An integrated method for quantifying and managing extreme weather risks and liabilities for industrial infrastructure and operations

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Abstract
The physical forces and environmental stressors that occur during extreme weather events place facilities at risk for infrastructure failures, loss of operation and production, and highly impactful chemical releases, all of which directly affect a company’s bottom line. Hurricane Harvey (2017) resulted in over 100 such failures and chemical releases. There is a pressing need today for risk predictions that incorporate and account for evolving environmental factors such as continuous sea level rise. Such non-static (nonstationary) risk management approaches will allow us to more accurately predict storm surge flooding as a function of time and provide more realistic short-term and long-term (on the order of decades) predictions to assist in actionable planning. An integrated three-part approach to assessing the risk of infrastructure damage and chemical releases and the resulting business and legal consequences are presented in this work. This approach consists of (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 including structural, mechanical, and electrical elements based on the predictions from step (a); and (c) a quantitative means of scoring the environmental/financial risk and consequences of chemicals released as derived from step (b). This integrated approach, which assesses risk of losses in both the near term and out to 50 years in the future, includes the assessment of ecological and human impact levels and provides actionable information for resiliency and risk mitigation planning.

KEYWORDS
extreme weather events, risk management

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. The year 2018 is ranked as the fourth highest in total cost, behind years 2017, 2005, and 2012. Additionally, when evaluating data from 1980 to 2018, the annual average number of events is 6.2 (Consumer Price Index [CPI]-adjusted), while the annual average from 2014 to 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. It is therefore important for corporations and government entities alike to consider the changing, nonstationary conditions when assessing the risk of infrastructure destruction, business interruption, and consequences of chemical releases resulting from extreme weather events. It is this information that can best assist in mitigating these risks.

Weather-related vulnerabilities to multiple sectors, including the energy sector, 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. While flood maps do 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 30 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, and changes in land use and habitat. The third and most proactive approach to extreme-weather-related risk management focuses on using nonstationary 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.

Today’s standard of care in developing infrastructure and protecting against the increasing severity of extreme weather events does not explicitly require that nonstationarity be considered. In fact, the development of such new standards and codes may well be a slow process due to its technical and scientific complexity as well as the broad and varied make-up of their stake holders. Furthermore, ambiguity exists on how owners, designers, and engineering procurement and construction contractors should consider the changing environment. On the other hand, recent flooding events and the destruction these events have caused to infrastructure and society is well documented. As a result, new facilities that are designed and built using traditional methods based on stationary weather models may face liability exposure associated with losses caused by extreme weather events. Such claims may allege that the owners, designers, and/or builders knew or should have known of the risks and should have therefore protected against them by exceeding current codes and standards requirements. Such liability exposure constitutes a part of the overall risk exposure.

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.

To properly and rigorously address the risk assessment of infrastructure damage, chemical releases, and business and legal consequences as described above, an integrated three-part approach was developed that consists of (a) time-dependent probabilistic predictions of flooding and forces related to flooding with unprecedented resolution; (b) detailed impact predictions on facility infrastructure including structural, mechanical, and electrical elements resulting from step (a); and (c) a quantitative means of scoring the environmental/financial risk and consequences of chemicals released 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 | Extreme Weather Impacts and Failures

The physical forces and environmental stressors that occur during extreme weather events place facilities at risk for infrastructure failures, loss of operations and production, and highly damaging chemical releases, all of which directly affect a company's bottom line. These physical forces can impact the structural, mechanical, and electrical aspects of the infrastructure. Specific examples of recent mechanical and electrical impacts from Superstorm Sandy are presented and discussed below. These examples illustrate in part the significant damage Sandy caused to the Manhattan electrical infrastructure.

### 2.1 | Electrical substation failure

One of the many dramatically visible effects of Superstorm Sandy was the darkening of the skyline of most of lower Manhattan, which is shown in Figure 1. Flooding at two Con Edison transmission substations at the East River Complex accounted for the outages of 10 electrical distribution networks in lower Manhattan. In addition to the loss of these ten networks, two networks were preemptively deenergized...
by Con Edison and one network shutdown due to flooding at a substation near the East River in the Seaport area.6-8

The peak water level as measured at the Battery (at the southern tip of lower Manhattan) was 14.06 ft above mean lower water level (MLLW). This peak level was 2 ft higher than the maximum National Weather Service forecast and also exceeded any known historical flood level by several feet.9 The peak water level observed in the vicinity of the Con Edison East River Complex was 13.8 ft (MLLW), which similarly exceeded the forecasted values, and resulted in several feet of flooding at street level.10 As Figure 2 shows, the streets became rivers and flood waters overtopped or dislodged the temporary protective measures at the East River Complex that had been installed up to an elevation of 13.6 ft (MLLW).6,7 Therefore, the damage sustained at the East River Complex was the result of a peak water level only 0.2 ft above the temporary protective measures. Figure 3 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.11

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.6,7 Published photographs, such as that shown in Figure 410 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 this event is shown in Figure 5.12

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 was not 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 fires and explosions.

2.2 | Generator dual tank air vent failure

Another example illustrates how Superstorm Sandy, and the associated flooding, caused an unexpected power outage in a building that had been specifically protected against this scenario. As depicted in Figure 6, emergency generators and a suspended fuel tank were located at the top of a building to eliminate the risk of water damage and maintain electricity during a weather event. In this design, the suspended 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” scenario, which was ultimately only slightly below the actual flood water level. When the water that entered the basement fuel tank was pumped to the emergency generators, the generators malfunctioned, causing a power outage. Relocating a vent is among the simpler and easier measures available for preventing flood intrusion. With a proper risk assessment, the risk could have been identified, and the vent moved to 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. It does not utilize data from the present or use forward-looking probabilities for future flooding events. The present framework is designed to specifically address this inconsistency between the past, present, and future.

3 | 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.

3.1 | 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 to the peril as well. While only one hazard may not be extreme in isolation, multiple hazards together 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 constructed environment. These physical factors combine nonlinearly. The best approach to modeling flooding where multiple factors are involved is to couple the flood simulation with
forecasting modeling. The approach used by Jupiter involves the coupling of many models as is further explained below.

3.2 | Jupiter’s Model Workstream

Ensemble techniques lead to a probabilistic view of forecasts. A multimodel ensemble of 43 global weather forecasts provide boundary conditions to a hydrodynamic (coastal ocean) model as well as a hydrologic and hydraulic (H&H) modeling framework that simulates flooding in river channels and over land. Both the hydrodynamic and H&H models are described below in more detail. The ensemble of coastal ocean model forecasts provides a distribution of the forecasted water levels along the coast and over the coastal flood plain. The H&H model, which includes rainfall from the atmospheric forecasts, provides bounds on the probabilities of flood depths and velocities, given that the surge or rain levels are sufficient to lead to flooding.

To evaluate flooding more accurately at a specific location, the global weather forecasts are dynamically downscaled to provide more localized atmospheric information to use in the modeling. The weather research and forecasting (WRF) model is the state-of-the-art regional atmospheric model and is used for deriving atmospheric information on a smaller grid when compared to the global forecasts, allowing for regional optimization. For example, WRF can be used to create forecasts on a grid scale spacing of 1 km from global forecast models that range from approximately 9 to 20 km grid spacing. The resulting rain and winds are further bias-corrected via a recursive algorithm that minimizes the forecast errors compared to observations by using recent data. The WRF output supplies wind, atmospheric pressure, and density information to the hydrodynamic (coastal ocean) model, rainfall, and temperatures to the hydrologic (WRF-Hydro), and rainfall to the hydraulic model (HEC-RAS).

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 the one executed by Mercator Ocean, provides initial and lateral boundary conditions to the Jupiter Ocean model. Multiple global atmospheric models provide the ocean surface boundary conditions (as described above) and a hydrologic and river routing model provides the upstream boundary conditions for both the Jupiter Ocean model and H&H modeling framework.

The Jupiter Ocean model is currently executed at 50-m grid spacing or smaller, with information updated twice daily (0000 UTC and 1200 UTC). Each run of the Jupiter Ocean model uses a unique atmospheric forecast from the 43-member ensemble global ensemble, downscaled with WRF. The resulting water levels predicted by the Jupiter Ocean model are corrected based on the recent history of errors measured by comparison against available water level gages. The coastal ocean forecasts from the ensemble of model runs are subselected to create three flooding scenarios: 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 and hydraulics 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 the scale of the digital elevation model (DEM), which is most often a 3-m pixel size. The hydraulic model also incorporates run-off and upstream river boundary conditions from a hydrology model, which is currently a regionally optimized implementation of the national water model WRF-Hydro configuration.

The more computationally intensive high-resolution (typically 3-m grid spacing) HEC-RAS model 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 provides the distribution of water depth above ground, water surface elevation, and velocity for each of the flood scenarios. Figure 7 gives a schematic of Jupiter’s FloodScore Operations (FSO) modeling system release for predicting floods. An example of the Jupiter Ocean model and HEC-RAS domains is shown in Figure 8.

4 | IMPACT PREDICTION AND RISK EVALUATION THROUGH FRAGILITY CURVES

The output from Jupiter’s flooding prediction model of the distribution of water depth and velocity over previously dry land are then used in combination with fragility curves to estimate the risk and impact of various flooding scenarios. This approach integrates all critical elements of infrastructure (structural, mechanical, and electrical) in a comprehensive manner that has not previously been applied to flooding but is routinely used for other hazards, such as earthquakes. 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). Damage states are typically defined to capture repair or disruption details. Figure 9 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: (a) rust on the transformer not requiring immediate repair for
operation; (b) partial repair required for operation; and (c) permanent replacement required for operation. The fragility curves ultimately show, given a water height, the conditional probability of exceeding a damage state.

### 4.1 Use of fragility curves for complex facilities

For assessing the risk of damage to critical infrastructure and equipment during flooding events, it is necessary to use multiple fragility curves both in series for cascading events and in parallel for events impacting independent systems that are driven by the flood. 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.

Cascading and interdependent fragility curves are especially important for evaluating complex energy and industrial facilities. Different combinations of correlated events can disrupt facility operations or cause one or more failures. For example, there are typically redundant power systems, all of which need to fail to disrupt operations, and all of which have different fragility curves (because they are different systems) and different exposure to hazards (because they are not co-located). The hazard intensities experienced by the redundant systems are correlated through the extent of flooding; therefore, the probabilities of failures are correlated. Commercial software generally accounts for a stationary hazard, where fragility curves rely on a single intensity measure and repair costs use a single damage state, without consideration for nonstationary hazards, chained events, and correlated component behavior.

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.\cite{17} 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 deenergized when the water arrives. In many cases when flooding is expected, electrical equipment is deenergized 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. Fragility curves are typically created through observations after events occur, such as for electrical substation equipment performance during earthquakes,\cite{18} 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, and then a curve is fit through the data (ie, 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. The following section outlines the use of fragility curves.

### 4.2 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 a substantial risk. Figure 10 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 (a) relatively frequent flood events were enough to breach the levee and flood walls, (b) only a small amount of flood water and debris contacting the tank would likely cause tank failure, and (c) 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 reducing the probability of failure of the floodwalls or of overtopping the levee, reducing the probability of tank failure and/or the tank inventory, given flooding, or relocating the facility to somewhere more remote.

### 5 Evaluation of Environmental Risk and Chemical Release Consequences

Section 4 presented the concept of site vulnerability as a function of multiple intensity measures, such as 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 (ie, the risk profile) arising from the identified vulnerability.

#### 5.1 Development of relative risk factors and a risk profile

The risk profile can be quantified by assessing specific elements of the nature of the release. This includes factors describing the release, such as the type of chemicals released, volume released, instantaneous vs slow release, time to leak detection, and so forth, in addition to factors describing both the potential human health exposure and potential ecological exposure. The human health and ecological exposure includes considerations such as the human health and ecological
toxicity of the released material, the mobility of the released material, and scenarios describing the various types of exposure (i.e., adult vs. child, resident vs. worker, aquatic wildlife vs. terrestrial wildlife, etc.). The final element to consider is the potential financial exposure, which includes costs of responding to the release, costs of remediation, and litigation and/or civil liabilities associated with the release.

Development of the various release, exposure, and financial factors that are related to the vulnerability involves a process where these factors are scored on a relative ranking scale. For example, the likelihood of a release may be characterized as negligible (0%), low (50%), or high (100%) and similarly, the size of the release can be characterized as negligible (0%), medium (50%), or large (100%). These release factors are then integrated into a relative ranking scale. The same is done to describe and score relative to exposure/toxicity and the degree of financial impact. These scores are then combined to estimate relative environmental and financial risk.

A matrix describing the change in risk profile as a function of exposure condition is created by combining the relative risk values.
determined for a given scenario with the likelihood of a specific outcome and is shown in Figure 11. Incorporation of nonstationary data into the vulnerability analysis allows us to determine and assess the evolution of the risk profile at a given site.

5.2 Facility risk score

The sections above describe the risk flooding (through the FloodScore Operations model), imposes on infrastructure (through fragility curves), human health, and the environment. These are inherently linked

**FIGURE 11** Example risk profile [Color figure can be viewed at wileyonlinelibrary.com]

**FIGURE 12** Facility risk score (FRS) diagram. This diagram outlines the integration of the FloodScore Operations model with facility-specific information and external factors in the form of an integrated software tool. This tool quantifies the risks to infrastructure, human health, and local ecology. These are combined into an estimate of the financial impact that includes remediation and the liability associated with off-site impacts [Color figure can be viewed at wileyonlinelibrary.com]
and interwoven with one another. The challenge industry faces today is (1) how to understand and quantify each of the possible impacts of flooding on complex infrastructure installations and (2) how to quantify what the overall combined magnitude of all the relevant outcomes. To that end, Exponent has integrated the FloodScore Operations model with facility-specific information and potential compounding failure factors, such as utility shutdown and loss of power, in the form of an integrated software tool. This tool quantifies the risks to the infrastructure itself, off-site human health, and risks to the local ecology. The tool combines these risks in the form of an estimate of the total cost, including the liability associated with off-site impacts from predicted flooding scenarios and is illustrated in Figure 12.

6 | CONCLUSIONS

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, nonstationary set of conditions and to assess, quantify, and mitigate the associated 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, continue to increase.

The standard of care in developing infrastructure and protecting against the increasing severity of extreme weather events and more specifically how to address the nonstationary aspect of these events is a subject that is receiving great attention and serious consideration by the public sector, developers and writers of codes and standards, insurance underwriters, EPC companies, and owners. However, the development of new rules can be a slow process due to the technical and scientific complexity of this issue, as well as the broad and varied make-up of the stake holders. In light of the well documented recent flooding events and the destruction, these have caused to infrastructure and society, new facilities that are being designed and built using the traditional methods based on stationary assumptions may face liability caused by extreme weather events. Such claims may allege that the owners, designers, and/or builders knew or should have known of the risks and should have therefore protected against them more than is currently required by current codes and standards. This extreme weather event liability exposure now constitutes part of the overall risk.

The clear path forward for companies wishing to more rigorously assess, quantify, and mitigate extreme weather-related risk is to implement an approach that integrates detailed weather, engineering, environmental, and health analyses into a systematic methodology.

In this article, we presented an integrated three-part approach to assessing risk of infrastructure damage and chemical releases and the resulting business and legal consequences. This includes a nonstationary methodology to quantify the extent of flooding and its related forces, the resulting impact on infrastructure, 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 and management.

ENDNOTES

1 http://marine.copernicus.eu
2 The mobility of released material is also informed by the depth, velocity, and direction of the flood water at the time of the release.

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How to cite this article: Kytomaa HK, Boehm P, Osteraas J, et al. An integrated method for quantifying and managing extreme weather risks and liabilities for industrial infrastructure and operations. Proc Safety Prog. 2019;38: e12087. https://doi.org/10.1002/prs.12087