A Non-Stationary Approach to Conducting Site-Specific Integrative Risk Management Assessments at Industrial Facilities at Risk from Extreme Weather Events

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Prepared for Presentation at
American Institute of Chemical Engineers
2019 Spring Meeting and 15th Global Congress on Process Safety
New Orleans, LA
March 31 – April 3, 2019

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Keywords: Extreme Weather Events, Risk Management

Abstract

The physical forces and environmental stressors that occur during extreme weather events can place facilities at risk for multiple infrastructure failures, loss of operations, product loss, and major impactful chemical releases, all of which affect directly a company's bottom line. Hurricane Harvey (2017) resulted in over 100 such failures and chemical releases. Going forward, non-static (non-stationary) risk management approaches, wherein risk predictions incorporate and account for evolving environmental factors such as continuous sea level rise, will allow us to more accurately predict storm surge flooding as a function of time and provide more realistic long-term (decades) predictions to assist in actionable planning. An integrated three-part approach to assessing risk of infrastructure damage and chemical releases and the business and legal consequences therefrom will be presented. This approach consists of developing: a) temporally variant and spatially localized probabilistic predictions of flooding and forces related to flooding (FloodScore™) with unprecedented resolution; b) detailed impact predictions on facility infrastructure and structural and supporting elements thereof based on these predictions; and c) a quantitative means of scoring the environmental/financial risk and consequences of chemicals releases as derived from (b). This integrated approach, which assesses risk of losses in the near term and out to 50 years, includes the assessment of ecological and human impact levels and provides actionable information for resiliency and risk mitigation planning.

1 Introduction

Recent extreme weather events have had profound social and economic impacts in the United States. In 2018 alone, there were 14 weather and climate events that each resulted in losses exceeding $1 billion, and the National Oceanic and Atmospheric Administration (NOAA) estimated the total losses in 2018 to be $91 billion. [1] The year 2018 is ranked as the fourth highest in total cost, behind years 2017, 2005, and 2012. Additionally, when evaluating data from 1980-2018, the annual average number of events is 6.2 (Consumer Price Index (CPI)-adjusted), while the annual average from 2014-2018 is 12.6 (CPI-adjusted). While the growing frequency of extreme weather event occurrence is still debatable, experts agree that climate change will only compound the already increasing severity of tropical cyclones, coastal flooding, and wildfires. [1] It is therefore important for corporations and government entities alike to consider a changing, non-stationary set of conditions when assessing and mitigating the risk of infrastructure destruction, business interruption, and consequences of chemical releases resulting from extreme weather events.

Weather-related vulnerabilities to multiple sectors, including the energy sector [2], continue to increase. In response, companies typically adopt one of three approaches to extreme-weather-related risk mitigation. The most common approach builds reactive response plans based on static or stationary data such as historical flood maps and information from past events. [3] While flood maps can provide valuable historical insight, they do not account for other factors such as sea level rise and associated increases in the severity of storm surges that are expected over the next thirty years. A more progressive risk management approach leverages dynamic sets of data that account for both the changing environment and the accelerated pace of data availability. Dynamic data sets include information on rising sea levels, rising ocean surface water temperatures, increasing severity of storms, increasing forces on facilities, and changes in the land and habitat. The third and most proactive approach to extreme-weather-related risk management focuses on using non-stationary data in a longer-term planning horizon. Companies who subscribe to this approach plan for weather-related occurrences with an agreed-upon risk tolerance and leverage probabilistic predictions to build risk mitigation and resiliency around their facilities. This proactive assessment and mitigation approach can help inform not only the risk management of existing facilities, but also the location of new and future facilities, design specifications, and the degree of resiliency that should be built into the design.

Companies wishing to more rigorously assess and mitigate extreme-weather-related risk can benefit from an approach wherein detailed weather, engineering, environmental, and health analyses are integrated into a systematic methodology. Sole reliance on information from past occurrences and use of historical data sets can inadvertently result in plans that are ill-equipped to withstand the future environment. Leveraging dynamic data sets instead, which account for future changes, can greatly improve risk management outcomes. This improvement is especially enhanced when proactive engineering analyses that examine failure modes resulting from extreme weather forces are coupled with assessments of environmental and health risks and consequences of potential chemical releases. To underscore this point, during the 2017 weather event known as Hurricane Harvey, over 100 sites released hazardous pollutants. [4]

An integrated three-part approach to assessing risk of infrastructure damage and chemical releases and the business and legal consequences therefrom consists of developing: a) temporally variant and spatially localized probabilistic predictions of flooding and forces related to flooding (FloodScore™) with unprecedented resolution; b) detailed impact predictions on facility infrastructure and structural and supporting elements thereof based on these predictions; and c) a quantitative means of scoring the environmental/financial risk and consequences of chemicals releases from these predictions. This integrated and localized approach to determining facility-level asset vulnerabilities, quantifying potential impacts, identifying risk management actions, and implementing risk transfer strategies provides actionable information for resiliency and risk mitigation planning.

2 Jupiter's Prediction of Flooding from Extreme Weather Events

As presented in Section 1, the first step in assessing infrastructure risk and potential damage is to develop temporally variant and spatially localized predictions of flooding related to an extreme weather event. In this section, the development of Jupiter's methodology and modeling workstream is presented to illustrate the real-time (operational) prediction of events that appear imminent.

2.1 Methodology

By definition, predicting compound extreme events requires modeling multiple hazards that can contribute to a peril. In coastal zones, the canonical compound event is a storm surge combined with heavy rain. Often antecedent conditions, such as nearly-to-completely saturated soils or a high water table, can contribute as well. While one or the other may not be extreme in isolation, together they can produce an impactful flood.

Predicting floods is accomplished through modeling each of the physical factors that can lead to flooding, and their interactions with the natural and built environment. Those factors combine nonlinearly. The best approach to modeling flooding where multiple factors are involved is to couple the models in flood simulation and forecasting. Here, a hydraulic model forced by coastal ocean and precipitation predictions ultimately provides the flooding prediction. The coastal ocean model, forced by far-field ocean lateral boundary conditions and a bias-corrected wind prediction, is the basis for surge and provides tailwater (downstream) boundary conditions for the hydraulic model. A groundwater model and a land hydrology model provide the over-land sources and sinks that constrain the hydraulics, and a high-resolution meteorological model provides precipitation. Figure 1 gives a schematic of Jupiter's FloodScore Operations (FSO) modeling system release for predicting floods up to five days in advance. Some details are given below.

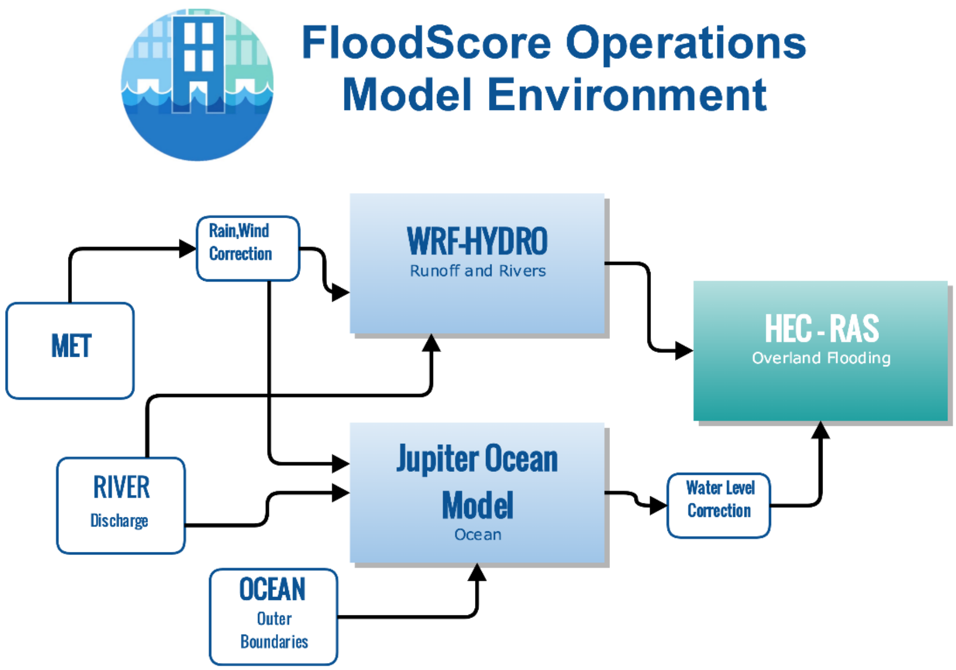

Figure 1. FSO Diagram.

2.2 Jupiter's Model Workstream

Ensemble techniques lead to a probabilistic view of forecasts from zero to 5 days. A multi-model ensemble of 43 global weather forecasts, downscaled to provide finer-scale details in wind, temperature, and rainfall provide boundary conditions to a coastal ocean model (hydrodynamic) as well as a hydrologic and hydraulic (H&H) modeling framework. The ensemble of coastal ocean model forecasts provides a sample from the distribution of forecast water levels along the coast and over the coastal flood plain. A limited set of H&H model executions, which include rainfall from the downscaled atmospheric forecasts, provide bounds on the probabilities of flood depths and velocities, given that the surge or rain levels are sufficient to lead to flooding.

The atmospheric forcing (primarily rain and winds) result from dynamically downscaling global weather forecasts. The Weather Research and Forecasting (WRF) [5] model is the state-of-the-art community regional atmospheric model and is suitable for deriving 1-km gridded forecasts from global forecasts models that range from approximately 9 to 20 km grid spacing. Use of the WRF model allows for regional optimization; the resulting rain and winds are further bias-corrected via a recursive algorithm that minimizes the forecast errors compared to observations, over the recent history of forecasts. The output forces both the hydrodynamic and H&H models.

The Jupiter Ocean Model, based on two open-source ocean models, provides currents, water elevations, and other oceanic variables to indicate the potential for flooding. It is an advanced free-surface, terrain-following, primitive equation ocean model. The model includes wetting and drying in the coastal plain and the ability to accept river and sewer discharges dynamically, enabling accurate simulation of estuarine environments. A global ocean model such as executed by Mercator Ocean (http://marine.copernicus.eu) provides initial and lateral boundary conditions; multiple global atmospheric models provide ocean surface boundary conditions, and a hydrologic and river routing model provides upstream boundary conditions for both the Jupiter Ocean Model and the over-land H&H modeling framework. The Jupiter Ocean Model is currently executed at 50-m grid spacing or smaller, twice daily (0000 UTC and 1200 UTC), with each forecast corresponding to a unique atmospheric forecast from the 43-member ensemble. Resulting water levels are corrected based on the recent history of errors measured by comparison against available water level gages. The forecasts from the ensemble of model runs are sub-selected to create three flooding scenarios for the next 5 days: a low-potential-impact (5%), most-probable-impact (50%), and a high-potential-impact (95%). These three timeseries of water levels are then provided as downstream (tailwater) boundary conditions to force a hydraulic model to predict the water level and velocity over ground.

Various approaches to hydrology are available on Jupiter's platform, and the Hydrologic Engineering Center's River Analysis System (HEC-RAS) is designed to perform one and two-dimensional hydraulic calculations for a full network of natural and constructed channels at DEM-scale. The hydraulic model also incorporates run-off from a hydrology model, which is currently a regionally optimized implementation of the National Water Model WRF-Hydro [6] configuration.

HEC-RAS is triggered for operation in a scalable cloud-based system when the hydrodynamic forecast water level is near a level that could flood over land. Once the model is triggered, the output from HEC-RAS includes: water depth above ground, water surface elevation, and velocity for each of the flood scenarios.

3 Impact Prediction and Risk Evaluation through Fragility Curves

The output from Jupiter's flooding prediction model of water depth and velocity can be used in combination with fragility curves to estimate the risk and impact of various flooding scenarios. Conditional fragility relations, or fragility curves, relate the probability of a damage state (DM) to an engineering demand parameter (EDP), or directly to a hazard intensity measure (IM). [7,8] Damage states are typically defined to capture repair or disruption details. Figure 2 shows example fragility curves relating water height to the functional condition of a transformer. The fragility curves describe the probability of a given damage state as a function of water height. The three damage states are based on the following repair conditions: (1) rust on the transformer not requiring immediate repair for operation; (2) partial repair required for operation; and (3) permanent replacement required for operation. Figure 2a shows, given a water height, the conditional probability of exceeding a damage state; and Figure 2b shows the conditional probability of experiencing a particular damage state.

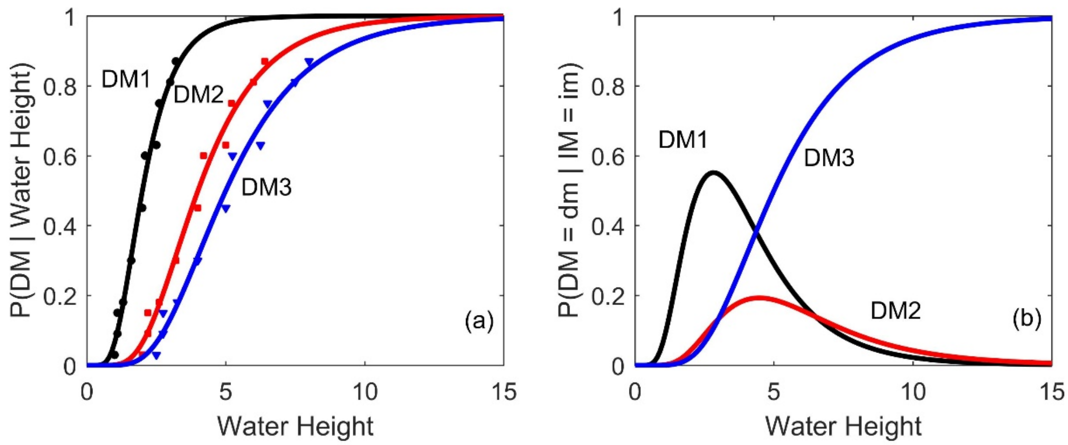

Figure 2. Example fragility relationships for an electrical box for three damage states conditioned on water height: a) shows the conditional probability of exceeding a damage state; and b) shows the conditional probability of experiencing a particular damage state.

For assessing the risk of damage to critical infrastructure and equipment during flood events, it can be necessary to use multiple fragility curves in series. For example, a piece of electrical equipment or a tank containing a hazardous substance may be behind a levee, in which case fragility curves must be used to estimate the probability of levee failure or overtopping, followed by fragility curves to estimate the probability of damage states to the electrical equipment or rupture of the tank, given that water has breached the levee.

Fragility curves for electrical equipment or hazardous substance tanks may be constructed using multiple intensity measures because of the numerous intensity measures that relate to damage states. These include: water depth; velocity on arrival, duration of submersion; and wind speed. Multiple intensity measures can be incorporated into fragility curves by using multinomial logistic regressions. [9] Important additional considerations for developing fragility curves for water-sensitive equipment include whether there is freshwater or saltwater, the nature of flood-borne silt, debris and contaminants, and if the equipment is energized or de-energized when the water arrives. In many cases when flooding is expected, electrical equipment is de-energized in order to prevent catastrophic damage to the equipment including downstream and upstream effects.

Development of detailed impact predictions on electrical infrastructure requires an understanding of the multifarious effects of flooding on individual items of electrical equipment, as well as an understanding of how each item interacts with the facility-wide electrical system and how it in turn interacts with the facility as a whole.

The process for creating fragility curves for equipment in water events can be challenging, namely because of the numerous relevant intensity measures, and because they must be created for each piece of equipment. They are typically created through observations after events, such as for electrical substation equipment performance during earthquakes [10] prior experience with such equipment, or laboratory testing of the equipment at numerous intensities. In case of the latter, the probability of a damage state at each intensity is observed, then a curve is fit through the data (i.e. a lognormal cumulative distribution function using the method of moments) for each damage state. For larger infrastructure, such as a protective levee where laboratory test data does not exist and is impractical to perform, the fragility curves may be determined through numerical simulation.

4 Evaluation of Environmental Risk and Chemical Release Consequences

Section 3 presented the concept of site vulnerability as a function of flood levels. Incorporating an understanding of the human health and environmental risks associated with specific outcomes from the vulnerability analysis provides greater insights regarding the types and the magnitude of potential risks (i.e., the risk profile) arising from the identified vulnerability.

This risk profile can be further explored by assessing specific elements of the nature of the release including factors describing the release (type of chemicals released, volume released, catastrophic vs. slow release, time to leak detection, etc.) as well as factors describing both the potential human health exposure and potential ecological exposure. These include the human health and ecological toxicity of the released material, the mobility of the released material[1], and scenarios describing the various types of exposure (e.g., adult v. child, resident vs. worker, aquatic wildlife vs. terrestrial wildlife, etc.). The final element to consider is the potential financial exposure; including costs of responding to the release, costs of remediation, and any other litigation and/or civil liabilities associated with the release.

Development of the various release, exposure, and financial factors that are related to the vulnerability is followed by a process whereby these factors are scored on a relative ranking scale (Figure 3). For example, the likelihood of a release may be characterized as negligible (0%), low (50%), and high (100%). Similarly, the size of the release can be characterized as a fraction of the maximum: negligible (0%), medium (50%), and high (100%). These release factors are then integrated into a relative ranking scale. The same is done to describe and score relative exposure/toxicity scales and the degree of financial impact (e.g., small scale vs. large scale remediation, statute-driven litigation, etc.). For a given set of conditions identified at a given time, an estimate of relative environmental and financial risk can be determined by combining the scores of the release factors, the exposure/toxicity factors, and the financial exposure factors.

[1] The mobility of released material is also informed by the depth, velocity and direction of the flood water at the time of the release.

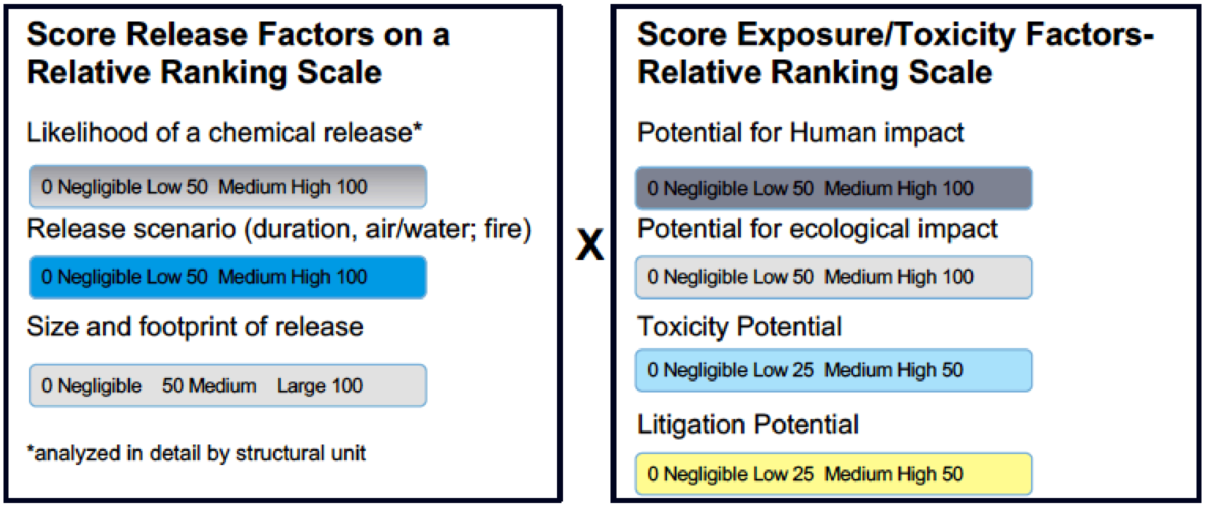

Figure 3. Development of Relative Risk Factors.

Finally, combining the relative risk values determined for a given scenario with the likelihood of a specific outcome from the vulnerability analysis allows for the creation of a matrix which describes the change in risk profile as a function of exposure condition (Figure 4). Further, incorporation of non-stationary data into the vulnerability analysis allows us to determine and assess the evolution of the risk profile at a given site.

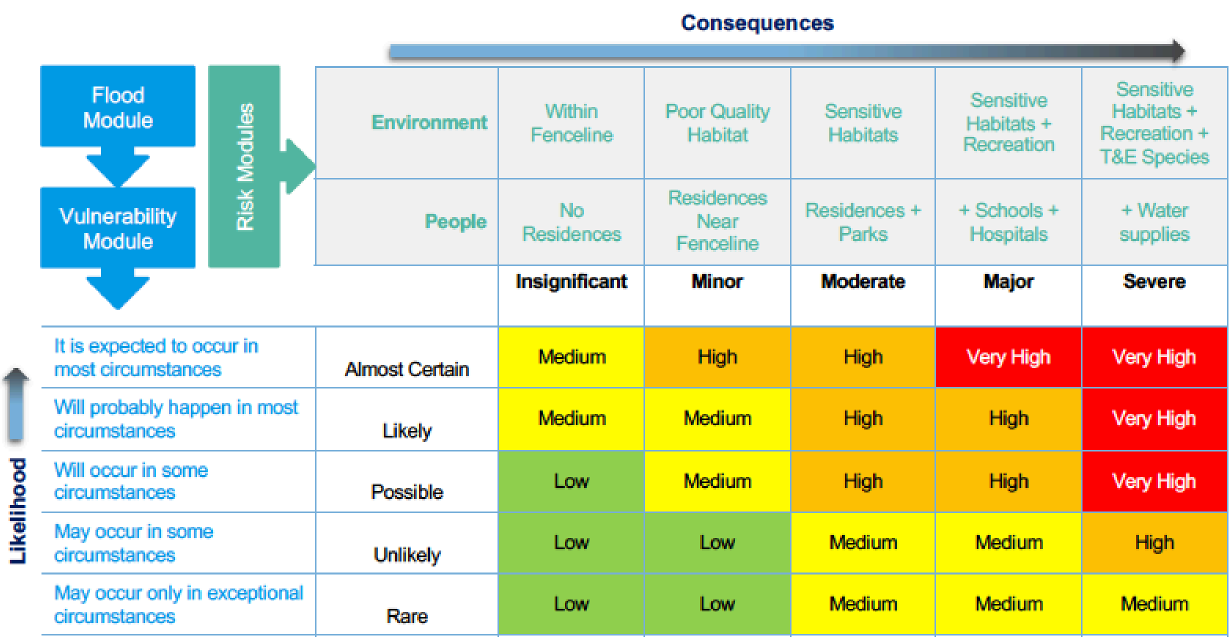

Figure 4. Example Risk Profile.

5 Extreme Weather Impacts and Failures

The physical forces and environmental stressors that occur during extreme weather events can place facilities at risk for multiple infrastructure failures, loss of operations, product loss, and major impactful chemical releases, all of which affect directly a company's bottom line. Some examples of recent impacts from extreme weather events is presented and discussed in this section.

5.1 Levee/Flood Wall Breach

Flood protection systems, such as the levees and floodwalls in New Orleans, can provide the illusion of safety, while risk assessments reveal that there is substantial risk. Figure 5 illustrates a situation in which the storm surge from a hurricane breached floodwalls and overtopped levees, flooding a processing plant at which chemicals were stored in large tanks. A tank failed, releasing chemicals that spread beyond the property line. A risk assessment before the event would have identified that: relatively frequent flood events were enough to breach the levee and flood walls; only a small amount of flood water and debris contacting the tank would likely cause tank failure; and tank failure with even minimal flood water height would transport the tank contents off the property and into the community before a response team could be deployed to mitigate the situation. This type of chemical release could be prevented by any number of measures, such as (1) reducing the probability of failure of the floodwalls or of overtopping the levee, (2) reducing the probability of tank failure, given flooding, or (3) relocating the facility to somewhere more remote.

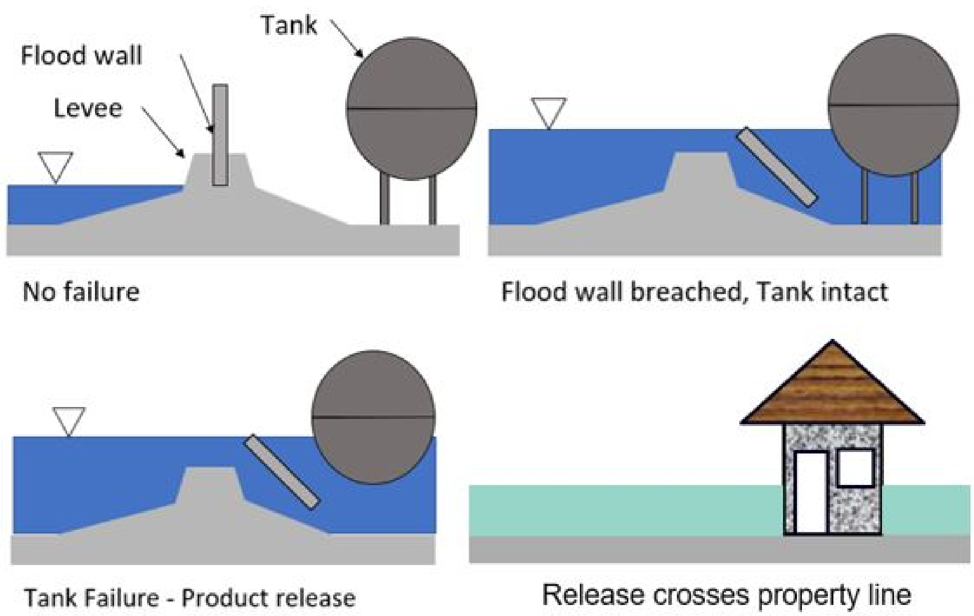

Figure 5. Levee/flood wall breach and subsequent chemical release.

5.2 Generator Dual Tank Air Vent Failure

Failures suffered during past events stress the urgency of risk assessments to identify and quantify potentially unknown hazards. For example, Superstorm Sandy caused flooding in a metropolitan area and an unexpected power outage in a building. As depicted in Figure 6, emergency generators and a suspended fuel tank were located at the top of the building to eliminate the risk of water damage and maintain electricity during a weather event; however, the tank was supplied by pumping fuel from a tank in the basement. Water entered the basement fuel tank through a vent located at the elevation of the "100-year flood", that ultimately was barely below the actual flood water level. When water was pumped to the emergency generators, they malfunctioned causing a power outage. Relocating a vent is among the easiest measures available for preventing flood intrusion. With a proper risk assessment, the risk could have been identified, and the vent moved to even the "10,000-year flood" elevation at minimal cost. Additionally, the notion of a "100-year flood" is only meaningful as an indication of the past now that water levels are non-stationary. It does not provide forward looking probabilities for future flooding events. The present framework is designed to specifically address this inconsistency between the past, present and the future.

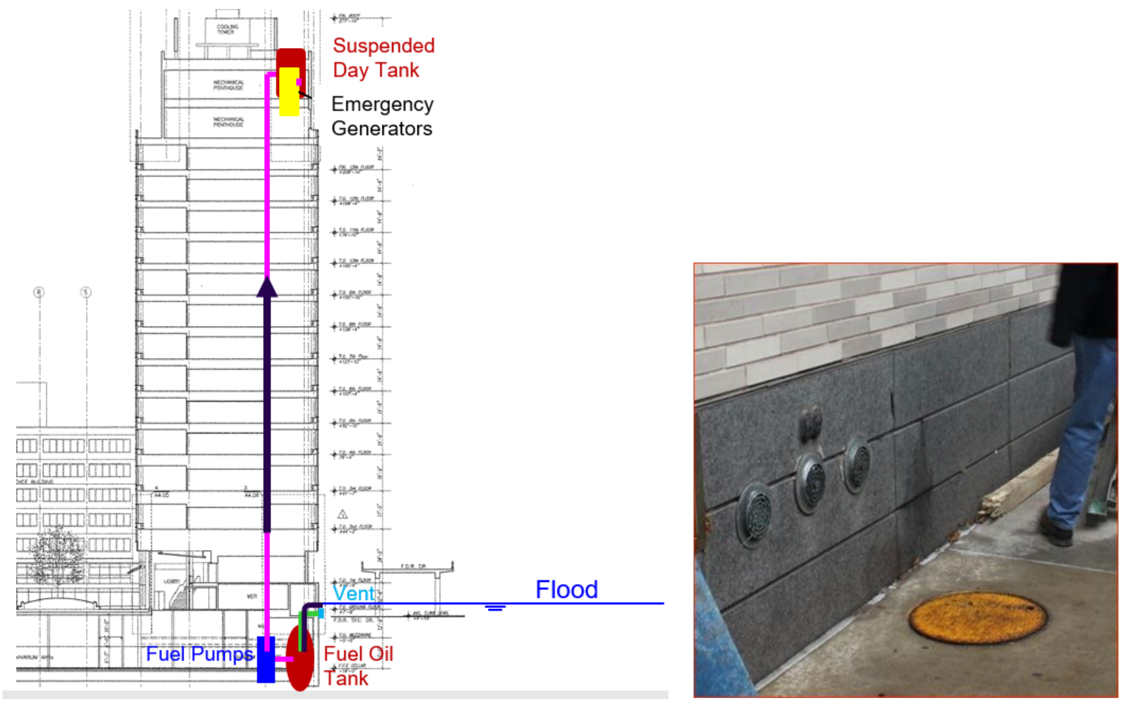

Figure 6. Schematic diagram of water intrusion through a vent, and pumping to emergency generators.

5.3 Electrical Substation Failure

One of many dramatically visible effects of "Superstorm" Sandy, to say nothing of the human costs, was the darkening of the skyline of most of lower Manhattan, which is shown in Figure 7. [11] Flooding at two Con Edison 345 kV transmission substations at the East River Complex (adjacent to the East River at East 14th Street) accounted for the outages of ten electrical distribution networks in lower Manhattan. Separately, three more lower Manhattan Con Edison networks shut down during the storm: two networks were preemptively de-energized by Con Edison and one network shutdown due to flooding at a substation near the East River in the Seaport area. [12, 13, 14]

Figure 7. Aerial photograph published on the cover of New York Magazine of Manhattan during Sandy power outage.

The peak water level as measured at the Battery (at the southern tip of lower Manhattan) was 14.06 feet above mean lower water level ("MLLW"), two feet higher than the maximum National Weather Service forecast and exceeding by several feet any known historical flood level. [15] The peak water level observed in the vicinity of the Con Edison East River Complex was 13.8 feet (MLLW), similarly exceeding forecasts, resulting in several feet of flooding at street level, as shown in Figure 8. [16] Flood waters overtopped or dislodged temporary protective measures at the East River Complex, such as sandbags and water-filled polyethylene berms, that had been installed up to an elevation of 13.6 feet (MLLW) based on forecasts and historical observations. [12, 13]

Figure 8. Photo published by Con Edison showing street-level flooding during Sandy in the vicinity of the Con Edison East River Complex.

Con Edison reported that the typical elevations for the top of foundations at the East River Complex are at 10.6 feet (MLLW) and the lowest elevation of critical equipment at 11.2 feet (MWWL). [12, 13] Figure 9 shows a datum diagram published by Con Edison indicating the elevations of the forecast and observed flooding levels as compared to the general equipment elevation at the East River Complex. [17]

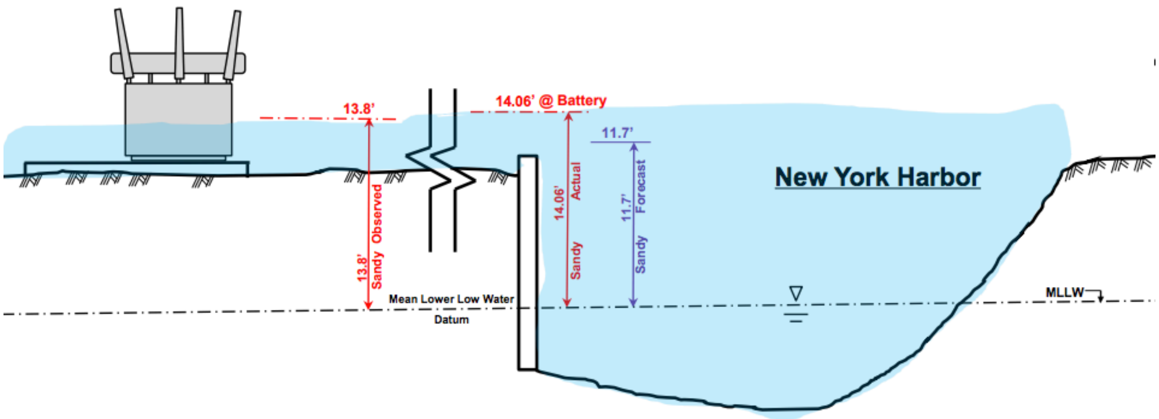

Figure 9. Datum diagram published by Con Edison comparing the 11.7 feet (MLLW) forecast flood height at the Battery to the observed 13.8 feet (MLLW) flooding height observed in the vicinity of the Con Edison East River Complex during Sandy.

Con Edison reported that the outages at the East River Complex were due to flooding of critical components of the low-voltage protective relay system as well as components of the system that maintains flow of pressurized dielectric oil for insulating feeders. [12, 13] Published photographs, shown in Figure 10 [18] and Figure 11 [19] demonstrate the effects of flood waters on relay equipment. Also during Sandy, failures at the East River Complex produced arcing and explosions that were visible from across the East River in Brooklyn. A sequence of still images from a video of the event is shown in Figure 12. [20]

Figure 10. Photo published by Con Edison of protective relay equipment damaged during flooding at East River Complex during Sandy.

Figure 11. Photo published by Con Edison of protective relay equipment damaged by flooding during Sandy at Con Edison facilities. Yellow arrow indicates horizontal water mark suggesting maximum flood water level at this location.

Figure 12. Sequence of still images from a video published on YouTube of an apparent arcing and explosion event at the East River Complex during Sandy.

A typical Con Edison substation layout cross section is shown in Figure 13. [21] The low voltage protective relay and control equipment mainly reside in the Relay House and Control Room and are connected by low voltage cables to terminal boxes on the breakers and other equipment in the facility. The pumping plant typically houses the pumps and associated control system for the pressurized dielectric oil that is fed through oil lines to the transmission and distribution cables.

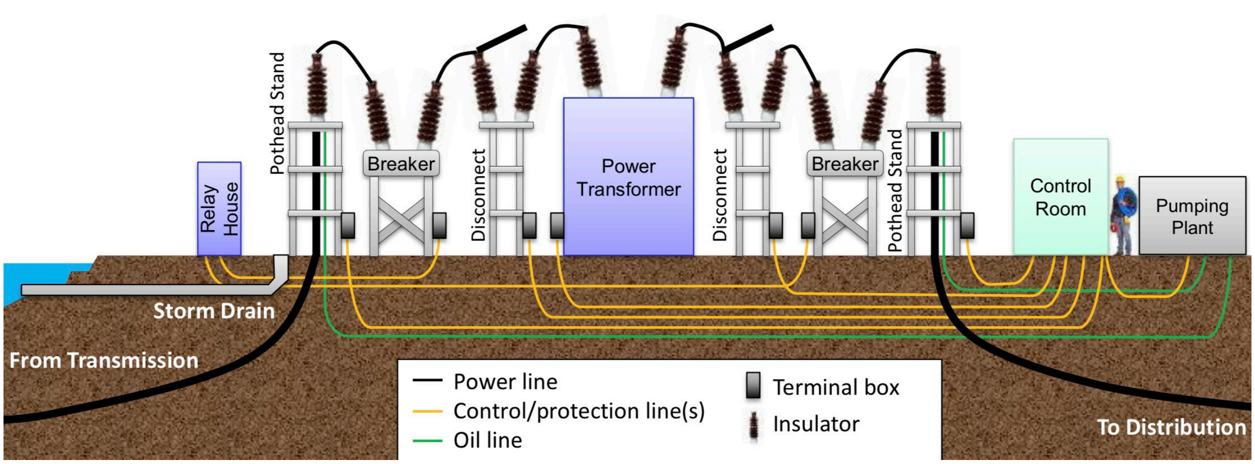

Figure 13. Diagram published by Con Edison showing cross section of typical substation layout.

Protective relay equipment may include electromechanical or electronic relays, cables, current and potential transformers, and metering. Such equipment that is still energized will tend to rapidly fail to perform its intended function when submerged in flood water, unless specifically designed for submersion. For example, if an electromechanical protective relay is submerged while energized, the power supply for the trip coil may short out, resulting in the failure for the circuit breaker to open if a fault occurs. Alternately, if submerged, the relay itself may experience a short at the contacts, causing the circuit breaker to open without an actual fault present.

In the first case (unprotected fault), severe damage can occur to both upstream and downstream transmission and distribution equipment and facilities if a fault occurs and is not detected. Resulting damage can include system disruption due to voltage drop, thermal stress and mechanical stress on equipment due to high currents and associated magnetic fields, and arcing, explosions, and burning due to, for example, failure of insulation. In the second case (open breaker without a fault present), an open breaker may cause other feeders to unnecessarily carry more load or cause other system disruptions.

Protective relay equipment that has been pre-emptively shut down will also tend to be damaged when submerged in flood water, unless specifically designed for submersion. A detailed technical evaluation along industry guidelines is generally required when assessing how flood waters may damage electrical equipment. [22] For instance, the mechanical operation of breakers and switches can be impaired by corrosion, deposited silt, and the removal of lubricants. The dielectric properties of insulating materials and insulators will tend to degrade, depending on the insulating materials and contaminants in the flood water. It is possible for certain electromechanical equipment, breakers, and motors to be reconditioned by properly trained personnel in close consultation with the manufacturer. However, most other electrical equipment such as transformers, batteries, communications systems and electronic protective relays, breakers, and meters are in general severely damaged due to flooding and require replacement.

Switchgear are key components of an electrical power distribution system at an industrial facility. Components of a typical switchgear include the chassis, conductive busbars, circuit breaker, sensors, and protective relay. Electronic protection relays are essentially special-purpose computers, with built in display and touchpad, and which receive input from current and voltage sensors and provide output to activate the circuit breaker. A fragility curve for this type of equipment may include two separate curves: if the switchgear is energized or if it is de-energized. In the case of an energized switchgear, one can assume catastrophic damage if energized high voltage terminals are exposed to floodwater. In the case of de-energized switchgear, depending on the nature of the flood water, a degree of damage would be expected to occur to the chassis, busbars, and other mechanical parts of the circuit breaker with the possibility to recondition these parts in close consultation with the manufacturer. Once the sensors are submerged, however, there is an increased risk of complete damage to the sensors, low-voltage cables, and electronic protection relay due to the potential for flood water to infiltrate the electrical connectors and cables that connect these components.

As demonstrated by the Con Edison experience during Sandy, the failure of energized equipment caused catastrophic damage both to equipment that was directly submerged, as well as damage to upstream and downstream equipment that may not have been directly submerged. The overall damage at the East River Complex was sufficient to cause the outage of ten electrical distribution networks for several days. A similar phenomenon of cascading effects can be expected at industrial sites that experience severe flooding. For example, failure of electrical distribution equipment or cables may stop the operation of powered ventilation equipment in areas where a hazardous classification exists. In this scenario, explosive vapors and/or dust may accumulate, increasing the hazardous classification of the area, and increasing the risk of an explosion.

6 Conclusion

In the United States, recent extreme weather events have resulted in profound social and economic impacts. These events highlight the importance for corporations and government entities alike to consider a changing, non-stationary set of conditions when assessing and mitigating the risk of infrastructure destruction, business interruption, and consequences of chemical releases resulting from extreme weather events. Weather-related vulnerabilities to multiple sectors, including the energy sector [2], continue to increase. Companies wishing to more rigorously assess and mitigate extreme-weather-related risk can benefit from an approach wherein detailed weather, engineering, environmental, and health analyses are integrated into a systematic methodology.

In this paper, an integrated three-part approach to assessing risk of infrastructure damage and chemical releases and the resulting business and legal consequences was presented. This includes a non-stationary methodology to quantify flooding and its related forces, impact predictions on infrastructure based on this flooding model, and a method to quantify environmental and financial risk associated with these predictions. This localized approach to determining facility-level asset vulnerabilities, quantifying potential impacts, identifying risk management actions, and implementing risk transfer strategies provides actionable information for resiliency and risk mitigation planning.

7 References

[1] NOAA National Centers for Environmental Information (NCEI) U.S. Billion-Dollar Weather and Climate Disasters (2019). https://www.ncdc.noaa.gov/billions/, Accessed on February 11, 2019.

[2] U.S. Department of Energy, "U. S. Energy Sector Vulnerabilities to Climate Change and Extreme Weather," July 2013, DOE/PI-0013.

[3] U.S. Department of Homeland Security, Office of Inspector General, "FEMA Needs to Improve Management of Its Flood Mapping Programs," September 2017, OIG-17-110.

[4] F. Bajak and L.Olsen, Silent Spills, Houston Chronicle, https://www.houstonchronicle.com/news/houston-texas/houston/article/In-Houston-and-beyond-Harvey-s-spills-leave-a-12771237.php, accessed February 15, 2019.

[5] Skamarock, W. C., and Coauthors, 2008: *A Description of the Advanced Research WRF Version 3*. NCAR Technical Note NCAR/TN-475+STR, doi:10.5065/D68S4MVH.

[6] Gochis, D. J., M. Barlage, A. Dugger, K. FitzGerald, L. Karsten, M. McAllister, J. McCreight, J. Mills, A. RafieeiNasab, L. Read, K. Sampson, D. Yates, W. Yu, (2018). The WRF-Hydro® modeling system technical description, (Version 5.0). NCAR Technical Note. 107 pages. Available online athttps://ral.ucar.edu/sites/default/files/public/WRF-HydroV5 Technical Description. Source Code DOI:10.5065/D6J38RBJ.

[7] Deierlein, G.G., 2004, June. Overview of a comprehensive framework for earthquake performance assessment. In Performance-Based Seismic Design Concepts and Implementation, Proceedings of an International Workshop (pp. 15-26).

[8] Krawinkler, H. and Miranda, E., 2004. Performance-based earthquake engineering. Earthquake engineering: from engineering seismology to performance-based engineering, 9, pp.1-9.

[9] Jampole E, Hunt J. Structural performance factors and building damage following the 19 September 2017 Puebla, Mexico Earthquake. 17th U.S.-Japan-New Zealand Workshop on the Improvement of Structural Engineering and Resilience, Applied Technology Council, Queenstown, New Zealand, 2018.

[10] Development of an Electrical Substation Equipment Performance Database for Evaluation of Equipment Fragilities (PG&E).pdf, pg. 51.

[11] I. Baan. The City and the Storm, New York Magazine, November 12, 2012. Available at http://nymag.com/nymag/letters/hurricane-sandy-editors-letter-2012-11/ Accessed on February 13, 2019.

[12] Consolidated Edison Company of New York, Inc. Report on 2012 Performance under Electric Service Reliability Performance Mechanism. April 1, 2013. Available at http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7BF996CF89-4A2C-4409-8C62-9E69AF5A9B19%7D Accessed on February 13, 2019.

[13] Consolidated Edison Company of New York, Inc. Report on Preparation and System Restoration Performance Sandy October 29 through November 12, 2012. January 11, 2013. Available at http://documents.dps.ny.gov/search/Home/ViewDoc/Find?id=%7B2D1BF3D9-95DC-4C2D-9F24-6DE65926275B%7D&ext=pdf Accessed on February 13, 2019.

[14] Con Edison, Inc., Edison Electric Institute Finance Conference, Southern Manhattan Outage Map November 11-13, 2012. Available at http://phx.corporate-

ir.net/External.File?item=UGFyZW50SUQ9NDg1NDc3fENoaWxkSUQ9NTM2MjYwfFR5cGU9MQ==&t=1 Accessed on February 13, 2019.

[15] A. Freedman. Hurricane Sandy Set to Deliver Massive Blow to East Coast. October 28th, 2012. Available at https://www.climatecentral.org/news/hurricane-sandy-to-deliver-historic-blow-to-mid-atlantic-northeast-15176 Accessed on February 13, 2019.

[16] K. Field. Con Ed Nearing Completion of $1B Post-Sandy Fortification Effort. T&D World, Nov 21, 2017. Available at https://www.tdworld.com/substations/con-ed-nearing-completion-1b-post-sandy-fortification-effort Accessed on February 13, 2019.

[17] F. A. Cuomo, M. Mangan, J. O'Hagan. Consolidated Edison Company of New York Steam Operations Storm Hardening: Impacts and Solutions. Available at https://www.districtenergy.org/HigherLogic/System/DownloadDocumentFile.ashx?DocumentFileKey=4589eb65-3ffd-2761-1fa3-687615efbcae. Accessed on February 13, 2019.

[18] K. Field. Con Ed Nearing Completion of $1B Post-Sandy Fortification Effort. T&D World, Nov 21, 2017. Available at https://www.tdworld.com/substations/con-ed-nearing-completion-1b-post-sandy-fortification-effort. Accessed on February 13, 2019.

[19] P. Di Lillo and A. Martello. Con Edison E. 13th Street Substation - ABB PASS Business Case. Available at http://aieq.net/wp-content/uploads/2018/03/panel_3_PatDilillo_and_Andrea_Martello_Con_Edison.pdf Accessed on February 13, 2019.

[20] J. Mattiuzzi. Hurricane Sandy Causes Huge Explosion NYC at Con Ed. Available at https://www.youtube.com/watch?v=3K2OWYG61GY Accessed on February 13, 2019.

[21] Con Edison Storm Hardening & Resiliency Collaborative, Substation Operations Update, May 20, 2014. Available at http://documents.dps.ny.gov/public/Common/ViewDoc.aspx?DocRefId=%7BC73D6658-896D-4AE0-B909-ADB468421421%7D Accessed on February 13, 2019.

[22] Evaluating Water-Damaged Electrical Equipment, National Electrical Manufacturers Association. August 25, 2016. Available at https://www.nema.org/Standards/Pages/Evaluating-Water-Damaged-Electrical-Equipment.aspx. Accessed on February 13, 2019.