Going Beyond Design Basis Floods

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Abstract

The design of all facilities, implicitly or explicitly, is based on a design-basis flooding event. The U.S. government has conducted a thorough analysis and provides the possibility of flooding events at various parts of the country in terms of return periods (e.g., 100-year flooding). Recent devastating events in Japan and Houston have shown the potential for rainfall and flooding events that go well beyond design bases of the facilities or a degradation in the design bases making the facility more vulnerable to such events. In this article, the following topics are addressed:

(a) The proper interpretation of return periods is discussed to help the analysts use such frequencies in Process Hazard Analysis (PHA) and Layer of Protection Analysis (LOPA).
(b) A method is presented for estimating site-specific flooding event frequencies including very rare, severe events.
(c) An overall method for analyzing a plant for the impact of severe flooding event.

Specific examples are provided for each topic discussed.

1. Introduction and Background

All industrial facilities, whether existing or in the design phase, are (either explicitly or implicitly) designed to withstand the effects of a major flooding event. Recent events have shown that flooding can pose a severe safety risk at industrial sites. Disasters such as Hurricane Harvey and the Tohoku earthquake and tsunami in Japan have led to flooding at facilities which have gone well beyond what was anticipated. Unanticipated flooding events can have severe impacts on facility operation and can even lead to potential safety concerns both within the facility and to the surrounding community.

In order to prevent such consequences from being realized, facility design must account for the full range of potential flooding events (both internal and external) possible at the site. Facilities which lie within flood hazard zones, as it will be shown in this article, stand a significant chance of experiencing a major flooding event within the facility lifetime. Therefore, it is prudent to consider flooding events as one of the external hazard categories to design against.

In order to mitigate the effects of major flooding events, facilities must carefully review the design of their facility, and ensure that the underlying assumptions are well understood and truly reflect the potential range of worst-case flooding events possible at the facility. As part of such review, equipment design and location must be evaluated to ensure that safety critical equipment is protected from the effects of severe floods.

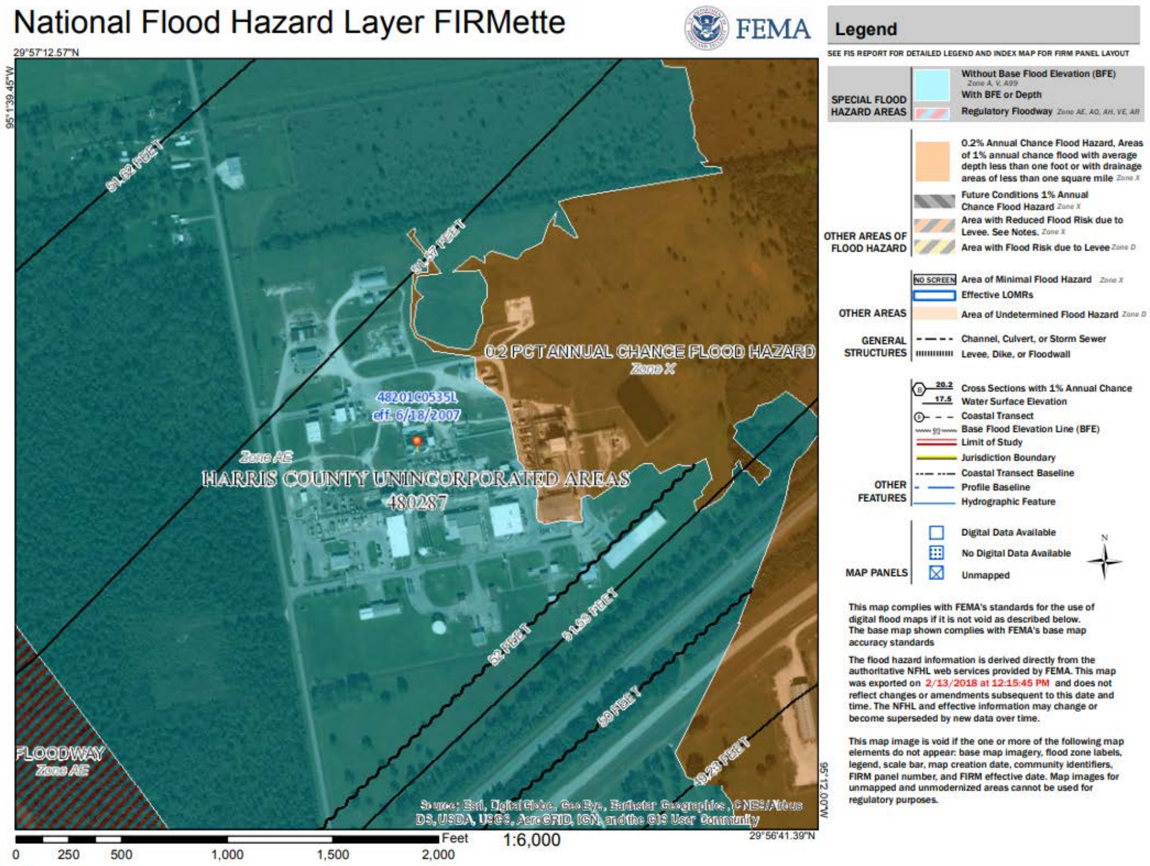
2. Notable Flooding Incidents in Recent Years

Recent events have shown that large-scale flooding can have severe impacts on the continued safe operation of a facility. In particular, floods resulting from Hurricane Harvey and the tsunami affecting Fukushima Nuclear Power Plant, Japan caused industrial incidents with lasting consequences on the surrounding communities and the environment. These events are summarized below to illustrate the impact of large floods on plants which are not adequately protected against their effects.

2.1. Hurricane Harvey

In August 2017, Hurricane Harvey devastated the gulf coast of Texas, causing major flooding across the region, particularly concentrated in the city of Houston and its surrounding areas. The Arkema, Inc. facility in Crosby, Texas was one of many facilities inundated by floodwaters during the hurricane. The Arkema facility manufactures and stores organic peroxides, which can be used as initiators in polymerization reactions at various manufacturing facilities around the country. These peroxides thermally decompose at approximately 20°F. The decomposition reaction is exothermic, and if it is not controlled can result in a runaway reaction which may lead to ignition of the decomposing material. To prevent this, peroxides at the Arkema, Inc. facility are stored in refrigerated structures before being transported off-site in refrigerated trailers.

The facility is located a few miles northeast of Houston. The FEMA Flood map [Reference 1] for the facility is presented in Figure 1 below:



Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

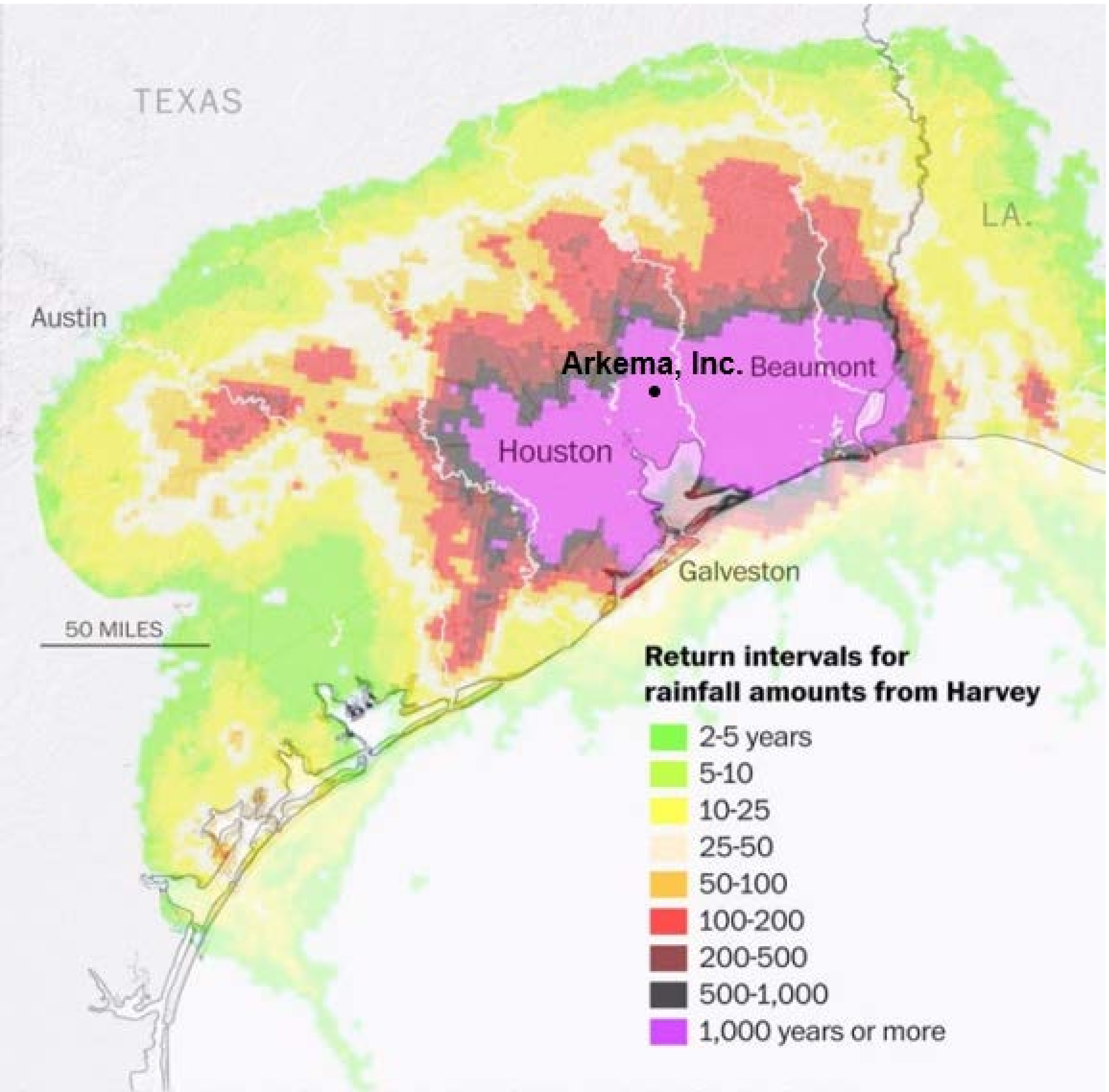
This map complies with FEMA's standards for the use of digital flood maps if it is not void as described below. The base map shown complies with FEMA's base map accuracy standards

The flood hazard information is derived directly from the authoritative NFHL web services provided by FEMA. This map was exported on 2/13/2018 at 12:15:45 PM and does not reflect changes or amendments subsequent to this date and time. The NFHL and effective information may change or become superseded by new data over time.

This map image is void if the one or more of the following map elements do not appear: base map imagery, flood zone labels, legend, scale bar, map creation date, community identifiers, FIRM panel number, and FIRM effective date. Map images for unmapped and unmodernized areas cannot be used for regulatory purposes.

Figure 1. Arkema Inc., FEMA Flood Map

As can be seen in Figure 1, the facility lies on the boundary between the 100-year flood region (blue) and the less likely 500-year flood region (orange), with the majority of the process and storage areas just within the 100-year flood zone. During Hurricane Harvey, rainfall totals in the area exceeded even the predicted 1,000-year return interval, as seen in Figure 2 [Reference 2].



Source: Dr. Shane Hubbard, Cooperative Institute for Meteorological Satellite Studies

Figure 2. Return Intervals for Rainfall Amounts from Harvey

The extensive flooding at the Arkema, Inc. facility resulted several large fires in the following days, which were subsequently investigated by the U.S. Chemical Safety Board (CSB) [Reference 3]. While the final investigation is not yet complete, the CSB has produced a timeline of the events surrounding the fires [Reference 4].

Flooding brought on in the wake of Hurricane Harvey resulted in flooding of the facility's primary and backup power sources. Without power, the refrigeration units on the organic peroxide storage rooms failed, causing temperature in the rooms to begin to increase. The peroxides were moved to the refrigerated trailers to delay the onset of decomposition, but these, too were eventually flooded as water levels continued to rise. Plant personnel were evacuated in anticipation of the upcoming fire, and eventually the surrounding community was evacuated as well. Finally, two of the refrigeration trailers ignited, and emergency responders performed a controlled burn on the rest of the trailers containing the organic peroxides.

While no one was injured as a result of the events at the Arkema, Inc. facility, the potential impact of large scale flooding events is clearly illustrated. Beyond design basis floods can have serious impacts on safe plant operation. Careful consideration of the worst-case flooding event is critical to proper facility design, in order to prevent significant losses during facility operation.

2.2. Fukushima Daiichi Nuclear Power Plant

In addition to heavy rainfall events such as Hurricane Harvey, beyond design basis floods can occur from a variety of terrestrial sources. Coastal facilities must contend with heavy storm surge, and, depending on the location, the potential for flooding in the aftermath of a tsunami. The most notable tsunami-related incident is the 2011 Fukushima Daiichi nuclear disaster. The International Atomic Energy Agency (IAEA) provides a sequence of events in their five-part report on the disaster [Reference 5].

On March 11, 2011, the magnitude 9.0 Tohoku Earthquake resulted in a loss of offsite power to the Fukushima Daiichi Nuclear Power Plant. This resulted in automatic activation of the on-site backup diesel generators. Additionally, the ground motion also resulted in automatic shutdown of the plant's operating reactors (reactors 1-3). Less than an hour later, multiple tsunamis generated by the earthquake reached the facility. The first wave had a height of approximately 5 meters, which was contained by the 5.5-meter seawall installed to protect the facility from such events. The second wave, however, reached a height of 15 meters, well above the design basis for the facility.

The second wave flooded the lower floors of the power plant, resulting in damage to electrical equipment, as well as the seawater intake pump motors, resulting in a loss of water supply to the reactor cooling systems. The resulting loss of backup power and cooling water supply caused rapid temperature rises in the plant's reactors, as there was now no way to remove heat generated by radioactive decay in the reactor cores. Over the next few days, various measures were taken in attempts to maintain temperature in the reactors, and to avoid damage to the core. However, a series of releases and explosions in reactors 1-4 resulted in partial core meltdowns and releases of radioactive material to the atmosphere.

The causes of the Fukushima event show the importance of proper definition of the design basis for a facility, and the consideration of the impacts of beyond design basis events. The IAEA report [Reference 6] indicates that the consideration of beyond design basis events was not adequately addressed at the Fukushima Daiichi Nuclear Power Plant. The plant's deterministic risk assessment did not address the potential for total loss of cooling and power, while the plant's probabilistic risk assessment did not consider the potential for most external events (e.g., seismic or tsunami-related events). Additionally, it was found that previous flooding events at the plant had provided indication of the potential for flooding in the lower levels of the facility to result in a major loss of power incident. However, plant management did not consider such an event likely enough to warrant further action, and so no modifications were made to improve facility layout.

Changes to the design of the Fukushima Daiichi Nuclear Power Plant may have helped to avoid core damage during the 2011 tsunami. In particular, raising the level of the seawater pumps and emergency diesel generators may have prevented power failure and loss of cooling for the facility. Careful review of the plant design basis may have led facility management to implement these changes, which in turn would have prevented the large-scale disaster, and potentially saved the operating company billions of dollars in remediation costs.

3. Flood Return Period in the Context of PHA and LOPA

In order to minimize the risk of devastating floods, industrial facilities that are within flood planes should be designed to withstand a certain magnitude of flooding event. Currently, there are a variety of sources which may be used in industry to define such a design basis event. Most commonly, flood maps developed by the US Federal Emergency Management Agency (FEMA) [Reference 1] are used to determine whether a facility is located within a known flood plane.

FEMA provides maps detailing the 100-Year and 500-year flood boundaries, which are typically based on historical flood data. For example, in Figure 1, the contours of the 100- and 500-year floods are shown on the map. To define these contours, a probability distribution is used to determine the worst extent of a flood with the given return period. A 100-year flood, for example, is defined as an event with a probability of occurrence of once per 100 years. Or, put another way, the 100-year flood is that flood which has a 1% chance of occurring in a given year.

Using the 100-year flood definition described above, FEMA flood maps provide a graphical representation of the 100-year flood boundary. These maps can be used to quickly determine whether a location is considered to be at risk during a 100-year flooding event. While a 100-year flood has only a 1% chance to occur within any given year, the probability of occurrence increases when looking at a longer timespan. To illustrate, a Poisson distribution can be used to determine the probability that a 100-year flooding event will occur within a given time period. The probability is calculated as:

$$P_e = 1 - e^{-(\lambda \mathrm{T})}$$

Where:

P_e = Probability of one or more floods occurring within the time period
λ = Frequency of occurrence or return period (i.e., λ = 1/100 for a 100-year flood)
T = Time period of interest

For example, consider a facility that lies within the 100-year flood boundary with an expected life of 50 years (T = 50). The probability that the facility will experience at least one 100-year flood (λ = 1/100) is then calculated as 39%. This means that facilities within a 100-year flood boundary are somewhat likely to experience at least one 100-year flood within their lifetime. Similarly, a 500-year flood has a 9.5% probability of occurrence in a 50-year timeframe.

When considered within the framework of a typical facility risk analysis, such as a Process Hazard Analysis (PHA) or Layer of Protection Analysis (LOPA), a 100 (or even 500)-year flood is considered a relatively high likelihood event. A 1% annual chance of occurrence is on the same order of magnitude as other events which have an Initiating Cause Likelihood (ICL) of 0.01 per year. This ICL is typically assigned to events such as heat exchanger tube failure or spurious opening of a Pressure Relief Valve. Typically, there are several safeguards (e.g., inspections, alarms, instrumented controls, etc.) to reduce the likelihood of these events from escalating to their worst-case endpoint. In the case of severe flooding, however, facility design is one of the only measures which can be taken to prevent severe consequences as a result of a flooding event.

It should be noted that the above example is not a perfect comparison. A flooding event would impact a large part of or the entire plant, whereas tube failure in a heat exchanger is limited to failure of one device. One can argue that when all the heat exchangers of a facility are grouped together, a single flooding event would be less likely than a tube failure in one of the multiple exchangers on-site. However, since a flooding event has the potential to impact multiple devices at the same time, the overall risk associated with flooding may be greater.

Given the relatively high likelihood of occurrence of a 100- or 500-year flood within the life of a facility, it will be prudent for facilities which fall within the given flood boundaries to consider significant flooding as part of their facility design basis, and take measures to ensure that the facility is capable of withstanding such events. For facilities which lie within a given flood boundary, if flooding was not considered as a credible event, the facility may lack critical design features to ensure safe operation during extreme flooding.

4. Flood Level Determination

As demonstrated in the previous sections, facilities which lie within a given flood boundary stand at significant risk for a large flooding event at some point during the facility lifetime. Such events have been shown to have potentially severe impacts on the facility and the surrounding community. An improved understanding of the risk posed by floods is necessary to prevent major incidents during large flooding events.

Determining the impact of a flood on a facility requires the analysts to establish: (1) potential flood scenarios and (2) facility vulnerabilities given those scenarios. To establish flood scenarios to be considered in the vulnerability assessment, the analysts should identify all flood sources that can impact the plant. In addition to the high water level provided on the FEMA flood maps, the analysts should look into all internal and external flood sources. Some examples include large liquid storage tanks on site, or the potential for inundation due to failure of nearby dams or levees. Based on these scenarios, the analysts can establish water levels at different parts of the plant as a function of likelihood of occurrence.

To enable proper design of a facility, a design basis flooding event needs to be defined. One method to arrive at a design basis flood is presented by the United States Nuclear Regulatory Commission (NRC) in NUREG/CR-7046 “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America” [Reference 7]. This document presents a lengthy discussion on proper techniques for determining a design basis flood at a given site. The NRC recommends a combination of deterministic and probabilistic models, which account for all potential flood sources relevant to the facility such as precipitation, rivers, dams, coastal surge, and tsunamis.

The approach presented in NUREG/CR-7046 uses a large variety of sources for hydrometeorological data, and recommends the use of modeling to assist in determining the effects of various flooding sources. Such an effort is lengthy and resource-intensive, and may not be feasible for many facilities. In this case, a more simplistic deterministic methodology may be more appropriate. Such an analysis should consider flood sources both external and internal to the facility.

5. Flood Impact Determination

To establish vulnerability, the analysts should examine location and exposure of electrical equipment and possibility of vessels experiencing upward forces due to floatation. There are a few major considerations which should be addressed at all facilities to which they are applicable. As seen in both events discussed in Section 2 above, loss of power (both offsite and onsite backups) is a serious concern when discussing flooding events. The location and elevation of electrical-driven equipment, as well as electrical supply systems, relays, and breakers can be greatly impacted by the choice of the design basis flood.

Rising water levels can cause significant upsets in a facility’s electrical equipment, including total loss of site power. Critical equipment such as emergency generators and electrical breakers for important equipment should be located at an elevation which would not be affected by a large flooding event so as to maintain power to the equipment during a flood. A similar consideration should be made regarding critical equipment itself. High water levels may flood pump motors, compressors, or other equipment items, rendering them ineffective. Safety critical equipment should also be at an elevation such that severe flooding would not affect critical equipment operation.

Other specialty design considerations should be made for specific equipment types and operating conditions relevant to the facility under review. For example, due to the density of their contents, tanks and vessels containing hydrocarbons will become buoyant when submerged in water. Therefore, these vessels will have the potential to float during a flooding event, which may lead to damage to the equipment or associated piping, leading to a chemical release. Proper anchorage is critical to ensure that equipment containing low density material stays in place during a flood. Similarly, loose items such as cylinders and ton containers which are attached to a process may lift and move during a flood, potentially resulting in detachment and leakage.

6. Conclusion

Recent events have shown that flooding can pose a severe safety risk at the industrial sites. Unanticipated flooding events can have severe impacts on facility operation and can even lead to potential safety concerns both within the facility and to the surrounding community. In order to prevent such consequences from being realized, facility design must account for the full range of potential flooding and other water borne events possible at the site.

Facilities which fall within flood zones defined by FEMA can be shown to be at a significant risk of experiencing a severe flood. During an estimated 50 year facility lifetime, these sites may experience 100- or 500-year flood events with probabilities of occurrence of 39% and 9%, respectively. Therefore, it is prudent that detailed analysis of a major flood be undertaken by all such facilities to ensure that the frequency of the design basis flood, as well as its effects, are clearly defined and fully understood.

Improvements to facility design should be considered to ensure that the facility is capable of safely withstanding a severe flooding event. All vulnerable equipment and storage vessels should be designed to withstand the postulated extreme flood.

Additionally, however, as recent history has shown, beyond design basis floods can also occur. Therefore, facility operations should also consider the possibility of beyond design basis flood events, and establish any actions that may be taken to ensure the safety of personnel and the community.

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