External Flooding Hazard Analysis

State of Knowledge Assessment

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J. Weglian

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ELECTRIC POWER RESEARCH INSTITUTE
3420 Hillview Avenue, Palo Alto, California 94304-1338 ▪ PO Box 10412, Palo Alto, California 94303-0813 ▪ USA
800.313.3774 ▪ 650.855.2121 ▪ askepri@epri.com ▪ www.epri.com

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THE FOLLOWING ORGANIZATION, UNDER CONTRACT TO EPRI, PREPARED THIS REPORT:

ERIN Engineering and Research, Inc.

NOTE

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The following organization, under contract to the Electric Power Research Institute (EPRI), prepared this report:

ERIN Engineering and Research, Inc.
2001 N. Main St., Suite 510
Walnut Creek, CA 94596

Principal Investigators
U. Farradj
A. Miller
D. True

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ABSTRACT

Following the earthquake and subsequent tsunami that led to core melt in three units at Fukushima Dai-ichi, the nuclear industry has begun to reassess the risk to nuclear sites from external flooding sources. This report examines the current methods used to assess risk to nuclear sites from the most common sources of external flooding: local intense precipitation (LIP), riverine flooding, dam failure, and storm surge. The focus of this report is on the manner in which these methods have been employed in the United States. The conclusions, however, are generally relevant for nuclear power plants in other parts of the world as well.

Since the regulatory requirements for U.S. nuclear sites have evolved over the years, many existing nuclear sites were licensed to meet requirements that are different from those that new sites must meet. All U.S. plants have been asked to reassess their sites based on the current regulatory requirements. This report examines the current design basis methods for addressing these risks and identifies the conservative assumptions in those methods.

Because of the increased concern about the potential risks posed by external flooding and the potential difficulty in demonstrating a site's ability to conform to the current design basis requirements, there may be a need to incorporate external flooding hazards into some plants' probabilistic risk assessments (PRAs). Probabilistic methods may also be used to address specific risks to nuclear sites without directly incorporating them into the PRA. This report examines the probabilistic methods currently available to assess the external flooding risks and their uncertainties for LIP, riverine flooding, dam failure, and storm surge.

Finally, this report identifies areas for future research in the area of the PRA of external flooding. In particular, research areas are identified that could be accomplished in the near term that would improve the hazard assessment and reduce the associated uncertainties.

Keywords

Dam failure
External flood
Local intense precipitation (LIP)
Probabilistic risk assessment (PRA)
Riverine flooding
Storm surge

EXECUTIVE SUMMARY

Following the earthquake and subsequent tsunami that led to core melt in three units at Fukushima Dai-ichi, the nuclear industry has begun to reassess the risk to nuclear sites from external flooding sources. This report examines the current methods used to assess risk to nuclear sites from the most common sources of external flooding: local intense precipitation (LIP), riverine flooding, dam failure, and storm surge. The focus of this report is on the manner in which these methods have been employed in the United States. The conclusions, however, are generally relevant for nuclear power plants in other parts of the world as well.

U.S. nuclear power plants are required by General Design Criteria (GDC) 2 to be protected from severe natural phenomena, including external flooding. The design basis requirements for U.S. nuclear power plants have evolved over time. As a result, plants have not all been licensed to meet the same requirements. Most plants were evaluated based on the concept of a probable maximum event, which attempts to assess the worst possible event based on historical data, with additional margin representing the physical limits of natural phenomena. The external flooding phenomena examined in this report are LIP, riverine flooding, dam failure, and storm surge.

All U.S. nuclear plants have been required by the Nuclear Regulatory Commission (NRC) to reassess the external flooding hazards for their sites as part of the Fukushima response. These assessments are to be conducted using “present day methods,” that is, the current design basis methods that new reactor sites are required to employ for licensing. Some existing plants do not meet the current requirements, but this does not necessarily mean that external flooding poses a significant risk for these plants. Utilities must understand the conservative assumptions in the design basis approach in order to effectively assess whether a particular site has safety vulnerabilities that require mitigation. Probabilistic risk assessments of the external flooding hazard may be useful in gaining a better understanding of possible vulnerabilities associated with any particular flooding mechanism.

Deterministic Approaches

The present day deterministic external flooding hazard assessment for LIP and riverine flooding both use the concept of probable maximum precipitation (PMP) to assess risk. In the case of LIP, the PMP is based on an assessment of the maximum rainfall that could fall in 1 hour over 1 mi^2. For riverine flooding, the impact is based on a storm that affects the watershed that drains into the river adjacent to the plant. The assumed level of precipitation is generally taken from documents developed by the National Oceanic and Atmospheric Administration (NOAA), based on the location of the site in the United States. These precipitation levels are based on historical storms that are scaled up by a moisture maximization technique to define the possible rainfall that could have fallen in the area. For riverine flooding, in addition to the maximized precipitation similar to that used in the LIP analysis but applied to the watershed, further conservatism is added by using maximum reservoir levels prior to the PMP, additional runoff from snowmelt, assumed failures of dams, minimal precipitation losses, and maximum wind-generated wave effects.

The deterministic failure assessment for dams includes using the maximum reservoir level prior to dam failure, allowing no credit for human action to manage reservoir levels (for example, operation of a spillway), and the potential for a “sunny day” failure of a dam without a precipitation event to cause the failure.

There are two deterministic approaches for assessing the effect of a storm surge. In the deterministic storm surge approach, the probable maximum hurricane (PMH) is assessed with parameters for the forward speed, radius of maximum winds, and track direction. These variables are adjusted in a series of simulations, and the simulation with the worst-case storm surge is used to determine the maximum storm surge. The second approach, the joint probability method (JPM), uses a probabilistic approach to determine the base probable maximum storm surge (PMSS) at a chosen frequency (for example, 1E-6/yr) to which is added margin in the form of additional surge height due to uncertainties, climate change effects, and tidal effects.

Probabilistic Approaches

Probabilistic methods are available for assessing LIP, riverine flooding, dam failure, and storm surge. The difficulty with assessing these external flooding hazards at very low frequencies is that the limited data available necessitates extrapolation and associated wide uncertainty bands. One possibility to address varied models and expert opinions on external flooding hazards is to use an approach similar to the Senior Seismic Hazard Analysis Committee (SSHAC) process, but tailored to address external flooding hazards. This process would be site- and hazard-specific, so it would not generate a generic result that would be applicable to the industry as a whole.

The probabilistic approach for LIP involves the collection of precipitation data from monitoring stations in the region of interest. With many stations available, the effective historical data can generally be extended below the 1E-3/yr range. The data can then be extrapolated to the frequency of interest. This approach, even with the wide uncertainty bands associated with the extrapolation, demonstrates that in most cases, the PMP estimates used in the design basis assessments represent extremely rare events. The probabilistic approach to addressing LIP is addressed in Electric Power Research Institute (EPRI) report 3002004400.

The probabilistic approach for riverine flooding is addressed in detail in EPRI report 3002003013. Two models, the Runoff Routing Monte Carlo (RORB_MC) and the Stochastic Event Flood Model (SEFM) were examined to model precipitation in a pilot watershed and to assess the frequency at which a peak river level would be exceeded at the site. Both models produced similar results.

Federal agencies such as the U.S. Bureau of Reclamation use probabilistic tools for assessing the frequency of dam failure. However, dam failure estimates are specific to a particular dam and cannot be easily generalized. The NRC has published papers that examine the historical record of dam failures and found that the frequencies are in the 1E-4/yr range. There are, however, reasons why this estimate may be of very limited applicability to any specific dam. A significant complication for many nuclear sites is that the dams upstream of the site are not owned or controlled by the utility and data for assessing the frequency and nature of failure for these dams may be difficult to obtain.

The probabilistic risk assessment for storm surge can be based on the same tools used for the deterministic assessments. The JPM method provides a sound foundation for performing a probabilistic assessment of the storm surge, but instead of adding margin for variables such as tides, these effects can also be treated probabilistically to generate the most realistic hazard frequency for the site.

Conclusions

Understanding the assumptions inherent in the deterministic external flooding assessments is key to evaluating a potential plant vulnerability. This is of particular relevance if a plant does not meet the “present day” design basis. Also, some plants may face challenges due to external flooding at flood levels below that of the design basis flood. Probabilistic techniques for assessing external flooding risk provide insights that may be used to identify vulnerabilities and determine effective mitigating actions to address these vulnerabilities. However, the uncertainties in probabilistically assessing external flooding risks can be large at low frequencies. Additional research is needed to develop consensus methods for determining the frequency and characterization of the various external flooding hazards and, where possible, to reduce the uncertainties associated with these hazards.

ACRONYMS AND ABBREVIATIONS

ANSI	American National Standards Institute
ANS	American Nuclear Society
APM	available physical margin
CFR	Code of Federal Regulations
CLB	current licensing basis
EPRI	Electric Power Research Institute
FEMA	Federal Emergency Management Agency
FERC	Federal Electric Regulatory Commission
FHR	flood hazard reevaluation
GDC	general design criteria
HMR	hydrometeorological report
IPEEE	individual plant examination for external events
JPM	joint probability method
LIP	local intense precipitation
MPI	maximum probable intensity
NEI	Nuclear Energy Institute
NOAA	National Oceanic and Atmospheric Administration
NPDP	National Performance of Dams Program
NPP	nuclear power plant
NRC	Nuclear Regulatory Commission
PFHA	probabilistic flood hazard analysis
PMF	probable maximum flood
PMH	probable maximum hurricane
PMP	probable maximum precipitation
PMS	probable maximum storm
PMSS	probable maximum storm surge
PRA	probabilistic risk assessment

RORB_MC	Runoff Routing Monte Carlo
SEFM	Stochastic Event Flood Model
SHAC-F	Structured Hazard Analysis Committee for Flood
SSC	system, structure, or component
SSHAC	Senior Seismic Hazard Analysis Committee
USBR	U.S. Bureau of Reclamation

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1 INTRODUCTION

The risk posed to nuclear power plants (NPPs) by external flooding has become an area of increased attention since the tsunami that led to the three core-damage accidents at the Fukushima Dai-ichi site in 2011. This report summarizes the understanding of external floods and flood risks, focusing on experience and practices in the United States. The insights from this report are intended to inform decision makers regarding what is generally understood about the key external flooding hazards and the tools available to assess the risks from these hazards. In addition, the evaluation of this state of knowledge is used to make some recommendations for further research in order to better characterize these risks and the associated uncertainties. Although the focus of this report is on U.S. approaches and methods, the insights are valuable for NPPs outside the United States as well.

1.1 Background

In the United States, the protection of NPPs from natural phenomena such as external flooding is governed by General Design Criteria (GDC) 2 of 10 CFR 50, Appendix A [1]. GDC 2 states that structures, systems, and components important to safety shall be designed to:

> "…withstand the most severe of the natural phenomena that have been historically reported for the site and surrounding area, with sufficient margin for the limited accuracy, quantity, and period of time in which the historical data have been accumulated…"

What is clear from this criterion is that plant safety is to be confirmed for the worst historical events, with additional margin. While GDC 2 defines this high-level regulatory expectation of the U.S. Nuclear Regulatory Commission (NRC), in practice the requirements for identifying and addressing design basis floods at U.S. NPPs have evolved over time. As shown in Figure 1-1, many of the nuclear power plants operating in the United States were licensed before these evolutions led to the present day requirements.

The consequence of this evolving regulatory framework is that not all U.S. flood design bases were created to the same requirements. To some extent, differences in design bases for external flooding necessarily result from differences in the site-specific geography and plant characteristics. However, the evolving regulatory expectations have led to a wide variety of flood challenges in terms of the site-specific hazards addressed and the relative likelihood (or margin) considered. Some U.S. plants can be challenged by relatively frequent floods. An example of this occurred in 2011 when the Ft. Calhoun plant was surrounded by flood waters for months as the result of a controlled release following sustained heavy rainfall on the Missouri River. The likelihood of a flood of this magnitude has been estimated to be approximately 1 in 100 years, that is, 1E-2/yr. Although less severe than the Ft. Calhoun design basis flood, this relatively frequent flood presented a challenge to the plant.

Many plants have been sited and evaluated based on the concept of a probable maximum event. The probable maximum event, which is determined by accounting for the physical limits of the natural phenomenon, is the event that is considered to be the most severe reasonably possible at the location of interest and is thought to exceed the severity of all historically observed events.

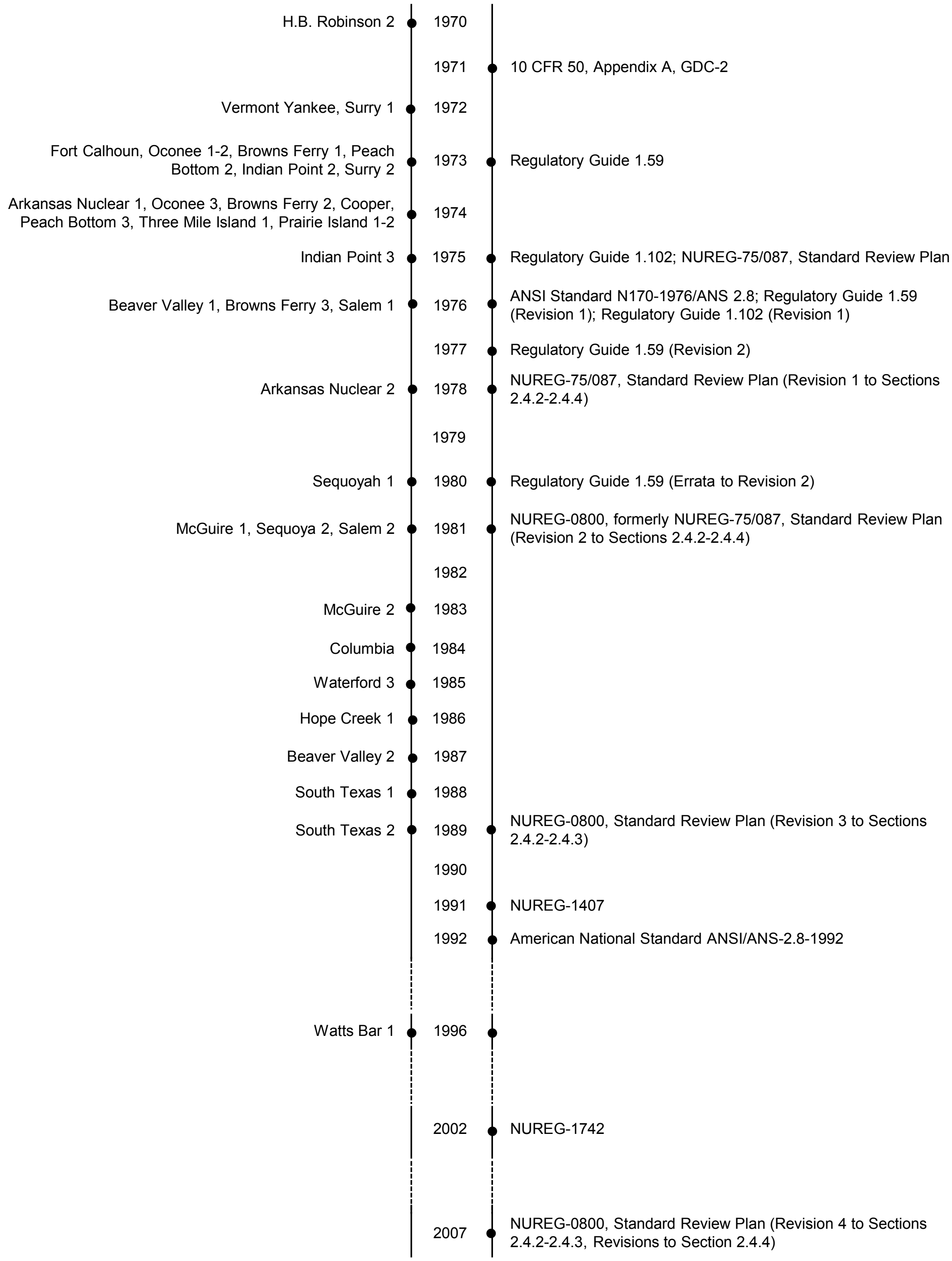

Figure 1-1
Chronology of plant licensing and flood requirements [2]

For example, a probable maximum flood (PMF) is the hypothetical flood generated in an identified drainage area by the probable maximum precipitation (PMP), combined with the probable maximum storm (PMS) and the probable maximum storm surge (PMSS) generated by the probable maximum hurricane (PMH) or the probable maximum windstorm. These events are defined by the American National Standards Institute (ANSI) and American Nuclear Society (ANS) in ANSI/ANS-2.8-1992 [3].

It is widely recognized, however, that the probable maximum event concept is, in fact, neither "probable" nor "maximum." These events do not address the probability of the event, nor do they define the maximum condition that could occur. A simple depiction of the probable maximum event concept for the PMF is shown in Figure 1-2. The starting point is the set of worst historical precipitation events. The potential effects of these events are "maximized" by considering how much more moisture could have been present at the time they occurred. These conditions define a PMP event that is used as an input to the evaluation of the flood. In assessing the PMF, the PMP is combined with additional impacts intended to add margin to the evaluation. These might include assumptions regarding antecedent storms that would saturate the soil and fill reservoirs, maximum runoff assumptions (for example, minimal absorption in soil), additional runoff from a hypothetical snow pack, and non-mechanistic assumptions of dam failures.

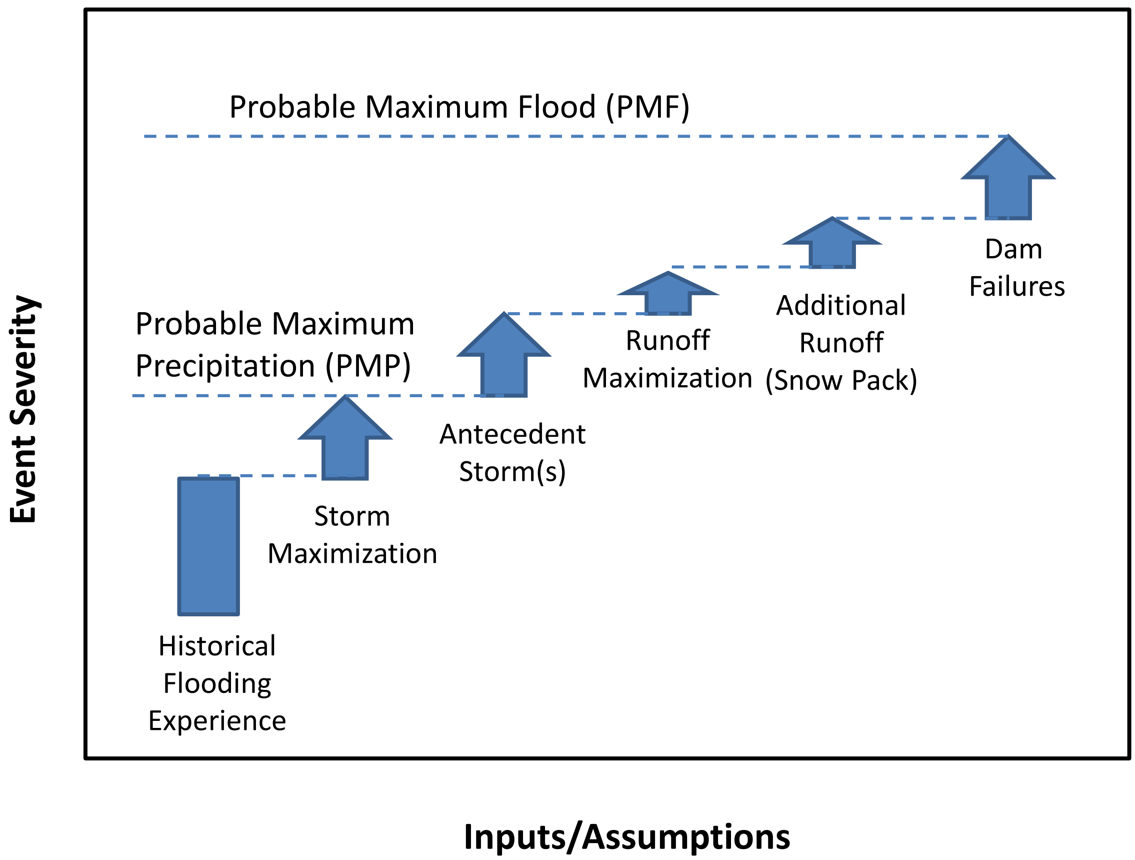

Figure 1-2
Simplified characterization of the development of a PMF

Coincident occurrence of these conditions is not treated probabilistically; it is simply a combined set of assumptions. Further, there have been a few historical events that led to flooding that is nearly as severe as the computed PMF. Those instances call into question the extent to which the PMF represents the “maximum” flood that should be considered in the plant’s design. For example, while the Three Mile Island plant was under construction, the PMF for the Susquehanna River was increased due to the rainfall and runoff observed on the river from Hurricane Agnes.

In the mid-1990s, all U.S. plants were requested to complete an individual plant examination for external events (IPEEE). External floods were within the scope of the IPEEE, but the guidance available at the time led to a generally cursory treatment of external floods for many plants [4]. Even the small number of plants that performed probabilistic risk assessments (PRAs) for external flooding were hampered by limited data and limited statistical and modeling tools. Consequently, external flooding was effectively screened out for most U.S. plants in the IPEEE.

Following the accident at Fukushima Dai-ichi, the NRC recognized that there was variability in the consideration of external floods and requested that all U.S. plants consistently reevaluate site flooding hazards using present day methods [5]. The present day methods were those that have been applied to the most recent siting and combined operating license applications for new reactors. These methods are largely summarized in NUREG/CR-7046, *Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America* [6]. These present day methods make use of the best available deterministic approaches to defining design basis floods, but they largely exclude the use of probabilistic methods. They rely on the traditional compounded conservative assumptions to define the reevaluated hazard. While the NRC has used these methods for siting of new reactors and in defining the levels of protection required, they are more difficult to use in decision making for operating reactors. Since nearly all U.S. plants have completed the reevaluations using these present day methods, the challenge becomes how to determine whether new requirements should be promulgated for existing sites. That is, the reevaluated hazard may be greater than the original flooding design requirements for a particular site without implying that external flooding presents a significant safety issue at that facility.

In these cases, the challenge is to determine whether new hazard information presents a significant challenge to safety. In the United States, PRA techniques are typically used as the tools to assess new information to gain a better understanding of the risks associated with a hazard. Unfortunately, there is only limited experience in performing PRAs for external flooding. Although there is a section of the PRA standard [7] that addresses external flooding PRAs, the requirements it establishes are stated at a relatively high level. The most challenging aspect of an external flood PRA is defining the flood hazard in probabilistic terms: the probabilistic flood hazard analysis (PFHA), which defines the relationship between the flood severity and its frequency of occurrence.

PFHA methods are increasingly being used by government agencies in the United States and abroad. In particular, both the U.S. Bureau of Reclamation (USBR) and the Federal Electric Regulatory Commission (FERC) are applying PFHA methods and other PRA techniques in their decision making for dam safety.

One challenge for the nuclear industry is that the safety standards for nuclear power plants (NPPs) are generally more restrictive (that is, reflect a lower tolerance for risk), than is typical in other industries. In some cases, understanding the risk posed to a NPP may require assessing the external flooding hazard to a lower frequency than is required in most non-nuclear applications. Estimating these lower frequencies often requires extrapolation far beyond the available data and necessarily is subject to large uncertainties.

An additional challenge for external flooding is that there are a variety of potential sources of flooding that may need to be considered. Each of these different flood hazards may need to be evaluated using a different technical approach. For example, the assessment of the likelihood of a precipitation-driven riverine flood has technical issues that are different from those for a dam-failure-driven flood, which has issues different from a storm-surge-induced flood. Further, much like the plant PRA model itself, the performance of a technically defensible PFHA requires the combination of statistical information and mechanistic modeling. This can be a fairly resource-intensive undertaking and is highly site specific. Thus, it is not feasible to draw generic conclusions about the likelihood of external flooding events for all sites—the assessments of external flooding frequency are, necessarily, site specific.

Although these challenges are real, there are other mitigating factors that can be beneficial in assessing the reevaluated hazards for existing NPP sites. For currently sited, operating NPPs, it is not necessary to demonstrate that the external flooding risks are *de minimis*. Rather, it is more important to understand the nature of the risks and whether the general likelihood of flood challenges are acceptably low. This means that it is generally not necessary to demonstrate that the frequency of a flood that could challenge plant safety is, for example, much less than 1E-6/yr. Rather, it can be acceptable to find that the contribution from flooding is in the range of other plant risk contributors, for example, core-damage frequencies on the order of 1E-4/yr to 1E-5/yr. This brings the consideration of the likelihood into a probabilistic regime that is less uncertain and more readily assessed. For consideration of siting of new reactors, it may be difficult to provide a basis for screening a particular flood hazard, because such an analysis would likely require demonstration of much lower levels of risk, consistent with NRC policies for new reactors.

1.2 Purpose

In light of this background regarding the nature of flooding design bases and the assessment of flood hazards and risks, the purposes of this report are to:

- Summarize what is known about the safety margins inherent in present day deterministic methods for key flood hazards including:
  - Precipitation-driven flooding
  - Riverine flooding
  - Dam failures
  - Storm surge
- Summarize what is generally known about the probabilistic methods for these hazards
- Summarize insights and provide recommendations on:
  - Assessing the safety implications of reevaluated flood hazards
  - Determining more specifically the areas in which additional research on PFHA issues is needed

The focus of this report is to provide a high-level summary of these issues in order to inform stakeholders on the state of knowledge related to external floods. This requires an understanding of the basic approach to deterministic estimations and the results of various probabilistic studies.

1.3 Approach

The effort that led to this report included three primary areas of focus:

- Review of present day methods – Section 2 provides an overview of present day deterministic methods to provide an understanding of the margins inherent in these methods.
- Review of current understanding of flood event frequencies – Section 3 provides a collection of information relating to probabilistic methods for assessing flood event frequencies for the key hazards: precipitation-driven flooding, riverine flooding, dam failures, and storm surge.
- Assessment of gaps in the context of decision making – Section 4 provides an assessment of the key gaps that could be addressed to support decision making on external flood risks.

1.4 Measurement Units Used in This Report

The English units of measurement used in this report and their SI equivalents are the following:

1 inch = 2.54 centimeters

1 foot = 0.3 meter

1 square mile = 2.59 square kilometers

2

PRESENT DAY DETERMINISTIC HAZARD DEFINITION

This section presents an overview of the general approach to defining various types of flood hazard. Each of these types is then addressed in more detail.

2.1 General Approach to Hazard Definition

Consistent with the design basis philosophy used for nuclear power plant design and the regulatory requirements of GDC 2, the definition of the deterministic flood hazard using present day methods is predicated on assessing historical experience and incorporating a safety margin. The focus is on defining a singular design basis characterization for each prescribed hazard that is intended to bound other considerations. This characterization accounts for historical experience, but it is not limited to historical events. Additional analytical biases are included to provide margin on top of the limited historical record.

In late 2011, the NRC issued NUREG/CR-7046 to define methods and assumptions to be used in defining design basis flooding hazards. This report was actually completed prior to the accident at Fukushima, but it was not published until late 2011. NUREG/CR-7046 was originally developed to standardize analyses for new plant applications. In 2012, when the NRC requested that all U.S. sites perform a flood hazard reevaluation (FHR) based on present day methodologies and regulatory guidance, NUREG/CR-7046 provided the primary guidance on the appropriate approaches.

In a number of cases, the FHRs have identified the potential for flood conditions outside of the current licensing basis (CLB) of the plant. Three specific flooding mechanisms are expected to be the most applicable to the U.S. fleet:

- Precipitation-driven flooding, for example, local intense precipitation (LIP) and river flooding driven by regional PMP
- Dam failures
- Extreme storm events, for example, a storm surge

Confirmation that these three are the most relevant mechanisms was determined from the snapshot provided by the most recent data collected by the Nuclear Energy Institute (NEI) from member utilities [8]. The NEI data distinguish plants with FHRs that exceed the CLB with no significant impact from plants where the reevaluated hazard could challenge safe shutdown due to loss of available physical margin (APM). APM is the difference between the flood protection height in a plant's licensing basis and the flood height at which water could affect a system, structure, or component (SSC) that is important to safety. For plants with negative APM, the reevaluated flood could impact safety-related SSCs. For plants with positive APM, the FHR may exceed the CLB, but it does not impact safety-related SSCs.

The most recent data compiled by NEI represent 35 of the total 61 U.S. sites. A summary of the recent NEI data is provided in Tables 2-1 and 2-2.

Table 2-1
Causes of negative APM (13 of 35 sites)

Flooding Mechanism	Number of Sites
Dam failure	5 (2 dam and river)
LIP	4
River	5 (2 dam and river)
Storm surge	1

Of thirteen sites with negative APM, five are associated with dam failures, four are associated with LIP, five are associated with river flooding, and one is associated with storm surge flooding. Two of the sites had negative APM associated with both dam failures and riverine flooding.

Table 2-2
Causes of FHR>CLB with positive APM

Flooding Mechanism	Number of Sites
LIP/PMP	32
Precipitation-driven river flooding	21
Storm surge	13
Dam failure	13
Tsunami/seiche	7

Table 2-3 provides the key assumptions in present day methods that bias the reevaluated hazards to provide margin.

Table 2-3
Summary of key assumptions in reevaluated hazards

Flooding Mechanism	Key Methodology Assumptions
LIP/PMP	• Single station observations of extreme precipitation, coupled with theoretical methods for moisture maximization, transposition, and envelopment, are used. • There is no credit for active drainage when available. • Runoff losses are ignored. • Openings below the highest flood elevation are protected without evaluation of the impact of flooding. • Conservative assumptions are made with respect to blockage of the drainage network. • There is maximum moisture in the atmosphere for the storm location and the month of occurrence.
Flooding in rivers and streams	• Peak discharge, volume, and hydrograph shape are used. • Maximum flood runoff, such as sequential storms and snowmelt, is used. • PMP is assumed (see LIP/PMP assumptions above). • Adjustments to peak discharge and lag time are a 5%–20% increase for the peak discharge and a 33% reduction in lag time.
Dam failure	• Dam breach parameters are conservatively assigned to maximize discharge rates. • All dams in the system are assumed to be at maximum capacity. • Cascading dam failures are analyzed to establish that the most severe of the possible combinations has been accounted for. • All dams upstream of the site are assumed to fail during the PMF event, regardless of their design capacity to safely pass a PMF. • The peak discharges from individual dam failures reach the site at the same time. • Flood waves from the failures, augmented by PMF inflows, arrive at the site at the same time. • Other impacts are combined with wind-induced waves.
Storm surge	• The PMH is defined as a hypothetical steady-state hurricane having a combination of values of meteorological parameters that will give the highest sustained wind speed that can probably occur at a specified coastal location. • Maximum envelope of water for various hypothetical hurricanes of a specific storm category is used.

2.2 Precipitation

The primary consideration associated with precipitation-driven flooding is generally PMP. The PMP is defined as "the theoretically greatest depth of precipitation for a given duration that is physically possible over a particular drainage area at a certain time of year" [9]. The NRC has deemed the PMP to be an adequate design criterion for the definition of U.S. NPP design basis floods. PMP, in one form or another, is typically associated with LIP and floods in rivers and streams (riverine flooding).

The primary sources for PMP estimates are two hydrometeorological reports (HMRs) that were developed over 30 years ago by the National Oceanic and Atmospheric Administration (NOAA):

- HMR 51 – *Probable Maximum Precipitation Estimates, United States East of the 105th Meridian* [9]
- HMR 52 – *Application of Probable Maximum Precipitation Estimates – United States East of the 105th Meridian* [10]

These reports use the most extreme historical events, along with moisture maximization techniques, to provide regional estimates of precipitation for varying durations and areas, for example, 1-hr, 1-mi^2 and 6-hr 10-mi^2. The fundamental bases for most of these regional estimates are forensically estimated precipitation amounts and durations. Few are based on actual measurements. HMR 51 includes storms over a nearly 100-year period, 1878–1972. The LIP portion of HMR 52 is focused on nine storms over a roughly 40-year period, 1935–1973. For sites located west of the 105th meridian, other NOAA HMR reports are used to estimate PMP, based on the location.

These precipitation estimates are from actual storms that are scaled up by the moisture maximization technique to define possible rainfall that could have occurred. Storm transposition, mathematically moving the impact of the storm to a new location where it had not been observed, is used to account for a limited data set. These estimates are then combined using expert judgment to define *isohyets* (lines defining the rainfall amounts) for different durations and areas. Figure 2-1 provides an example of a 1-hr, 1-mi^2 map from HMR 52.

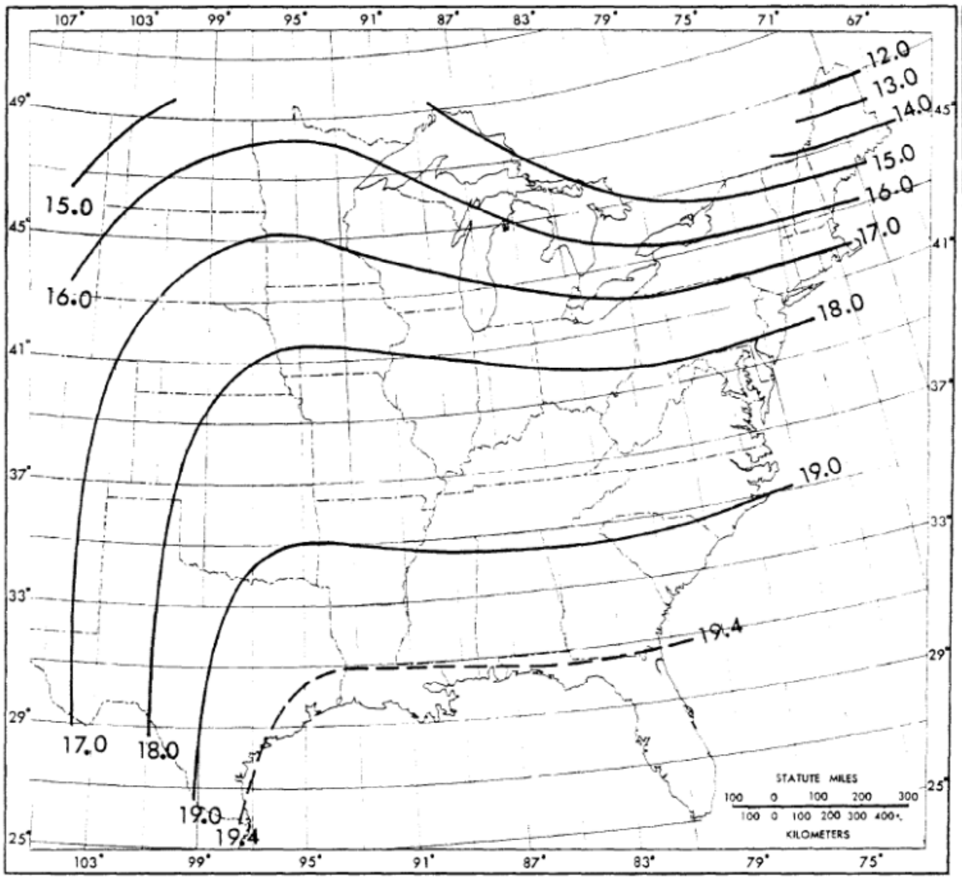

Figure 2-1
1-hr, 1-mi^2 isohyet map [10]

The map in Figure 2-1 was based on the nine extreme precipitation events listed in Table 2-4. The isohyets shown on Figure 2-1 are all in excess of the largest observed event. This is due to the storm maximization technique.

It should be noted that NUREG/CR-7046 encourages the use of a hierarchical hazard assessment, which progressively refines the estimation of site-specific hazards. Sites that cannot withstand the most conservative assumptions may refine the analysis to include site-specific data to evaluate the probable maximum event [6]. This process has allowed sites to complete a site-specific PMP analysis to better characterize their flood hazards. River sites with a watershed in excess of 20,000 mi^2 are required to develop a site-specific PMP analysis because HMR-51 does not provide PMP estimates for watersheds beyond this limit. Other regulatory agencies such as FERC routinely use location-specific PMPs.

Table 2-4
Summary of HMR 52 events used for 1-hr, 1-mi^2 precipitation estimates [10]

Location	Date	1-hr Precipitation	Basis For Estimation	Notes
Elbert, CO (Cherry Ck.)	5/30–31/35	11.0	Estimated from mass curves prepared for storm study. Same value determined for several stations.	
Woodward Ranch, TX	5/31/35	9.3	Pertinent data sheet for storm study published in “Storm Rainfall” (U.S. Army Corps of Engineers 1945).	
Simpson P.O., KY	7/4–5/39	13.4	From reconstructed depth-duration curve.	Precipitation is for a 10-mi^2 value, not 1-mi^2 value.
Smethport, PA	7/17–18/42	15.0	From mass curve for station with maximum observed storm amount. Mass curve constructed using recorders about 4 mi away. Original bucket survey data used to aid in analysis.	
Holt, MO	6/18–23/47	12.0	Published bucket survey data indicates amount at maximum station in primary burst occurred in 42 min.	
Cove Creek, NC	6/30/56	10.12	See Schwartz and Helfert (1969). We adopted 11.0 as an appropriate value to use in these comparisons.	
Buffalo Gap, Saskatchewan, Can.	5/30/61	10.5	From depth-area-duration curves published in Canadian Storm Rainfall.	Non-U.S. event.
Glen Ullin, ND	6/24/66	7.89	From pertinent data prepared by USBR.	
Enid, OK	10/10–11/73	6.7	From mass curve developed for station with maximum storm total. Mass curve modeled on data from National Weather Service station at Enid, OK. Enid station was approximately 6 mi from maximum observed amount.	

2.3 Riverine Flooding

Riverine flooding is based on an estimate of the PMF. *PMF* is defined as "… the hypothetical flood (peak discharge, volume, and hydrograph shape) that is considered to be the most severe reasonably possible, based on comprehensive hydrometeorological application of PMP and other hydrologic factors favorable for maximum flood runoff such as sequential storms and snowmelt" [6].

HMR 52 outlines the process for applying PMP estimates from HMR 51 to a specific drainage basin by developing spatial and temporal patterns in an effort to create the PMS. Hydrological models use the time history of PMP and PMS as inputs to estimate the PMF runoff hydrograph, given a set of watershed parameters that describe precipitation losses, rainfall-to-runoff transformation, antecedent streamflow conditions, and travel time within the stream network.

As discussed above, these evaluations are biased to add margin to the evaluation and include compounded conservatisms in hydrologic models such as:

- Maximum reservoir levels prior to PMP
- Additional runoff from snowmelt
- Non-mechanistic failures of dams; that is, failure is simply postulated, not calculated
- Minimal precipitation losses
- Maximum wind-generated wave impacts irrespective of predominant wind direction

The intent of these deterministic analyses is to generate what is expected to be the worst-case flooding condition without regard to the likelihood of its occurrence.

2.4 Dam Failure

In addition to precipitation-driven events, both individual and cascading dam failures must be considered as part of the reevaluation of flood hazards. This is often accomplished by taking the most conservative approach, assuming dam failure in addition to PMF flow to maximize computed water level. If such a conservative approach is not taken, then "sunny day" dam failures must also be assessed. A *sunny day failure* is one that occurs without notice and without a specific cause and typically assumes very bounding dam failure parameters.

Dam failure evaluations are treated in such a way as to add margin to the evaluation and include compounded conservatisms in the models such as:

- Maximum reservoir levels prior to dam failure
- No human intervention to manage reservoir levels
- Subjective "sunny day" failure mechanisms assumed even for well-constructed dams
- Dam breach parameters that lead to the highest water level at the site

2.5 Storm Surge

Storm surge is the rise in offshore water elevation caused principally by the sheer force of the winds acting on the surface. In general, two approaches are possible:

- Deterministic storm surge – is based on the wind field for PMH from NOAA and a coastal hydrodynamics simulation model that predicts the water-surface rise. PMH has three variable parameters: (1) the forward speed (T), (2) the radius of maximum winds (R), and (3) the track direction (θ). Each of the parameters of the PMH wind field has a range associated with it. A set of hypothetical PMSS simulations is performed for a given location by varying the three parameters over their stated ranges to determine the maximum storm surge level. This approach incorporates conservativisms associated with picking the worst combination of wind speed, radius, and track direction.
- Joint probability method (JPM) [11] – provides a probabilistic framework for quantifying exceedance probabilities of surges, including quantification of the effects of uncertainty on these estimates. The JPM examines the relative magnitudes of surges obtained via the asymptotic upper-limit method to estimate surge levels associated with a selected annual frequency, for example, 1E-6/yr. The PMSS is based on the maximum probable intensity (MPI) storm for the region, defined by NOAA. The JPM approach requires quite sophisticated probabilistic and hydrodynamic simulations. Under the JPM method defined in NUREG/CR-7134, the PMSS is increased to account for uncertainty in the modeling, climate, and tidal effects using the equation below:

$$PMSS = PMSS_{Base} + Uncert_{MPI + Models} + Uncert_{Climate} + Tidal\ Effects$$

Where:

$PMSS_{Base}$ = the base resultant PMSS for the frequency of interest

$Uncert_{MPI + Models}$ = a bias to address uncertainties in the estimate of the MPI and the hydrodynamic models used in the analysis

$Uncert_{Climate}$ = a bias to address the potential for climate change

Tidal Effects = a bias to address the fact that the simulations are based on mean sea level, but the storm could coincide with a higher sea level

The net result of the JPM is a conservative estimate that begins with a frequency-based PMSS, but explicitly adds margin on top of that estimate. For the FHR, some utilities have applied the JPM method in a slightly different manner that does not contain this bias, basing their reevaluated hazard on only the $PMSS_{Base}$ and frequencies greater than 1E-6/yr.

3
PROBABILISTIC HAZARD METHODS

3.1 General Approach

The characterization of flood hazards in probabilistic terms requires sophisticated probabilistic simulation models that combine the likelihood of discrete conditions with appropriate meteorological and hydrologic/hydrodynamic models. These methods are generally based on approaches that characterize the extreme flood as a random event, describe the properties of random and correlated phenomena using probability distributions, and use these probability distributions to estimate a range of extreme flood severities based on the probability of exceedance. The results from a representative PFHA are shown in Figure 3-1.

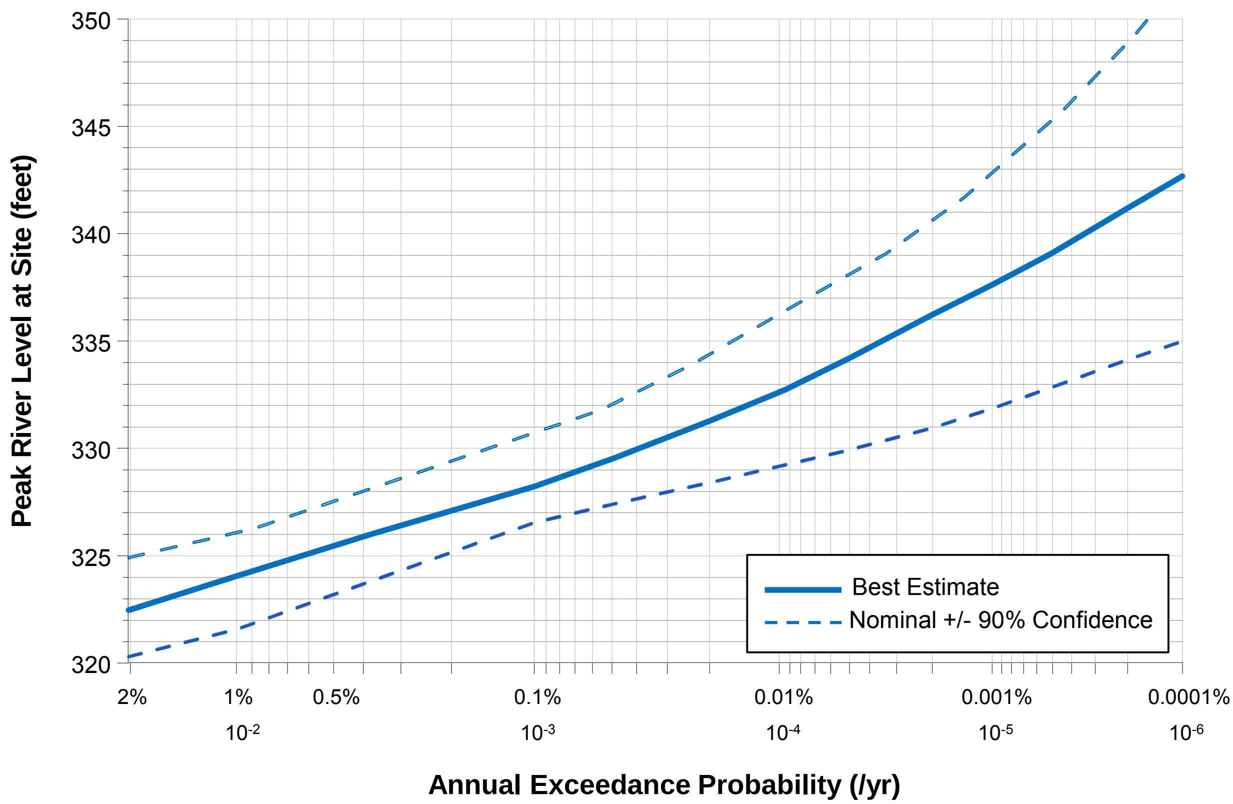

Figure 3-1
Representative PFHA result

An advantage of a probabilistic treatment is that it allows not only an understanding of the general likelihood, but also an understanding of uncertainties. In general, as the flood severity increases, the uncertainties increase as well. This can make for more challenging decision making.

While probabilistic external flooding hazard analysis has not been applied often in the nuclear power industry, both FERC and the USBR employ probabilistic flood modeling techniques for rivers and dams. The USBR has been using risk analysis as the primary support for decision making related to dam safety for about 15 years and has developed procedures to analyze risks for a multitude of potential failure modes. The USBR has created a Best Practices Training Manual that contains what are considered the "best practices" currently in use for estimating dam safety risks [12]. A recent USBR paper on dam risk management [13] draws the following conclusions regarding risk assessment and management:

- USBR's risk management process is mature.
- Risk information generates more defendable decisions and more informed decision makers.
- Risk information makes prioritization and decision making consistent.
- Risk assessment does not necessarily make difficult decisions easier.
- USBR senior managers embrace the risk management concept.
- Risk is here to stay.

FERC has gone so far as to say that the characterizations of PMF and (single) deterministic floods are no longer adequate to support effective decision making and that more information is required to make sound decisions. FERC is in the process of documenting its own flooding risk assessment methods.

A common perception is that the NRC's regulatory threshold of occurrence is significantly lower than other government agencies' thresholds. Specifically, it has been suggested that the USBR is concerned with dam failure rates in the range of 1E-3/yr to 1E-4/yr, whereas the NRC is concerned with events that range as low as 1E-5/yr to 1E-7/yr. While in some instances this may be true, it does not appear to be the case based on USBR dam risk assessment methods. Figure 3-2 provides a plot of the USBR dam risk assessment results that are used for prioritization of dam upgrades in one USBR region [13]. While this figure shows that the USBR does have dams with failure rates in the 1E-2/yr to 1E-4/yr range, they also have dam risk assessments that demonstrate failure rates for some dams in the 1E-5/yr to 1E-7/yr range. Thus, decision making by the various agencies is supported by risk assessment techniques in regimes that overlap.

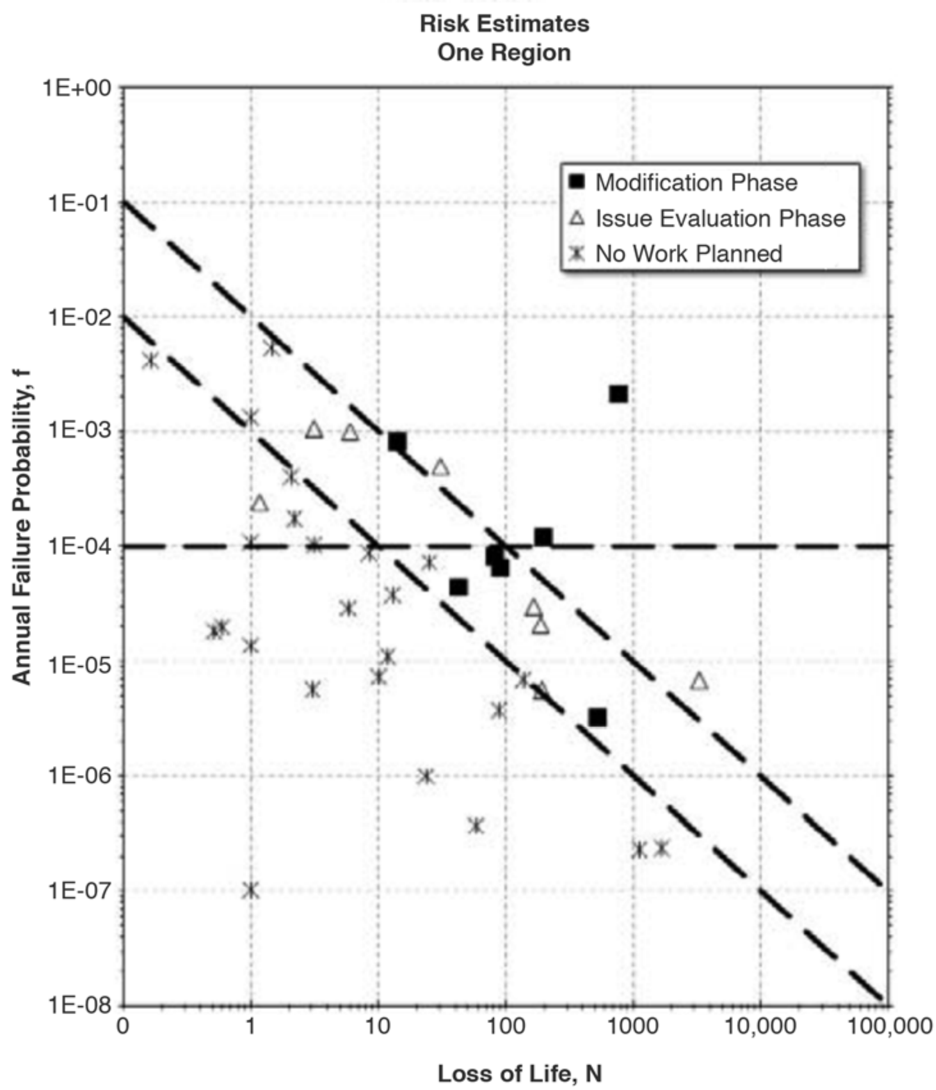

Figure 3-2
USBR regional risk results [13]

The NRC has recently initiated a research project on external flooding. One of the first areas being investigated is extreme precipitation. The NRC appears to have opted for a structured expert elicitation process much like that used in defining seismic hazards through the Senior Seismic Hazard Analysis Committee (SSHAC). This process, termed the Structured Hazard Analysis Committee for Flood (SHAC-F), has the potential to be very resource intensive, especially if it requires an expert elicitation for each and every site and for every hazard of potential relevance. Further, based on the seismic hazard results created by the SSHAC process, it appears that the end result of a SSHAC process can be somewhat intractable. Updates require a repeat of the same processes.

While a SHAC-F process may have a role in defining precipitation hazards, it will be extremely challenging for a hazard-by-hazard SHAC-F process to yield significant benefit in the near term.

The following sections discuss, in general terms, the available resources and methods that have been used to assess different flooding mechanisms from a probabilistic perspective.

3.2 Extrapolating from Historical Data

The set of historical data is the most common starting place to determine an appropriate design basis flood. For example, the definition provided in GDC 2 refers to the use of the historical maximum flooding levels. This is why extrapolation methods have been so common in past applications for extreme flood frequency estimations. The *Hydrologic Hazard Curve Estimating Procedures,* published by the USBR, details the theoretical maximum limits for flood frequency analysis that are shown below in Table 3-1 [24].

The USBR recommends that when using streamflow data to estimate flood frequency, the extrapolation should not be extended beyond twice the length of the historical record. With typical data records extending back less than 100 years, this places the limit of extrapolation from stream flows to on the order of 1 in 200 years (5E-3/yr), which would be inadequate for estimating the frequencies for floods that could be contributors to risk at a NPP site. When determining precipitation frequency, the data available are much richer and can benefit from regional analysis. Credible extrapolation can be extended into the range of 1 in 40,000 years (2.5E-5/yr) through the process of combining regional data sets.

Table 3-1
USBR guidance on the limits of flood frequency estimation [24]

Type of Data Used for Flood Frequency Analysis	Range of Credible Extrapolation for Annual Exceedance Probability	
	Typical	Optimal
At-site streamflow data	1 in 100	1 in 200
Regional streamflow data	1 in 500	1 in 1,000
At-site streamflow and at-site paleoflood data	1 in 4,000	1 in 10,000
Regional precipitation data	1 in 2,000	1 in 10,000
Regional streamflow and regional paleoflood data	1 in 15,000	1 in 40,000
Combinations of regional data sets and extrapolation	1 in 40,000	1 in 100,000

The approach described in EPRI 3002004400 [15] can serve as a good starting point for precipitation frequency estimates, which can be used to derive rough stage-frequency relationships and estimate the risk in rare flooding events well below the LIP/PMF levels. It should be noted that extrapolation beyond these limits carries with it very large and often unquantifiable uncertainties. A different method of frequency estimation may be needed for frequencies below these levels.

3.3 Precipitation

As described in Section 2, NOAA reports HMR 51 and HMR 52 (which are now 30 or more years old) provide the basis for most of the deterministic precipitation assumptions used in the United States for flood hazard characterization today. More recently, NOAA has published precipitation frequency estimates for most of the central and eastern United States in what is referred to as *Atlas 14* [14].

Atlas 14 provides frequency-versus-rainfall estimates for storm durations from 5 minutes to 60 days for recurrence intervals of 1 to 1000 years (occurrence rates of ~1/yr to 1E-3/yr), with statistical uncertainty estimates. An example set of results extracted from one of the Atlas 14 tables is provided in Table 3-2.

Table 3-2
Example NOAA Atlas 14 precipitation frequency estimates [14]

Duration	Annual Occurrence Interval (yrs)									
	1	2	5	10	25	50	100	200	500	1000
5 min	0.411 (0.326-0.521)	0.474 (0.376-0.601)	0.576 (0.456-0.731)	0.660 (0.521-0.839)	0.774 (0.597-0.992)	0.860 (0.655-1.11)	0.946 (0.705-1.23)	1.03 (0.749-1.35)	1.14 (0.811-1.51)	1.23 (0.857-1.64)
10 min	0.601 (0.478-0.763)	0.694 (0.551-0.880)	0.843 (0.668-1.07)	0.966 (0.763-1.23)	1.13 (0.874-1.45)	1.26 (0.959-1.62)	1.39 (1.03-1.80)	1.51 (1.10-1.98)	1.68 (1.19-2.22)	1.80 (1.25-2.40)
15 min	0.733 (0.583-0.930)	0.846 (0.672-1.07)	1.03 (0.815-1.31)	1.18 (0.930-1.50)	1.38 (1.07-1.77)	1.54 (1.17-1.98)	1.69 (1.26-2.19)	1.84 (1.34-2.42)	2.04 (1.45-2.70)	2.19 (1.53-2.92)
30 min	1.03 (0.821-1.31)	1.20 (0.951-1.52)	1.46 (1.16-1.86)	1.68 (1.33-2.14)	1.98 (1.52-2.53)	2.20 (1.67-2.83)	2.42 (1.80-3.15)	2.64 (1.92-3.46)	2.93 (2.08-3.88)	3.14 (2.19-4.19)
60 min	1.32 (1.05-1.68)	1.54 (1.22-1.95)	1.90 (1.51-2.41)	2.21 (1.75-2.81)	2.65 (2.06-3.42)	3.00 (2.29-3.89)	3.36 (2.51-4.39)	3.74 (2.72-4.92)	4.25 (3.02-5.64)	4.64 (3.24-6.19)
2 hr	1.61 (1.30-2.02)	1.88 (1.51-2.35)	2.34 (1.88-2.93)	2.74 (2.19-3.44)	3.33 (2.62-4.26)	3.80 (2.94-4.88)	4.30 (3.25-5.58)	4.83 (3.56-6.32)	5.56 (3.99-7.35)	6.14 (4.32-8.13)
3-hr	1.77 (1.44-2.20)	2.07 (1.68-2.57)	2.60 (2.10-3.23)	3.07 (2.47-3.82)	3.77 (3.00-4.82)	4.36 (3.40-5.58)	4.98 (3.80-6.44)	5.65 (4.19-7.38)	6.60 (4.76-8.70)	7.36 (5.19-9.71)
6-hr	2.06 (1.69-2.52)	2.41 (1.98-2.95)	3.04 (2.49-3.73)	3.62 (2.95-4.44)	4.49 (3.62-5.68)	5.22 (4.13-6.62)	6.01 (4.64-7.70)	6.87 (5.14-8.90)	8.09 (5.88-10.6)	9.07 (6.44-11.9)
12-hr	2.37 (1.97-2.85)	2.77 (2.31-3.35)	3.49 (2.90-4.22)	4.14 (3.42-5.01)	5.10 (4.15-6.36)	5.90 (4.71-7.38)	6.75 (5.25-8.55)	7.67 (5.79-9.83)	8.96 (6.56-11.6)	10.0 (7.15-13.0)
24-hr	2.72 (2.29-3.23)	3.17 (2.67-3.76)	3.94 (3.31-4.70)	4.63 (3.87-5.52)	5.63 (4.62-6.91)	6.45 (5.19-7.95)	7.31 (5.74-9.14)	8.23 (6.25-10.4)	9.51 (7.01-12.2)	10.5 (7.58-13.6)
2-day	3.13 (2.67-3.66)	3.61 (3.08-4.23)	4.43 (3.77-5.20)	5.15 (4.36-6.06)	6.19 (5.14-7.48)	7.03 (5.72-8.55)	7.92 (6.27-9.77)	8.85 (6.78-11.1)	10.1 (7.53-12.9)	11.2 (8.10-14.3)

Table 3-2 (continued)
Example NOAA Atlas 14 precipitation frequency estimates [14]

Duration	Annual Occurrence Interval (yrs)									
	1	**2**	**5**	**10**	**25**	**50**	**100**	**200**	**500**	**1000**
3-day	3.38 (2.92-3.93)	3.91 (3.36-4.54)	4.79 (4.12-5.58)	5.56 (4.75-6.49)	6.65 (5.55-7.96)	7.53 (6.16-9.07)	8.43 (6.71-10.3)	9.38 (7.22-11.7)	10.7 (7.96-13.5)	11.7 (8.52-14.9)
4-day	3.61 (3.12-4.16)	4.16 (3.60-4.81)	5.10 (4.40-5.90)	5.90 (5.06-6.84)	7.03 (5.89-8.36)	7.93 (6.52-9.51)	8.86 (7.08-10.8)	9.83 (7.58-12.2)	11.1 (8.32-14.1)	12.2 (8.88-15.5)
7-day	4.22 (3.69-4.81)	4.82 (4.21-5.49)	5.83 (5.08-6.66)	6.69 (5.81-7.67)	7.91 (6.70-9.30)	8.89 (7.37-10.5)	9.89 (7.96-11.9)	10.9 (8.50-13.4)	12.3 (9.29-15.5)	13.5 (9.88-17.0)

The highlighted values for the 60-minute precipitation estimates for this site are plotted in Figure 3-3. As can be seen, even the upper bound NOAA estimates for the 1000-year (1E-3/yr) precipitation are small compared to the typical HMR 52 estimates for LIP (see Figure 2-1).

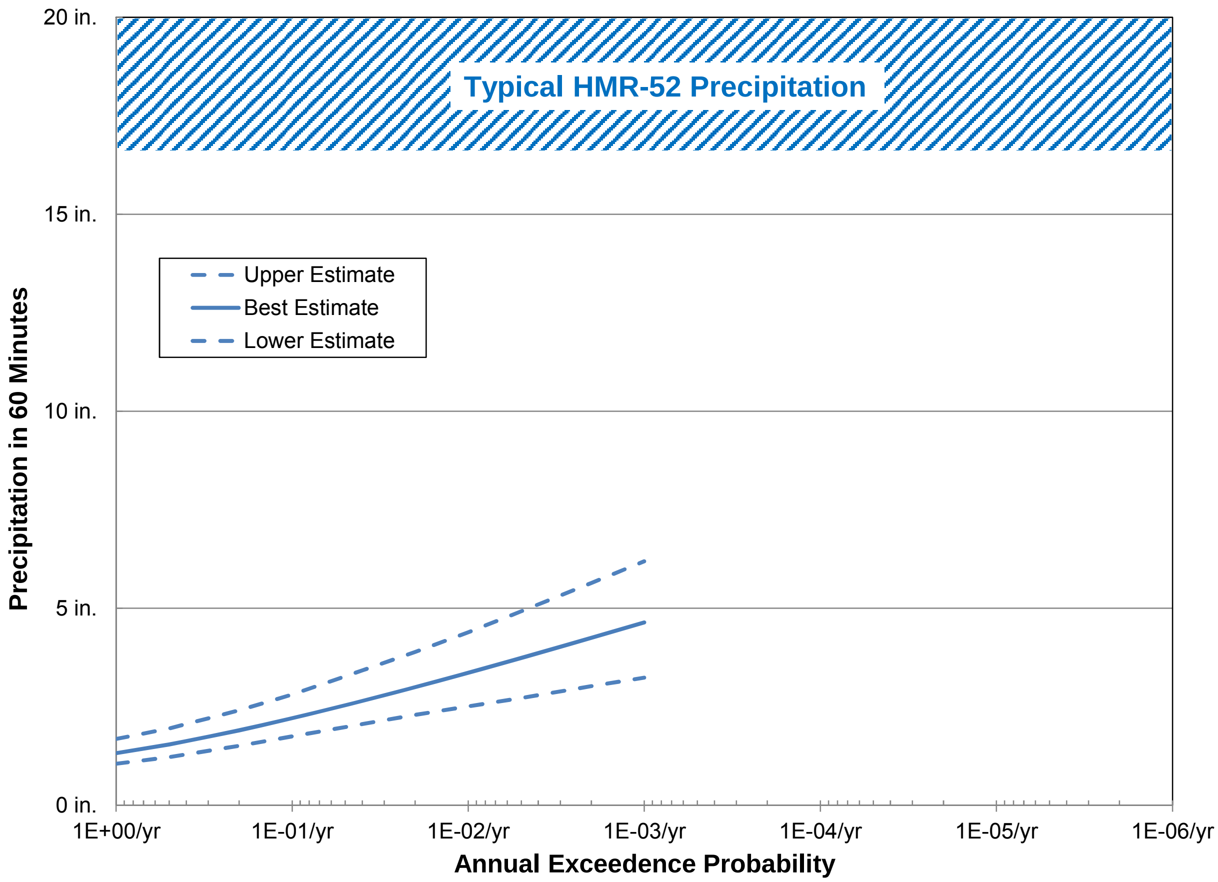

Figure 3-3
Example Atlas 14 location-specific LIP frequency estimate

Further investigation of the Atlas 14 raw data [14] demonstrates the magnitude of data that is available. As shown in Figure 3-4, measurements from 1,993 weather stations are used in compiling these estimates. However, when considering data, it is also important to understand the number of station-years of data that is represented.

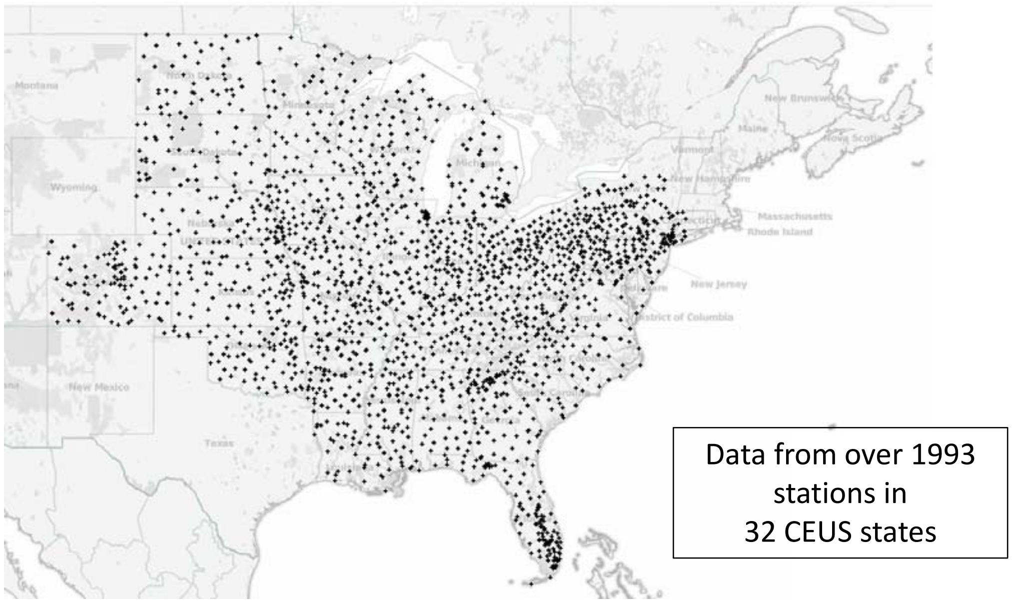

Figure 3-4
Weather stations supporting Atlas 14 estimates

Figure 3-5 denotes the number of station-years of data by state for a total of 86,000 station-years of data. This is equivalent to nearly three-quarters of a billion hourly precipitation measurements that relate to the 60-minute precipitation estimates.

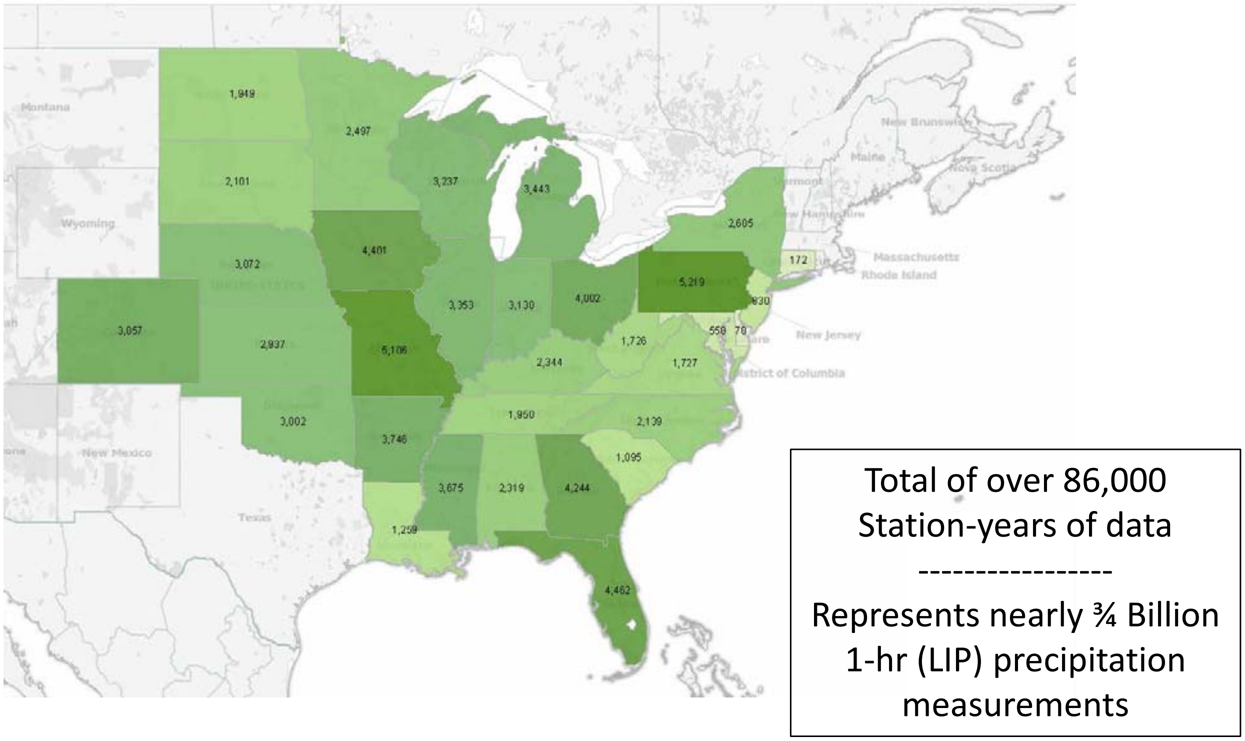

Figure 3-5
Total station-years of data included in Atlas 14 estimates

In evaluating the specific data readings, a summary was extracted from the Atlas 14 data on annual maximum 1-hr precipitation measurements. Within the Atlas 14 data, a total of 75 stations reported a precipitation measurement exceeding 4 in. in 1 hr with the maximum measured 1-hr precipitation being slightly more than 6 in. in Florida, as shown in Figure 3-6.

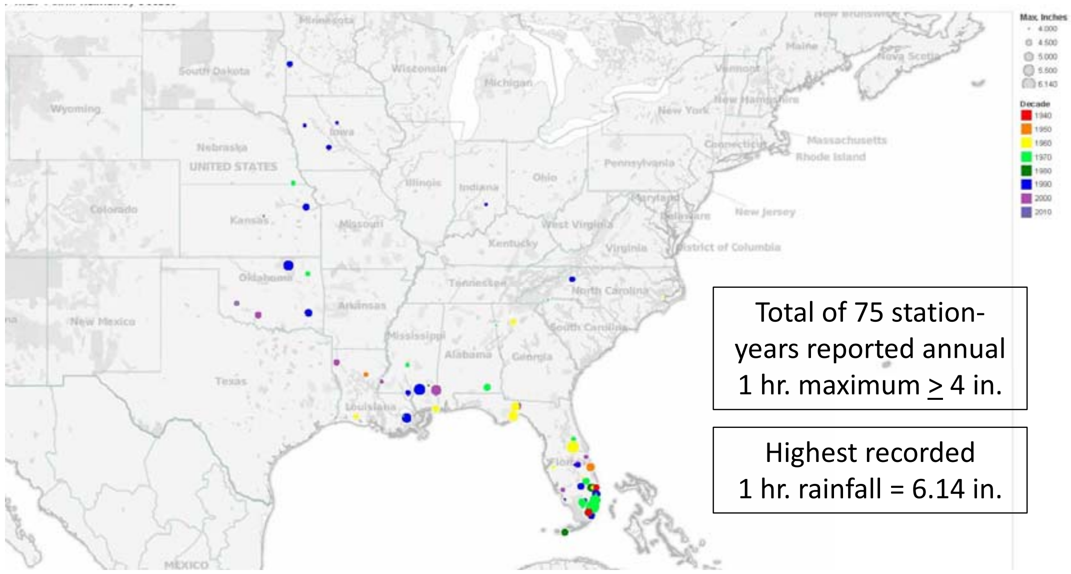

Figure 3-6
Reported annual maximum 1-hr rainfalls exceeding 4 in.

Thus, the raw NOAA Atlas 14 data do not identify any LIP measurements that approach the HMR 52 levels. This is not to say that a more extreme event than the ones measured has not occurred, but this fairly robust sample of data does indicate that precipitation events exceeding rainfall amounts of 7 in. are extremely rare.

In 2014, EPRI performed specific technical work that built from the Atlas 14 data to evaluate the relationship between 1-hr, 1-mi^2 (LIP) precipitation and frequency for two NPP sites: one coastal and one inland (midwest) site [15]. The results are shown in Figures 3-7 and 3-8. In both cases, the frequency of the HMR 52 LIP intensities are found to be much less than 1E-6/yr, even considering upper bound values. The results for the two sites are fairly similar, although the uncertainties are larger for the coastal site due to smaller number of measurements (there are no stations over the ocean).

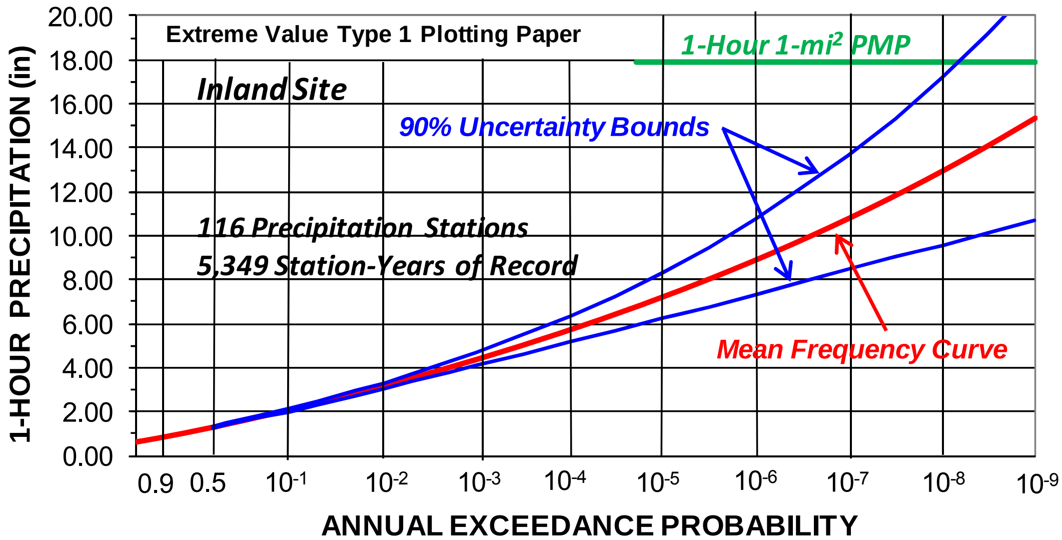

Figure 3-7
EPRI precipitation frequency estimates for inland site [15]

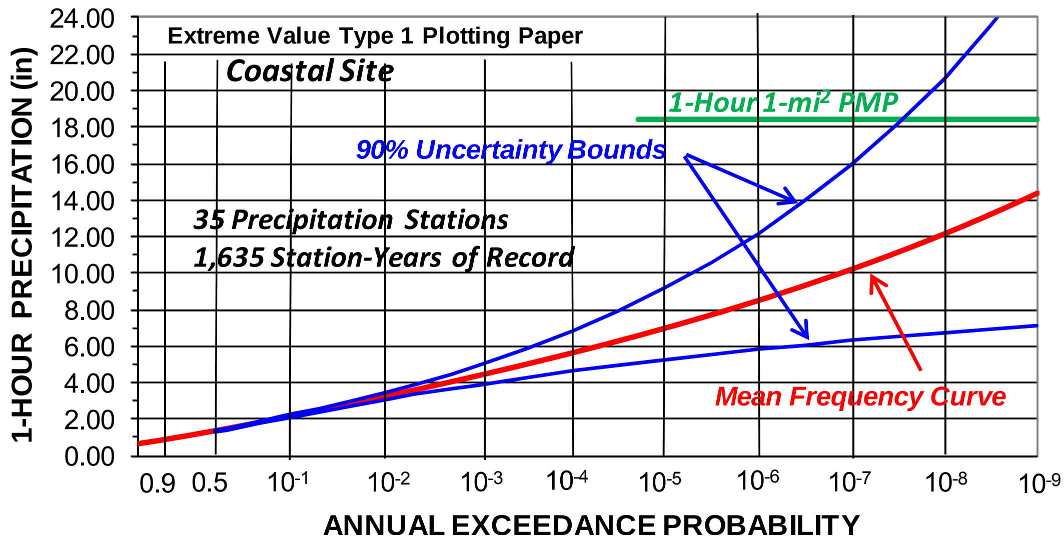

Figure 3-8
EPRI precipitation frequency estimates for coastal site [15]

The EPRI results indicate that for the representative sites investigated, the 1E-5/yr LIP event would have a mean estimate on the order of 7 in. with the $95^{th}/5^{th}$ percentiles ± 2 in. from that value (5 to 9 in., respectively).

As an independent means to assess these results, a crude estimate of extreme storm frequencies can be made from the data contained in HMR 52. As shown in Table 2-4, nine events were used in providing the 1-hr, 1-mi^2 LIP precipitation estimates. However, one of these events was in Canada, and another event used data for a 10 mi^2 area. A total of four of the remaining events involved precipitation estimates greater than 10 in. The area addressed by HMR 52 includes all of the states east of the 105^{th} meridian. The total land area of those states is roughly 1.9 million mi^2. The data in Table 2-4 include events that span a period of 38 years (1935–1973). So, as a first approximation, one could estimate the frequency of these extreme events to be:

$$F(>10 \text{ in. precipitation}) = 4 \text{ events}*1 \text{ mi}^2/(1.9 \text{ E6 mi}^2 * 38 \text{ years}) = 5.5\text{E-8/year}$$

The EPRI estimates for the mean frequency of precipitation greater than 10 in. in 1 mi^2 were approximately 3E-7/yr and 1E-7/yr for the inland and coastal sites, respectively. Thus, the EPRI mean estimates exceed this relatively crude estimate. This may be expected because there is no way of knowing whether the HMR 52 data include all of the large precipitation events that occurred in the 38-year period. It is reasonable to expect that most of the events would be captured, but some could have been missed. Even if the HMR 52 data captured only 10% of the most extreme events (that is, those producing precipitation in excess of 10 in.), the estimate would only increase to 5.5E-7/yr, which is still comparable to the value from the LIP study. If it were to be assumed that the HMR 52 data captured only 1% of the extreme events, then the simple estimate would be on the order of 5E-6/yr, comparable to the 95% value for both sites in the LIP study.

The purpose of this simple example is not to assert that these four data points constitute a comprehensive data set, but simply to show that the estimates in the LIP study are not inconsistent with the HMR 52 data.

3.4 Riverine Flooding

The probabilistic precipitation models discussed above provide a key input into a probabilistic riverine flooding model since precipitation is the driver for riverine floods. Even in the deterministic assessments, the PMP estimates from HMR 51 are used to define the storms that drive riverine flood hazards.

The probabilistic characterization of riverine flooding starts with precipitation as the major input to the model. This input is characterized probabilistically using the same methods as described above, that is, those that entail combined regional data analysis. Additional modeling is, however, required to understand the nature of riverine flooding adequately. Spatial and temporal patterns of historical storms can be analyzed to develop a model that can be used stochastically to generate additional storms and determine their effects on the watershed. These additional storms effectively add to the data set and provide a better case for extrapolation into the portion of the hazard curve that accounts for extremely low-frequency events.

After the precipitation and storm frequency relationship is understood, this information can be used in a hydrologic model where key parameters are varied over a multitude of simulation runs. These simulations can then be used to characterize the river system probabilistically over the entire watershed, to produce an understanding of the response to regional rainfall events. In addition to the mean frequency of flooding for a particular site, the uncertainties associated with all the modeling assumptions, data gaps, and other factors can be quantified and represented.

An extensive effort is needed to perform a rigorous evaluation that is adequate to characterize the riverine flood hazard probabilistically. Furthermore, the effort associated with the analysis grows significantly with several key attributes that may need to be incorporated into the model, including the presence of downstream dams and the size and complexity of the watershed. Some very limited projects are underway at select NPPs, and stochastic techniques have been used for applications other than for NPPs.

In 2014, EPRI completed a proof-of-concept study that focused on computing a probabilistic flooding hazard analysis for a riverine site [16]. This evaluation was performed by two of the world's experts, who used their own separate methodologies to provide a robust proof of concept. The two methods resulted in quite similar results, considering the different methodologies and the uncertainties involved. Figure 3-9 provides the high-level PFHA results. The two methods used were referred to as the Stochastic Runoff Routing Monte Carlo method (RORB_MC) and the Stochastic Event Flood Model (SEFM).

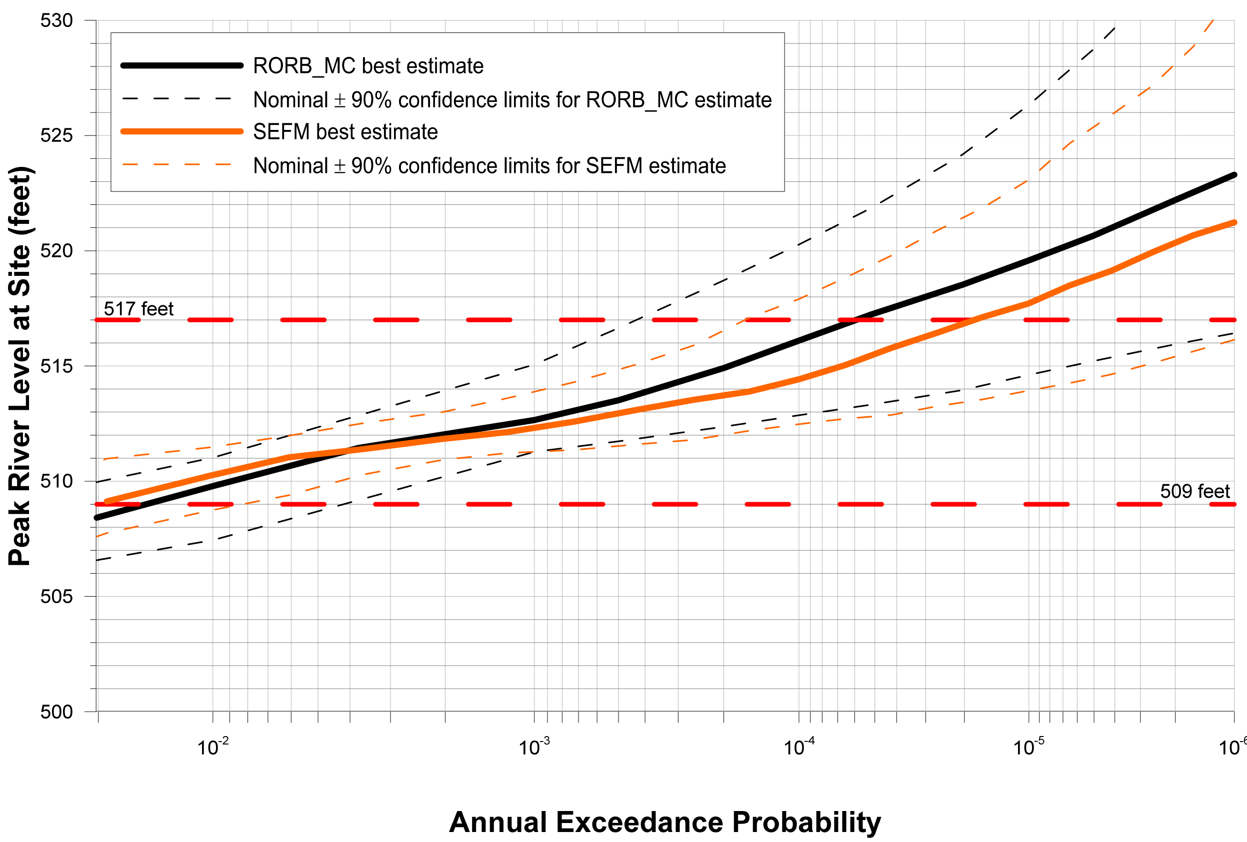

Figure 3-9
EPRI riverine PFHA proof-of-concept results [16]

Another useful insight from the EPRI work was the capability provided by these two methods to explicitly investigate the inputs contributing significantly to uncertainties. The EPRI report [16] identified the following as the two primary contributors to uncertainties in the results:

- Reliance on simplified hydrologic models
- Precipitation frequencies

Both of these would benefit from additional data and analysis and are candidates for development of consensus methods.

On a site-specific basis, it was found that the mean frequency of a flood level that exceeded the PMF level (525 ft) was estimated to be less than 1E-6/yr for this proof-of-concept study. However, due to the large uncertainties, the 95th percentile frequency was on the order of 1E-5/yr. Additional analysis and a focus on key uncertainties that would be part of a more comprehensive study could help to reduce those uncertainties.

Other studies of this type are being undertaken by U.S. utilities for various reasons. In at least one instance, probabilistic meteorological models are being used in combination with hydrologic models to assist a utility in defining the best river and dam management strategies.

One challenge in this area of riverine PFHA is that there are a very limited number of experts to support required plant-/hazard-specific evaluation.

The above examples provide insight into how the deterministic flood hazards align with recent PFHA work. However, some U.S. sites are challenged well before the most extreme PMF. These sites are generally in areas where widespread flooding either has previously occurred or is likely to occur. An example involves consideration of the Federal Emergency Management Agency (FEMA) flood maps that are provided for insurance purposes [17]. One U.S. plant is within the 100-year FEMA flood zone, and the river causing the flood would be approximately 7 miles wide at the site. Even with a design basis flood far larger than the 100-year FEMA flood, these conditions can present a real challenge to the nuclear power plant.

The 2011 flood that affected Ft. Calhoun was actually considered a controlled release. This is due to the fact that the U.S. Army Corps of Engineers intentionally released water from upstream dams in order to protect other societal considerations. The Ft. Calhoun station was known to be prepared for a far greater water level, so the decision was made to increase river flows and increase water levels around Ft. Calhoun and other locations downstream. The best estimates of the likelihood of such conditions are on the order of ~1E-2/yr. Therefore, the 2011 flood that challenged Ft. Calhoun was not an extremely rare flood. As was observed at the Ft. Calhoun station, riverine floods can present a sustained challenge to the plant over a long period of time.

3.5 Dam Failure

The possible failure of dams that create large reservoirs is another external flooding consideration at a number of U.S. plants. The generalized historical experience for U.S. dams supports the need for such considerations. A significant number of substantial dam failures have occurred in the United States, even within the last 20 years. As shown in the USBR data presented in Figure 3-2, the estimates of dam failure frequency can range from 1E-2/yr to 1E-7/yr, depending on the dam design, the watershed, and the dam risk management actions in place.

Stanford University maintains the National Performance of Dams Program (NPDP), which collects data on dam incidents and failures. Various other entities also compile information and use the NPDP data. An example is the Association of State Dam Safety Officials that compiled the data shown in Figure 3-10 [18] for modern dam failures.

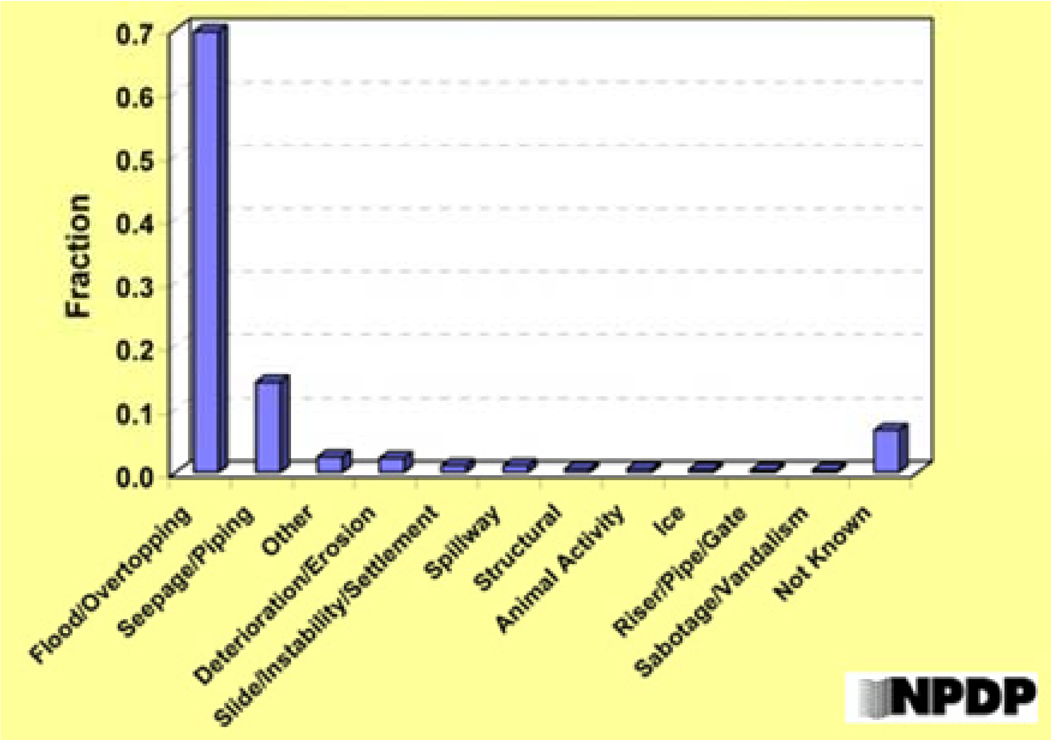

Figure 3-10
Causes of dam failures 1975–2001 [18]

This figure indicates that the largest contributor to dam failure is flooding and overtopping, followed by seepage/piping and unknown causes. However, as shown in the USBR data, the likelihood of dam failure is highly dam specific. Thus, it is difficult to draw conclusions from this high-level data that can be applied to a specific dam.

The USBR and FERC have both developed best practices and tools to assist in evaluating the risks of failure of a specific dam [12, 19]. Such tools are the only real means to understand the failure susceptibility and likelihood for any specific dam. Riverine PFHA modeling, like that described above, can be one important input in assessing the likelihood of different dam challenges and conditions, but the focus cannot be only on flooding/overtopping. Further, the importance of dam monitoring and risk management actions must be considered in order to understand the true site-specific risks.

Members of the NRC staff recently prepared two papers focused on dam failure rates and uncertainties [20, 21]. In both papers, the NRC staff asserts that the generic failure frequency for large dams is on the order of 1E-4/yr. Figure 3-11 provides the summary dam failure frequency and uncertainty results from Reference 21.

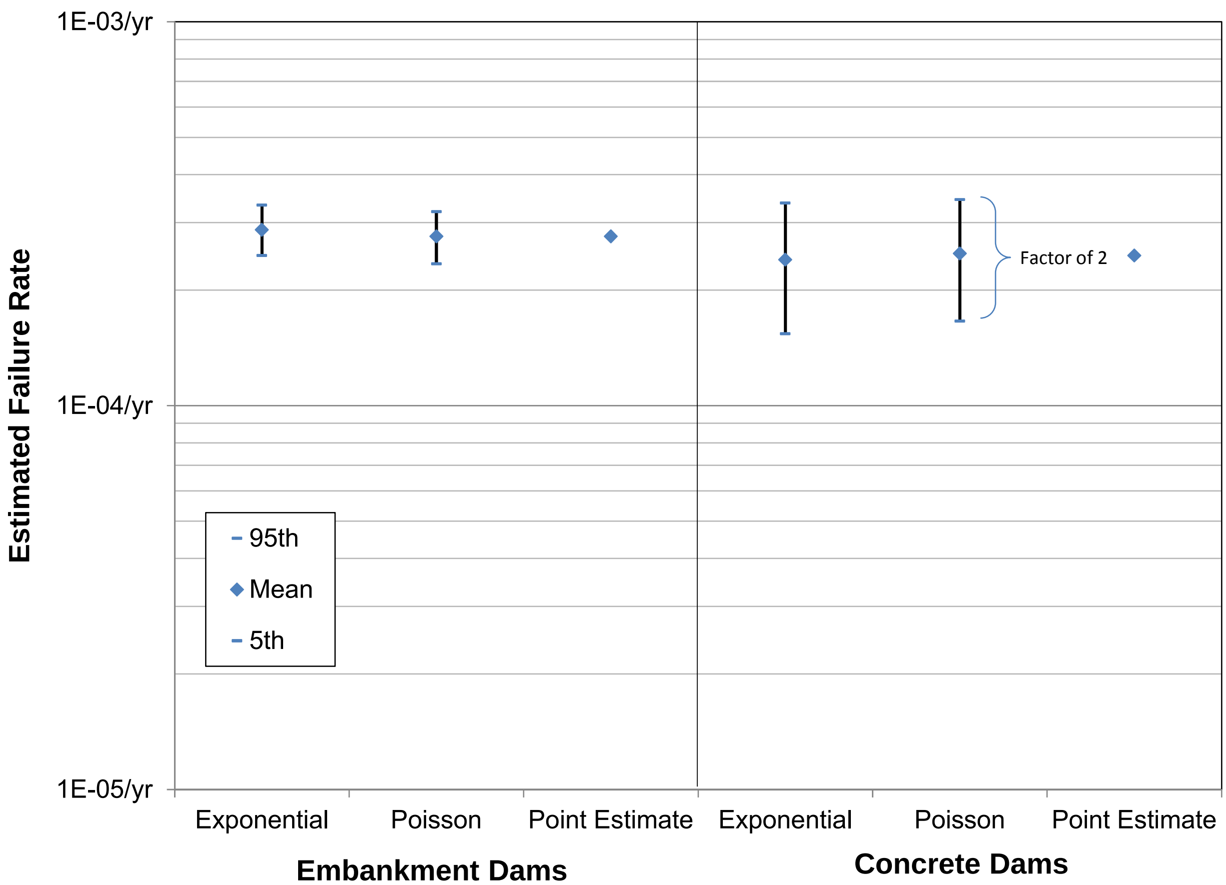

Figure 3-11
NRC staff dam failure uncertainty estimates

These estimates do not explicitly take into account the dam-to-dam variability for dam failure rates. As the USBR data in Figure 3-2 show, dam failure rates are very dam specific. While the overall "average" failure rate might be on the order of 1E-4/yr as computed by the NRC staff, the failure rate of any specific dam may be two orders of magnitude higher or lower, depending on dam-specific factors. In contrast, the NRC staff's estimates have a maximum range factor of approximately 2. Consequently, lumped statistics such as those posed by the NRC staff may be of limited use for a particular situation. A more useful understanding of the failure rate for a specific dam requires an evaluation for that specific dam.

There are two other aspects of the NRC staff's evaluations that make the use of the estimates a challenge. First, the dam "failures" included in the NPDP and other data sources are not all necessarily representative of the same severity of failure. The NPDP definition of failure is "breach and uncontrolled release of the reservoir" [22]. However, dam failure experience shows that not all breaches are catastrophic, nor is the release of the reservoir necessarily spontaneous. Care must be taken in equating a broad definition of "failure" with any specific consequence. In fact, detailed dam risk assessments identify a spectrum of failure scenarios with a corresponding range of failure characteristics [13].

This leads to a second issue: potential use of these dam failure frequencies as representative of the frequency of an assumed deterministic dam failure model used for design basis evaluations. The dam failure characteristics used in the deterministic analyses are intentionally biased to ensure margin. For example, conservative breach characteristics are selected for the analysis, and the initial reservoir water levels are assumed to be conservatively high. Such assumptions may or may not apply individually to a specific dam failure and there is no way to know which breach characteristics would apply unless a detailed dam risk assessment is performed.

3.6 Storm Surge

The JPM described in NUREG/CR-7134 appears to provide a reasonable foundation for a storm surge PFHA. The approach couples a probabilistic model of the storm conditions with the hydrodynamic model of the surge. There are two main extensions that would be necessary to address a full PFHA:

- Rather than simply adding margin for model uncertainties and sea levels separate from the probabilistic model, those aspects should be built into the probabilistic model.
- A more explicit treatment of uncertainties would support better decision making.

The work that has been done with the JPM method has yielded interesting insights:

- Storm surge risk may not be controlled by the largest storms (that is, Category 5 hurricanes). Depending on the location, the very large, extreme hurricanes may be very low in frequency. Further, although these storms are most severe in some respects, they can often be fast moving and may not cause a proportionally large surge.

More commonly, the moderate, but slower moving, hurricanes will control the probable maximum storm surge. This is because their likelihood is higher, and their durations can cause a larger surge buildup ahead of the storm.

4

INSIGHTS AND RECOMMENDATIONS

4.1 Context for Decision Making

One important consideration in evaluating flood hazard approaches is the context for decision making. The decision-making focus for an operating plant may be different from that for a new plant.

For operating plants, the need is to ensure that the applicable safety goals are not challenged by the external flood hazard. This means that the focus should be on floods with frequencies on the order of 1E-4/yr to 1E-5/yr. There may be no need to estimate the frequency for the entire spectrum of possible flood conditions unless a full flooding PRA is to be undertaken in accordance with the PRA standard. This focus on the relatively more likely flood hazards can limit the need to pursue floods with extremely low likelihoods, for example, <1E-6/yr, where the uncertainties can complicate decision making. However, as with all probabilistic approaches to safety, an understanding of the uncertainties is an essential element of the decision-making process, regardless of the frequency range of interest.

Also of importance for current operating plants is that not all flood design bases are equivalent. Important safety features for some plants can be challenged by relatively likely floods. Although the design basis flood heights may be much higher, this does not mean that the external flooding risk for these plants is necessarily very small. For example, "wet" sites (that is, sites where design basis flood levels exceed plant grade, and particularly sites that can be inundated for long periods of time) may have vulnerabilities at levels well below the extreme design basis flood heights that are calculated from the application of present day methods.

If PFHA techniques are to be used for siting new plants, there may be more emphasis on defining and characterizing the more extreme conditions. This is a consequence of policies that push new plants to have higher levels of safety than the current fleet. The result will be that very low frequency (that is, 1E-6/yr to 1E-7/yr) floods will likely merit consideration. With these low frequencies will come very large, possibly even unquantifiable, uncertainties that will be a challenge to characterize and a challenge for decision makers to address.

4.2 Understanding the Hazard Spectrum

With respect to decision making, there are a variety of situations to be considered.

For sites where the bounding PMF calculated by using present day techniques does not cause a challenge to the plant, the deterministic, bounding methods can be cost-effective tools in ensuring that the plant is safe from external flooding. For the plants that are not challenged by the present day design basis requirements, there is no significant evidence that external flooding would pose a significant contribution to plant risk.

For sites where the flood hazard can challenge the plant's SSCs that are important to plant safety at levels well below the ultimate PMF, there is greater value in understanding the spectrum of potential conditions and challenges presented by different flood events. Examples of such situations are "wet" sites, where floods are expected to affect the plant site, for example, restrict access to the site and structures, impact SSCs important to safety, etc., at severities below the maximum computed PMF. Furthermore, focusing on only the most extreme of flood conditions may lead to missing key insights on flooding susceptibilities. For example, some plants have found that relatively low LIP levels are sufficient to allow water into structures containing safety-related SSCs. A focus strictly on the unlikely extreme LIP event could lead to a lack of appreciation for the hazard posed by more likely—but less severe—LIP conditions.

4.3 Operating Experience

The industry has accumulated operating experience that indicates that flooding hazards merit careful considerations. There have been a number of NRC inspection findings related to flood susceptibilities, and some actual precipitation and flood events have uncovered unanticipated flood weaknesses.

As discussed in Section 3, some "wet" sites may be challenged at levels that are somewhat likely to be experienced, and these sites merit an evaluation of the spectrum of challenges that may impact the plant. That is, the risk does not start at the maximum flood levels, but rather it begins when the site is first impacted by the flood condition. It is particularly important that these "wet" sites, where flood seals provide protection of SSCs inside structures, consider a full spectrum of floods because the challenge to the plant may initiate long before the flood severity reaches the design basis characteristics. EPRI has initiated a project to develop maintenance recommendations associated with flood seals. These recommendations will be published in a flood protection systems guide.

4.4 The Role of PFHA

The ability of PFHA techniques to be applied is a function of the hazards involved and the decisions to be made. The following observations are made with respect to the specific hazards considered in this report.

4.4.1 Precipitation

- There appears to be ample evidence that HMR 51 and 52 estimates for precipitation and the present day methods used to evaluate precipitation-driven hazards yield conditions that are extremely rare. This is consistent with the intent that use of these methods results in margin to provide additional confidence in the safety of facilities. However, a reevaluation of external flood hazards at a site that shows a plant does not meet the present day design basis requirements does not necessarily mean that a significant safety issue exists for that site.
- As demonstrated in EPRI 3002003013 and 3002004400, the work that NOAA has done to assess precipitation frequencies can be extended to more rare conditions through readily available techniques for both LIP and riverine flooding.
- Consensus methods are needed on the statistical treatment of meteorological inputs, that is, extreme storm characteristics vs frequency.

4.4.2 Dam Failures

- The USBR and FERC have methods that appear to be useable for dam-specific risk assessments. These methods support estimation in the frequency ranges of interest to nuclear power plants and will be important tools to support decision making on dam-related flood hazards. It should be noted that a challenge can arise in applying these methods when detailed information on the design and operation of the dam is not available to the utility.
- Generic dam failure frequency estimates should not be employed in conjunction with the limiting dam failure characterization used in the flood reevaluations. These average failure rates do not address the dam-to-dam variability found in more detailed, dam-specific, risk assessments.
- More work is needed to establish consensus methods for the correlation of dam failure frequencies with dam failure mechanisms and corresponding water release characteristics. Without appropriate consideration of these correlations, there is a risk that bounding failure characterizations would be coupled with generalized failure frequencies, leading to misleading conclusions.
- As shown in the USBR work, risk management actions can directly affect the likelihood of dam failure. This can include dam monitoring systems, water management actions, and retrofits.
- Great care must be taken in using bounding or generic dam failure frequencies with bounding failure characterizations in a PRA. A recent parallel to this situation comes from use of the fire PRA methods provided in NUREG/CR-6850 [23] where bounding assumptions can mask risk insights that would be apparent if more realistic assumptions were used.
- Dam failures and associated failure rates are dam specific. Consensus approaches are needed to direct the appropriate combination of failure frequency with failure characterization.

4.4.3 Storm Surge

- The JPM methods described in NUREG/CR-7134 appear to provide useful tools to support PFHA development.
- Some consensus is needed on the manner in which to treat specific uncertainties within a fully probabilistic approach, rather than the current approach of adding margin after the baseline analysis is completed.

4.5 Research Needs

Based on this evaluation, the following recommendations are made regarding near-term research needs for precipitation and dam failure flood hazards. Storm surge methods appear sufficient for the near term.

4.5.1 Precipitation

- Development of consensus methods for characterizing the frequency of extreme precipitation events. These could be statistical methods or could involve an expert elicitation, but the expert elicitation should be on fundamental inputs and models, not site or regional characteristics. It is not feasible to require an expert elicitation for each hazard at each site.
- Further work to evaluate approaches to reduce uncertainties for floods in the key decision-making regime.

4.5.2 Characterization of Dam Failures

- Investigation of dam failure experience to better characterize the following:
  - Dam age at failure
  - Dam operational, maintenance, and monitoring characteristics
  - Cause of failure
  - Operator responses to limit the potential for dam failure or to manage the consequences following failure
  - Water release characteristics for the observed failure
  - Potential for consequential failures of downstream dams
- Development and application of simulation methods as a means to define dam failure characteristics based on dam features and characteristics
- Development of a basis for the use of existing methods for estimating the frequency of dam failure and the associated failure characteristics and uncertainties

4.6 Readily Available PFHA Tools

The previous sections lay out the important role that PFHA should play in decision making and also highlight the challenges, limitations, and future research needs for the various methods. This section identifies some of the PFHA tools that are readily available and that could be employed to better inform decision making as new flood information becomes available. It should be noted that each hazard has its own challenges that are associated with the tools available to estimate the frequency of severe flooding.

4.6.1 Local Intense Precipitation

Section 3 described an earlier report by EPRI that explored how LIP can be characterized probabilistically [15]. Data from Atlas 14 were used to perform a regional analysis for a more robust and complete picture of precipitation frequency. The use of the method described in that report produced a hazard curve that can extend into the extreme frequency regime. While the extrapolations can extend to frequencies much less than 1E-6/yr, the uncertainties at these low frequencies are very large. For some plants, however, the focus for decision making could be on risk contributions at higher frequencies (for example, greater than 1E-5/yr), which may be within what the USBR considers to be a credible extrapolation limit. The data from Atlas 14 are readily available, and most sites will have a very large quantity of station records within the analyzed region. Precipitation frequency analysis using regional data is a readily available tool that is appropriate to use in estimating the frequency of the 1-hr, 1-mi^2 (LIP) precipitation for the risk-significant range of frequencies.

4.6.2 Riverine Flooding

An alternative to a full PFHA would be to perform the regional precipitation and storm analysis, and use that as the input to a simplified, conservative hydrologic model. The various storms can be modeled and validated using a river system model to determine a stage-frequency relationship. Without all the variables being exercised, extrapolation of the hazard curve into the extreme event range is not appropriate, and the uncertainties would be large. However, for some plants, the storms that could be important to risk may have frequencies well above this extremely low range. These more frequent storms are amenable to more meaningful probabilistic evaluation that can be useful for decision making.

4.6.3 Storm Surge

Storm surge for coastal plants is most often controlled by hurricane and tropical storm patterns. The methods to develop a probabilistic framework for these weather patterns are more mature than for precipitation and riverine flooding. The JPM appears to serve as a reasonable foundation for developing a hazard curve and characterizing flooding events in the range that is important to safety. Section 3 identifies some of the limitations with the available methods and discusses some aspects that might require additional research; however, it seems that this approach could provide useful insights, even for flooding events that occur less frequently than1E-5/yr.

4.6.4 Conclusions Regarding PFHA Tools

Although the methods to complete a full PFHA have not been fully exercised in nuclear risk applications, there are a variety of methods to estimate the likelihood of flooding events. These methods necessarily produce results that include large uncertainties at very low frequencies, but are much less uncertain for the more frequent flooding hazards. These more frequent events may be the risk drivers for plants, and assessing these risks can lead to mitigation or prevention schemes that enhance safety at NPPs. Thus, there are technically sound methods that can help to characterize these floods within the risk-significant range of frequencies.

5
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Electric Power Research Institute
3420 Hillview Avenue, Palo Alto, California 94304-1338 • PO Box 10412, Palo Alto, California 94303-0813 • USA
800.313.3774 • 650.855.2121 • askepri@epri.com • www.epri.com