih.gov/pubmed/19051046>.
- ³² Megan Rothenberger, Andrea Armstrong and Mia Spitz, "Social–ecological System Responses to Hurricane Sandy in the Hudson-Raritan Estuary," *Ambio* 47, no. 3 (Apr, 2018), 284-297. doi:10.1007/s13280-017-0949-z. <https://www.ncbi.nlm.nih.gov/pubmed/29030755>.
- ³³ Ibid.
- ³⁴ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ³⁵ Timothy Reilly, Michael Focazio and Dale Simmons, "Potential Long-Term Contaminant Threats Resulting from Compromised Infrastructure, Beach Erosion, and Sediment Disturbance were Evaluated in the Coastal Environments of New Jersey and New York in the Aftermath of Hurricane Sandy." https://www.usgs.gov/mission-areas/environmental-health/science/persistent-contaminant-threats-following-hurricane-sandy?qt-science_center_objects=0#qt-science_center_objects (accessed March, 2020).
- ³⁶ A. Necci, S. Girgin and E. Krausmann, "Understanding Natech Risk due to Storms," 29507 (2018). <https://data.europa.eu/doi/10.2760/21366>.
- ³⁷ Ibid.
- ³⁸ Carolyn Cooper et al., EPA Provided Quality and Timely Information on Hurricane Hazardous Material Releases and Debris Management (Washington, D.C.: United States Environmental Protection Agency, Office of the Inspector General,[2006]).
- ³⁹ Stacy Young, Lina Balluz and Josephine Malilay, "Natural and Technologic Hazardous Material Releases during and After Natural Disasters: A Review," *Science of the Total Environment* 322, no. 1 (April 25, 2004), 3-20. doi:10.1016/S0048-9697(03)00446-7. [http://dx.doi.org/10.1016/S0048-9697\(03\)00446-7](http://dx.doi.org/10.1016/S0048-9697(03)00446-7).
- ⁴⁰ Ibid.
- ⁴¹ Young, Balluz and Malilay, "Natural and Technologic Hazardous Material Releases during and After Natural Disasters: A Review," *Science of the Total Environment* 322, no. 1 (2004), 3-20. doi:10.1016/S0048-9697(03)00446-7. [http://dx.doi.org/10.1016/S0048-9697\(03\)00446-7](http://dx.doi.org/10.1016/S0048-9697(03)00446-7).
- ⁴² Federal Emergency Management Agency, "Erosion, Scour, and Foundation Design," https://www.fema.gov/media-library-data/20130726-1644-20490-8177/757_apd_5_erosionscour.pdf (accessed February, 2020).
- ⁴³ Ibid.
- ⁴⁴ Marla Sink, "State Environmental Inspectors to Test Water Quality Near Swine Farms," <https://deq.nc.gov/press-release/state-environmental-inspectors-test-water-quality-near-swine-farms> (accessed February, 2020).
- ⁴⁵ Ibid.
- ⁴⁶ Timothy B. Erickson et al., "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* 22, no. 5-6 (Aug 18, 2019), 157-171. doi:10.1080/10937404.2019.1654422. <http://www.tandfonline.com/doi/abs/10.1080/10937404.2019.1654422>.
- ⁴⁷ Federal Emergency Management Agency, "Erosion, Scour, and Foundation Design," https://www.fema.gov/media-library-data/20130726-1644-20490-8177/757_apd_5_erosionscour.pdf (accessed February, 2020).
- ⁴⁸ Ana Maria Cruz, Laura J. Steinberg and Ronaldo Luna, "Identifying Hurricane-Induced Hazardous Material Release Scenarios in a Petroleum Refinery," *Natural Hazards Review* 2, no. 4 (Nov, 2001), 203-210. doi:10.1061/(ASCE)1527-6988(2001)2:4(203). [http://ascelibrary.org/doi/abs/10.1061/\(ASCE\)1527-6988\(2001\)2:4\(203\)](http://ascelibrary.org/doi/abs/10.1061/(ASCE)1527-6988(2001)2:4(203)).
- ⁴⁹ Ibid.
- ⁵⁰ Daisy Ramirez-Ortiz et al., "Efficacy of a School-Based Intervention to Bring Awareness about PCB Contamination and Exposure Avoidance in Guánica, Puerto Rico," *Environmental Science and Pollution Research* 26, no. 23 (Aug 1, 2019), 23337-23345. doi:10.1007/s11356-019-05587-z. <https://www.ncbi.nlm.nih.gov/pubmed/31197667>.

-
- ⁵¹ Naresh Kumar, Environmental PCB Redistribution and Community Exposure After Hurricane Maria, 2020).
- ⁵² Christopher Flavelle, "'Toxic Stew' Stirred Up by Disasters Poses Long-Term Danger, New Findings Show," *The New York Times* July 15, 2019. <https://www.nytimes.com/2019/07/15/climate/flooding-chemicals-health-research.html>.
- ⁵³ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ⁵⁴ Nick Santos and Nicholas Pinter, Hurricane Harvey Water Extent UC Davis Center for Watershed Services, 2018).
- ⁵⁵ Flavelle, "'Toxic Stew' Stirred Up by Disasters Poses Long-Term Danger, New Findings Show," *The New York Times* July 15, 2019. <https://www.nytimes.com/2019/07/15/climate/flooding-chemicals-health-research.html>.
- ⁵⁶ Britni McAshen, "Texas Medical Center Experts Assess Community Health Two Years After Hurricane Harvey," *Texas Medical Center* August 26, 2019. <https://www.tmc.edu/news/2019/08/texas-medical-center-experts-assess-community-health-two-years-after-hurricane-harvey/>.
- ⁵⁷ Ibid.
- ⁵⁸ Ibid.
- ⁵⁹ National Oceanic and Atmospheric Administration, "August/September 2017: Hurricane Harvey ," <https://oceanservice.noaa.gov/news/sep17/hurricane-harvey.html> (accessed February, 2020).
- ⁶⁰ Hiroko Tabuchi et al., "Floods are Getting Worse, and 2,500 Chemical Sites Lie in the Water's Path," *The New York Times* February 6, 2018. <https://www.nytimes.com/interactive/2018/02/06/climate/flood-toxic-chemicals.html>.
- ⁶¹ Ibid.
- ⁶² Ibid.
- ⁶³ Erickson et al., "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* 22, no. 5-6 (Aug 18, 2019), 157-171. doi:10.1080/10937404.2019.1654422. <http://www.tandfonline.com/doi/abs/10.1080/10937404.2019.1654422>.
- ⁶⁴ Ibid.
- ⁶⁵ Tabuchi et al., "Floods are Getting Worse, and 2,500 Chemical Sites Lie in the Water's Path," *The New York Times* February 6, 2018. <https://www.nytimes.com/interactive/2018/02/06/climate/flood-toxic-chemicals.html>.
- ⁶⁶ Ibid.
- ⁶⁷ Ibid.
- ⁶⁸ Government Accountability Office, Superfund: EPA should Take Additional Actions to Manage Risks from Climate Change. Congressional Publications United States Government Accountability Office, 2019).
- ⁶⁹ Ibid.
- ⁷⁰ Office of Land and Emergency Management and Environmental Protection Agency, Evaluation of Remedy Resilience at Superfund NPL and SAA Sites Environmental Protection Agency & Office of Land and Emergency Management, 2018).
- ⁷¹ Ibid.
- ⁷² Ibid.
- ⁷³ Erickson et al., "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* 22, no. 5-6 (Aug 18, 2019), 157-171. doi:10.1080/10937404.2019.1654422. <http://www.tandfonline.com/doi/abs/10.1080/10937404.2019.1654422>.
- ⁷⁴ Office of Land and Emergency Management and Environmental Protection Agency, *Evaluation of Remedy Resilience at Superfund NPL and SAA Sites* Environmental Protection Agency & Office of Land and Emergency Management, 2018).
- ⁷⁵ Cooper et al., EPA Provided Quality and Timely Information on Hurricane Hazardous Material Releases and Debris Management (Washington, D.C.: United States Environmental Protection Agency, Office of the Inspector General,[2006]).
- ⁷⁶ Ibid.
- ⁷⁷ Kendra Pierre-Louis, Nadja Popovich and Hiroko Tabuchi, "Florence's Floodwaters Breach Coal Ash Pond and Imperil Other Toxic Sites," *The New York Times* September 24, 2018. <https://www.nytimes.com/interactive/2018/09/13/climate/hurricane-florence-environmental-hazards.html>.
- ⁷⁸ Ibid.
- ⁷⁹ Julia Kravchenko et al., "Mortality and Health Outcomes in North Carolina Communities Located in Close Proximity to Hog Concentrated Animal Feeding Operations," *North Carolina Medical Journal* 79, no. 5 (Sep, 2018), 278-288. doi:10.18043/nmc.79.5.278. <https://www.ncbi.nlm.nih.gov/pubmed/30228132>.
- ⁸⁰ Ibid.

-
- ⁸¹ Pierre-Louis, Popovich and Tabuchi, "Florence's Floodwaters Breach Coal Ash Pond and Imperil Other Toxic Sites," *The New York Times* September 24, 2018.
<https://www.nytimes.com/interactive/2018/09/13/climate/hurricane-florence-environmental-hazards.html>.
- ⁸² Erickson et al., "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* 22, no. 5-6 (Aug 18, 2019), 157-171. doi:10.1080/10937404.2019.1654422.
<http://www.tandfonline.com/doi/abs/10.1080/10937404.2019.1654422>.
- ⁸³ Ibid.
- ⁸⁴ Pierre-Louis, Popovich and Tabuchi, "Florence's Floodwaters Breach Coal Ash Pond and Imperil Other Toxic Sites," *The New York Times* September 24, 2018.
<https://www.nytimes.com/interactive/2018/09/13/climate/hurricane-florence-environmental-hazards.html>.
- ⁸⁵ Environmental Protection Agency, Eden North Carolina Coal Ash Spill Environmental Protection Agency, (2014).
- ⁸⁶ Environmental Protection Agency, "Summary of Criminal Prosecutions,"
https://cfpub.epa.gov/compliance/criminal_prosecution/index.cfm?action=3&prosecution_summary_id=2746
(accessed February, 2020).
- ⁸⁷ Ibid.
- ⁸⁸ Felicia A. Rabito, Janet C. Rice and Whitney Arroyave, "Environmental Lead After Hurricane Katrina," *Environmental Health Perspectives* 120, no. 5 (May 1, 2012), a188-a189. doi:10.1289/ehp.1104909R.
https://www.openaire.eu/search/publication?articleId=od_____267::67181b99ae15f1f276e0a7b1571a0.
- ⁸⁹ Ibid.
- ⁹⁰ Roundtable on Environmental Health Sciences, Research, and Medicine, Christine Coussens and Lynn Goldman, *Environmental Public Health Impacts of Disasters* (Washington, D.C: National Academies Press, 2007).
doi:10.17226/11840. <https://www.nap.edu/11840>.
- ⁹¹ Ibid.
- ⁹² Stacy Young, Lina Balluz and Josephine Malilay, "Natural and Technologic Hazardous Material Releases during and After Natural Disasters: A Review," *Science of the Total Environment* 322, no. 1 (2004), 3-20.
doi:10.1016/S0048-9697(03)00446-7. [http://dx.doi.org/10.1016/S0048-9697\(03\)00446-7](http://dx.doi.org/10.1016/S0048-9697(03)00446-7).
- ⁹³ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020
- ⁹⁴ Ibid.
- ⁹⁵ Erickson et al., "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* 22, no. 5-6 (Aug 18, 2019), 157-171. doi:10.1080/10937404.2019.1654422.
<http://www.tandfonline.com/doi/abs/10.1080/10937404.2019.1654422>.
- ⁹⁶ Timothy Reilly, interview by Meighan Long, Philadelphia, March 5, 2020