U.S. NUCLEAR REGULATORY COMMISSION

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Revision 1

Proposed Revision 3 to Regulatory Guide 1.59

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DESIGN-BASIS FLOODS FOR NUCLEAR POWER PLANTS

A. INTRODUCTION

Purpose

This regulatory guide (RG) describes methods that the staff of the U.S. Nuclear Regulatory Commission (NRC) considers acceptable for use in the determination of design-basis floods for nuclear power plants (NPPs).

Applicability

This guidance applies to reactor applicants subject to Title 10 of the *Code of Federal Regulations* (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities" (Ref. 1); 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants" (Ref. 2); and 10 CFR Part 100, "Reactor Site Criteria" (Ref. 3). Though the guidance primarily reflects lessons learned from past reviews of large light-water NPP applications as well as additional lessons learned from staff reviews of operating NPP licensee's post-Fukushima flooding hazard reevaluations, this RG may also provide useful information for other types of power reactors (i.e., advanced reactors[1] and small modular reactors).

Applicable Regulations

- 10 CFR 50.34, "Contents of applications; technical information," states the requirements for the content of applications submitted under 10 CFR Part 50. Under its provisions, an application for a construction permit must include the principal design criteria for the proposed facility. Under the provisions of 10 CFR 52.47, 10 CFR 52.79, 10 CFR 52.137, and 10 CFR 52.157, an application for a design certification, combined license, design approval, or manufacturing license, respectively, must include the principal design criteria for the proposed facility. The principal design criteria establish the necessary design, fabrication, construction, testing, and performance requirements for structures, systems, and components (SSCs) that are important to safety—that is, SSCs that provide reasonable assurance that the facility can be operated without undue risk to public health and safety.

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[1] As used in this RG, the term "advanced reactor" includes but is not limited to non-light-water-reactors and microreactors.

This RG is being issued in draft form to involve the public in the development of regulatory guidance in this area. It has not received final staff review or approval and does not represent an NRC final staff position. Public comments are being solicited on this DG and its associated regulatory analysis. Comments should be accompanied by appropriate supporting data. Comments may be submitted through the Federal rulemaking Web site, http://www.regulations.gov, by searching for draft regulatory guide DG-1290. Alternatively, comments may be submitted to the Office of Administration, Mailstop: TWFN 7A-06M, U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, ATTN: Program Management, Announcements and Editing Staff. Comments must be submitted by the date indicated in the *Federal Register* notice.

Electronic copies of this DG, previous versions of DGs, and other recently issued guides are available through the NRC's public Web site under the Regulatory Guides document collection of the NRC Library at https://nrc.gov/reading-rm/doc-collections/reg-guides/index.html. The DG is also available through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html, under Accession No. ML23320A025. The regulatory analysis may be found in ADAMS under Accession No. ML12121A020. The response to public comments can be found under ADAMS Accession No. ML23320A026.

- 10 CFR Part 50, Appendix A, "General Design Criteria for Nuclear Power Plants," establishes minimum requirements for the principal design criteria for water-cooled NPPs.

    - General Design Criterion (GDC) 2, "Design bases for protection against natural phenomena," requires that SSCs important to safety be designed to withstand the effects of natural phenomena such as earthquakes, tornadoes, hurricanes, floods, tsunamis, and seiches without loss of capability to perform their safety functions. GDC 2 further requires that the design bases for these SSCs reflect (1) appropriate consideration of 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, (2) appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (3) the importance of the safety functions that the SSCs will perform.

- 10 CFR Part 100 establishes approval requirements for proposed sites for stationary power and testing reactors subject to 10 CFR Part 50 or 10 CFR Part 52.

    - 10 CFR 100.20, "Factors to be considered when evaluating sites," requires that physical characteristics of the site, including seismology, meteorology, geology, and hydrology, be considered when determining the suitability of a site for a nuclear power reactor.

    - 10 CFR 100.23, "Geologic and seismic siting criteria," requires that the potential for seismically induced floods and water waves be considered and incorporated into the design bases for NPPs.

- 10 CFR Part 52 governs the issuance of early site permits and combined licenses and contains application requirements to address the requirements in 10 CFR Part 50 and 10 CFR Part 100 mentioned above.

Related Guidance

- RG 1.29, "Seismic Design Classification for Nuclear Power Plants" (Ref. 4), identifies the SSCs that should be designed to withstand the effects of the design-basis flood and should remain functional.

- RG 1.102, "Flood Protection for Nuclear Power Plants" (Ref. 5), describes the types of flood protection that the NRC staff finds acceptable for the SSCs important to safety identified in RG 1.29. RG 1.102 does not address methods for estimating the flood hazard; RG 1.59 addresses these methods.

- RG 4.7, "General Site Suitability Criteria for Nuclear Power Stations" (Ref. 6), assists applicants in the initial stage of selecting potential sites for a nuclear power station. The safety issues discussed include geologic/seismic, hydrologic, and meteorological characteristics of proposed sites as they relate to protecting the public from the potential hazards of serious accidents. However, RG 4.7 does not discuss the details of the engineering analysis needed to support design-basis flood estimation or other information needed to prepare the safety analysis reports.

- RG 1.70, “Standard Format and Content of Safety Analysis Reports for Nuclear Power Plants (LWR Edition)” (Ref. 7), and RG 1.206,[2] “Combined License Applications for Nuclear Power Plants (LWR Edition),” (Ref. 8), provide general guidance on the types of information on the hydrologic setting and assessments of flood hazards that a license application for a light-water reactor power plant should include. This guide provides more specific information about analytical approaches, sources of site characterization data, and analytical methods for design-basis flood estimation that the NRC staff finds acceptable.

- Draft regulatory guide (DG)-1417 “Guidance for Assessment of Flooding Hazards Due to Water Control Structure Failures and Incidents,” (Proposed RG 1.256, issued in conjunction with DG-1290 [Ref. 9]), provides guidance to the staff for evaluating flood hazards due to failures and incidents at dams and other water control structures. DG-1417 is based on JLD-ISG-2013-01, “Guidance for Assessment of Flooding Hazards Due to Dam Failure,” dated July 29, 2013 (Ref. 10) which provided interim guidance to the staff for reevaluating flood hazards due to dam failure as described in the NRC’s “Request for Information Pursuant to Title 10 of the *Code of Federal Regulations* 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3, of the Near-Term Force Review of Insights from the Fukushima Dai-ichi Accident,” dated March 12, 2012 (Ref. 11). The NRC issued this request for information pursuant to 10 CFR 50.54, “Conditions of licenses,” regarding Recommendation 2.1 of the enclosure to SECY-11-0093, “Recommendations for Enhancing Reactor Safety in the 21st Century: The Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident,” dated July 12, 2011 (Ref. 12).

- NUREG-0800, “Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition” (Ref. 13), provides guidance to the NRC staff in performing safety reviews under 10 CFR Part 50 and 10 CFR Part 52. Chapter 2, “Site Characteristics and Site Parameters,” contains general review guidance related to site characteristics and site parameters, together with site-related design parameters and design characteristics, as applicable.

- Interim Staff Guidance (ISG) DNRL-ISG-2022-01, “Safety Review of Light-Water-Reactor Construction Permit Applications” (Ref. 14), issued October 2022, provides interim guidance to facilitate the safety review of light-water power reactor construction permit applications. Appendix A of this ISG provides clarification to existing review guidance in NUREG-0800, including siting.

- Interim Staff Guidance DANU-ISG-2022-02, “Advanced Reactor Content of Application Project Chapter 2 - Site Information” (Ref. 15), issued May 2023, provides guidance on the contents of a risk-informed, performance-based, nonlight-water reactor (non-LWR) application for a construction permit or operating license under Title 10 of the Code of Federal Regulations (10 CFR) Part 50, “Domestic Licensing of Production and Utilization Facilities”, or for a combined license, manufacturing license, standard design approval, or a design certification under 10 CFR Part 52, “Licenses, Certifications, and Approvals for Nuclear Power Plants”. The application guidance found in this ISG supports the development of the portion of non-LWR application associated with an applicant’s “Site Information,” and provides guidance to NRC staff on how to review such an application.

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[2] A more recent revision of RG 1.206 (Revision 1) issued October 2018 and now entitled “Applications for Nuclear Power Plants,” does not include detailed technical guidance on the content of a combined license final safety analysis report and is therefore not referenced.

Purpose of Regulatory Guides

The NRC issues RGs to describe methods that are acceptable to the staff for implementing specific parts of the agency's regulations, to explain techniques that the staff uses in evaluating specific problems or postulated events, and to describe information that the staff needs in its review of applications for permits and licenses. Regulatory guides are not substitutes for regulations and compliance with them is not required. Methods and solutions that differ from those set forth in RGs are acceptable if supported by a basis for the issuance or continuance of a permit or license by the Commission.

Paperwork Reduction Act

This RG provides voluntary guidance for implementing the mandatory information collections in 10 CFR Parts 50, 52, and 100 that are subject to the Paperwork Reduction Act of 1995 (44 U.S.C. 3501 et. seq.). These information collections were approved by the Office of Management and Budget (OMB), under control number 3150-0011, 3150-0151, and 3150-0093, respectively. Send comments regarding this information collection to the FOIA, Library, and Information Collections Branch (T6-A10M), U.S. Nuclear Regulatory Commission, Washington, DC 20555-0001, or by email to Infocollects.Resoource@nrc.gov, and to the OMB reviewer at: OMB Office of Information and Regulatory Affairs (3150-0011, 3150-0151, and 3150-0093), Attn: Desk Officer for the Nuclear Regulatory Commission, 725 17th Street, NW, Washington, DC, 20503.

Public Protection Notification

The NRC may not conduct or sponsor, and a person is not required to respond to, a collection of information unless the document requesting or requiring the collection displays a currently valid OMB control number.

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B. DISCUSSION

Reason for Revision

This revision of the RG (Revision 3) reflects lessons learned from the review of large light-water NPP applications under 10 CFR Part 52 since the issuance of RG 1.59, Revision 2, in August 1977 (Ref. 16), as well as additional lessons learned from staff reviews of licensees' responses to the NRC's "Request for Information Pursuant to Title 10 of the *Code of Federal Regulations* 50.54(f) Regarding Recommendations 2.1, 2.3, and 9.3, of the Near-Term Task Force Review of Insights from the Fukushima Dai-ichi Accident". The body of this RG applies to large light-water reactors. In view of the emerging innovations taking place in nuclear engineering science Appendix K is presented as an alternative approach for advanced reactors, which may be used in conjunction with the guidance in RG 1.247, "Acceptability of Probabilistic Risk Assessment Results for Non-Light-Water Reactor Risk-Informed Activities" (Ref. 17). (The glossary at the end of this RG defines "advanced reactors" and certain other concepts appearing in this document.)

Background

The evaluation of external flood hazards has improved significantly since the issuance of Revision 2 of this RG. Foremost among these improvements is in computational resources, supported by multiple types of geophysical data used in computer-based analyses. Analytical methods and computational resources for estimating the magnitude and extent of external flooding have also improved significantly since 1977. Databases on physical processes affecting floods have expanded and significantly supplement the information available before 1977, extending the length of meteorological records and flood histories available for use. This has enhanced the ability to assess the external flood potential at NPP sites.

Another reason for the revision relates to the flood hazard reevaluations performed in response to the 2011 accident at the Fukushima Dai-ichi NPP in Japan. The flood hazard reevaluations were to be performed using the methods then current (in 2012), as well as the regulatory guidance used by the NRC staff when reviewing external flooding analyses in early site permit and combined license applications under 10 CFR Part 52. The NRC prepared and issued interim staff guidance documents (ISGs) to clarify or address review issues not fully discussed in NUREG-0800. However, the ISGs were intended only for use in connection with the NRC's 2012 information request under 10 CFR 50.54(f), which was sent to all NPP licensees in response to the event at Fukushima. The ISGs were not intended to supersede existing NRC guidance used by the staff when reviewing new 10 CFR Part 52 applications such as early site permit or combined license applications, or amendments to existing licenses issued under 10 CFR Part 50. To integrate the ISG material more formally into the NRC's regulatory guidance framework, the staff, when updating this RG, incorporated material from JLD-ISG-2012-06, "Guidance for Performing a Tsunami, Surge, or Seiche Hazard Assessment," dated January 4, 2013 (Ref. 18), into appendices E and G to the RG. These two appendices address the evaluation of storm surge and tsunamis, respectively. RG 1.59, Revision 2, treated these two flood-causing mechanisms (along with seiches) in a single appendix. As well as providing separate treatment of storm surge and tsunamis, the revised appendices E and G discuss how hydrodynamic models developed since 1977, which are based on numerical methods and implemented on digital computers, can be used to estimate both storm surge and tsunami hazards at reactor sites. Similarly, JLD-ISG-2013-01, "Guidance for Assessment of Flooding Hazards Due to Dam Failure," dated July 29, 2013, was developed to support review of dam failure induced flooding hazard submittals. The issuance of RG 1.59, Revision 3 and RG 1.256, Revision 0, coincides with the closing of JLD-ISG-2012-06 and JLD-ISG-2013-01, respectively.

Regulations under 10 CFR Parts 50, 52, and 100 require that an application for an NPP identify the most severe flood conditions that can reasonably be predicted to occur at a candidate location because of severe hydrometeorological conditions, seismic activity, or accidents such as non-seismic, non-hydrologic dam failure. These regulations further require that the most severe flood conditions at the site not compromise the ability of the power plant's SSCs to protect against natural phenomena, including external flooding effects, or to perform their credited safety functions. This guide provides an overview of technical approaches, analysis methods, and authoritative data sources that the NRC staff finds acceptable for determining the design-basis flood. The guide discusses floods resulting from natural hydrometeorological, geologic, and seismic phenomena and those resulting from accidental events such as dam failure (floods due to dam failure are covered in more detail by RG 1.256). It also discusses flood hazards resulting from combined events and the treatment of associated flooding effects in flood hazard estimates. This RG does not address flooding due to the intrusion of ground water or channel migration.

Analysis Approaches

Traditionally, design-basis flood estimates for NPPs have been developed using deterministic analyses based on the concept of the "probable maximum" or "maximum credible" event (i.e., the hydraulic event thought to have "virtually no risk of exceedance"). The level of analysis may range from a conservative evaluation based on simplifying assumptions and risk insights, to an evaluation that relies on detailed analytical estimates of each facet of the flood-causing mechanism under consideration. Typically, applicants use progressive screening, which consists of a series of analyses that use increasingly detailed site-specific data, analysis methods, or both. The purpose of the screening approach is to demonstrate whether the plant SSCs important to safety are subject to external flooding, and if so, whether they are adequately protected from the adverse effects of those severe floods consistent with regulatory requirements under 10 CFR Parts 50, 52, and 100. To that end, the 1975 edition of the "Standard Review Plan for the Review of Safety Analysis Reports for Nuclear Power Plants: LWR Edition" (designated at the time as NUREG-75/087 (Ref. 19)) described a hierarchical risk-informed review philosophy that addressed how to differentiate between flood-causing mechanisms important and not important to design decision-making. Later, NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011 (Ref. 20), presented examples of how to implement this hierarchical hazard assessment (HHA) approach.

To effectively implement risk-informed reviews, the Commission also encouraged the use of probabilistic methods as a complement to traditional deterministic approaches in its final policy statement entitled "Use of Probabilistic Risk Assessment Methods in Nuclear Regulatory Activities," dated August 16, 1995 (Ref. 21). In the context of external flood hazard evaluations, probabilistic flood hazard assessment (PFHA) involves using analytical methods to estimate a range of floods and their probabilities, rather than focusing on some single probable maximum flood (PMF) that is construed to represent a physical upper limit. A few hydraulic engineering applications use this approach (e.g., the design of some small dams); however, the estimation of probabilities of extreme floods is widely recognized as challenging and subject to certain limitations. Consequently, no widely accepted framework or toolset is currently available for the probabilistic assessment of all potential flood hazards at a site, nor are there any standards available that are acceptable to the NRC staff for the review of this type of analysis.

This RG does not provide specific guidance on probabilistic methods for developing quantitative estimates of flood hazards; however, this should not be construed as prohibiting or discouraging their use. The staff expects that either probabilistic or frequency-based estimates, or some combination of the two, will be needed to inform the analysis of combined events. However, because there are not any widely used, well-established probabilistic frameworks for assessing the site-specific extreme precipitation and flooding events of interest for design-basis external flood determinations, the NRC staff will evaluate PFHAs on a case-by-case basis. Appendix A to this guide discusses PFHA further.

Flood-Causing Mechanisms

In establishing design-basis flood conditions for an NPP, applicants consider various flood-causing mechanisms. The appropriate mechanisms to consider depend on certain site-specific geographic factors. The examination of individual mechanisms commonly focuses on the most severe conditions considered physically possible for the site or region under consideration. Regardless of the flood-causing mechanisms involved, both hydrostatic effects (water elevation and forces caused by ponded water) and hydrodynamic effects (drag and impact forces caused by flowing water) may be relevant to the design of SSCs important to safety and any attendant flood protection measures. Collateral flooding effects caused by erosion, sedimentation, and water-transported debris may also be relevant.

In certain cases, a very simple analysis suffices to demonstrate the adequacy of the NPP flooding design. For example, this might be true for a site located well above any potential sources of river or stream flooding that might affect plant SSCs important to safety. American National Standards Institute (ANSI)/American Nuclear Society (ANS)-2.8-1992, “Determining Design Basis Flooding at Power Reactor Sites,” refers to such sites as “hilltop” or “flood-dry” sites (Ref. 22), although these terms are no longer used in the context of design-basis floods for NPPs. The determination that a site is not subject to flooding from nearby rivers or streams should be based on the consideration of appropriate combinations of factors and processes, including non-hydrologic dam failure. Such sites should also be evaluated for flooding caused by local intense precipitation (LIP) (see appendix C). If simplified analyses cannot clearly demonstrate that no credible postulated river or stream flooding event could possibly affect the site, detailed analyses should be performed.

The following paragraphs briefly discuss the individual flood-causing mechanisms to be evaluated to demonstrate compliance with regulations. Appendices A through H discuss general considerations, data sources, and applicable analysis techniques for these mechanisms. Appendices I and J, respectively, discuss the treatment of combined events and associated flooding effects. Lastly, some advanced reactor and small modular reactor designs, by virtue of their unique engineering, may have SSCs important to safety that are unaffected by exposure to external flood waters. Moreover, some of these next-generation reactor designs may not need makeup/cooling water or access to an ultimate heat sink (other than the atmosphere). In view of the emerging innovations in nuclear engineering, appendix K discusses general considerations for applying this RG to advanced reactor siting and design, as an alternative to RG 1.247 (Ref. 17). The appendices recommend the use of various computer codes and modeling methodologies; the use of specific computer codes or methodologies is acceptable so long it is consistent with their underlying purpose, the user’s manual, and applicable supporting documentation.

Flooding Caused by Local Intense Precipitation

External flood hazards due to LIP, by definition, occur at the immediate project site, regardless of the site’s grade elevation or physical proximity to a nearby river, lake, or other water body. The objective of the LIP analysis is to demonstrate that the elevations of power plant features, in relation to finished site topography (grade) and drainage features, have been designed to ensure that an LIP event does not compromise the function of SSCs important to safety. The extent of the LIP analysis domain is typically limited to the footprint of the power block and the contiguous controlled area that may contribute surface runoff to the power block’s location (typically about 2.6 square kilometers (or about 1 square mile) or less).

The simplest and most conservative LIP analysis postulates both that the site's (passive) drainage network is nonfunctional and that designated drainage components of the site's storm water management system are blocked and nonfunctional. Moreover, recent staff review experience suggests that a vehicle barrier system (VBS) can cause pooling at a plant site, by obstructing the free flow of rain runoff off site.

Flooding of Streams Caused by Precipitation

For project sites located along streams,[3] rainfall associated with extreme storm events elsewhere within the watershed often defines the design-basis flood. The most common analysis approach is to estimate the most extreme flood considered physically credible by applying the rainfall from the most extreme storm considered possible for the region to that portion of the watershed (or drainage basin) located above the plant site. However, the maximum credible estimate of flood elevation and flow velocities at the plant site can result from various combinations of factors and processes occurring elsewhere within the basin upstream of the site (e.g., sequential precipitation events; timing, centering, and duration of precipitation; seasonal variation of precipitation and antecedent soil moisture; snowpack accumulation, snowmelt, and meteorological factors influencing snowmelt timing; flood-caused dam failures; reservoir elevations; base flow) and those occurring at the site (e.g., superimposed wind waves). The appropriate sequences and combinations to consider are determined on a site-specific basis.

Flooding Caused by Dam Failure

The U.S. Army Corps of Engineers estimates that there are more than 91,000 dams in the United States, a portion of which share watersheds with locations of operating NPPs (Ref. 23). For convenience, this RG uses the term "dam" to include all water storage or water control structures whose failure may lead to external flooding. In common usage, the term "dam failure" refers to unplanned, uncontrolled releases from a reservoir impounded by a dam. However, even planned controlled releases (e.g., releases to prevent structural failure during a flooding event or after a seismic event) may pose a flood hazard to a downstream NPP. Therefore, for the purpose of estimating the design-basis flood for NPPs, this RG considers any release (i.e., unplanned, uncontrolled, planned, or controlled) that may pose a flood hazard to the NPP to be flooding caused by dam failure. In general, failure of any dam upstream of the plant site is a potential flood-causing mechanism. In addition, dams that are not upstream of the plant but whose failure would impact the plant because of backwater effects may present flood hazards. Failures of water storage or water control structures (such as onsite cooling or auxiliary water reservoirs and onsite levees) that are located at or above the grade of safety-related equipment are also potential sources of external flooding.

Dam failures can be broadly categorized according to the predominant mode of failure: (1) hydrologic dam failure, (2) seismic dam failure, or (3) dam failure from other, unattributed causes (sometimes called "sunny-day" failures). However, these categories are not mutually exclusive (Ref. 24). Hydrologic dam failure refers to those failures that are initiated by a hydrologic (flooding) event. The most common scenario is a large flood that overwhelms the dam spillway-discharge capacity with floodwaters overtopping the dam crest, which leads to erosion of the downstream face of the dam, foundation materials, or abutments and eventual failure (breach). Seismic dam failure occurs as the result of an earthquake (e.g., ground shaking, surface faults, landslides, or liquefaction). Strong ground shaking is the most common earthquake effect. Ground shaking may directly damage the dam structure and its appurtenances or may induce subsequent failure modes. Dam failures not caused by a concurrent extreme flood or seismic event may arise from a variety of causes, such as weakness or deterioration of

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[3] This RG uses "stream" as a general term for water flowing with measurable velocity in a channel. The channel may be natural, manmade, or natural with significant manmade modifications (e.g., dams, levees, revetments, dredging). A stream is also sometimes referred to as a "watercourse."

embankment material, foundations, abutments, or spillways. Malfunction of appurtenances such as flood gates, valves, conduits, and other components may also lead to dam failure.

Some sites may have the potential for flooding because of multiple dam failures or the sequential ("domino") failure of a series of dams located in succession along a common watercourse. For example, the project site may be located in a watershed containing dams that are close enough to one another for a single seismic event to cause multiple failures. Failure of a critically located dam that stores a large volume of water may produce a flood wave that triggers domino-type failures of downstream dams.

Flooding Caused by Storm Surge, Seiche, and Tsunami

NPP sites located near water bodies may be subject to coastal flooding caused by three types of water-wave phenomena: (1) storm surge, (2) seiche, and (3) tsunami. In the context of this guide, "coastal" refers to the nearshore regions of any large water body (e.g., ocean, bay, sound, lake, or estuary) where wind- or gravity-wave phenomena may occur, not just regions adjacent to the open ocean.

A storm surge is the free surface response to wind-induced surface shear stress and pressure fields associated with storms. Storm surges can produce short-term increases in water level to an elevation considerably above the mean water level. Extratropical cyclones, tropical cyclones, or hurricanes are generally responsible for the most severe storms and the most damaging storm surges encountered along the U.S. coastline.

A seiche is defined as an oscillation of the water surface in an enclosed or semi-enclosed water body that is initiated by an external cause (e.g., barometric pressure fluctuations, strong winds, rapid changes in wind direction, or surges associated with the passage of storms) that matches one of the natural periods of oscillation of the water body. Seiches are a gravity-wave phenomenon; once started, the amplitude and frequency of the oscillation of the free surface may continue for many cycles or may even grow because of resonance. The amplitude and frequency of oscillation are functions of the forcing phenomena together with the geometry and bathymetry (measured depth) of the water body. Local or regional forcing phenomena such as landslides may also cause seiches. Distant but large forcing mechanisms, such as storms, tsunamis, or earthquake-generated seismic waves, have also been known to produce seiches.

A tsunami is a series of water waves generated by a rapid, large-scale disturbance of some large water body caused by seismic, landslide, or volcanic sources (note that this definition is not limited to oceanic tsunamis). The most frequent source of oceanic tsunami generation is generally recognized to be a submarine earthquake associated with some plate tectonic feature along the sea floor. Earthquakes primarily generate tsunamis through vertical displacement of the sea floor that results in a simultaneous (often assumed identical) displacement of the overlying water column. A substantial amount of slip and a large rupture area are necessary to generate a major tsunami. Consequently, generally only large earthquakes (usually with magnitudes greater than 7) can generate measurable tsunamis. Landslide sources may include submarine mass failures along the continental shelf, subaerial landslides, and even ice falls, since these may displace a large volume of water. Volcanic effects due to pyroclastic (rock fragment) flows and caldera collapse (collapse of subsurface cavities formed by ejection of liquid molten rock or magma) have also been proposed as potential tsunami generators. The effects of a caldera collapse may be similar to a submarine or a subaerial landslide, depending on the location and the characteristics of the event. However, because they give rise to nonlinear wave forms, the geophysical events just described, when they occur, may not consistently generate tsunamis.

Flooding Caused by Ice Effects

Ice effects contribute to winter and early spring floods in many parts of the United States. At latitudes south of 37° N, streams and rivers generally do not freeze over, whereas for natural flow systems located north of that latitude, the situation may be different. Streams and rivers at latitudes higher than 37° N tend to form ice cover when temperatures reach 0 degrees Celsius (32 degrees Fahrenheit) or below. Ice events involving ice jams or ice dams may cause flooding at an NPP site through one of two scenarios: (1) a collapse of an ice jam or ice dam upstream of the site can lead to a flood wave similar to a wave resulting from a dam breach, which may propagate downstream to the site, or (2) an ice jam or ice dam downstream of a site may impound water upstream and thus cause flooding at the site through backwater effects. Ice jams occur during both the freeze up and warm-weather breakup periods. However, breakup jamming is usually the ice-related event of main concern because much higher flows usually prevail during breakup.

Ice-jam floods are usually not as extensive as open-water floods, but they present the following unique challenges:

- They often take place with little or no warning.

- Ice blockages forming in main stems of rivers and their tributaries cause flood stages to rise and force water out of the channel over the floodplain, even when discharges are low compared to those of warm-weather floods.

- The factors and relationships that determine the probability of ice jams and ice-jam flooding are more complex than those for open-water flooding; therefore, the statistical analysis methods used for normal flooding are not readily applicable to ice-related phenomena.

Combined Events

Analyses of only the most severe meteorological/hydrological conditions from the individual flood-causing mechanisms may fail to identify potential threats to safety-related systems from combinations (from coincident or correlated processes) of conditions thought to be less severe. For example, relatively high levees adjacent to a plant could fail during a flooding event less severe than the worst site-related flood; this could produce conditions more severe than those caused by any individual flood-causing mechanism. Clustering of lesser storm events within the watershed may also lead to flooding that is more extreme than that caused by an individual larger storm. Some of the largest floods observed on the Mississippi and Missouri Rivers in the last 50 years have resulted from the combined effects of rainfall and coincident snowmelt runoff.

To maintain a consistent level of conservatism, it is common to consider reasonable combinations of less severe flood conditions and to consider severe flooding from one mechanism along with less severe, but more frequent, conditions resulting from other mechanisms. Generally, such combinations are evaluated in cases where the probability of their occurring at the same time and having significant consequences is at least comparable to that associated with the most severe individual flood-causing mechanism. ANSI/ANS-2.8-1992 provides examples of possible scenarios to consider based on the geographic setting of the NPP.

Wind-Generated Wave Effects

Inclusion of wind-generated waves is probably the most common example of a combined-event effect to be considered in an external flood hazard analysis. Depending on the depth of water, wind-generated waves may produce severe flood-induced static and dynamic conditions either independent of or coincident with severe hydrometeorological or seismic flood-producing mechanisms. Either local or distant storms may cause wind-generated waves. For example, at coastal locations, a distant storm that is less severe than a local storm may nevertheless produce more severe wave action because of a very long wave-generating fetch.

Flood Protection

This RG does not discuss the design of specific flood protection features or structures, the equipment for flood mitigation, or the development of specific flood protection procedures to ensure safe operation of an NPP during a flood caused by a plausible flood-causing mechanism. Instead, RG 1.102 provides guidance on flood protection structures, equipment, and procedures.

Previous revisions of this guide addressed certain aspects of flood protection, such as conditions under which alternatives to providing hardened protection would be acceptable. The NRC staff has removed such topics from this revision because it is more logical to address them in RG 1.102, which presents guidance on design and maintenance of flood protection measures. However, if it is anticipated that safety-related SSCs will need some degree of flood protection, then it will be important to consider the rate of rise of the floodwaters and the duration of flood conditions in the design and specification of flood protection methods and procedures (e.g., to establish lead times and coping times).

Consideration of International Standards

The International Atomic Energy Agency (IAEA) works with member states and other partners to promote the safe, secure, and peaceful use of nuclear technologies. The IAEA develops Safety Requirements and Safety Guides for protecting people and the environment from harmful effects of ionizing radiation. This system of safety fundamentals, safety requirements, safety guides, and other relevant reports reflects an international perspective on what constitutes a high level of safety. To inform its development of this RG, the NRC considered IAEA Safety Requirements and Safety Guides under the Commission’s International Policy Statement (Ref. 23) and Management Directive and Handbook 6.6, “Regulatory Guides” (Ref. 26).

The following IAEA Safety Requirements and Guides were considered in the update of the Regulatory Guide:

- Safety Standards Series No. SSR-2/1, “Safety of Nuclear Power Plants: Design,” issued 2016 (Ref. 27)

- Safety Standards Series No. NS-R-3, “Site Evaluation for Nuclear Installations,” issued 2016 (Ref. 28)

- Safety Guide GS-G-4.1, “Format and Content of the Safety Analysis Report for Nuclear Power Plants,” issued 2004 (Ref. 29)

- Safety Standards Series No. NS-G-1.5, “External Events Excluding Earthquakes in the Design of Nuclear Power Plants,” issued 2003 (Ref. 30)

- Safety Standards Series No. NS-G-3.6, “Geotechnical Aspects of Site Evaluation and Foundations for Nuclear Power Plants,” issued 2004 (Ref. 31)

- Safety Standards Series No. SSG-18, “Meteorological and Hydrological Hazards in Site Evaluation for Nuclear Installations,” issued 2011 (Ref. 32)

Documents Discussed in Staff Regulatory Guidance

This RG endorses, in part, the use of one or more codes or standards developed by external organizations, and other third-party guidance documents. These codes, standards and third-party guidance documents may contain references to other codes, standards, or third-party guidance documents (“secondary references”). If a secondary reference has itself been incorporated by reference into NRC regulations as a requirement, then licensees and applicants must comply with that standard as set forth in the regulation. If the secondary reference has been endorsed in an RG as an acceptable approach for meeting an NRC requirement, then the standard constitutes a method acceptable to the NRC staff for meeting that regulatory requirement as described in the specific RG. If the secondary reference has neither been incorporated by reference into NRC regulations nor endorsed in an RG, then the secondary reference is neither a legally binding requirement nor a “generic” NRC approved acceptable approach for meeting an NRC requirement. However, licensees and applicants may consider and use the information in the secondary reference, if appropriately justified, consistent with current regulatory practice, and consistent with applicable NRC requirements.

C. STAFF REGULATORY GUIDANCE

1. Flood Hazard Assessments

The design-basis flood hazards comprise the conditions (i.e., water levels, water velocities) resulting from the worst site-related flood probable at the site of an NPP (e.g., LIP, stream flooding from precipitation, seiche, storm surge, seismically induced flood), with appropriate consideration of combined flooding events and attendant wind-generated wave activity. Consistent with the requirements of GDC 2, SSCs important to safety identified in RG 1.29 must be designed to withstand, or must be protected from, natural phenomena, including external flooding effects, to retain their capability to perform their safety functions. In connection with the requirements of GDC 2, hydrostatic and hydrodynamic effects are also important design considerations. Note that the design basis for hydrodynamic effects may arise from external flood-causing mechanisms and scenarios that are different from those that lead to the design basis for hydrostatic effects. The time sequencing (e.g., available warning time) and duration of flooding conditions should also be considered.

2. General Considerations

This section summarizes the general considerations that affect flood hazard assessments and design-basis flood estimation, regardless of the external flood-causing mechanism examined. Appendix A to this guide discusses these topics in more detail.

a. Deterministic versus Probabilistic Analysis Approaches. The NRC staff has traditionally relied on deterministic approaches for estimation of the design-basis flood necessary to comply with GDC 2. Such approaches (methods) are widely described in the literature and have been well validated over decades of use. In connection with its GDC 2 reviews, the staff has also relied on simple, common-sense screening methods to exclude those flood-causing mechanisms determined to be implausible from the specification of the design-basis flood. The staff's screening philosophy was formalized when the Commission published its views on the use of a risk-informed and performance-based approach to regulation (Ref. 21). Those views rely on the "risk triplet" (Ref. 33).[4] More recently, and consistent with the Commission's views on risk-informed regulation, NUREG/CR-7046 proposed a progressively refined, HHA-type screening process for estimating site-specific external flood hazards. NUREG/CR-7046 provides advice and case studies illustrating the HHA concept in various scenarios involving different external flood-causing mechanisms.

More recently, ANSI/ANS-2.8-2019, "Probabilistic Evaluation of External Flood Hazards for Nuclear Facilities" (Ref. 34), has also proposed a screening process for evaluating external flood-causing mechanisms. ANSI/ANS-2.8-2019 provides a graded approach that differs somewhat from the HHA-type or stepwise screening process described in NUREG/CR-7046. The graded approach, as described in sections 5.1.1 and 5.1.2 of ANSI/ANS-2.8-2019, includes (1) qualitative screening analysis, which resembles HHA-type screening, and (2) quantitative screening analysis, which differs significantly from HHA-type screening. The quantitative screening process considers aleatory and epistemic uncertainties during the evaluation of the physical attributes of the flood scenarios in the screening analysis (section 5.1.2 of ANSI/ANS-2.8-2019). ANSI/ANS-2.8-2019 provides high-level guidance on PFHA approaches but does not provide detailed review guidance.

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[4] The risk triplet focuses on addressing the following questions: what can happen, how likely is it, and what are the consequences?

ASME/ANS RA-S-1.1-2024, “Standard for Enhanced Nuclear Risk Management” (Ref 35), recently published by the ASME/ANS Joint Committee on Nuclear Risk Management, focuses on Level 1/Large Early Release Frequency Probabilistic Risk Assessment (PRA) specifically tailored for NPP operations. The standard is primarily designed for current operating LWR power plants. ASME/ANS RA-S-1.1-2024 requires that a PFHA be performed to support an external flooding PRA and, like ANSI/ANS 2.8 2019, provides a series of high-level and supporting requirements to ensure PFHAs address a range of technical issues. Like ANSI/ANS 2.8 2019, these requirements can serve as a basis for a framework for evaluating PFHAs, but do not provide detailed review guidance on PFHA methods.

The technical challenges of probabilistic analysis for extreme floods and the lack of widely accepted probabilistic methods for assessing the full suite of potential external flood hazards at a project site are the main reasons for the deterministic focus of this RG. Although the NRC does not currently provide specific guidance on PFHA techniques, the staff uses an average annual probability of exceedance of less than $1x10^{-6}$ as a metric to evaluate the reasonableness of combined-event flooding scenarios; this screening value may be estimated using qualitative or semiquantitative methods. The staff considers this metric a reasonable criterion to apply to design-basis flood estimates using frequency-based screening, assuming reasonable confidence limits can be established. The staff will review probabilistic characterization of extreme floods by various mechanisms or combinations of mechanisms on a case-by-case basis.

Regardless of which analysis approach an applicant adopts, the description of the approach should include an assessment of the sensitivity of the methods, data, and modeling attributes and inputs for design-basis flood estimates. Lastly, because measured data may be variable and sparse, and because modeling of the physical processes underlying flooding involves inherent uncertainty, the results of any PFHA are uncertain. Therefore, in conducting a PFHA it is important to quantify the sensitivity of the results to, and the uncertainty associated with, the values of input parameters.

b. Extreme Storm Data Compilations. Various Federal and State agencies have produced data compilations, atlases, or other reports that contain estimates of extreme winds, rainfall, and floods, to aid the designers of critical infrastructure such as dams, coastal protection systems, and power plants. When a technically accurate, publicly available, and up-to-date data source exists for a region, it can be employed to characterize flooding in the region. However, although these reports are valuable references, larger or more intense storms may have occurred in certain regions since their publication (many of the reports are over 30 years old and have not been updated since they were issued). Therefore, before using older reports to determine design-basis flood estimates for NPP sites, applicants should confirm that more recent storms or flood events occurring in the region of interest do not invalidate the conceptualizations, assumptions, parameterizations, or estimates in the reports. If the continuing utility of these older design aids is not confirmed, the more recent storm or flooding information should be used (along with updated methods, where appropriate). Appendices C, D, E, and F to this RG discuss known issues with specific design aids and ways to incorporate improved data and methods.

c. Nonstationary Effects. Design-basis flood estimates should include an assessment of nonstationary processes. Relative sea-level rise (SLR) is the combined effect of water level change (due to the thermal expansion of ocean water as well as contributions from melting glaciers and large continental ice sheets) and land subsidence (or uplift). SLR is a well-documented process that has been ongoing in many coastal regions since the end of the last ice age (generally about 11,700 years before the present). Recent developments in climate research have shown that significant global and regional warming trends have occurred in the past several decades and are expected to continue or even accelerate, with potential implications for SLR and hydrologic extremes. A design-basis flood analysis for coastal sites should include estimates of relative SLR observed and reported by the National Oceanic and Atmospheric Administration's (NOAA's) National Ocean Service (e.g., 20th-century relative SLR rate), as well as projected changes in these rates, provided by organizations such as the U.S. Global Change Research Program (USGCRP) and the Intergovernmental Panel on Climate Change. For example, Appendix 3 to USGCRP's Fifth National Climate Assessment (NCA5, Ref. 36) references reports and databases containing relative SLR observations in U.S. coastal regions. Appendix A to this RG also discusses the effects of climate change on sea levels (with supporting references) in detail and describes an acceptable approach for considering these effects in design-basis flood estimates. The staff considers the most conservative SLR scenario in provided in the NCA to be acceptable when considering SLR effects in the estimation of design-basis flood levels. Note that the NCA is updated periodically, so applicants should use the most recent NCA version. Applicants using the less conservative estimates described in the NCA will need to support these with additional site-specific analyses. Applicants should describe the basis for the selection of their preferred SLR estimates, supported by a review of the literature.

Because future natural changes in precipitation amounts and storm frequencies are very uncertain, this RG gives no specific guidance on these topics.

d. Site-Specific Analyses. In previous revisions of this RG, appendices B and C provided simplified map-based methods for deriving conservative estimates of the PMF on nontidal streams and of the probable maximum storm surge, respectively. The NRC staff has removed that material from this revision. Because the data and methodology supporting those methods are outdated, the conservatism of the methods can no longer be assumed a priori, even though the overall review goal is to define some PMF, consistent with GDC 2. In addition, there is now much less need for the maps and simplified methods, because advances in methods based on a geographical information system (GIS) have significantly reduced the level of effort necessary for a site-specific analysis (Ref. 37). Therefore, the staff position is that the methods described in appendices B and C to previous revisions of this RG have been overtaken by updated analysis methods and do not reflect the current best practice.

3. Hydrologic Setting

Descriptions of site facilities, site hydrologic features, and flood history are needed to provide an adequate basis for the identification of the plausible flood-causing mechanisms at the project site. These descriptions should also be sufficient to support the engineering analysis of external flooding phenomena that is necessary to define the design-basis flood consistent with GDC 2.

The elevations of exterior access openings for safety-related structures, as well as the staging elevations for flood mitigation equipment and systems, should be described from a hydrologic perspective. The location and orientation of the VBS, if present, should be described, with particular attention to how its placement or design might create ponding effects that would lead to retention of floodwater within the project site. The natural topography of the site and any proposed changes should be described, with attention to those hydrologic features of interest that might pose an external flood hazard. For example, the location, size, and other hydrologic characteristics of water bodies (e.g., streams, lakes, estuaries, shore regions, manmade channels) that may influence external flooding at the site should be identified. Any existing or proposed water control structures (e.g., dams, levees, diversions, channels), both upstream and downstream of the plant site, should be described. The flooding history of the site and region should be described, with details on all major historical flooding events (e.g., water levels, discharges, duration, and related information). When available, relevant information from paleo flood studies should be included.

Section 2.4.1 of RG 1.70 provides general guidance for describing hydrologic features of the site, the facilities, and the surrounding region, to help assess external flood potential and to support engineering analysis. Appendix B to RG 1.70 provides more detailed guidance. In particular, the appendix identifies Federally supported spatial referencing standards for cartographic, geographic, topographic, and hydrologic data. It also identifies various types of meteorological and hydrological data collected and disseminated by Federal, State, and local governments. Appendix A to NUREG/CR-7046 also examines and discusses some of these databases. ANSI/ANS-2.8-2019 contains another source of information on the physical characteristics of candidate reactor sites and the flood-causing mechanisms applicable to them.

The hydrologic features, data, and modeling needed to support engineering analysis of flooding hazards exhibit both spatial and temporal variability, making the constructs and philosophies GIS well suited for this purpose. In addition, the GIS environment is well suited for use as a data storage and visualization tool for modeling output. Accordingly, the staff finds the use of GIS tools acceptable for organizing, processing, and storing hydrologic data and for visualizing data and modeling results. Appendix A to NUREG/CR-7046 discusses the use of GIS and documents source data typically collected and processed to integrate GIS into hydrological modeling environments.

a. Flooding Caused by Local Intense Precipitation. External flood hazards from an LIP event occur within the immediate footprint of the power plant, regardless of the site’s geographic relationship to any generally recognized hydraulic (flood-causing) features. Thus, the effects of an LIP event within the footprint of the power plant, adjacent drainage areas, and site drainage features and systems (including drainage from roofs of structures) should always be examined. Models and associated parameters used to estimate the generation of surface runoff from the design-basis storm and the conveyance of the surface runoff away from the site should be described in sufficient detail to allow an independent review of their technical adequacy. The analysis should address the potential for waterborne debris or other blockage to compromise the effectiveness of the site drainage system.

Features of the site drainage system should be described in sufficient detail to support an engineering analysis of the effects of the probable maximum rainfall event at the power plant site scale. The analysis should include an evaluation of the potential for runoff effects on SSCs that are important to safety, as well as the adequacy of proposed design criteria intended to protect them. The analysis should also examine how potential blockage of storm water management systems in concert with proposed finished site grades is projected to affect the potential for ponding or surface flooding during the defined LIP event. Careful attention should be given to the effects of any ponding due to the presence of a VBS and surface flooding at locations of SSCs important to safety.

Key elements of the bounding probable maximum precipitation (PMP) storm (event), such as area, duration, and temporal distribution of rainfall intensities, should be consistent with guidance from the National Weather Service. Alternatively, applicants may propose to rely on a site-specific precipitation estimate. NUREG/KM-0015, “Considerations for Estimating Site-Specific Probable Maximum Precipitation at Nuclear Power Plants in the United States of America: Final Report,” issued September 2021 (Ref. 38), discusses considerations for an acceptable approach for estimating the site-specific PMP.

Section 2.4.2.3 of RG 1.70 discusses general criteria for examining the effects of LIP. Appendix C to this guide provides more detailed guidance. Section 3.1 and appendix C to NUREG/CR-7046 contain advice and case studies.

b. Stream Flooding Caused by Precipitation Events. For project sites located near streams (rivers), analyses should consider flooding hazards resulting from severe hydrometeorological conditions other than LIP (e.g., flooding at the NPP site caused by precipitation occurring over watersheds that communicate with the site). This RG uses “stream” as a general term for any body of water flowing with measurable velocity in a channel. The channel may be natural, manmade, or natural with significant manmade modifications (e.g., dams, levees, revetments, dredging).

For project sites where the effects of stream/riverine-based flooding are obvious from a cursory examination of the site’s topography in relation to some watercourse, a progressive, HHA-like screening approach may be used. Simplified procedures may be used; however, all methods and assumptions should be clearly conservative.

This RG focuses on deterministic analysis aimed at identifying the most extreme credible flood, also known as the PMF. The PMF is generally defined as the hypothetical flood (i.e., peak discharge, volume, and hydrograph shape) considered the most severe flood that can reasonably be expected to occur at the site. The PMF should be estimated by applying a hypothetical extreme rainfall event (e.g., PMP) along with other hydrologic factors favorable for maximum flood runoff. Examples of such factors include various combinations of processes occurring in the drainage basin above the site (e.g., sequential precipitation events; timing, centering, and duration of precipitation; seasonal variation of precipitation and antecedent moisture; snowpack accumulation, snowmelt, and meteorological factors influencing snowmelt timing; flood-caused dam failures; reservoir elevations; base flow) and those occurring at the site (e.g., superimposed wind waves). Estimates of the PMF should account for current and proposed land use and land cover. The appropriate combinations to consider should be determined on a site-specific basis. Key elements of the PMP storm, such as area, duration, and temporal distribution of rainfall intensities, should conform to National Weather Service guidance (and reflect considerations discussed in NUREG/KM-0015).

The preceding discussion notwithstanding, quantitative estimation of the stream flooding hazard should generally include the following steps: (1) evaluating the precipitation flux over the watershed as a function of space and time, (2) evaluating the precipitation excess or effective precipitation flux as a function of space and time (rainfall-runoff analysis), and (3) routing the precipitation excess to the plant site (i.e., flood routing) to determine the corresponding flood hydrograph.

The design rainfall estimate should be developed from the hypothetical extreme rainfall event (storm-centered, area-averaged PMP in most cases) by considering an optimal temporal distribution and optimal centering and orientation over the drainage basin (optimal as in producing the largest discharge). Movement of the storm along the basin axis should also be considered, because it may result in the largest discharge.

In the matter of the applicant’s preferred rainfall-runoff model, the documentation provided should describe (1) the physical properties of the watershed evaluated (e.g., area, topography, soil types, land cover), (2) the type of model used and the basis for its selection, (3) the rainfall-runoff transformation function used (e.g., a description of the unit or synthetic hydrograph) and the basis for its selection, (4) the validation method used (including the source of actual flood data used, if available), and (5) the sensitivity analysis method to be used to maximize the predicted water surface elevation (PMP source, routing parameters, and hydrograph parameters, as necessary). The documentation of the flood-routing results should describe (1) the stream channel network, (2) the specific flood-routing method used, (3) reach lengths, cross sections, and cross section locations, (4) the basis for the selection of the channel roughness coefficients used, (5) initial and boundary conditions, and (6) validation analyses or previous studies of floods at the site, if available.

Section 2.4.3.3 of RG 1.70 gives general guidance for estimating the PMF. Appendix D to this guide and NUREG/CR-7046, section 3.3 and appendix C, contain advice and case studies. Another important source of information, which might be more pertinent because it is site-specific, would be the riverine-based flood analyses performed by owners and operators in response to the 2011 Fukushima event. Those flood hazard reevaluations are publicly available in the NRC's Agencywide Documents Access and Management System (ADAMS).

c. Flooding Caused by Dam Failure. DG-1417 (RG 1.256), which is being issued in conjunction with this RG provides guidance that the NRC staff finds acceptable for screening and evaluating flooding hazards due to dam failure as well as failure of other water control structures.

d. Flooding Caused by Storm Surges, Seiches, and Tsunamis. In coastal regions, flooding hazards resulting from storm surges, seiches, and tsunamis, along with coincident wave action, should be examined. In the context of this guide, "coastal" refers to the nearshore regions of any water body (e.g., ocean, lake, bay, estuary) where surge, seiche, or tsunami phenomena may occur, not just regions adjacent to the open ocean. In general, analysis approaches that are comparable in conservatism to those used for flooding of rivers and streams are acceptable to the staff.

Storm surge can result from several types of severe meteorological events (e.g., tropical cyclones, extratropical cyclones, squall lines, and hybrid storms). For each event type appropriate for the region in which an applicant proposes to locate a facility, the analysis should also estimate extreme winds. Simplified conservative methods may be used to screen out project sites that clearly are not subject to significant storm surge flooding. When simplified HHA-like screening methods cannot eliminate from consideration a given mechanism for storm surge flooding, a detailed storm surge modeling analysis is necessary. The current state of practice in storm surge modeling relies on coupled hydrodynamic ocean circulation/wave models, both of which are driven by a planetary boundary layer model that provides the atmospheric forcing mechanism. These models are now computerized, and applicants can select from several modeling platforms.

Regardless of the circulation/wave model selected, the modeling results should be validated using data obtained from past storms in the region of interest. It should be noted that the cohort of historical storms available for study is limited. As a first step in any examination, historical storm events in the region of interest should be analyzed in detail to identify potential storm parameters for use in the requisite computer simulations. Because the historical storm catalog is limited, certain parameters may need to be assigned values that are more severe than those obtained from the historical record, but that are physically possible based on meteorological reasoning and state-of-the-art storm phenomenology.

A seiche is a transient response of the free surface of a water body in an enclosed or semi-enclosed basin that can occur when the water body is subjected to a disturbance. Rather than generating a wave of translation (i.e., a wave in which the water particles move forward in the direction of wave propagation), the disturbance causes the free surface of the water body to oscillate harmonically, producing short-period standing waves. Seiches and seiche-related phenomena have been observed on certain natural water bodies such as lakes, bays, harbors, and the open ocean, as well as in large manmade water bodies such as reservoirs. For project sites adjacent to any of these types of water bodies, the potential impact of seiche-like phenomena should be considered. The oscillatory modes for the water body in question should be compared to forcing mechanisms from a variety of potential sources, including (1) local or regional forcing phenomena such as barometric pressure fluctuations, strong winds, rapid changes in wind direction, and storm surge associated with the passage of local storms, and (2) distant but large forcing mechanisms, such as distant storms, tsunamis, or earthquake-generated seismic waves. For water bodies with simple geometries, modes of oscillation can be predicted from the shape of the basin using analytical formulas described in the literature. However, most natural water bodies have variable bathymetry and irregular shorelines, and water motion may be driven by a combination of forcing mechanisms. For such water bodies, seiche periods and water surface profiles should be determined through numerical long-wave modeling.

Surge and seiche flood hazard analyses should include wind-generated wave activity that can occur independently of, or concurrently with, a storm surge or seiche. The wave climate near the site should be characterized based on available records, using measures such as significant and maximum wave heights. The analyses should consider wave setup, wave runup, splash, or overtopping (as appropriate). The surge and seiche flooding estimates should also include the potential effect of tides.

The term “tsunami” refers to a sea wave that forms impulsively (suddenly) because of a disturbance over a large area. The most common tsunami-generating mechanisms described in the peer-reviewed literature are submarine earthquakes that occur when there is movement along a subduction zone boundary. The generation of tsunami waves has also been attributed to submarine volcanism, submarine landslides, and subaerial rock falls into the ocean along locations of high topographic relief. The design-basis flood estimation for power plant sites in areas susceptible to tsunami hazards should consider the effects of tsunamis or tsunami-like waves, including wave runup, flooding, erosion, and debris loads. The rundown or return flow of floodwater (and debris) into the water body should also be considered. A regional or site-specific survey and assessment of tsunamigenic sources should be performed to determine whether a tsunami could pose a hazard to the site. The survey and assessment should include all potential near- and far-field sources and mechanisms that could generate tsunamis. Analyses of coastal sites should consider hazards from oceanic tsunamis. Analyses of inland sites should consider the possibility of tsunami-like waves in water bodies in the region (e.g., from hillslope failure or seismic sources). Any relevant paleo tsunami evidence should be assessed. NOAA’s National Centers for Environmental Information maintains a database that includes global information on paleo tsunamis (Ref. 39).

If regional or site-specific screening does not eliminate the tsunami hazard, a detailed assessment should be undertaken to ensure that the plant design bases adequately account for this hazard. This step should include postulation of probable maximum tsunami (PMT) source mechanisms geographically, estimation of PMT source characteristics, initiation of the PMT wave, propagation of the PMT wave from the source toward the site, and estimation of tsunami hazards at the site. A detailed description of the controlling tsunami generator (e.g., location, dimensions, orientation, and maximum displacement) should be provided. The applicant should describe in detail the analysis procedure and models used to estimate the PMT wave height, wave period, and other input parameters selected for the site study, as well as the basis for their selection.

Section 2.4.5 of RG 1.70 gives general guidance for estimating flooding caused by storm surge and seiches. Section 2.4.6 of RG 1.70 gives general guidance for estimating PMT hazards. Appendices E, F, and G to this guide give more detailed guidance on storm surge, seiche, and tsunami flood hazards, respectively. Section 3.5 and appendix E to NUREG/CR-7046 contain advice and a case study on how to perform a probable maximum storm surge analysis. Section 3.6 and appendix F to NUREG/CR-7046 provide examples of how to analyze seiches. NUREG/CR-6966, "Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America," issued March 2009 (Ref 40), gives examples of how tsunami assessments might be performed consistent with current practice. Another important, and possibly more illustrative, source of information is the site-specific flood analyses performed by affected owners and operators in response to the 2011 Fukushima event. The flood hazard reevaluations for sites exposed to storm surge, seiches, and tsunamis are publicly available in ADAMS.

e. Flooding Caused by Ice Effects. In cold regions, the potential for flooding caused by ice effects should be examined and, where appropriate, should be assessed quantitatively. As noted earlier, locations south of latitude 37° N generally do not freeze over, whereas in natural flow systems located north of that latitude, streams, rivers, and lakes tend to form ice cover when temperatures reach or fall below 0 degrees Celsius (32 degrees Fahrenheit). The potential for ice-jam formation should be assessed based on regional hydroclimatic conditions (e.g., air temperature characteristics) and the regional ice accumulation and ice-jam formation history. The U.S. Army Corps of Engineers ice-jam database is a widely used source for ice-jam formation history (Ref. 41), and the staff finds it an acceptable source of information on ice jams.

Where the potential for ice formation cannot be ruled out or is not clearly bounded by other flood-causing mechanisms, flooding hazards caused by ice effects should be examined quantitatively. Two broad categories of ice effects that should be considered are (1) ice accumulation on site facilities where such accumulation may contribute to flooding from LIP (see paragraph d) and (2) ice-jam formation on nearby streams. Because much higher flows are common during the spring, breakup jamming is usually identified as the ice-related event of main concern for a flood hazard assessment. Flooding caused by backwater effects of ice-jam formation downstream of the plant and flooding caused by the breach of an upstream ice jam should be addressed. Predicting the location and severity of ice jams is generally infeasible; therefore, the effect of hypothetical ice jams at critical locations should be analyzed.

Section 2.4.7 of RG 1.70 discusses the need to examine flooding caused by ice effects (e.g., ice jams) in general terms. Section B of this guide gives an overview of ice-jam flood-causing mechanisms and scenarios and discusses key contrasts between ice-jam flooding and open-water floods. Appendix H to this guide and appendix G to NUREG/CR-7046 address the formation of different types of ice, types of ice jams, the assessment of ice-jam formation potential, and analysis approaches for estimating ice-jam flood hazards.

f. Combined Events. Extremely large floods of interest for design-basis purposes are seldom the result of a single event or process. Therefore, consideration of flooding resulting from a single event or process is generally not adequate to determine the design-basis flood. Reasonable sequences and combinations of processes and events based on regional or site-specific information need to be considered. In general, probable maximum flooding events from two separate phenomena should not be combined unless they depend on or result from a common cause. However, the maximum water surface elevation and maximum hydrostatic force may result from different combinations of events. Therefore, appropriate combinations of external flooding events should be chosen for each case to establish safety margins.

Many hydrometeorological flood-causing phenomena can occur sequentially or concurrently because they are not truly independent mechanisms. For example, floods from precipitation events may occur concurrently with snowmelt floods and wind-induced waves. In coastal regions, the precipitation event may be due to a tropical or extratropical cyclone; therefore, stream flooding could coincide with a storm surge and wind-induced waves. In general, the effects of coincident wind-generated wave activity on the water levels should always be added to the most severe flood at the site determined from paragraph a, b, c, d, e, f, or g.

Credible combinations and sequences of hydrometeorological and non-hydrometeorological events should also be considered. For example, astronomical high tides may combine with hydrometeorological events (e.g., a storm surge) or seismic events (e.g., a tsunami). Extreme PMP in a watershed may result in a flood that overtops a dam. The possible combinations of processes and events to consider are site-specific and depend on the geography of the project site. ANSI/ANS-2.8-1992 describes examples of possible scenarios to consider. It was withdrawn in 2002 and updated to a probabilistic standard (Ref 34). Nevertheless, as recently as 2012, many NRC licensees were still relying on the deterministic criteria in ANSI/ANS-2.8-1992 for their Fukushima flood hazard evaluations.

The NRC staff currently uses an average annual probability of exceedance of less than $1\text{x}10^{-6}$ as a metric to evaluate the reasonableness of combined flooding event scenarios. The staff notes that ANSI/ANS-2.12-1978, "Guidelines for Combining Natural and External Man-Made Hazards at Power Reactor Sites" (Ref. 42) and ANSI/ANS-58.21-2007, "External Events in PRA Methodology" (Ref. 43) (although now withdrawn[5]), describe methods for evaluating and combining flood hazard events for design purposes. However, guidance on formal PFHA approaches for consistent treatment of combined events is lacking. Therefore, the NRC will assess the reasonableness of qualitative and quantitative probability estimates for combined events on a case-by-case basis.

4. Flood Protection

Although flood protection structures and procedures are not the subject of this RG, their design and development call for an estimate of the warning time that might reasonably be available and the coping time to be endured. Therefore, a flood hazard analysis should include an estimate of the elapsed time between initiation of the flood-causing mechanism and the arrival of floodwaters at the plant site, as well as the expected duration of flood conditions. Figure 1 depicts the flood duration parameters of interest in the evaluation of flood protection plans. The staff has found that the preparation of inundation maps is especially useful in understanding both the magnitude of flooding associated with a flood-causing mechanism and the extent of flooding across the power block and controlled area where SSCs may be located. These maps illustrate the maximum flood elevation in relation to the reactor building and other SSCs important to safety. As inundation maps are computer-generated, the time-step feature of the computer simulation can be manipulated to show how the floodwaters are expected to advance across the project site as a function of time. This allows for an evaluation of the flooding event against the time credited for any manual (operator) flood preparation or procedural actions that applicants might propose.

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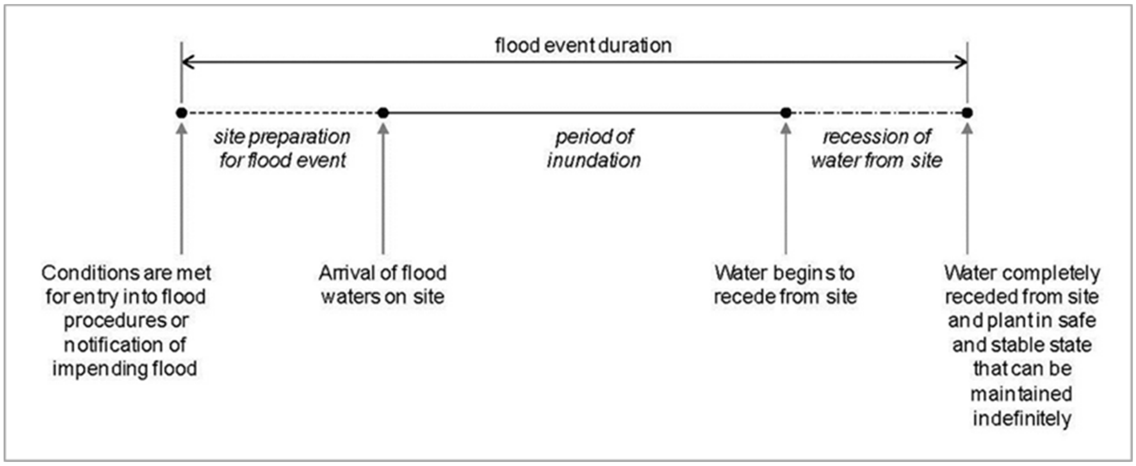
[5] ANSI/ANS 2.12 1978 was administratively withdrawn in 1988. A revision was not initiated because ANS determined that there was a low-level of interest in this standard (any standards over 10 years from an ANSI approval/reaffirmation are administratively withdrawn by ANSI for lack of maintenance). ANSI/ANS 58.21 2007 was withdrawn administratively because it was superseded by ANSI/ASME/ANS RA-S-2008, "Standard for Level 1/Large Early Release Frequency Probabilistic Risk Assessment for Nuclear Power Plant Applications." There have been a couple of revisions of this standard. The current version is ANSI/ASME/ANS RA-S-1.1-2024, "Standard for Enhanced Nuclear Risk Management" (Ref. 35).

Figure 1 Flood duration parameters



D. IMPLEMENTATION

The NRC staff may use this RG as a reference in its regulatory processes, such as licensing, inspection, or enforcement. However, the NRC staff does not intend to use the guidance in this RG to support NRC staff actions in a manner that would constitute backfitting as that term is defined in 10 CFR 50.109, "Backfitting," and as described in NRC Management Directive 8.4, "Management of Backfitting, Forward Fitting, Issue Finality, and Information Requests," (Ref. 44), nor does the NRC staff intend to use the guidance to affect the issue finality of an approval under 10 CFR Part 52. The staff also does not intend to use the guidance to support NRC staff actions in a manner that constitutes forward fitting as that term is defined and described in Management Directive 8.4. If a licensee believes that the NRC is using this regulatory guide in a manner inconsistent with the discussion in this Implementation section, then the licensee may file a backfitting or forward fitting appeal with the NRC in accordance with the process in Management Directive 8.4.

REFERENCES[6]

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APPENDIX A

GENERAL CONSIDERATIONS

This appendix provides general guidance on aspects of design-basis flood estimation that are common to most types of external flooding.

A-1. Information on Recent Storm and Flood Events

To aid the designers of critical infrastructure such as dams, coastal protection systems, and power plants, various Federal and State agencies have produced data compilations, atlases, or other reports that derive estimates of extreme winds and rainfall. Prominent examples include reports on meteorological criteria for design hurricane winds for coastal regions (Ref. 1, 2) and design rainfall depths for various area sizes and durations (Ref. 3, 4, 5, 6, 7, 8, 9, 10, 11, 12). Although these reports are valuable references, their estimates are derived from historical storm databases that, in many instances, are several decades old and have not been updated. In some cases, larger or more intense storms have occurred in certain regions since the publication of these design references. Before using such design references to estimate design-basis floods at nuclear power plant sites, applicants should confirm that more recent storms or flood events in the region of interest do not invalidate the conceptualizations, assumptions, parameterizations, or estimates in the references.

A-2. Deterministic versus Probabilistic Analyses

Since the last revision of this regulatory guide, significant advances have been made in probabilistic modeling of hydrologic processes important to design-basis flood estimation. Mature, well-tested methods are available for techniques such as stochastic weather simulation (Ref. 13, 14, 15, 16, 17, 18, 19); frequency analysis of extreme events (Ref. 16, 20, 21); and continuous and distributed watershed simulation models (Ref. 22, 23, 24, 25, 26, 27). Modeling frameworks have been developed by the U.S. Bureau of Reclamation and the U.S. Army Corps of Engineers for including probabilistic flood hazard estimates in risk analyses (Ref. 28, 29). The U.S. Army Corps of Engineers recently completed a report detailing the results of a probabilistic study to address coastal storm and flood risk in the United States' North Atlantic and South Atlantic regions. (Ref. 30, 31).

However, despite recent advances, it remains technically challenging to develop reliable probabilistic estimates for the events of very low probability that are of interest in the design-basis load problem. Therefore, many practitioners still favor deterministic methods. For example, section 5.6 of NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America,” issued November 2011 (Ref. 28), which discusses the relative advantages and disadvantages of deterministic and probabilistic approaches to design-basis flood estimation, concludes that deterministic methods are still useful and that a comprehensive probabilistic flood hazard assessment methodology has not been developed.

Therefore, the NRC staff will accept both deterministic and probabilistic analyses on a case-by-case basis. Regardless of which approach an applicant adopts, the rigor of the analysis (e.g., appropriate choice of assumptions, site- or region-specific data, appropriate process models, and assessment of sensitivities and uncertainties) should suffice to clearly demonstrate that the NRC’s safety goals are met.

Regarding safety goals, American National Standards Institute (ANSI)/American Nuclear Society (ANS)-2.8-1992, “Determining Design Basis Flooding at Nuclear Power Plant Sites” (Ref. 33), considered an annual exceedance probability of 1×10^{-6} to represent a reasonable criterion for selecting the design-basis flood at a nuclear power plant site. The NRC staff uses this metric to evaluate the reasonableness of combined flooding event scenarios. Therefore, the staff considers this metric a reasonable criterion to apply to design-basis flood estimates from probabilistic methods, assuming that reasonable confidence limits can be established.

In considering the 1×10^{-6} screening criterion, the staff recognizes that the definitions of some design-basis floods may rely not on a single flood-causing mechanism but, potentially, on two or more contemporaneous flooding events. ANSI/ANS-2.12-1978, "Guidelines for Combining Natural and External Man-Made Hazards at Power Reactor Sites" (Ref. 34), and ANSI/ANS-58.21-2007, "External Events in PRA Methodology" (Ref. 35) (although now withdrawn), describe methods for evaluating and combining flood hazard events for design purposes. However, guidance on formal PFHA approaches for consistent treatment of combined events is lacking. Therefore, the NRC will assess the reasonableness of qualitative and quantitative probability estimates for combined events on a case-by-case basis (see Section C, Regulatory Position 3f).

A-3. Non-stationarity: Climate Variability, Climate Change, and Sea Level Rise

Although geologists, paleoclimatologists, and other researchers have long known that the Earth's climate exhibits significant variability over a range of time scales (Ref. 29), the conventional wisdom until fairly recently has been that the near-term envelope of variability is stable enough at the decade-to-century time scale to allow design and management of water resources infrastructure under the assumption of stationarity. However, recent developments in climate research have shown that significant global and regional warming trends at these time scales have occurred in the past several decades and are expected to continue or even accelerate, with implications for hydrologic extremes including tropical cyclones, precipitation, and floods (Ref. 36, 37, 38, 39), as well as sea-level rise (SLR).

Relative SLR is the combined effect of water level change (due to thermal expansion and glacier and ice sheet melting) and land subsidence (or uplift). SLR is a well-documented process that has been ongoing in most places since the end of the last ice age. Design-basis flood analyses for coastal sites should include trends in mean sea level observed and reported by the National Oceanic and Atmospheric Administration's National Ocean Service (Ref. 40, 41). However, global climate warming has been identified as a cause of the recent acceleration of SLR, and climate change is expected to increase the rate of SLR in the future, although the magnitude of the increase is uncertain. Applicants should consult the most recent authoritative climate assessments provided by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. Global Change Research Program (USGCRP) (e.g., Ref. 37, 38). The applicant should describe the basis for the selection of its preferred SLR estimate.

Prevailing climate theory states that mean and extreme behaviors of hydroclimate elements should change as the global climate warms. The theory is that warming will increase the moisture load within the atmosphere, which in turn will intensify the hydrologic cycle, with postulated increases in the mean state and extremes of key hydrologic fluxes such as evapotranspiration, tropospheric water vapor content, precipitation, and runoff (Ref. 42, 43). In agreement with the theory, both global climate model simulations and observations point to more intense precipitation worldwide, compared to the past 40 to 50 years, and to increases in precipitation levels in the United States over the 20th century (Ref. 43, 44, 45, 46, 47). However, observed increases in precipitation levels have not been directly tied to increases in extreme floods. In fact, recent analyses of long-term streamflow records by the U.S. Geological Survey (USGS) show few statistically significant trends in floods from annual maximum stream flows as a result of intense precipitation events within the United States (Ref. 48).

Findings on tropical cyclone activity are similar. Current theory and modeling indicate increasing tropical cyclone intensity with warming of the global climate (Ref. 49, 50, 51), where the usual metric for intensity is central pressure deficit. For example, an average 8 percent increase in hurricane intensity is estimated for every 1 degree C (1.8 degrees F) of sea surface temperature rise Ref (49, 52). On the other hand, as with stream flows, the available record does not show significant trends in tropical cyclone intensity linked to observed global warming (Ref 53, 54, 55). However, it has been noted that the full response to a given level of global warning may take 20 to 25 years (Ref. 56). Therefore, during the operating period of new nuclear power plants, the effects of global warming on extreme storms may be larger than currently observed.

The preceding discussion highlights the difficulty in translating climate research findings into practical applications for hydrologic design problems. Nonetheless, decisions need to be made, and several State and Federal agencies have developed frameworks for assessing climate change risks for water resource applications (Ref. 57, 58, 59, 60, 61, 62), mainly for river basins in the western United States. Similar efforts have been made for major European river basins (Ref 63, 64, 65). One approach involves downscaling the output from global climate models to the regional scale by applying statistical bias correction using historical meteorological data (Ref 66, 67, 68). An alternative approach is to use a regional climate model to dynamically downscale relevant hydrometeorological data (Ref. 69). Regardless of the downscaling approach, the downscaled hydrometeorological data are then used as input to a hydrologic model that simulates regional or catchment-scale hydrological processes (Ref. 59, 61, 70).

With respect to coastal flooding, a common way to account for potential climate change and SLR effects in flood estimates is to add an SLR factor to flood estimates from other mechanisms (e.g., coastal flooding, tides, or storm surge). Although this straightforward approach is appealing, recent research using detailed storm surge and wave models has shown pronounced nonlinear effects for coastal portions of southeast Louisiana (Ref. 71) and Texas (Ref. 72). Therefore, such assessments should include the coupled effect of both storm intensification and SLR. Approaches for coupling storm intensification and SLR for have been developed for tropical cyclones (Ref. 72) and non-tropical storms (Refs. 74, 75, 76, and 77).

SLR caused by either climate variability or secular trends may also lead to increased coastal erosion. A study published in 2011 concerning the California coast presents a methodology for assessing erosion potential and subsequent flooding effects caused by SLR for both cliff- and dune-backed coastlines (Ref. 73).

There is not a widely accepted, standardized method of analyzing shoreline changes due to SLR, such as sediment erosion and deposition. The current edition of the U.S. Army Corps of Engineers *Coastal Engineering Manual* discusses this topic broadly. However, before undertaking a study of this topic, an applicant should consult the USGS "National Assessment of Shoreline Change" series applicable to the site of interest, as a first step in estimating the potential effects of SLR on a candidate project site (Ref. 78). These reports are publicly available on the USGS website.

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APPENDIX B
SITE HYDROLOGIC DESCRIPTION

This appendix describes the site hydrologic features and flood history that are needed to build an adequate basis for identifying credible flood-causing mechanisms at the site and to support the engineering analysis of flooding phenomena to determine the design-basis flood. As noted in the main body of this regulatory guide, some small modular reactor and advanced reactor designs may not need makeup water or access to an ultimate heat sink (other than the atmosphere).

B-1. Use of a Geographical Information System

The hydrologic features, data, and modeling needed to support an engineering analysis exhibit both spatial and temporal variability, which makes the constructs and philosophy of a geographical information system (GIS) well suited for external flood hazard analyses (Ref. 1). A GIS makes it possible to capture, store, manipulate, analyze, manage, and present all types of geographically referenced data. In the simplest terms, a GIS merges cartography and database technology. It is also useful as a data storage and visualization tool for modeling output. Appendix A to NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011 (Ref. 2), (Ref. 1) discusses the use of GIS and documents source data typically collected and processed for integrating GIS into hydrological modeling environments.

B-1.1 Spatial Datum

Hydrologic features have geospatial attributes that need to be referenced consistently. Therefore, spatial data should be referenced to an appropriate horizontal (map) and vertical (elevation) datum. The National Oceanic and Atmospheric Administration's (NOAA's) National Geodetic Survey (NGS) defines, maintains, and provides access to the National Spatial Reference System, which is a consistent coordinate system that defines latitude, longitude, height, scale, gravity, and orientation throughout the United States.

B-1.2 Horizontal Datum

The North American Datum of 1927 (NAD27) and the North American Datum of 1983 (NAD83) are two horizontal datums currently used in the United States (Ref. 3). Several NGS technical reports detail the relationship between NAD83 and commonly used plane coordinate systems, such as the State Plane Coordinate System and the Universal Transverse Mercator System (Refs. 4, 5, and 6). NGS provides a horizontal datum conversion tool as part of the NGS Geodetic Toolkit, which can be used to convert position coordinates from NAD27 to NAD83 (Ref. 7). GIS software packages also provide conversion tools.

B-1.3 Vertical Datum

All elevations should be referenced to a clearly defined vertical datum. Historically, Federal agencies have used the National Geodetic Vertical Datum of 1929 (NGVD29). NGVD29 was originally called the Sea Level Datum of 1929; however, in 1972, the name was changed to dispel the common misconception that NGVD29 and mean sea level were equivalent sea level datums.[1] Although many existing maps (and hence flood analyses) still reference NGVD29, it is no longer supported by NGS. The North American Vertical Datum of 1988 (NAVD88) has replaced NGVD29 as the national standard geodetic reference for heights. (As with NGVD29, NAVD88 should not be used as mean sea level.) Benchmark elevations relative to NAVD88 are available from NGS through the internet. NGS provides a vertical datum conversion tool as part of the NGS Geodetic Toolkit, which can be used to convert elevations from NGVD29 to NAVD88 (Ref. 7). GIS software packages also provide conversion tools.

B-1.4 Hydrographic Datum

Tidal and bathymetric measurements are typically referred to as a hydrographic or tidal datum (a standard elevation defined by a certain phase of the tide). Tidal data are used as references to measure *local* water levels and should not be extended into areas that have different oceanographic characteristics without substantiation of the measurements. Such data are referenced to fixed benchmarks (i.e., the station datum) so that they can be recovered when needed. Because of periodic and secular trends, tidal data are standardized over a fixed time interval. NOAA's National Ocean Service has adopted a 19-year period as the official time segment over which observations are taken and reduced to obtain mean values for tidal data (e.g., mean lower low-water). This period is called the National Tidal Datum Epoch (NTDE). The present NTDE is 1983–2001; the NTDE is actively considered for revision every 20 to 25 years. Tidal data in certain regions with anomalous sea level changes (e.g., Alaska, Gulf of Mexico) are calculated on a modified 5-year epoch.

Traditionally, tidal and bathymetric measurements have been collected independently of topographic measurements; therefore, depth and height data are referred to different vertical benchmarks, which create inconsistencies across the land/sea interface. Geodetic data relationships to tidal data can be established at tide stations by connecting tidal benchmark networks to the National Spatial Reference System, which is maintained by NGS (Ref. 8). The elevation relationship between geodetic data and tidal data should not be extrapolated away from a particular location without correction or interpolation, because the relationships vary with parameters such as range of tide, bathymetry, topography, geoid variations, and vertical land movement. Any interpolation should be done carefully and should be guided, where possible, by the use of the NOAA National Ocean Service VDatum tool (Ref. 7).

Chapter 5, "Water Levels and Long Waves," in Part II of the U.S. Army Corps of Engineers (USACE) *Coastal Engineering Manual*, issued 2008 (Ref. 9), discusses water surface elevation datums in detail. This manual defines commonly used coastal (tidal) and Great Lakes datums and discusses their relationship to geodetic datums.

B-2. Site and Facilities Description

The physical characteristics of the project site and associated facilities should be described in sufficient detail to allow independent analysis of how power plant construction might alter existing drainage patterns and thus affect projected flood levels intended to define the design-basis flood.

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[1] NGVD29 was originally derived from a general adjustment of the first-order leveling networks based on cadastral surveys of the United States and Canada after holding mean sea level observed at 26 long-term tide stations as fixed. Local mean sea level (LMSL) varies from place to place because of astronomical phenomena, local winds, river stages, storms, local gravity anomalies, and local subsidence or uplift. In NGVD29, Galveston, Texas, was selected as the "Primary Benchmark of the United States," and the LMSL there was set equal to 0.00 ft. Because many variables affect sea level and because the geodetic datum represents a best fit over a broad area, the relationship between the geodetic datum and the LMSL is not consistent from one location to another in either time or space (i.e., the LMSL is not equal to 0.00 ft everywhere). For this reason, NGVD29 should not be used as the mean sea level.

B-2.1 Project Site

The geographic location and areal extent of the project site (power plant footprint and exclusion zone) should be described unambiguously on a map, with special attention to pertinent topographic and hydrologic features. This map should also delineate both existing and planned roadways and utility infrastructure. The coordinates of the project site's proposed boundaries should be established using procedures that satisfy the Federal Geographic Data Committee's spatial accuracy standards and should be reported using an approved plane coordinate system (e.g., the Universal Transverse Mercator coordinate system or an appropriate State plane coordinate system). The site's proposed location should also be stated in terms of distances and directions from the nearest town, city, or U.S. Geological Survey (USGS) control base and meridian. The location of the proposed site with respect to nearby streams, lakes, reservoirs, and oceans should also be stated in terms of horizontal distances and directions.

A topographic map of the proposed site should be provided, with a contour interval that is consistent with the natural character of the topography. Additional topographic maps should be included that clearly show any proposed changes to the site's topography due to the construction of the power plant. The elevation datum and adjustment to be used and their relationship to other locally used datums should be defined.

The design-basis flood level(s) proposed for the site should be depicted on a map in relation to the modified, postconstruction topography of the project site. This map should also depict the maximum flood elevation that each plausible flood-causing mechanism is projected to achieve. The applicant should analyze any potential for flooding caused by a plausible mechanism to affect access routes to the project site.

B-2.2 Facilities

Maps should be provided that show the locations of all major structures in relation to the finished site grade for the project site. The maps should specify the elevations of all structures, systems, and components (SSCs) important to safety, to demonstrate that the SSCs can withstand the design-basis flood level(s) proposed and that flood protection features are adequate. Regulatory Guide 1.29, "Seismic Design Classification for Nuclear Power Plants" (Ref. 10), identifies the SSCs that should be designed to withstand conditions resulting from the design-basis flood and to retain their capability to perform their safety functions. Any openings in safety-related or non-safety-related SSCs that may provide a pathway for external floodwaters to come in contact with safety-related equipment should be considered. Such openings include, but are not limited to, access doors, access hatches, vents, ductwork, cable, or piping penetrations, below-grade conduits, and drains.

The applicant should analyze the potential for flooding to affect access to safety-related equipment within the site area. Similarly, if proposing to rely on the deployment of flood mitigation equipment, the applicant should identify the locations of staging areas and analyze the potential for flooding of those areas, as well as the potential for flooding to interfere with deployment of flood mitigation equipment.

B-3. Hydrologic Features

Both existing and planned local or regional hydrologic features that might affect the project site should be described. For inland sites, such natural drainage features include, for example, streams, rivers, swamps, lakes, and ground water systems. Any drainage features regulated by a dam or other engineered feature should be identified. Manmade features such as dams, reservoirs, canals, and other impoundments should be also depicted. At coastal sites, the list should be expanded to include open coasts, estuaries, sounds, bays, and tidal marshes.

Particular attention should be given to hydrologic features intended as surface water supply sources for both safety-related and non-safety-related power plant operations (Ref. 11).

B-3.1 Site Drainage

The applicant should provide the areas and slopes of drainage features of the project site (e.g., both the power block and controlled area), including any anticipated changes in topography or grades resulting from power plant construction (e.g., preconstruction and postconstruction drainage areas should be described and delineated).

B-3.2 Watercourses

The lengths, slopes, and contributing drainage areas for those watercourses identified (e.g., creeks, streams, rivers) that are contiguous with the project site should be delineated and described. This description should include existing and planned land use practices within the watershed of interest, with particular attention to the types of existing and planned surface cover. The introduction of several nationwide datasets (described below) has made it much easier to collect and organize this information.

The USGS National Geospatial Program (Ref. 12) manages the National Hydrography Dataset (NHD), Watershed Boundary Dataset (WBD), and NHDPlus High Resolution (NHDPlus HR). These geospatial datasets represent the surface water of the United States for mapping and modeling applications.

The Watershed Boundary Dataset defines the areal extent of the surface water drainage system to some specified location, accounting for all physical features within the domain specified. It is based on the hydrologic unit code boundaries system, which is a consistent hierarchical method of dividing major drainage basins throughout the United States (Ref. 13). The levels of subdivision used for organizing hydrologic data are called hydrologic units. A hydrologic unit is a drainage area nested in a multilevel, hierarchical drainage system. Its boundaries are defined by hydrographic and topographic criteria that delineate an area of land upstream from a specific point on a river, stream, or similar surface water body. A hydrologic unit can accept surface water directly from upstream drainage areas and indirectly from associated surface areas such as remnant, noncontributing areas, and diversions, to form a drainage area with single or multiple outlet points. The hydrologic unit codes describe the relationships among the hydrologic units, to represent the way smaller watersheds drain areas that together form larger watersheds.

The NHD represents the water drainage network of the United States with features such as rivers, streams, canals, lakes, ponds, coastline, dams, and streamgages. The NHD is a comprehensive set of digital spatial data that represents the surface water of the United States using common features such as lakes, ponds, streams, rivers, canals, stream gauges, and dams. Polygons are used to represent area features such as lakes, ponds, and rivers; lines are used to represent linear features such as streams and smaller rivers; and points are used to represent point features such as stream gauges and dams (Ref. 14).

The NHDPlus HR (Ref. 15) is a geospatial dataset depicting the flow of water across the Nation's landscapes and through the stream network. NHDPlus HR is built by integrating high resolution NHD and Watershed Boundary Dataset (WBD) data with 3D Elevation Program (3DEP, Ref. 16) 10-meter digital elevation model (DEM) data into a suite of vector, raster, and tabular datasets.

Detailed topographic data are needed to support detailed hydrologic and hydraulic modeling. The USGS National Geospatial Program (Ref. 17) provides a foundation of digital geospatial data representing the topography, natural landscape, and manmade environment of the United States. The National Map is a collaborative effort among the USGS and other Federal, State, and local partners to improve and deliver topographic information for the Nation. 3DEP is the elevation component of the National Map. In addition, some State and local agencies have produced detailed topographic datasets in cooperation with the Federal Emergency Management Agency's (FEMA's) national flood map modernization program (Ref. 17).

FEMA provides flood hazard and risk data products including flood insurance rate maps (FIRMS) to support the National Flood Insurance Program, as well as non-regulatory Flood Risk Maps (Ref. 18).

B-3.3 Dams, Reservoirs, and Levees

The applicant should provide an inventory of the dams, reservoirs, and levees within the watershed occupied by the power plant project, as well as a description of future planned features. Ownership, history, and detailed engineering descriptions should be given for all upstream and downstream features judged to be mechanisms plausibly capable of contributing to the design-basis flood. The applicant should also identify those dams, reservoirs, and levees that would be relied on for the plant's safety-related water supply (Ref. 11). Detailed guidance on assessing flooding hazards due to water control structure failures and incidents is provided in RG 1.256 (Ref. 12).

B-3.4 Lakes

For natural lakes adjacent to or near the project site, the average water level elevation, normal and extreme ranges of elevation, and representative depths should be given.

Water levels and other information on the Great Lakes and St. Lawrence River is developed and maintained by several organizations: USACE (Ref. 13), NOAA (Ref. 14), Canadian Hydrographic Service (Ref. 15), and the Coordinating Committee on Great Lakes Basic Hydraulic and Hydrologic Data (Ref. 16).

Great Lakes water levels are officially measured from the International Great Lakes Datum of 1985 (IGLD (1985)). Because the crust of the Earth in the Great Lakes region is continuously rising with respect to sea level and because the rate of movement is not uniform throughout the region, the International Great Lakes Datum of 1985 is updated every 25 to 30 years. At the time of this RG, IDLG (2020) is in preparation, with adoption targeted for 2027 (Ref. 16).

Some State and local government agencies provide information for lakes within their jurisdiction. For small lakes, mapping protocols using digital echosounder equipment connected to a Global Positioning System unit allow very accurate bathymetric maps to be created.

B-3.5 Coastal Sites

For project sites on an ocean shoreline or along an estuary, bay, or sound, the range of tides experienced should be specified. To support storm surge and wind-wave calculations, detailed topographic and bathymetric information is needed. The flooding assessments should also include rates of relative sea-level rise (SLR).

NOAA's National Ocean Service operates the National Water Level Observation Network, which provides long-term observations of tides, water levels, and trends (i.e., relative SLR). This information, as well as technical reports, is available from the NOAA Tides and Currents website (Ref. 17).

Topographic and bathymetric data can be obtained from Federal, State, and local agencies. NOAA's National Geophysical Data Center builds and distributes high-resolution coastal digital elevation models that integrate ocean bathymetry and land topography (Ref. 19). They can be used to model coastal processes (e.g., tsunami inundation, storm surge, SLR), hazard mitigation, and emergency preparedness. NOAA's National Ocean Service has developed the U.S. Estuarine Bathymetry Dataset, (Ref 20.) which is a digital raster compilation of hydrographic survey data for selected U.S. estuaries. Approximately 70 estuarine bathymetric datasets are available in both 30 m (98 ft) and 3-arc-second resolutions. In addition, some State and local agencies have produced detailed topographic datasets and bathymetric datasets in cooperation with FEMA's national flood map modernization program.

B-4. Flood History

The hydrologic description of the proposed nuclear power plant site should identify significant regional flooding events that have been recorded by instrument (e.g., on gauged streams) or in historical reports. Where available, paleo flood information should also be provided. The applicability of historical flood records and paleo flood information should be assessed in the context of any subsequent changes, especially manmade changes such as dams, reservoirs, levees, dredging, channel control structures, sediment control efforts, or shore protection structures. Major flooding events should be described. The descriptions should include the flood-causing mechanisms and observations or estimates of peak discharges and maximum water levels.

A key step in estimating (forecasting) likely future flood magnitudes is to examine recorded observations. The complexity of flood-producing systems precludes the exclusive use of analytical or numerical modeling to estimate future floods. Local information on observed floods is essential to calibrate models so that they are valid for a particular site or region. In addition to instrument records, observations of debris or flood marks on riverbanks and flood plains can sometimes provide useful information on relatively recent flooding events.

Historical flood information should supplement recorded observations. This information may be obtained from old newspaper reports; interviews with longtime residents; and records of Federal, State, or local government agencies, highway authorities, port authorities, river commissions, coastal commissions, and railroad or utility companies. Literature reviews, including internet searches, are a useful research tool for this topic.

Useful information can also be obtained from paleo flood studies that examine botanical, geological, or geomorphological information indicating the occurrence (or nonoccurrence) of large floods that predate human observation (Ref. 21). Information from these studies, when available can be used to estimate the probable maximum flood. Examples of relevant botanical data indicative of paleo flood stages include scars on trees, abnormal tree rings, and tipped trees along a stream or river. Geophysical evidence of paleo flood stages includes slack water deposits, scour lines, and terraces (or the absence of these features). Combined with radiocarbon or other dating techniques, botanical and geophysical data can significantly enhance the flood record in favorable environments with stable channels.

For coastal sites, the flooding history should include available information on major tropical or extratropical storms. Measurements or estimates of storm intensity, size, windspeeds, surge heights, inundated areas, and coincident astronomical tides and SLR should be included.

Certain Federal agencies, such as the U.S. Bureau of Reclamation, NOAA, USGS, USACE, FEMA, and Tennessee Valley Authority, collect and analyze flooding information. State and local government agencies, river basin commissions, and local water or power utilities may also have streamflow and water level data. Some State and local government agencies and coastal commissions collect information on coastal flooding within their jurisdictions.

For its part, the USGS collects and publishes discharge data for watercourses (e.g., streams, rivers, canals) and water-stage data for rivers, streams, reservoirs, and lakes in the United States. Much of this information can be downloaded from the USGS Groundwater and Streamflow Information Program website (Ref. 22). In addition, water supply papers, hydrologic investigation atlases, open file reports, and circulars may include USGS flood data (e.g., frequencies, discharges, water levels, water surface profiles); summaries and inundation maps of notable past floods; paleo flood studies; and hydrologic descriptions of major river basins. NOAA's National Weather Service (NWS) River Forecast Centers also provide information on historical floods within their regions, including reanalysis maps of associated heavy precipitation (Ref. 23).

Several organizations within NOAA collect and maintain information on past storms affecting U.S. coastal regions. NOAA's National Climatic Data Center, in cooperation with the National Hurricane Center (NHC), publishes summaries of tropical and subtropical cyclone climatology for the North Atlantic and North Pacific (Ref. 24,25). The NHC publishes periodic updates listing the most intense hurricanes to make landfall in the United States, along with additional statistics on U.S. hurricanes and tropical cyclones in general (Ref. 26). The *Mariners Weather Log*, published by the NOAA NWS, provides meteorological information to the maritime community, and contains a comprehensive chronicle of marine weather in the North Atlantic and North Pacific (Ref. 27). In addition, the *Monthly Weather Review*, a peer-reviewed scientific journal of the American Meteorological Society, publishes annual summaries of the Atlantic hurricane season (Ref. 28).

Historical information on tsunami sources and wave runup can be obtained from NOAA's National Geophysical Data Center and World Data Center Global Historical Tsunami Database (Ref. 29). This database provides information on tsunami events (sources and wave runup) from approximately the last 4,000 years in the Atlantic, Indian, and Pacific Oceans and the Mediterranean and Caribbean Seas.

B-5. Winds

The NOAA Storm Prediction Center (SPC) produces severe weather forecasts and daily severe weather event summaries and reports for tornadoes and severe thunderstorm events (Ref. 30). The SPC also maintains severe weather and severe wind databases that cover the years from 1950 to the present. These databases are available at the SPC Severe Weather GIS (SVRGIS) website (Ref. 31).

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APPENDIX C

FLOODING CAUSED BY LOCAL INTENSE PRECIPITATION

This appendix describes the estimation of external flooding caused by local intense precipitation (LIP). Evaluation of external flooding due to an LIP event is typically limited to the area in and around the immediate nuclear power plant (NPP) site, regardless of the proposed finished grade elevation or the proximity of the site to nearby hydraulic features such as rivers, lakes, or other water bodies capable of generating an external flood. The flood hazard reevaluations performed in connection with the 2011 accident at the Fukushima Dai-ichi NPP in Japan revealed that most NPP sites were vulnerable to LIP-based flooding to varying degrees. Therefore, applicants need to analyze this flooding mechanism to demonstrate that the site drainage has been designed so that facility structures, systems, and components (SSCs) credited to perform safety functions are protected from ponding water (hydrostatic effects) and from the drag and impact forces of flowing water (hydrodynamic effects) during an LIP event.

C-1. General Considerations

Many publications describe the principles and practice of storm water management. Manuals and standards published by the American Society of Civil Engineers (Refs. 1 and 2) are among the most widely used and should be adequate to manage LIP. The following summarizes the typical steps in evaluating external flooding caused by LIP:

a. Develop and organize the following site information:

   (1) detailed topographic maps of the design area (e.g., the power plant site and controlled area) including proposed power plant structures

   (2) channels located upstream and downstream of the design area

   (3) locations, areas, and slopes for paved surfaces

   (4) locations, areas, slopes, and land cover for natural surfaces

   (5) locations, sizes, and types of storm sewers or other drainage components

   (6) location of the vehicle barrier system (VBS), if any, including key design features

b. Select the values of parameters for the most severe storm with respect to LIP.

c. Estimate surface runoff for contributing areas.

d. Analyze conveyance of surface runoff.

The LIP analysis should examine the potential for blockage of the designated site drainage features. The simplest and most conservative conceptual model for evaluating site drainage is to assume that no active components are functional and that the passive site drainage network is also compromised owing to obstruction. Waterborne sediment or other debris (e.g., sticks, leaf litter, tree limbs, trash) are the most common causes of blockage. (Hydrometeorological evidence suggests that it is extremely rare for the passive site drainage network to remain completely unblocked during an LIP event (Ref. 3).) In regions with cold winters, the potential for onsite ice accumulation to contribute to blockages or otherwise change drainage patterns should be assessed. If a VBS is proposed for the project site, the analysis should also include the effects of the VBS on surface flow.

If the water surface elevation or dynamic forces estimated from the LIP analysis are determined not to affect any SSCs that perform safety functions, it can be concluded that the proposed plant design is adequate to withstand the hazards of LIP flooding for the estimated water surface elevation and associated effects.

C-2. Local Intense Precipitation Events

LIP refers to an extreme rainfall event postulated to occur at the immediate plant site. Precipitation events are quantified by the (uniform) depth of rainfall accumulating over a given area during a specified time interval (e.g., inches of rainfall in x hours for an area of y square miles). The duration of the event and the area are needed to fully quantify an extreme precipitation event such as LIP. Generally, the amount of extreme precipitation decreases with increasing duration and increasing area.

Because of the limited length of instrument records and the generally sparse distribution of recording rain gauges, it is highly unlikely that adequate single-site precipitation records exist at any proposed NPP site. It is therefore common to use the concept of probable maximum precipitation (PMP) instead. PMP is theoretically defined as the greatest depth of precipitation for a given duration that is thought to be physically possible over a particular geographic area at a given time of year (Ref. 4). PMP estimates have been derived using single-station observations of extreme precipitation coupled with theoretical models for moisture maximization, transposition, and envelopment. The National Weather Service has published PMP estimates for much of the United States in a series of hydrometeorological reports (HMRs) (Refs. 5, 6, 7, 8, 9, 10, 11, 12, 13, and 14). Examples include HMR 51, “Probable Maximum Precipitation Estimates, United States East of the 105th Meridian,” issued 1978 (Ref. 7), and HMR 52, “Application of Probable Maximum Precipitation Estimates, United States East of the 105th Meridian,” issued 1982 (Ref. 8).

Following the guidance in HMR 52, it is common to use the 1-hour, 1-square-mile (mi^2) PMP at the site location to develop an estimate of LIP. HMR 52 describes a procedure for combining scaled values of the 1-hour, 1 mi^2 PMP to construct hyetographs (temporal distributions) of LIP. NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America,” issued November 2011 (Ref. 3), provides an example application of this procedure. However, the appropriate area size and event duration to produce a conservative LIP estimate are site-specific. It is not sufficient to evaluate LIP simply by adopting the 1-hour, 1 mi^2 PMP without investigating other areas and durations. The basis for the specific PMP value used in the LIP analysis needs to be explained.

Because the time variability of rainfall intensity can significantly affect the resulting hydrograph, overly smooth temporal patterns are discouraged. In addition, the time variability of rainfall intensity has been observed to increase with the storm return period, and many extreme storms have multiple peaks of high rainfall intensity (Refs. 15, 16, and 17).

As discussed in appendix A, the validity of PMP values provided by HMRs should be assessed in light of precipitation events that have occurred in the region since the HMRs were published. Several NPP licensees developed site-specific PMP estimates during the post-Fukushima flooding reevaluations. Applicants estimating PMP using any source other than a NWS HMR need to explain the basis for the specific PMP value used. NUREG/KM-0015, “Considerations for Estimating Site-Specific Probable Maximum Precipitation at Nuclear Power Plants in the United States of America: Final Report,” issued

September 2021 (Ref. 18), discusses considerations for an acceptable approach to estimating a site-specific PMP as an alternative to an HMR-based estimate.

C-3. Estimating Surface Runoff

Rainfall-runoff models should be applied to estimate the direct runoff hydrograph and thus demonstrate the ability of the site grading to drain water away from the locations of SSCs that perform safety functions under the conditions of the postulated LIP scenario. To simplify calculations and ensure a conservative estimate, all rainfall should be assumed to be converted to direct runoff (i.e., no credit should be taken for losses resulting from infiltration, evaporation, or other factors). Therefore, no credit should be taken for hydraulic sinks in the runoff model. The complexity of the rainfall-runoff modeling will vary case by case.

For small single watersheds or areas with simple grading plans and a well-characterized type of surface cover, simplified analytical approaches such as the Rational Method (Refs. 19, 20, and 21) may apply. Although there is an extensive literature describing software packages that implement these methods and discussing representative parameter values to use with them (e.g., time of concentration, runoff coefficient, runoff curve number) (Refs. 21, 22, 23, and 24), it is critical to check these values against observed flood data in a given region. In addition, much of the literature is devoted to flooding events of relatively short return periods (e.g., 10 years, 20 years, 100 years); therefore, parameters for larger floods may need adjustment to capture nonlinearity in flood response. For example, studies have shown that the runoff coefficient used in the Rational Method increases as the return period of the design-basis storm increases (Ref. 25). Therefore, although these simplified methods are appealing, the validity of the results will depend on careful selection and justification of the input parameter values.

The most widely used method for converting a rainfall hyetograph into a discharge hydrograph for a drainage basin is the unit hydrograph approach. As first defined by Sherman (Ref. 26), the unit hydrograph is the discharge hydrograph resulting from one unit (usually a 1-inch or 1-millimeter unit) of excess precipitation applied uniformly over the basin at a constant rate for a given duration. Once the unit hydrograph has been determined, the discharge for rainfall hyetographs of arbitrary shape and duration can be constructed through scaling and superposition of the unit hydrograph. Many standard hydrology texts (Refs. 20, 22, 24, and 27) present the theory and application of the unit hydrograph method. Traditionally, the unit hydrograph is derived from observed rainfall-runoff events on gauged watersheds. Where adequate rainfall-runoff observations are not available, regionalized, synthetic unit hydrographs based on rainfall and runoff from similar drainage catchments have been developed. Widely used examples include the U.S. Department of Agriculture National Resource Conservation Service’s unit hydrograph (Ref. 28), Snyder’s unit hydrograph (Ref. 29), and Clark’s unit hydrograph (Ref. 30).

A key feature of the unit hydrograph approach to estimating runoff from rainfall excess is that the modeling relies on the linear response of the watershed to some precipitation event. This means that the direct runoff hydrograph from a unit depth of rainfall excess is the unit hydrograph and that the direct runoff hydrograph for any other amount of rainfall excess can be estimated by scaling the ordinates of the unit hydrograph by that amount. For example, the ordinates of the direct runoff hydrograph corresponding to two units of rainfall excess are simply twice the ordinates of the unit hydrograph.

It is important to understand that the unit hydrograph linear model starts to give nonconservative results as the rainfall intensity and volume increase to the magnitudes of the PMP event. During the PMP event, the large amount of rainfall excess causes the runoff mechanism to be dominated by highly nonlinear hydraulic effects in the overland flow process. Surface roughness resulting from small irregularities may be subsumed by the greater depth of the overland flow, increasing the likelihood of quicker delivery of overland flow to the channel network. When possible, unit hydrographs based on severe storms approaching the magnitude of a PMP event in the drainage basin of concern should be used.

If this type of data is not available, applicants need to adjust the traditional unit hydrograph derived from observations of storms of smaller magnitudes to account for the more rapid overland flow response during storm events that approach the PMP. In addition, the U.S. Army Corps of Engineers reduces the time to peak discharge for the unit hydrographs estimated from smaller storms before applying it to large storms (Refs. 21 and 31) and increases the peak discharge of smaller storm unit hydrographs before applying it to large storms (Ref. 2). NUREG/CR-7046 provides an example of applying these adjustments. Where possible, applicants may use a different adjustment method supported by data in the drainage basin of concern. In these instances, they should completely describe the method, the supporting data, and a justification.

Often, because of the number and complexity of drainages and subdrainages at the site, the staff recommends modeling the site as a network of drainages. Software packages are available for implementing such modeling approaches. Many of these software packages use some version of the unit hydrograph approach; therefore, the preceding discussion of the treatment of nonlinear effects applies equally to modeling conducted using such software.

C-4. Conveyance of Surface Runoff

Hydraulic modeling should be used to analyze the capacity of both natural and engineered drainage channels that convey the surface runoff discharge produced by LIP away from the power block area to some receiving stream, river, lake, or other surface water body. In many instances, because of the number and complexity of drainages and subdrainages at the project site, it may be necessary to model the site as a network of drainages to demonstrate that the site drainages and subdrainages have adequate capacity for an LIP event. The complexity of this modeling will vary case by case; however, a steady-state analysis using the peak runoff discharge should usually be sufficient to demonstrate drainage channel conveyance capacity. Ultimately, the hydraulic model will need to demonstrate that the design-basis flood level from an LIP event will not exceed specified elevations for SSCs that perform safety functions.

Multiple software packages are available for implementing such modeling approaches. NUREG/CR-7046 discusses considerations for selecting hydrologic modeling software to analyze site drainage in an LIP scenario. Many of the commercially available software packages rely on some version of the unit hydrograph approach; therefore, the preceding discussion of the treatment of nonlinear effects applies equally to modeling conducted using such software.

Regardless of the software package selected to evaluate the LIP-based external flood-causing mechanism, the following determinations may be needed to demonstrate the adequacy of drainage channel conveyance capacity: (1) the mass balance errors in the computer model are acceptably small, (2) the flow pathways and areas of inundation in the computer model are reasonable, (3) the flow velocities depicted in the computer model are reasonable, and (4) there are no indications of numerical instabilities or unexpected supercritical flow conditions in the computer model in areas potentially susceptible to LIP-based flooding.

C-5. Consideration of Associated Flooding Effects

Past review experience suggests that secondary flooding effects, such as wind/wave effects that could coincide with the estimated flooding due to LIP, are marginal, owing to the shallow flood depths occurring within the project site during an intense precipitation event. The same can be said for any associated hydrostatic and hydrodynamic forces, debris and waterborne projectile loads, and the effects of sediment erosion and deposition. Consequently, the types of analyses described in appendix J to this regulatory guide may not be needed. If choosing not to analyze associated flooding effects, the applicant should explain this choice.

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[1] Documents from ASCE are available through the ASCE website at http://www.asce.org/ or by contacting the ASCE home office at American Society of Civil Engineers, 1801 Alexander Bell Drive, Reston, VA 20191; telephone (800) 548-2723.

[2] Publicly available NRC published documents are available electronically through the NRC Library on the NRC's public website at http://www.nrc.gov/reading-rm/doc-collections/ and through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html.. For problems with ADAMS, contact the Public Document Room staff at 301-415-4737 or (800) 397-4209, or email pdr.resource@nrc.gov. The NRC Public Document Room (PDR), where you may also examine and order copies of publicly available documents, is open by appointment. To make an appointment to visit the PDR, please send an email to pdr.resource@nrc.gov or call 1-800-397-4209 or 301-415-4737, between 8 a.m. and 4 p.m. eastern time (ET), Monday through Friday, except Federal holidays.

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APPENDIX D

FLOODING ON STREAMS CAUSED BY PRECIPITATION

This appendix describes the estimation of external flooding on streams and rivers resulting from precipitation events other than local intense precipitation (e.g., flooding at the nuclear power plant (NPP) site caused by precipitation occurring over watersheds upstream of the site). For the purposes of this guide, "stream" is used as a general term for any natural body of water flowing with measurable velocity in a channel. The channel may be natural, manmade, or natural with significant manmade modifications (e.g., dams, levees, revetments, dredging).

D-1. General Considerations

This appendix focuses on deterministic analysis aimed at determining the most extreme credible flood (probable maximum flood (PMF)). The PMF is defined as the hypothetical flood (i.e., peak discharge, volume, and hydrograph shape) considered the most severe physically possible. It is typically estimated by applying a hypothetical extreme rainfall event (probable maximum precipitation (PMP)), along with other hydrologic factors favorable for maximum flood runoff (e.g., sequential storms, coincident snowmelt, minimal infiltration) (Ref. 1). Both hydrostatic effects (caused by flood elevation) and dynamic forces (caused by flow velocities) should be considered.

The maximum credible estimate of the depth and flow velocities at the project site owing to some riverine-based flood can result from various combinations of factors and processes occurring in the watershed upstream of the project site (e.g., sequential precipitation events; timing, centering, and duration of precipitation; seasonal variation of precipitation and antecedent moisture; snowpack accumulation, snowmelt, and meteorological factors influencing snowmelt timing; flood-caused dam failures; reservoir elevations; base flow) and those occurring at the site (e.g., superimposed wind waves). The appropriate combinations to consider should be determined on a site-specific basis.

For a given precipitation event, the analysis of the riverine flood hazard will generally involve the following steps:

a. Evaluate the rainfall flux over the watershed as a function of space and time.

b. Evaluate the rainfall excess or effective rainfall flux as a function of space and time. (Effective rainfall is the rainfall available for runoff after accounting for infiltration and other modeled losses.)

c. Route the rainfall excess to the watershed outlet (or plant site) to determine the corresponding flood hydrograph.

Although this guide treats runoff and flood routing as separate topics, available computer programs combine hydrologic runoff and hydraulic routing models to simulate the outflow response of an entire watershed (Refs. 2, 3, and 4). These computer programs may be appropriate for estimating design-basis floods such as the PMF if adequate data are available and if the computer simulations can be validated for large flooding events (combined models typically use simplified hydraulic routing methods in place of solving the full dynamic wave equation). Documentation of a riverine-based flood analysis using a combined model should contain all the elements described in sections D-6 and D-7.

A riverine-based flood analysis should also consider the seasonal variation of storm and precipitation characteristics, watershed characteristics, and reservoir operating rules to ensure that the controlling storms and controlling flood have been identified.

Appendix A presents a general discussion of probabilistic flood estimation; however, specific guidance on probabilistic approaches is beyond the scope of this guide. Publications by the U.S. Bureau of Reclamation, which has developed a framework for including probabilistic flood hazard estimates in its risk-analysis approach to dam safety, may be useful in this regard (Refs. 5, 6, and 7).

The variety and amount of data described in the following paragraphs may be challenging to aggregate, organize, and use effectively without employing state-of-the-art computer-based geographical information processing tools. Therefore, the staff encourages the use of geographical information system (GIS) technology (Refs. 8 and 9). Standalone GIS software packages may be used to organize the necessary hydrologic data, or hydrologic modeling software with integrated GIS capabilities may be available in some cases. The analyses performed by such software are essentially deterministic. Appendix C to NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011 (Ref. 10), contains a case study that illustrates the use of GIS tools to develop the watershed description and create an input framework for the hydrologic modeling software package. There are many other examples in the literature.

Regardless of the computer code selected to evaluate a riverine-based external flood-causing mechanism, the analysis should demonstrate (1) the mass balance errors in the computer model are acceptably small, (2) the flow pathways and areas of inundation in the computer model are reasonable, (3) the flow velocities depicted in the computer model are reasonable, and (4) there are no indications of numerical instabilities or unexpected supercritical flow conditions in the computer model in areas potentially susceptible to riverine-based flooding.

D-2. Simplified Analyses

In some cases, the NPP site may be located topographically well above any potential sources of external flooding, and it would be immediately obvious from an inspection of a contour map (or from a simple analysis) that designated structures, systems, and components that perform safety functions are not at risk. In such cases, applicants may use a progressive screening approach, such as the hierarchical hazard assessment discussed in NUREG/CR-7046, to evaluate the potential for riverine-based flooding. That evaluation should include a description of the site relative to major hydraulic features including flood plains, the nature and extent of past flooding, and the topographic elevation of the site in relation to reports of past floods. As discussed in NUREG/CR-7046, simplified procedures may be used; however, all methods and assumptions should be clearly conservative.

If it cannot be demonstrated clearly that no credible postulated river or stream flooding event could affect the site, a detailed analysis of this external flood-causing mechanism should be performed.

D-3. Watershed Description

The estimation of potential external flooding on rivers and streams calls for the description of certain parameters related to the physical properties of the watershed, which depend on the level of detail of the analysis methods selected. In most cases, the description will need to include delineation of the drainage basins (and subbasins), topographic (elevation) information, soil types, land cover and land use data, delineation of flood plains and stream channels, stream channel slopes, stream channel profiles, water control structures, and any other structures that may affect streamflow in the event. If the watershed is regulated, the nature and extent of regulation should be described. Evidence of past stream-channel diversion and the potential for future channel diversions should also be considered. Appendix A discusses potential sources for some of these data.

D-4. Flooding History

The flooding history of the NPP site, the portion of the watershed upstream of the project site, and the surrounding region should be examined and factored into the analyses, as appropriate. All available information (e.g., instrument records, historical reports, and paleo flood information) should be used to the extent practical. Applicants should summarize major historical flooding events, providing the dates of occurrence, observation stations, instantaneous peak discharges, and crest elevations. They should also describe the flood-causing processes. As mentioned above, if the watershed is a regulated entity, the nature and extent of regulation should also be described. Appendix A discusses information sources useful for developing a flooding history.

Flood frequency information is important for characterizing the flooding behavior of a watershed. When sufficient data (e.g., gauge data, historical records, or paleo flood information) are available, a flood frequency analysis can provide useful information about the magnitude and frequency of selected flood discharge scenarios. Frequency is commonly expressed in terms of annual exceedance probability or as a recurrence interval (i.e., the reciprocal of exceedance probability) in years. In general, flood frequency analysis by itself is not an adequate basis for estimating the extreme floods of interest in the design-basis flood problem. However, it can provide the basis for selecting less severe floods for a combined-event analysis.

Flood frequency analysis commonly is performed on records of annual maximum instantaneous peak discharges collected systematically at streamflow gauging stations. U.S. Geological Survey (USGS) Bulletin 17C, "Guidelines for Determining Floodflow Frequency," issued 2018 (Ref. 11), and prepared by the Hydrology Subcommittee of the Interagency Advisory Committee on Water Data, defines consistent procedures for determining flood flow frequency from peak-flow records. The USGS and the U.S. Army Corps of Engineers (USACE) have developed computer software that implements the Bulletin 17C procedures (Refs. 12 and 13). In addition, the USGS National Streamflow Statistics Program has developed databases and other software programs that provide simplified methods for estimating streamflow statistics for ungauged sites (Refs. 14 and 15).

D-5. Precipitation Estimates

In most parts of the world, variations in streamflow reflect natural variations in rainfall. Therefore, estimates of extreme precipitation are essential to estimating flood hazards. Generally, at higher latitudes and altitudes, more precipitation falls as snow instead of rain. When precipitation falls as snow, a snowpack accumulates until warmer weather allows for melting. In such regions, snowmelt runoff becomes an important factor in estimating flood hazards.

Snowmelt and rainfall may combine to generate larger floods than either process alone. Therefore, for drainage areas with significant snowpack accumulations, two modeling scenarios should be considered: (1) extreme precipitation falling on snow and (2) extreme snowpack melt combined with rain. The 100-year average exceedance rainfall and snowpack are typically used in combination with the extreme snowpack melt and rainfall, respectively.

D-5.1 Precipitation as Rainfall

Designs for critical infrastructure such as NPPs need to anticipate external flooding attributable to infrequent but extreme precipitation events occurring over the watershed in which the facility is located.

In general, two major sources of precipitation data, both developed by the National Oceanic and Atmospheric Administration's (NOAA's) National Weather Service (NWS), can be used to estimate precipitation: (1) precipitation frequency atlases and reports containing precipitation frequency information, and (2) hydrometeorological reports (HMRs) containing PMP estimates.

D-5.1.1 Precipitation Frequency

NOAA's NWS Hydrometeorological Design Studies Center (HDSC) collects, analyzes, and publishes precipitation frequency information for the United States, Puerto Rico, and the Virgin Islands. NOAA Atlas 14 (Refs. 16, 17, 18, and 19) contains precipitation frequency estimates with associated confidence limits for the United States and additional information such as temporal distributions and seasonality. NOAA Atlas 14 is divided into multiple volumes based on geographic divisions of the country and is intended as the official source of point precipitation frequency estimates and associated information for the United States, Puerto Rico, and the Virgin Islands. It also discusses the development methodology and intermediate results for point precipitation frequency estimates.

The HDSC also maintains online repositories of precipitation frequency information. The Precipitation Frequency Data Server was developed and published in tandem with NOAA Atlas 14 to allow delivery of the results and supporting information in multiple forms through the internet (Ref. 20). An online repository of point precipitation frequency reports organized by State/territory and duration is also available (Ref. 21). The point precipitation frequency data in NOAA Atlas 14 and other HDSC reports may be useful in developing flooding estimates that are appropriate for the analysis of combined events (see appendix I). However, the NWS does not recommend extrapolation of point precipitation frequency information beyond that presented in its reports, nor does the U.S. Nuclear Regulatory Commission (NRC) staff recommend such extrapolation. Therefore, in most cases, point precipitation frequency data alone will not be a sufficient basis for the extreme precipitation estimates needed for determining the PMF. In addition, because of the limited length of instrument records and the extremely sparse distribution of recording rain gauges, it is highly unlikely that adequate site-specific precipitation records exist for any proposed NPP site to support an approach based purely on precipitation frequency.

D-5.1.2 Probable Maximum Precipitation

Because of the temporal and spatial limitations of the instrument record, analyses often use the concept of PMP. PMP is theoretically defined as the greatest depth of precipitation for a given duration that is thought to be physically possible over a particular area at a given time of year (Ref. 22). PMP estimates have been derived using single-station observations of extreme precipitation coupled with theoretical models for moisture maximization, transposition, and envelopment. The NWS has published PMP estimates for much of the United States in a series of HMRs (Refs. 22, 23, 24, 25, 26, 27, 28, 29, 30, and 31). Examples include HMR 51, "Probable Maximum Precipitation Estimates, United States East of the 105th Meridian," issued 1978 (Ref. 22), and HMR 52, "Application of Probable Maximum Precipitation Estimates, United States East of the 105th Meridian," issued 1982 (Ref. 25).

As discussed in appendix A, the validity of PMP values provided by the HMRs should be evaluated in light of precipitation events that have occurred in the region since the HMRs were published. For example, the most recent storms analyzed in HMR 51, which covers most of the eastern United States, occurred in the early 1970s. In addition to concerns about dated PMP estimates, certain regions (e.g., regions in the eastern United States where orographic uplift is important) have never been included in any of the HMRs.

If there are no PMP estimates for the drainage basins that may present a flood hazard to the NPP site, or if existing estimates lack input from recent significant storms, an analysis should be performed to provide such estimates. Various HMRs and manuals published by the United Nations World Meteorological Organization (Refs. 32, 33, and 34) describe procedures for developing PMP estimates (certain details of the methods have changed over the years). The USACE has published precipitation data for notable extreme storms that occurred between 1945 and 1973 (Ref. 35). Many of the HMRs also provide precipitation data on storms used in the respective reports. In general, for recent storms, precipitation data from NWS rain gauge networks combined with data from NWS weather radar provide the best basis for PMP estimates (Ref. 36). In particular, the PMP pilot study report for North Carolina and South Carolina (Ref. 37) describes in detail the procedures for using radar data for PMP estimations.

D-5.1.3 Design Rainfall

The rainfall depths developed in a PMP analysis (or estimated from HMRs) are storm-centered, area-averaged values for a watershed of a particular size. However, alternative temporal and spatial distributions of PMP estimates are needed to estimate which storm configuration produces maximum flood discharges from a particular drainage basin.

The size of the drainage basin of interest determines the storm size and duration appropriate for a given situation. In general, the critical storm size will be approximately equal to the basin size, and the critical event duration will be approximately equal to the time of concentration for the watershed (Ref. 37). To estimate a PMF, an optimal temporal distribution and optimal centering and orientation over the watershed should be applied. In some cases, movement of the storm along the basin axis may result in the largest discharge (storms moving generally in the downstream direction tend to produce larger peak flows than storms moving upstream). To optimize (maximize) the precipitation event selected for the PMF analysis, different storm orientations and durations need to be evaluated.

HMR 52 (Ref. 25) presents an extensive discussion of procedures for applying PMP estimates to actual drainages to arrive at design rainfall estimates needed as input for flood estimation models. HMR 52 describes a stepwise approach for estimating the temporal and spatial distribution of PMP estimates from HMR 51 (Ref. 22) for an actual drainage basin. This approach considers the size of the basin and size and orientation of the PMP storm. NUREG/CR-7046, appendix C, contains a case study that demonstrates the application of the HMR 52 concepts using both a GIS and a software package that automates the HMR 52 procedures.

As an alternative to an HMR-based precipitation estimate, applicants may propose to rely on a site-specific estimate. NUREG/KM-0015, “Considerations for Estimating Site-Specific Probable Maximum Precipitation at Nuclear Power Plants in the United States of America: Final Report,” issued September 2021 (Ref. 39), discusses considerations for an acceptable approach to estimating a site-specific PMP.

D-5.2 Snow and Snowmelt

When precipitation falls as snow (not rain), a snowpack accumulates until warmer weather allows melting. Therefore, a snow-based runoff analysis requires the determination of the quantity and distribution of snow (more specifically, of the water content or snow water equivalent (SWE) that exists in the basin before the onset of melting and runoff). The SWE will likely be the primary determinant governing the magnitude of the snowmelt-runoff volume, and the distribution of the snowpack in the basin (whether it is at low or high elevations) will be a factor in the rate of melting during the melt season. The SWE estimate should either directly or indirectly consider the process of snow accumulation and distribution, which involves a variety of meteorological and topographical interactions in the basin during the winter accumulation period. Meteorological factors include air temperature, wind, precipitable water, atmospheric circulation patterns, frontal activity, temperature lapse rate, and stability of the airmass. Topographical factors include elevation, slope, aspect, exposure, and vegetation cover.

Detailed guidance on estimating snowpack accumulation is beyond the scope of this regulatory guide. The applicant should consult USACE guidance documents (Ref. 40) and standard hydrology texts (Refs. 41 and 42). Information for estimating snowpack can be obtained from the Parameter-Elevation Regressions on Independent Slopes Model (PRISM) Climate Program, which is maintained at Oregon State University (Ref. 43). The PRISM program illustrates high-resolution gridded estimates of monthly and annual means for temperature and precipitation (rain and snow) as a function of elevation.

D-6. Estimating Surface Runoff

D-6.1 Rainfall-Runoff Modeling

Appendix C (section C-2) to this guide examines rainfall-runoff modeling for local intense precipitation at the NPP site. The discussions in appendix C of hydrologic models, unit hydrographs, and the application of unit hydrographs to extreme rainfall events apply equally to the problem of determining PMF on streams. Section 3.3 and appendix C to NUREG/CR-7046 contain additional discussion and a case study illustrating the application of a widely used hydrologic computer modeling software package. Standard hydrology texts (Refs. 38, 42, 44, 45, 46, and 47) should be consulted for descriptions of rainfall-runoff modeling approaches and available software packages. The authors of these texts are recognized experts in surface water hydrology, and the texts, which are primarily academic in nature, describe rainfall-runoff modeling approaches acceptable to the NRC staff. Nonetheless, each applicant should demonstrate the adequacy of the chosen software package and the applicability of the chosen approach to its site.

The documentation of the rainfall-runoff analysis should include (1) a description of the watershed (e.g., area, topography, soil types, land cover), (2) the type of computer modeling software used, (3) the rainfall-runoff transformation function used (e.g., a description of the unit or synthetic hydrograph) and the basis for its selection, (4) a validation exercise using actual flood data, if available, and (5) a sensitivity analysis of input rainfall, routing parameters, and hydrograph parameters, as necessary, to demonstrate the conservatism of the estimated PMF.

D-6.2 Snowmelt-Runoff Modeling

At higher latitudes and altitudes, more precipitation falls as snow instead of rain, and runoff depends on the heat supply for snowmelt rather than the timing of precipitation. Meltwater is routed by the same pathways as rainfall; therefore, snowmelt runoff is typically estimated using rainfall-runoff models with extra model features (computer routines) added to store and subsequently melt precipitation that falls as snow (Refs. 5, 48, 49, and 50). The application of these snowmelt simulation models typically involves calibrating the transformation models in warm (non-snowmelt) conditions and then calibrating the snowmelt routine to input the melt for the transformation model for the accumulation-ablation period. In addition, dedicated snowmelt-runoff models that are not intended for use in non-snowy environments are available, although even these models need to allow for precipitation that falls as rain during the melt season (Ref. 51).

D-7. Flood Routing

Flood routing refers to procedures to determine the outflow hydrograph at a point downstream in a stream (or reservoir) as a function of the inflow hydrograph at a point (or points) upstream. The shape of the outflow hydrograph depends on the inflow hydrograph, channel geometry and roughness, bed slope, length of the channel reach, and initial and boundary flow conditions.

Standard hydrology texts (Refs. 27, 38, 42, 44, 45, 46, and 47) should be consulted for descriptions of modeling approaches and available software packages for flood routing. The authors of these texts are recognized experts in surface water hydrology, and the texts, which are primarily academic in nature, describe flood route modeling approaches acceptable to the NRC staff. Nonetheless, each applicant should demonstrate the adequacy of the chosen software package and the applicability of the chosen approach to its site. In general, full dynamic wave (hydraulic) flood-routing models are preferred because they can simulate unsteady, nonuniform flows, including backwater effects, which are often encountered in modeling the movement of a flood wave in a system of channels with tributaries, reservoirs, or downstream controls, or a combination of these. Simpler approaches (e.g., hydrologic or storage-routing models) may be appropriate in certain cases. The documentation of the analysis should provide sufficient technical justification for the model simplifications adopted. Contemporary hydrology texts such as those referenced above and studies and reports published by the USGS (e.g., Refs. 51, 52, 53, 54, 55, 56, 57, and 58) should be used to guide the selection of roughness coefficients and other model parameters. Applicants should document the data used to develop the storage-routing model, including parameters and coefficients.

The documentation of the flood-routing analysis should include (1) a description of the stream channel network, (2) a description of the flood-routing method, (3) a detailed description of reach lengths, cross sections, and cross section locations, (4) development of channel roughness coefficients, (5) initial and boundary conditions, and (6) validation exercises that apply the analysis to historical floods, if available.

Appendices C and D to NUREG/CR-7046 contain additional discussion of flood-routing methods and a case study that illustrates the application of a widely used hydraulic modeling package.

D-8. Consideration of Associated Flooding Effects

Past review experience suggests that riverine-based flooding can be important in defining the design-basis flood for an NPP site. Consequently, the types of analyses described in appendix J to this regulatory guide will likely be needed.

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APPENDIX E

FLOODING CAUSED BY STORM SURGE

This appendix discusses the estimation of coastal flooding caused by storm surge. In the context of this regulatory guide, “coastal” refers to the nearshore regions of any water body (e.g., ocean, lake, bay, estuary) where storm surge may occur, not just regions adjacent to the open ocean. The discussions of storm surge below use the generic terms “hurricane” and “hurricane storm surge” to refer to any tropical cyclone and tropical-cyclone-induced storm surge, respectively.

Storms are atmospheric disturbances characterized by low pressures and high winds. A storm surge represents the water surface response to wind-induced surface shear stress and pressure fields. Storm-induced surges can cause short-term increases in water level to elevations considerably above mean water level.

A progressive screening approach such as the hierarchical hazard assessment, as proposed in NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America,” issued November 2011 (Ref. 2), may be used to evaluate the potential for storm surge flooding. As discussed in that report, simplified procedures may be used; however, all methods and assumptions should be clearly conservative. If it cannot be demonstrated clearly that no credible postulated storm-surge-based flooding event could affect the site, a detailed analysis of this external flood-causing mechanism should be performed.

E-1. Storm Types

Several types of storms are associated with storm surge in coastal regions of the United States, including tropical cyclones, extratropical cyclones, squalls, and “hybrid storms”.

E-1.1 Tropical Cyclones

Storms that originate in the tropics are called tropical cyclones. These events include tropical depressions, tropical storms, and hurricanes and are characterized by organized convection around a low-pressure center. Tropical cyclones primarily affect the East Coast and Gulf Coast of the United States, the Caribbean Sea, and the islands in the Pacific Ocean. However, less frequently, tropical cyclones can also occur on the western coast of Mexico and southern coast of California. Tropical cyclones are typically classified according to windspeed and central pressure using the Saffir-Simpson scale (Ref. 3), as shown in table E-1.

Recently, integrated kinetic energy has been proposed as a measure of the destructive potential of tropical cyclones (Ref. 4). The integrated kinetic energy is computed from the surface wind field by integrating the 10-meter-level kinetic energy per unit volume over portions of the storm domain volume that contains sustained surface windspeeds within specific ranges. However, the Saffir-Simpson scale is still the most widely known indicator of hazard or potential damage. Although the Saffir-Simpson scale is appropriate for wind damage, its use as an indicator of potential storm surge hazards is discouraged, because factors such as storm size and offshore bathymetry are also very important to storm surge generation (Ref. 5).

E-1.2 Extratropical Cyclones

Storms that result from instabilities along the interface between warm and cold fronts are called extratropical storms. Extratropical storms affect the east and west coasts of the United States, Alaska, and the Great Lakes; however, storm-generated surges are most significant along the upper East Coast, where they are often called “nor’easters”. Nor’easters move along the Atlantic coast with winds from the northeast onto the shoreline, typically producing winds ranging from 48 to 64 kilometers per hour (km/h) (30 to 40 miles per hour (mph)), with gusts that can exceed 119 km/h (74 mph). Although below hurricane force, these winds can persist for several days to a week and generate large waves and storm surges. In comparison, windspeeds and storm surge elevations resulting from hurricanes are more severe; their shoreline effects tend to be more localized, and they are generally confined to stretches of coastline of about 105 km (65 mi) or less.

Table E-1 Saffir-Simpson Hurricane Scale

TYPE AND CATEGORY	WINDSPEED (km/h, mph)	CENTRAL PRESSURE (millibars, in Hg)
Tropical Depression	< 62 (< 39)	
Tropical Storm	63–117 (39–73)	
Category 1 Hurricane (H1)	118–153 (74–95)	> 980 (> 28.94)
Category 2 Hurricane (H2)	154–177 (96–110)	965–980 (28.50–28.94)
Category 3 Hurricane (H3)	178–209 (111–130)	945–965 (27.91–28.50)
Category 4 Hurricane (H4)	210–249 (131–155)	920–945 (27.17–27.91)
Category 5 Hurricane (H5)	> 250 (> 155)	< 920 (< 27.17)

E-1.3 Squalls

In addition to the two major types of storms just discussed, severe windstorms or moving squall lines (also called “straight line winds” or “derechos”) can also cause storm surge (and seiches). Gusts as high as 209 km/h (130 mph) have been measured for these convective system windstorms (Ref. 6). In the United States, severe windstorms are most common in late spring and summer (May through August) in the upper and mid-Mississippi Valley, the Ohio Valley, and the southern Great Plains (Refs. 6 and 7). During the cool season (September through April), they are less frequent and are most likely to occur from eastern Texas into the southeastern states (Refs. 6 and 7).

E-1.4 Hybrid Storms

The storm categories outlined above are not necessarily strict or mutually exclusive. Many tropical cyclones move into the middle latitudes and turn into extratropical cyclones; this process is generally called an “extratropical transition” (Ref. 8). In addition, different types of storm systems may interact. For example, the Halloween Storm of October 1991 (also widely known as the 1991 Perfect Storm) resulted from the interaction of three significant meteorological systems, including a hurricane and an intense winter storm (Ref. 9). The systems combined to create very strong winds over an extremely long fetch, which lasted for days.

E-2. Storm Surge Winds

When examining the effects of storms, it is important to be aware of and to use the proper averaging interval for wind information, because different averaging intervals may be appropriate for estimating wave generation in water bodies of differing sizes. In small lakes and reservoirs or in riverine settings, a 1- to 5-minute windspeed may be enough to attain a fetch-limited condition. In this case, the fastest 1- to 5-minute windspeed will produce the largest waves and will therefore be the appropriate choice for the design-basis wave (Ref. 8). In large lakes and in locations adjacent to the ocean, the wave generation process tends to achieve a maximum wave height response to average winds over a 15- to 30-minute interval (Ref. 10).

E-3. Sources of Historic Storm Information

Storms in and around the coasts of the United States have been reported since the late 1800s. The National Oceanic and Atmospheric Administration's (NOAA's) National Hurricane Center maintains databases on tropical cyclones that are continually updated to reflect both recent and historical events. The U.S. Army Corps of Engineers (USACE) Coastal Hydraulics Laboratory has developed a hindcast database that covers over 30 years of extratropical storms (Ref. 11). Appendix B discusses other sources of information. Despite these documentation efforts, detailed geophysical data for specific storm surge event parameters are limited and not always available.

For the requisite storm surge hazard assessments, the applicant should examine the historical record for each storm type appropriate for the region to estimate the extreme winds associated with the storm type. This detailed historical analysis should be augmented by synthetic storms parameterized to account for conditions that are physically reasonable but more severe than those in the historical record. In the matter of selecting synthetic storms for the probable maximum hurricane (PMH) analysis, section E-4.5.1 of this appendix describes techniques for developing a synthetic PMH database.

E-4. Approaches to the Analysis of Storm Surge

Storm surge is a complex phenomenon involving the interactions of several geophysical processes, including a direct forcing mechanism from the storm's wind and pressure fields, additional effects of wind-driven waves, and Coriolis effects due to the Earth's rotation (Ref. 12). Although storm surges may arise from different types of storms (e.g., hurricanes or extratropical storms), the analysis should consider the common aspects of all storm surges.

The geometry of the ocean basin and the continental shelf leading up to the coastal floodplain strongly influences storm surges, and topography and land cover strongly influence propagation of the surge over land (Ref. 13). As a storm makes landfall, the storm surge (wave) may interact significantly with the astronomical tides and, in some cases, with riverine-based flooding caused by rainfall (Refs. 14 and 15). In all cases, the storm surge estimate should include the combined effects of wave setup and wave runup. Contemporary texts and manuals on coastal engineering (Refs. 16, 17, and 18) describe methods for estimating wave setup and wave runup. Despite the complexities discussed above, a simplified analysis may sometimes suffice to demonstrate that a site is flood-dry with respect to storm surge (Ref. 1). Obvious reasons for concluding that a site is flood-dry with respect to storm surge include sufficient distance from the coastline or other large water bodies where a surge could form and ample elevation above those water bodies.

Another potentially useful source of site-specific information is the storm surge analyses performed by nuclear power plant (NPP) owners and operators in response to the 2011 accident at the Fukushima Dai-ichi NPP in Japan. These analyses indicated that storm surge was generally the bounding flood-causing mechanism at NPP sites located along coastlines. The analyses are publicly available in the NRC's Agencywide Documents Access and Management System (ADAMS).

E-4.1 Simplified Hurricane Storm Surge Analysis

Through research supported by the NRC, the USACE has developed a simplified analysis method based on additive consideration of surge, wave setup, inland surge propagation, wave runup, tides, sea-level rise, and uncertainty. This method can be used to determine whether storm surge is likely to affect a particular project site (Ref. 17). In addition, several storm surge forecast modeling systems developed for use by Federal, State, and local authorities (Refs. 18, 19, and 20) may be appropriate for this task, especially for locations along the open coast with favorable nearshore bathymetry (e.g., a steep or narrow continental shelf).

Another example of a simplified storm surge analysis method is the PMH approach described in NUREG/CR-7046. However, as explained in appendix A, the National Weather Service (NWS) reports from which PMH parameters are usually determined are limited and out of date, as they do not reflect hurricane activity from the past 30 years. Furthermore, since the last revision of this regulatory guide, researchers have identified thermodynamics-based maximum windspeeds ("maximum potential intensities") and corresponding minimum storm-core pressures that are increasingly used in preference to the PMH (Refs. 22, 23, and 24). In addition, it cannot always be assumed, a priori, that the PMH will cause the largest storm surge (Ref. 19). Therefore, the use of a simplified storm surge analysis approach will need to be justified case by case.

E-4.2 Coupled Wind, Wave, and Hydrodynamic Modeling

When methods such as those outlined above cannot eliminate storm surge flooding from consideration as a potential design-basis flood, detailed storm surge modeling is necessary. The current state of the art in hurricane storm surge modeling is to use coupled hydrodynamic ocean circulation and wave models, both of which are driven by a hurricane boundary layer model (hurricane wind model) that provides the atmospheric forcing mechanism responsible for the incipient storm (Refs. 19, 25, and 26). Effective use of a coupled modeling approach to estimate storm surge calls for high-resolution bathymetric and onshore topographic data, historical tidal information, meteorological data, and significant computational resources. However, hindcasting studies have clearly demonstrated the value of the approach, especially in regions of complex bathymetry (Ref. 25). A recent report on storm surge research supported by the NRC presents an example of a coupled modeling approach (Ref. 19). Reports by other Federal agencies (Ref. 1) and the coastal and ocean engineering literature provide other examples (Refs. 14, 15, and 27).

Ocean circulation models have been widely used to model storm surge in the coastal zone and are described in the literature (Refs. 28, 29, 30, 31, 32, and 33). The literature further indicates that storm surge estimations have been carried out using hurricane wind modeling approaches of varying complexity, including simple parametric models (Refs. 34 and 35), steady-state planetary boundary layer models (Refs. 36 and 37), non-steady-state planetary boundary layer models (Refs. 38, 39, and 40), and kinematic hindcast models (Refs. 41, 42, and 43). A 2009 paper assesses several of these approaches (Ref. 44). Lastly, several publicly available two-dimensional wave models are now widely used that can estimate wave impacts in conjunction with storm surge modeling (Refs. 45, 46, 47, 48, and 49). The literature cites other hydraulic computer codes available to model PMH behavior (Refs. 50, 51, and 52). The application should explain the choice of the model used and why the results are adequate.

Studies have shown that several factors are important when developing storm surge estimates for any particular project site. These include (1) adequate model grid resolution, (2) specification of model domain and boundary conditions, (3) representation of bottom friction coefficients and wind stress coefficients, and (4) selection and parameterization of a sufficient set of storms to model. These factors are discussed briefly below. The published coastal and ocean engineering literature provides more information.

In general, the modeling domain should be sufficient to ensure that boundary effects do not influence any storm surge prediction results. The location and specification of open boundary conditions are especially critical when resonant modes may exist in the modeled basin (Ref. 53). In addition, for regions with complex bathymetry, nearshore topography, or irregular shorelines, detailed grid resolution is generally needed to predict storm surge and inundation effects (Refs. 25, 54, and 55). In some cases, it may be necessary to understand the influence of manmade structures such as breakwaters, levees, highways, railroads, and canals in the computer simulations (Refs. 19 and 25). The need for large modeling domains together with fine resolution of nearshore bathymetry and topography has led to the use of unstructured meshes in several storm surge computer modeling platforms. However, some platforms are designed mainly for open-coast storm surge forecasting applications and still rely on structured grid systems (Ref. 21); such platforms may not be appropriate for detailed storm surge modeling at sites near estuaries, bays, inlets, and other such areas with complex geography (Ref. 19).

Storm surge estimates are also sensitive to the choice of bottom friction coefficients and wind stress coefficients used in the analysis, especially in shallow-depth areas. In general, these coefficients will depend on the area under investigation and on the hurricane storm surge model used in the analysis. A parametric sensitivity analysis, together with calibration and validation procedures using historical storms in the region of interest, should be employed to develop reasonable estimates for these coefficients.

Although the examination (and modeling) of historical storms that have affected the region is necessary, an analysis limited to historical storms is seldom sufficient, because relatively few large storms may have occurred in the region under study or because there may be few instrument records for the reported events. Therefore, the selection and parameterization of a reasonable set of synthetic storms is an important part of estimating a design-basis storm surge. NUREG/CR-7134, “The Estimation of Very-Low Probability Hurricane Storm Surges for Design and Licensing of Nuclear Power Plants in Coastal Areas,” issued October 2012 (Ref. 19), identifies several key parameters that influence storm surge generically at a particular site. As mentioned above, useful site-specific information may also be obtained from the storm surge flood analyses performed by NPP owners and operators in response to the 2011 Fukushima event, which are available in ADAMS. In general, the latter analyses revealed that the storm surge parameters of interest include the following: (1) the along-coast and cross-coast location of the site, (2) the strength of the storm, measured as central pressure deficit, (3) the size of the storm, measured as distance from the storm eye to the maximum winds, (4) the storm’s forward velocity, (5) the angle of the storm heading (azimuth), (6) the shape of the storm’s pressure profile, (7) the along-coast location of the storm’s landfall, and (8) stochastic fluctuations.

For cases where the 100-year or perhaps 500-year inundation levels are of interest, it may be possible to apply statistical storm surge estimation approaches using actual or modeled distributions for the parameters identified in the preceding paragraph (Refs. 56 and 57). However, as a rule it is not practical to extend this approach to very large, very-low-probability storm surges when determining design-basis floods at NPPs, because of the large uncertainties in the resulting estimate. Instead, applicants can use a combined deterministic-probabilistic approach, as described in NUREG/CR-7134 (Ref. 19), to evaluate storm surge events of very low probability. The combined approach attempts to determine which factors affecting hurricane storm surges at a specified site can be shown to have asymptotic upper limits, and which factors must be treated in a context that allows for natural uncertainty in the upper limit.

E-4.3 Extratropical Storm Surge

Generally, extratropical events have lower wind magnitudes and generate smaller maximum surge elevations than hurricanes. However, surges from storms of this class can cause substantial damage because of their large areas of influence and extended durations. For example, nor'easters can deliver high winds with accompanying storm surges over large geographical areas (hundreds of square miles) for several days and even weeks (Ref. 58). In addition, extratropical events are generally much more frequent than hurricanes. As for hurricane storm surge, the estimation of an extratropical storm surge (ETSS) should include the effects of wave setup and wave runup. Coastal engineering texts and manuals describe methods of estimating wave setup and wave runup (Refs. 16, 17, and 18).

The mechanics of an ETSS are fundamentally the same as those of tropical cyclone storm surges. The same estimation approach (using coupled shallow-water hydrodynamic and wave propagation models, both driven by a model of the storm pressure and wind fields) can be applied. The modeling considerations discussed above for a hurricane storm surge (e.g., adequate resolution of bathymetry and topography, coupled treatment of wave-induced momentum transfer, boundary conditions, storm set selection) apply equally to ETSS estimation.

However, the ETSS estimation needs to address the significant differences in the atmospheric forcing mechanism. Extratropical cyclones differ structurally from tropical cyclones. Specifically, an extratropical cyclone is associated with a frontal boundary, and its pressure and wind field are highly asymmetrical. Thus, the relatively simple parameterizations used in hurricane boundary layer models do not apply to extratropical storms. Instead, the hydrodynamic and wave models use surface winds and pressures generated by an atmospheric boundary layer model. Several such models have been applied to ETSS prediction and forecasting (Refs. 59, 60, 61, and 62). In many ocean areas along continental margins, moored buoys, offshore platforms, and automatic coastal weather stations provide sufficient in situ wind data for the reanalysis of well-documented extratropical storms (Ref. 44).

Operational ETSS models have been developed (Refs. 63 and 64). For example, the NWS has developed an ETSS forecast model (ET-Surge) based on the Sea, Lake, Overland Surge from Hurricanes (SLOSH) computer code (Ref. 65).

E-4.4 Tide and Storm Surge Interaction

The timing of storm events with respect to the phase of the astronomical tide is critical in storm surge estimation. For example, when a storm surge coincides with a spring high tide, the resulting total surge can be much larger than the storm surge alone (Ref. 66). Therefore, when developing extreme storm surge estimates, the 10 percent exceedance high tide should be assumed to occur coincidentally with the storm surge. This tide can be determined from the recorded tide or from predicted astronomical tide tables (see appendix A and its references). If predicted tides are used, estimations should account for local sea level anomalies.

E-4.5 Integrated Hydrologic and Hydrodynamic Modeling

At sites along estuaries or in low-lying coastal areas, antecedent storms, or hurricane-driven rainfall, or both, may produce external flooding that coincides with the arrival of a storm surge. In such situations, integrated hydrologic and storm surge models may be needed to estimate flooding accurately (Refs. 14, 15, 67, and 68).

American National Standards Institute (ANSI)/American Nuclear Society (ANS)-2.8-1992, "Determining Design Basis Flooding at Power Reactor Sites" (Ref. 1), provides detailed guidance on extratropical windstorms (section 7.2 of ANSI/ANS-2.8-1992) and squall lines (section 7.3). For the Great Lakes, the standard provides a set of fixed values of extratropical storm parameters instead of a meteorological study (sections 7.2.2.3.1 and 7.2.2.3.3). In addition, section 7.2.3.1 of the standard states that "[a] moving squall line should be considered for the locations along Lake Michigan where significant surges have been observed because of such a meteorological event. The possible region of occurrence includes others of the Great Lakes.…"

E-4.5.1 Storm Surge Modeling Based on Synthetic Storms

As mentioned earlier, a review of the literature indicates that the number of hurricane records for the United States is limited, and that the values of key parameters for those hurricane events have not always been recorded. Recent review experience indicates that applicants are therefore likely to estimate the PMH at a particular project site by evaluating synthetic storms generated by computer simulations. A detailed site- or region-specific meteorological study should be conducted to identify applicable mechanisms and to verify that the ANSI/ANS-2.8-1992 model and inputs reflect the most severe treatment of meteorological parameters. This applies to all coastal sites, including the Great Lakes (ANSI/ANS-2.8-1992).

Probabilistic-only and deterministic-only approaches to estimating very-low-probability storm surges each have strengths and weaknesses, depending on the safety hazard assessment objective. As noted earlier in this regulatory guide, previous staff review experience indicates that storm surge flood hazard assessments for project sites have relied on a deterministic-only approach. More recently, Federal agencies have begun to use a combined approach, which has some advantages over either approach used alone (Ref. 19). The USACE, for example, has developed a probabilistic-deterministic methodology for storm surge hazard assessment that can be combined with the hierarchical hazard assessment approach to generate a design-basis storm surge estimate with risk information. The methodology uses an integrative, interdisciplinary approach that incorporates state-of-the-art knowledge in hurricane science, hydrology, and probabilistic methods. It involves the following steps:

(1) selection of a stochastic set of simulated storm tracks affecting the region of interest

(2) hydrodynamic simulation of the region of interest using a high-resolution surge model and the simulated storm tracks to generate predicted time histories of windspeeds and corresponding time histories of storm surge heights at sites within the affected region

(3) use of predicted windspeed and storm surge height information generated in steps (1) and (2) to develop probabilistic information on the joint probability of windspeed and storm surge height events (Ref. 68)

Regardless of the method used, applicants should identify and assess sensitivities and uncertainties for model parameters that may significantly influence design-basis storm surge estimates.

This guidance considers four techniques for synthetic storm generation: the estimation of PMH, the use of the Joint Probability Method (JPM), an evaluation based on the recommendations of ANSI/ANS-2.8-1992, and the use of the empirical simulation technique (EST). The PMH and JPM are used to generate synthetic hurricanes. ANSI/ANS-2.8-1992 and the EST have been used to generate synthetic extratropical storms and squall lines.

E-4.5.1.1 Hurricane Parameters

This section applies to all coastal sites, excluding the Great Lakes, as described in ANSI/ANS-2.8-1992.

Probable Maximum Hurricane. NOAA NWS Technical Report 23, "Meteorological Criteria for Standard Project Hurricane and Probable Maximum Hurricane Windfields, Gulf and East Coasts of the United States," issued 1979 (Ref. 69), describes the PMH method in detail. PMH meteorological parameters, as described in NUREG-0800, section 2.4.5 (Ref. 70), define the physical attributes of the PMH used to derive wind fields that can serve as input for an atmospheric model. Storm surge model simulations are performed with numerous combinations of PMH parameters to obtain the highest design-basis storm surge at the site.

NOAA NWS Technical Report 23 provides methods for estimating PMH wind fields. The PMH is defined as a hypothetical steady-state hurricane with a combination of values of meteorological parameters that will give the highest sustained windspeed that can reasonably be expected to occur at a specified coastal location. (The term "steady-state" indicates that the values of hurricane wind field parameters do not change during, at least, the last several hours before the PMH makes landfall.) The meteorological parameters that define the PMH wind field include the hurricane's peripheral pressure, central pressure, radius of maximum winds, forward speed, and track direction. Note that the NWS 23 method provides no risk information (e.g., return period) and applies only to the deterministic storm surge analysis of hurricanes.

The PMH parameter values in NWS 23 are based on data from historical hurricanes from 1851 to 1977 and are presented for multiple locations along the Gulf of Mexico and Atlantic Ocean coastlines corresponding to their milepost distances from the U.S.-Mexico border. Comparisons of hurricane climatology during the period evaluated in NWS 23 with hurricanes making landfall after 1975 indicate that the NWS 23 parameters for the PMH still apply (Refs. 71, 72, and 73). However, consistent with NUREG-0800, section 2.3 (Ref. 70), a detailed site- or region-specific hurricane climatology study should be provided to show that the PMH parameters are consistent with the current state of knowledge.

Surge elevation increases with increasing hurricane size. However, based on site-specific topography or bathymetry, this increase may reach an upper bound. Applicants should investigate this behavior further by varying the PMH size (radius of maximum wind) beyond the upper bound specified in NWS 23 for a PMH approaching the site (Refs. 11 and 74). ANSI/ANS-2.8-1992, section 7, provides additional guidance on the critical combinations of PMH parameters.

Appendix E to NUREG/CR-7046 contains an example of how to estimate the PMH wind field using the NWS 23 procedure.

Joint Probability Method. The JPM approach quantifies the return periods of storm surges. Statistical simulation methods such as the JPM are needed for coastal flood frequency analysis primarily because there is no sufficient historical record from which to derive frequencies by more conventional means, such as gauge analysis. Hurricanes, for example, are both sporadic and of limited spatial extent, contributing to a great deal of sample variation (sample error) in local tide gauge records. Consequently, the JPM is widely used in coastal flood studies performed by the USACE and the Federal Emergency Management Agency. For example, Federal agencies adopted the JPM for critical post-Katrina determinations of hurricane surge frequencies (Ref. 75).

The JPM has been used for simulating hurricanes since the late 1960s. The original JPM application, while not called the JPM, was developed for predicting wave loads on offshore structures in the Gulf of Mexico (Ref. 76). The JPM described was a full Monte Carlo analysis in which model hurricanes were simulated using straight line segments, with wind and wave fields computed using hurricane wind and wave models. The methodology was introduced because there are too few historical events (hurricanes) at any one location to enable the use of standard statistical techniques (such as extreme value analyses) to estimate flood risk, wave height risk, windspeed risk, and other factors. The JPM can be used as an alternative to PMH for deterministic storm surge analysis, or as an option in a combined deterministic-probabilistic analysis for risk information.

The JPM is a simulation methodology that consists of developing statistical distributions for key hurricane input parameters (central pressure, radius of maximum winds, translation speed, and heading) and sampling from these distributions to develop model hurricanes. The simulation results in a family of modeled storms that preserves the relationships between the various input parameters but still allows one to model the effects and probabilities of storms that have not yet occurred. An alternative to the JPM is the method known as JPM-OS (Joint Probability Method—Optimum Sampling), which requires fewer JPM-simulated storms (Ref. 77).

In 2007, Resio et al. (Ref. 78) introduced long-duration tracks that mimic the behavior of hurricanes while they are offshore (and generating a wave field). Vickery et al. (Ref. 79) introduced modeling of the full storm track from a wind-only point of view. Both Resio et al. (Ref. 78) and Vickery et al. (Ref. 79) used simulation methodologies that attempted to properly model the correlations between storm intensity (central pressure) and radius to maximum winds. Vickery et al. (Ref. 80) also modeled a relationship between the radius to maximum winds and the Holland B parameter[1] (Ref. 81). Overall, the JPM has the conceptual advantage of accounting for all possible storms consistent with the local climatology, each weighted by its predicted rate of occurrence. Unlike the NWS 23 method, the JPM uses key hurricane parameter values developed through an analysis of continuously updated local climatology data from NOAA's historical hurricane database (HURDAT; Refs. 82, 83, 71, 84, and 85). All parameter value combinations analyzed (each defining a synthetic storm) should be simulated using a surge model constructed to accurately represent the site's bathymetry, topography, and ground cover. For detailed discussions and guidance on applying the JPM to coastal issues, see Refs. 75, 86, 87, 88, 89, 90, and 91. Divoky and Resio (Ref. 92) compare the JPM and the EST.

The NRC and the American Society of Civil Engineers have used the JPM for design-basis hurricane windspeeds for NPPs (Refs. 93 and 94) and minimum design loads for buildings and other structures (Ref. 95).

5. Associated Flooding Effects

Past review experience indicates that a maximum estimated water surface elevation alone is not sufficient to define the probable maximum flood; this is especially true for storm surge, which has generally been found to be the bounding flood-causing mechanism at project sites in both coastal and shoreline settings. Associated flooding effects such as wind-wave and runup effects can, in some cases, increase both the magnitude of flood inundation and the dynamic consequences of the event. The application should consider associated flooding effects consistent with the guidance in appendix J.

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[1] The Holland B parameter is a dimensionless parameter that defines the radial width of the maximum windspeed in a hurricane.

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APPENDIX F

FLOODING CAUSED BY SEICHE

This appendix discusses the estimation of coastal flooding caused by seiche. In this guide, “coastal” refers to the nearshore regions of any water body (e.g., ocean, lake, bay, estuary) where seiche-like phenomena may occur, not just regions adjacent to the open ocean.

A seiche is defined as an oscillation of the water surface in an enclosed or semi-enclosed water body that is initiated by an external cause. Lakes and reservoirs are examples of enclosed water bodies. Semi-enclosed water bodies include bays, lagoons, estuaries, rivers, and even the semi-enclosed seas. Once started, the oscillation of the water surface may continue for many cycles or may even grow because of resonance, if the frequency of the forcing phenomena matches one of the natural frequencies of oscillation of the water body. The amplitude and frequency of oscillation are functions of the forcing phenomena, together with the geometry and bathymetry of the system. Over time, oscillations decay because of friction.

A progressive screening approach such as the hierarchical hazard assessment, as proposed in NUREG/CR-7046, “Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America,” issued November 2011 (Ref. 2), may be used to evaluate the potential for seiche-based flooding. As discussed in that report, simplified procedures may be used; however, all methods and assumptions should be clearly conservative. If it cannot be demonstrated clearly that no credible seiche-based flooding event could affect the site, a detailed analysis of this external flood-causing mechanism should be performed.

F-1. Discussion[1]

Local or regional forcing phenomena, such as barometric pressure fluctuations, strong winds, rapid changes in wind direction, and surge associated with passage of storms (Refs. 3 and 4), may cause seiches. Distant but large forcing mechanisms, such as distant storms, tsunamis, or earthquake-generated seismic waves (Refs. 5 and 6), may also cause seiches. For example, earthquake-generated seiches have been observed on inland water bodies and at coastal sites thousands of miles away from the epicenter of the earthquake (Refs. 6, 7, and 8). Another example is that of a train of long-period waves arriving at a coastal embayment, inducing like-period oscillations. If the frequency of the incoming waves matches one of the local free oscillation modes, resonant amplification leading to large motions might occur (Ref. 9).

Most seiches have small amplitude (small rhythmic seiches are almost always present on larger lakes). However, large seiches that arise very quickly have been observed on the North American Great Lakes (Ref. 10). Such seiches can happen when high, sustained winds from one direction push the water level up at one end of the lake (storm surge or wind setup) and lower the level by a corresponding amount at the opposite end. Then a sudden change in atmospheric pressure or wind direction or a sudden drop in windspeed initiates a seiche. Note that in the Great Lakes area, any sudden rise in the water of a harbor or a lake, whether oscillatory or non-oscillatory, is called a seiche. (Although this usage of “seiche” is inaccurate in a strict sense, it is well established in the Great Lakes area.)

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[1] At certain places, seiche waves due to atmospheric forcing (atmospheric gravity waves, pressure jumps, frontal passages, squalls) can also cause significant harbor oscillations. (Such waves have been referred to as meteorological tsunamis.) The application should include a literature review to determine how pervasive these other forcing factors might be at a candidate site.

The period of oscillation of seiches can vary from a few minutes in bays to more than 10 hours in the Great Lakes region; resonance may persist in the Great Lakes for periods of 2 to 10 hours (Ref. 11). In some cases, it is sufficient to provide an analysis showing that the natural modes of oscillation of the subject water body are dissimilar from that of any credible forcing function. If this cannot be shown, a more detailed analysis using numerical models is necessary.

In areas of simple geometry, modes of oscillation can be predicted from the shape of the basin. Methods are available to estimate free oscillations in long, narrow lakes of variable width and depth (Refs. 12, 13, 14). However, natural water bodies have variable bathymetry and irregular shorelines and may be driven by a combination of forcing mechanisms. For such bodies, seiche periods and water surface profiles are determined most accurately through numerical long-wave modeling (Refs. 11, 15, and 16).

The literature indicates that there is no standard (mathematical) approach to estimating seiches. Most, if not all, approaches rely on approximations to estimate seiche wave amplitude (Ref. 15). An approach described in the literature—the Zuider Zee formula, used to estimate wind setup (Ref. 18)—has been used as a numerical surrogate to calculate seiches; the value of this approach is that it is based on observed wind velocity, which, as noted, is the most common forcing mechanism for seiches. Section 3.6 and appendix F to NUREG/CR-7046 further discuss seiche phenomena and provide an example calculation for the natural oscillation period of a small lake. The U.S. Army Corps of Engineers *Coastal Engineering Manual* (Ref. 11) discusses considerations for selecting long-wave models (i.e., those that rely on the shallow-water equation approximation).

F-2. Associated Flooding Effects

Past review experience indicates that a maximum estimated water surface elevation alone is not sufficient to define the probable maximum flood. Associated flooding effects such as wind-wave and runup effects can, in some cases, increase both the magnitude of flood inundation and the dynamic consequences of the event. The application should consider associated flooding effects consistent with the guidance in appendix J.

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APPENDIX G

FLOODING CAUSED BY TSUNAMIS

This appendix discusses the estimation of coastal flooding caused by tsunamis. In this guide, "coastal" refers to the nearshore regions of any water body (e.g., ocean, lake, bay, estuary) where tsunami phenomena may occur, not just regions adjacent to the open ocean.

A tsunami is a series of impulsively generated water waves that propagate radially from the point of generation toward the shores of some water body. Typically, the term "tsunami" refers to an oceanic tsunami; however, tsunamis or tsunami-like waves can also be generated in inland water bodies. Tsunamis are caused by the rapid, large-scale vertical displacement of a water column. Therefore, only geophysical events that release a large amount of energy in a very short time into a water body will generate measurable tsunamis. The literature suggests that earthquakes are the most frequent cause of tsunamis. Less frequently reported generating mechanisms in the literature include submarine and subaerial landslides and volcanic activity (e.g., pyroclastic flows and caldera collapses). However, these are not strict classifications. For example, a landslide that causes a tsunami could result from seismic or volcanic activity. In addition, rare events such as meteorite impacts, and ice falls may cause tsunamis. The literature suggests that tsunamis are geophysically rare events; about a dozen measurable tsunamis occur in any year, with approximately one damaging tsunami occurring every decade or so. The U.S. Nuclear Regulatory Commission (NRC) staff has supported research to identify best modeling practices and summarize state-of-the-art technology for tsunami inundation modeling (Ref. 1).

When estimating a design-basis flood for a nuclear power plant (NPP) site in an area for which tsunamis have been historically reported or recorded by instruments, applicants should consider the effects of runup, flooding, erosion, and debris loads. In addition, the rundown or return of water (and debris) to the sea could also damage the landward sides of structures that have withstood the initial runup. It is worth noting that the flood hazard reevaluations performed in response to the 2011 accident at the Fukushima Dai-ichi NPP in Japan generally revealed that storm surges, not tsunamis, are typically the bounding flood-causing mechanism at NPP sites in coastal settings in the United States.

A progressive screening approach such as the hierarchical hazard assessment, as proposed in NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011 (Ref. 3), may be used to evaluate the potential for flooding due to tsunamis. As discussed in that report, simplified procedures may be used; however, all methods and assumptions should be clearly conservative. If it cannot be demonstrated clearly that no credible tsunami-based flooding event could affect the site, a detailed analysis of this external flood-causing mechanism should be performed.

G-1. Tsunami Hazard Factors

Four basic factors determine the effects of a tsunami at a particular location: (1) the magnitude and extent of the earthquake or other geophysical triggering event, (2) the location of the triggering event, (3) the offshore bathymetry and configuration of the shoreline, and (4) the coastal topography.

The magnitude of the geophysical triggering event determines the period of the resulting waves and generally (but not always) the tsunami magnitude and damage potential. Unlike typical wind-generated water waves, whose periods range from 5 to 20 seconds, tsunamis can have wave periods ranging from a few minutes to well over 1 hour. As wave periods increase, the potential for coastal inundation also increases owing to the conservation of wave energy. The wave period is also important because of the potential for resonance and wave amplification within bays, harbors, estuaries, and other semi-enclosed coastal water bodies.

The location of the geophysical triggering event has two important consequences. First, the distance between the point of tsunami generation and the shoreline determines the maximum available warning time. For fixed water depths, tsunamis generated at a remote (distal) source will take longer to reach a given shoreline than locally generated tsunamis. Second, the point at which a tsunami is generated determines the direction from which it approaches a given site. The direction (azimuth) of the wave front approach can affect tsunami characteristics at the shoreline because of the sheltering or amplification effects of other landmasses and offshore bathymetry.

The configuration of the offshore bathymetry and shoreline affects the impact of the tsunami at the shoreline through wave reflection, refraction, and shoaling. Variations in offshore bathymetry and shoreline irregularities can focus or disperse the wave energy of the tsunami along certain shoreline reaches, thereby increasing or decreasing the impact of the tsunami.

The elevation (topography) of the project site also contributes to the potential impact of a tsunami wave. Low-lying coastal sites are more susceptible to inundation, tsunami runup, and damage than sites at higher elevations. However, coastlines with broad continental shelves allow tsunami effects to attenuate, thereby moderating their consequences on land.

G-2. Tsunami Hazard Assessment

The NRC staff's support of tsunami-related research extends back to the 1970s. However, the Indian Ocean tsunami of December 2004 prompted the staff to reexamine its criteria for evaluating the siting of NPPs against tsunami hazards. As part of its reexamination, the NRC supported studies by Pacific Northwest National Laboratory in collaboration with the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL). The NRC collaborated with NOAA PMEL staff to ensure that its guidance on site evaluation of tsunami hazards was consistent with national tsunami hazard mitigation and reduction programs initiated by Congress and the President.[1]

NOAA Technical Memorandum OAR PMEL-136, "Scientific and Technical Issues in Tsunami Hazard Assessment of Nuclear Power Plant Sites," issued 2007 (Ref. 4), sponsored by the NRC staff, recommends a technical basis that may be applied to tsunami hazard assessments in NPP license applications. A second NRC-sponsored contractor report, NUREG/CR-6966, "Tsunami Hazard Assessment at Nuclear Power Plant Sites in the United States of America," issued March 2009 (Ref. 5), recommends procedures for applying a hierarchical assessment strategy for tsunami hazard assessment.

The first step in the recommended hierarchical assessment approach is to perform a regional screening analysis of past reports of tsunamis in the region of interest. A regional survey and assessment of tsunamigenic sources should be based on a review of the literature. Significant tsunami hazards may arise from both near- and far-field sources corresponding to different generating mechanisms. The

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[1] NOAA has national responsibility for reducing the loss of U.S. life and property caused by tsunami hazards. The PMEL established the National Center for Tsunami Research (NCTR) to conduct research and development in support of NOAA's mission by providing tsunami warning and hazard mitigation products. NCTR research and development focuses on improving and applying tsunami measurement and modeling technology. The U.S. Geological Survey (USGS) also has national responsibility for minimizing the loss of life and property caused by tsunami hazards, by providing reliable geoscientific information whenever possible. Tsunami research conducted by the USGS Coastal and Marine Geology Program focuses on identifying, describing, and modeling potential tsunami sources. For this reason, USGS and NOAA collaborate closely on tsunami research.

regional survey should include all potential tsunamigenic sources and mechanisms. For example, analyses for coastal sites should consider hazards from oceanic sources; analyses for inland sites adjacent to large water bodies should consider the possibility of tsunami-like wave generation in those water bodies. NOAA's National Geophysical Data Center/World Data Center Global Historical Tsunami Database (Ref. 6) can provide historical information on tsunami occurrences, generating sources, and wave runup. The database provides information covering the last 2,000 years, for the Atlantic, Indian, and Pacific Oceans and the Mediterranean and Caribbean Seas. The NRC has supported research to characterize tsunamigenic sources and potential hazards for the U.S. East Coast and Gulf of Mexico (Refs. 7 and 8). Another useful reference is a tsunami hazard report derived from the NOAA database specific to U.S. coastal waters (Ref. 9).

NUREG/CR-6966 (Ref. 5) details the steps in the hierarchical tsunami hazard assessment approach. It also describes (1) the effects of tsunamis at NPP sites, (2) existing tsunami databases and data collection methods, (3) tsunamigenic mechanisms and sources, and (4) estimation methods for the initial tsunami's wave form, wave propagation, and inundation.

If the regional screening approach does not rule out the potential for tsunamis, the hierarchical assessment proceeds to a site screening test. This step determines whether an NPP's structures, systems, and components (SSCs) important to safety are exposed to hazards from tsunamis (Refs. 10 and 11). It may be possible to determine that, even though the general site region is subject to tsunamis, the plant itself is sited and designed so that a tsunami will not affect SSCs performing safety functions. For example, if all SSCs important to safety are located at an elevation higher than the maximum credible wave runup estimated for a tsunami, a more detailed tsunami flood assessment may not be needed.

If the site screening test does not establish the safety of the NPP site from potential tsunamis, a detailed flood assessment should be undertaken to ensure that the plant design bases adequately account for tsunami hazards. This step involves postulation of probable maximum tsunami (PMT) source mechanisms, estimation of PMT source characteristics, initiation of the incipient tsunami wave, propagation of the modeled tsunami wave from the generating source toward the site, and estimation of the PMT hazard at the site. The applicant should describe in detail the controlling tsunami generator (e.g., location, dimensions, orientation, and maximum displacement); the analysis procedure and models used to estimate tsunami wave height and period at the site; and the development of input parameters. Recent flood hazard reevaluations at NPP sites in the United States indicate that predicted tsunamis are estimated to be bounded by storm surge.

G-3. Tsunami Computational Modeling Tools

This section describes the tsunami generation and propagation phase, as well as the state-of-the-art computational tsunami modeling tools that the NRC and other Federal agencies currently use. The computer programs listed use known mathematical solutions for tsunami propagation, tsunami-shoreline interaction, and wave runup. They generally rely on bathymetric terrain data compiled by NOAA, and they typically have predefined parameter values for certain fixed seismogenic sources recognized as potential tsunami generators for a range of near- and far-field tsunami-generating mechanisms. Based on recent NRC staff review experience, the modeling results obtained from these computer simulations, while subject to many simplifying assumptions, are considered acceptable for demonstrating compliance with Title 10 of the *Code of Federal Regulations* Part 50, "Domestic Licensing of Production and Utilization Facilities," Appendix A, "General Design Criteria for Nuclear Power Plants," General Design Criterion 2, "Design bases for protection against natural phenomena". As tsunamis are geophysically rare and difficult to predict, the current state of the art is to perform tsunami computer simulations deterministically, based on physical analogs of tsunamigenic generating sources identified in the geologic record.

NOAA's National Tsunami Hazard Mitigation Program uses several complex computational modeling tools to produce tsunami inundation and evacuation maps for Alaska, California, Hawaii, Oregon, and Washington. The computational modeling packages include the Method of Splitting Tsunami (MOST) package, developed originally by University of Southern California researchers (Ref. 12), and the Cornell Multi-grid Coupled Tsunami Model (COMCOT), developed at Cornell University (Ref. 13). The two packages solve the depth-integrated and two-dimensional horizontal nonlinear shallow-water equations using differing finite-difference algorithms. Several other computational modeling tools can be used to solve shallow-water wave propagation problems, including the finite element model ADCIRC (Advanced Circulation Model) (Ref. 14).

These computational modeling environments are based on the shallow-water equation approximation. Based on recent staff review experience, the models have been shown to be reasonably accurate throughout the evolution of a tsunami wave. However, the software packages lack the capability to simulate dispersive waves, which could be the predominate features in a landslide-generated tsunami and for tsunamis traveling a long distance. Several higher-order, depth-integrated wave hydrodynamics models (Boussinesq-based models) are now available for simulating nonlinear and weakly dispersive waves; these include the COULWAVE (Cornell University Long and Intermediate Wave) (Ref. 15) and FUNWAVE (Fully Nonlinear Boussinesq Wave) models (Ref. 16). The major difference between the two models is in their treatment of moving shoreline boundaries. In 2003, for example, the COULWAVE model was applied to the 1998 Papua New Guinea tsunami with a landslide source; the results agreed reasonably well with field surveys and observed data. Recently, several finite element models also have been developed based on Boussinesq-type equations. It should be noted that in evaluating potential tsunami hazards due to submarine mass failures, it has become customary to transpose analog events described in the geologic record from the location where they were originally observed to a location immediately offshore from the NPP site where the event was numerically recreated, and the results evaluated. This modeling technique based on a proxy event and location is intended to conservatively maximize the estimated tsunami water surface elevation for the site under review. The computer programs cited above are acceptable to the staff for the purposes of the analysis.

The site-specific tsunami flood hazard assessments performed along the domestic coastline by NPP owners and operators in the United States in response to the 2011 Fukushima event constitute another important source of information. Many of these assessments use the computer programs described above. The assessments are publicly available in the NRC's Agencywide Documents Access and Management System. As mentioned above, these assessments reveal that tsunami flood hazards at U.S. NPPs are bounded by the storm surge flood-causing mechanism.

G-4. Associated Flooding Effects

Past review experience indicates that a maximum estimated water surface elevation alone is not sufficient to define the probable maximum flood. Associated flooding effects such as wind-wave and runup effects can, in some cases, increase both the magnitude of flood inundation and the dynamic consequences of the event. The application should consider associated flooding effects consistent with the guidance in appendix J and in ASCE/SEI 7-22 (Ref. 17). Also see ASCE 7-16 (Ref. 18).

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APPENDIX H

FLOODING CAUSED BY ICE EFFECTS

H-1. General

Ice effects may contribute to winter and early spring floods in many parts of the United States. Therefore, flooding attributable to ice effects should be examined and assessed quantitatively at nuclear power plant (NPP) sites where appropriate. Two broad categories of ice effects should be considered: (1) onsite ice accumulation that may contribute to flooding from local intense precipitation (see appendix C) and (2) ice jam formation on nearby streams.

In riverine settings, ice events involving ice jams or ice dams may result in flooding through either of two scenarios: (1) collapse of an ice jam or ice dam upstream of the site can cause a dam-breach-like flood wave that may propagate downstream to the project site, and (2) an ice jam or ice dam downstream of a project site may impound water, thus causing flooding through backwater effects upstream. Ice jams occur during both the freeze up and break up periods. However, because much higher flows usually prevail during breakup, breakup jamming is usually the ice-related event of main concern.

Flooding due to ice jams is usually less extensive in aerial coverage and elevation than open-water floods that occur in warm weather. This type of external flooding, however, presents some unique design challenges, such as the following: (1) they often take place with little or no warning, (2) ice blockages in the main stems and tributaries of rivers cause stages to rise and force water out of the channel over the floodplain, even when discharges are low compared to those of warm-water floods, and (3) the factors and relationships that determine the probability of ice jams and ice-jam flooding are more complex than those for open-water flooding. Therefore, the statistical analysis methods used for normal (warm-weather) flooding are not readily applicable to ice-related phenomena.

In addition to inundation and dynamic forces associated with ice-induced flooding, ice-generated forces on specific plant structures (e.g., intake structures, racks, gates, dams, control works) that may be exposed need to be assessed. All reasonable loading scenarios in which ice may exert forces on structures should be considered. For rivers, streams, and canals, all forms of moving ice (e.g., frazil ice floes, detached anchor ice, moving surface ice sheets or fragments) should be considered. On lakes and reservoirs, phenomena such as ice ridges and ice windrows should be examined. The weight of ice accumulation should be considered wherever it affects the operation of structures, systems, and components.

A progressive screening approach such as the hierarchical hazard assessment, as proposed in NUREG/CR-7046, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," issued November 2011 (Ref. 2), may be used to evaluate the potential for flooding due to ice jams or ice dams. As discussed in that report, simplified procedures may be used; however, all methods and assumptions should be clearly conservative. If it cannot be demonstrated clearly that no credible external flooding event due to ice jams could affect the site, a detailed analysis of this external flood-causing mechanism should be performed.

H-1.1 Ice Types

Ice begins to form in freshwater bodies when the water near the surface cools to 0 degrees Celsius (C) (32 degrees Fahrenheit (F)). The modes of formation and evolution can be quite varied and result in many types of ice. U.S. Army Corps of Engineers (USACE) Engineer Manual 1110-2-1612, "Ice Engineering," issued 2006 (Ref. 3), presents a thorough review of ice formation and ice types.

Sheet ice can form in calm water (e.g., lakes, reservoirs, slow-moving river reaches) where flow velocities are less than about 0.5 meters (m) per second (or about 1.6 feet (ft) per second). Ice crystals form at the water surface and freeze together into skim ice, which then gradually thickens downward. Sheet ice normally first forms along the shore or bank, then expands into the main water body.

Frazil ice forms in supercooled, turbulent water (e.g., river rapids and riffles). Supercooling normally occurs on cold clear nights (air temperature usually must be -8 degrees C (17.6 degrees F) or lower) when heat loss to the atmosphere is very high. Frazil ice forms where water is free of ice or snow cover because such cover would inhibit heat loss to the atmosphere. Frazil ice crystals appear as small ice particles throughout the depth of the stream. As the frazil particles are transported downstream, they join to form disk-shaped floes. These disks gradually rise to the surface, where they stick together to form frazil pans, which may in turn form large ice floes. In some cases, frazil ice may become attached to submerged objects or to the river bottom. This type of ice is often called anchor ice.

Fragmented ice and brash ice are accumulations of ice pieces. Fragmented ice originates as consolidated frazil ice pans or from the breakup of sheet ice growing at the surface of slow-moving water. Brash ice is an accumulation of ice pieces up to about 2 m (6.6 ft) in maximum dimension, caused by the breakup of an ice cover due to an increase in waterflow or the passage of a vessel.

H-1.2 Types of Ice Jams

An ice jam is any stationary accumulation of ice that restricts flow. Ice jams may be categorized as freeze up jams (made primarily of frazil ice), breakup jams (made primarily of fragmented ice pieces), and jams that combine both.

Freeze up jams consist primarily of frazil ice, with some fragmented ice. Floating frazil ice may slow or stop moving because of a decrease in the slope of the free surface, obstructions to movement (including sheet ice cover), or other hydraulic conditions. A jam forms when floating frazil ice stops moving downstream (often making a characteristic arch across the channel) and begins to accumulate. Freeze up jams usually occur between early winter and midwinter.

Breakup jams occur during periods of thaw (generally in late winter and early spring) and consist primarily of fragmented ice formed by the breakup of an ice cover or freeze up jam. Broken ice pieces move downstream until they encounter an intact downstream ice cover, some other surface obstruction to flow, a significant reduction in water surface slope, or other adverse hydraulic conditions. Here, the ice pieces stop moving, begin to accumulate, and form a jam. The size of the jam depends on the size of the ice supply from the upstream reaches of the river and the strength and size of the ice pieces. The severity of the resulting flooding depends on the flow conditions. Late winter and early spring ice cover breakup is usually associated with a rapid increase in runoff and in the corresponding river discharge attributable to significant rainfall or snowmelt (Ref. 4).

H-2. Assessment of Potential for Ice-Jam Formation

An ice jam begins at a location to which the river collects more ice than it can carry away. The ice-jam flooding threat at a specific riverine location is mainly determined by weather characteristics and river geometry. USACE publications present general observations about locations prone to ice-jam formation (Refs. 3 and 5). The most common location is a reach where the river slope decreases significantly. Other common locations include river bends and areas near obstructions, such as bridge or dam piers. Confluences of tributary streams with larger rivers or confluences of rivers with lakes or reservoirs are also prone to ice-jam formation.

H-2.1 Regional Hydroclimatic Conditions

USACE Engineer Pamphlet 1110-2-11, "Ice Jam Flooding: Causes and Possible Solutions," issued 1994 (Ref. 5), identifies the States with climatic conditions favorable for ice-jam formation and provides a map showing States where ice jams have been reported. For definitive determinations, the regional hydro-climatology near a proposed NPP site should be analyzed for meteorological conditions that may support the formation of ice cover and subsequent ice jams in rivers and streams. Air temperature data for meteorological stations near the site should be collected. The National Oceanic and Atmospheric Administration's National Centers for Environmental Information (NCEI, formerly the National Climatic Data Center) archives daily air temperature data that can be searched and obtained interactively at the NCEI website (Ref. 6). For all NCEI stations near the reactor project site, data on the following air temperature properties should be collected and evaluated:

a. minimum daily mean air temperature

b. number of days with air temperature below freezing

c. duration of freezing spells

d. duration of spells during which daily mean air temperature is at or below -8 degrees C (17.6 degrees F)

These properties may be used to determine whether the water temperature for any rivers and streams near the proposed project site can fall to near-freezing levels and whether sustained cold spells enabling the formation of frazil ice are possible.

H-2.2 Regional Ice and Ice-Jam Formation History

Although it is feasible to assess whether the hydroclimatic conditions at a site may lead to ice-jam or ice-dam formation, it is not possible to accurately predict the location and severity (e.g., the width, height, and volume) of an ice blockage. Instead, historical records of ice jams and ice dams should be used to determine the most severe historical event near the site.

The USACE Ice Jam Database (Ref. 7) contains information on historically reported ice jams and ice dams on rivers and streams; it can be queried to obtain information on the prevalence of ice events near the project site. The database gives dam heights and flood stages for past ice-jam and ice-dam events. When assessing the potential for external flooding at a proposed NPP site, applicants should use information from the Ice Jam Database to determine the most severe historical ice jam or ice dam conditions, including the dam height and flood stages. These properties should be the basis for a hypothetical ice jam or ice dam near the proposed site.

Regional air temperature characteristics from the NCEI archives and historical data from the Ice Jam Database can be used in combination to determine whether conditions at a given site could be favorable to the formation of frazil ice, ice jams, or ice dams, particularly if there are no records of ice jams or ice dams near the site. Conditions necessary to eliminate the potential for frazil ice at a site include minimum air temperatures that remain substantially above freezing, and the absence of periods when the air temperature is -8 degrees C (17.6 degrees F) or lower. If the data do not conclusively demonstrate the absence of meteorological conditions that could lead to the formation of frazil ice, the potential for ice-jam and ice-dam formation should be investigated further through a more formal flood hazard assessment.

H-3. Analysis of Flooding Hazards Caused by Ice Jams

If an applicant cannot establish the absence of historic analog events that could lead to the formation of frazil ice or cannot conclusively rule out potential ice-jam and ice-dam formation, then the ice-jam flooding hazard needs to be formally evaluated. Such an analysis starts with a review of observed ice conditions as reported in the Ice Jam Database or in other historical records. The most severe historical conditions reported should be used to determine whether the resulting flood is bounded by floods from other causal events (e.g., the probable maximum flood or floods due to upstream dam breaches). If the floods from other causal events are unambiguously larger than the flood caused by the most severe ice jam or ice dam, this should be documented, and no further analysis of ice events is needed. Otherwise, the applicant should use the data to specify a hypothetical ice-jam or ice-dam event, then analyze it in sufficient detail to estimate the flooding effects at the site as discussed below. NUREG/CR-7046 includes a case study of flooding from ice-induced events.

H-3.1 Upstream Ice-Dam Breach

Based on observations in the USACE Ice Jam Database or other historical records, a hypothetical ice jam or ice dam upstream of the site should be specified. Its size, location, and breach parameters should be postulated conservatively to maximize the flood caused by the release of impounded water. The routing of the resulting flood wave to the proposed site can be analyzed using the methods and tools described in appendix D.

H-3.2 Downstream Ice Jam

The most severe ice jam or ice dam estimated as discussed above, placed downstream of the site on the adjoining stream, should be used to postulate conditions leading to the most severe backwater profile adjacent to the proposed site. The most severe backwater conditions would occur during an upstream flood just before the breach of the ice jam or ice dam, when its height and thus its ability to block the channel conveyance are greatest. State-of-the-art hydraulic modeling methods (see appendix D) should be used to estimate the water surface elevation in the stream reach under these conditions.

H-4. References

1. American National Standards Institute (ANSI)/American Nuclear Society (ANS), "Determining Design Basis Flooding at Nuclear Power Plant Sites," ANSI/ANS-2.8-1992, La Grange Park, Illinois.

2. U.S. Nuclear Regulatory Commission, "Design-Basis Flood Estimation for Site Characterization at Nuclear Power Plants in the United States of America," NUREG/CR-7046, November 2011 (ML11321A195).[1]

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[1] Publicly available NRC published documents are available electronically through the NRC Library on the NRC's public website at http://www.nrc.gov/reading-rm/doc-collections/ and through the NRC's Agencywide Documents Access and Management System (ADAMS) at http://www.nrc.gov/reading-rm/adams.html.. For problems with ADAMS, contact the Public Document Room staff at 301-415-4737 or (800) 397-4209, or email pdr.resource@nrc.gov. The NRC Public Document Room (PDR), where you may also examine and order copies of publicly available documents, is open by appointment. To make an appointment to visit the PDR, please send an email to pdr.resource@nrc.gov or call 1-800-397-4209 or 301-415-4737, between 8 a.m. and 4 p.m. eastern time (ET), Monday through Friday, except Federal holidays.

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APPENDIX I

FLOODING CAUSED BY COMBINED EVENTS

This appendix discusses approaches for considering combined processes and events when estimating a design-basis flood at a nuclear power plant (NPP) site. Many hydrometeorological phenomena capable of generating an external flood can occur concurrently because they are not truly independent mechanisms. For example, a riverine flood due to basin wide precipitation may coincide with spring snowmelt, increasing the magnitude of flooding. In coastal regions, precipitation associated with a hurricane may coincide with storm surge. Astronomical high tide may coincide with storm surge or a tsunami. Therefore, consideration of flooding resulting from a single process or event is generally not adequate to determine the design-basis flood. Reasonable sequences and combinations of processes and events based on site-specific information should be considered.

I-1. General Considerations

I-1.1 Hazard-Specific Combinations

External flood hazards may result from various plausible geophysical combinations of hydraulic events. For example, the maximum water surface elevation, and consequently the maximum hydrostatic force, may result from a river flood combined with wind-wave effects; however, the maximum hydrodynamic force in an absolute sense may result from a different flood-causing mechanism—such as storm surge combined with wind waves—based on geographic factors. Therefore, the design-basis flooding event selected to demonstrate compliance with Title 10 of the *Code of Federal Regulations* Part 50, “Domestic Licensing of Production and Utilization Facilities,” Appendix A, “General Design Criteria for Nuclear Power Plants,” General Design Criterion 2, “Design bases for protection against natural phenomena,” should be chosen to represent the most severe hydraulic events historically reported for the site, together with sufficient margin to account for the limited accuracy and quantity of historical data and the limited period of time in which they were gathered.

I-1.2 Combined Event Flood

In general, no single flood-causing event (predictable by present technology) is adequate to define the design-basis flood in accordance with General Design Criterion 2. Consequently, a combination of events should be used to estimate design-basis floods at proposed reactor sites. American National Standards Institute (ANSI)/American Nuclear Society (ANS)-2.8-1992, “Determining Design Basis Flooding at Power Reactor Sites” (Ref. 1), identifies combinations of flood-causing mechanisms that might occur at NPP sites based on geographic considerations. The information in this reference is reasonable for deciding which combination of events to consider. Ultimately, applicants should describe their reasoning for selecting the specific hydrodynamic/meteorological/geologic scenarios they use to define the design-basis flood. The combination of scenarios considered should be physically reasonable.

I-1.3 Wind-Wave Effects

Wind-wave effects are almost always combined with other flood-causing mechanisms. Although windspeeds of differing probabilities may be technically appropriate in different combinations of flood-causing events, this type of information is generally not available on a nationwide basis. In lieu of performing generalized or specific analyses, applicants may use the 2-year annual extreme mile wind, which accounts for geographic variation in windspeeds, as a starting point for analysis. These data are typically available as the fastest mile speeds. (The fastest mile is the fastest 1-minute observed windspeed taken from a multiple register that contains a time record of the passing of each mile of wind.) The 2-year value for a specific location should be adjusted from fastest mile speeds for durations appropriate to the site's effective fetch lengths. These adjusted windspeeds should be applied from the most critical direction and coincident with the maximum still-water level.

In addition, the applicant should demonstrate that structures, systems, and components necessary to protect against natural phenomena, including external flooding effects, are designed to withstand the static and dynamic effects of frequent flood levels. (In this context, "frequent flood levels" means the maximum operating level in reservoirs and the 10-year flood level in streams.) This demonstration should reflect consideration of coincident wind-wave and runup effects expected for the site based on a study of historical regional meteorology.

I-1.4 **Combined Extreme Events**

For the purposes of this regulatory guide, the design-basis flood at an NPP site is estimated using deterministic approaches that rely on the notion of a probable maximum event. Probable maximum events are understood to exceed all historically reported occurrences and to approach the credible physical limits of the phenomenon of interest. (Despite the term "probable," probable maximum events are deterministic rather than statistical in nature.) Because of their extreme nature, probable maximum events from two separate phenomena should not be combined unless they are dependent or have a common cause. For example, a seismic-driven tsunami event should not be combined with a hydrometeorological event. An exception occurs for the probable maximum flood and probable maximum hurricane for relatively small drainage basins in regions where the probable maximum precipitation may result from a hypothetical and maximized hurricane event (see Ref. 2).

I-1.5 **Probabilities of Combined Events**

ANSI/ANS-2.8-1992 (Ref. 1) considers an annual exceedance probability of $1\text{x}10^{-6}$ to represent a reasonable criterion for selecting the design-basis flood at an NPP site.

The U.S. Nuclear Regulatory Commission staff has applied the $1\text{x}10^{-6}$ criterion in previous safety reviews and considers it an appropriate goal for considering combined events. However, ANSI/ANS-2.8-1992 does not include guidance on formal probabilistic flood hazard assessment approaches needed for a consistent treatment of combined events. ANSI/ANS-2.8-2019 (Ref. 3) proposes a graded screening process for evaluating external flood-causing mechanisms but does not provide detailed review guidance. There are few consistent, well-established methods for estimating the exceedance probability of probable maximum events. (For example, Refs. 4 and 5 offer recommendations on how to treat external events, including floods, in a risk assessment.) Generally, the reasonableness of qualitative and quantitative probability estimates for combined events must be assessed case by case.

APPENDIX J

CONSIDERATION OF ASSOCIATED FLOODING EFFECTS

This section relates to the wave dissipation phase, in which the effects of wave action due to a storm surge, seiche, or tsunami can, upon reaching land, directly affect the project site. Wave action effects include both deep- and shallow-water wave generation. Wind-generated wave activity that can occur independently of, or coincidentally with, these types of flooding events should be included in the flood hazard analyses. Available records should be used to characterize wave behavior near the site using measures such as significant and maximum wave heights. The analyses and flooding estimates should also consider tides, wave setup, wave runup, splash, and overtopping, as appropriate.

Potential inundation effects of floodwater actions at project site structures, systems, and components (SSCs) should be evaluated. Section C of this regulatory guide describes the methods typically available for performing these evaluations. After estimating the potential water surface elevation due to some flood-causing mechanism, to demonstrate compliance with Title 10 of the *Code of Federal Regulations* Part 50, “Domestic Licensing of Production and Utilization Facilities,” Appendix A, “General Design Criteria for Nuclear Power Plants,” General Design Criterion 2, “Design bases for protection against natural phenomena,” it is necessary to determine the impact, if any, of certain associated flooding effects on SSCs important to safety (Ref. 1). Section J-1 provides guidance on calculating wind waves that can coincide with the highest estimated still-water level. For some specific inundation levels, other associated effects design factors such as wave runup (section J-2) and drawdown (section J-3) should be considered.

In addition to these associated flooding effects, “structural” flooding effects (i.e., the application of hydrostatic and hydrodynamic forces or loads on SSCs) are possible. To address the guidance in Regulatory Guide 1.102, “Flood Protection for Nuclear Power Plants,” Revision 1, issued September 1976 (Ref. 2), this guide also examines hydrostatic and hydrodynamic forces (section J-4) and debris and waterborne projectiles (section J-5). The effects of sediment erosion and deposition (section J-6) should be considered, as appropriate. The publications of the U.S. Army Corps of Engineers (USACE) [1], as well as the American Association of State Highway and Transportation Officials (AASHTO),[2] are other useful sources of information for reviewing the hydrodynamic effects of floodwaters on SSCs. Given these design considerations, the controlling flood-causing mechanisms may be different when evaluating structural effects compared to those associated effects attributed to inundation. The applicant should confirm that the guidance selected for associated flooding effects is consistent with its intended application.

J-1. Coincident Wave Heights

American National Standards Institute (ANSI)/American Nuclear Society (ANS)-2.8-1992, “Determining Design Basis Flooding at Nuclear Reactor Sites” (Ref. 3), recommends using the USACE *Shore Protection Manual* (Ref. 4) for analyzing wave action. However, the USACE *Coastal Engineering Manual* (CEM) (Ref. 5) has superseded the *Shore Protection Manual*. The CEM recommends methods to apply to shore locations with simple bathymetry. According to the hierarchical hazard assessment approach, a numerical model may be needed, depending on the complexity of the bathymetry.

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[1] USACE publications are available at https://www.publications.usace.army.mil/USACE-Publications/Engineer-Manuals.

[2] AASHTO publications are available at https://store.transportation.org/.

If needed, the current practice in storm surge modeling is to use coupled hydrodynamic ocean circulation and wave models, both driven by a planetary boundary layer model that provides the atmospheric forcing. Consistent with USACE CEM guidance, off-coast wave activity should be determined using either the WAM (Ref. 6) or the WAVEWATCH III model (Ref. 7). For nearshore and surf zone wave processes, the models Simulating Waves Nearshore (SWAN) and Steady-State Spectral WAVE (STWAVE) have the capability to compute the wave conditions. For detailed discussions and guidance on using these models, see Refs. 8, 9, and 10. The applicant should explain the choice of the model used and why the results are adequate. Other models and methods used in the past include those of Goda (Ref. 11), the Technical Advisory Committee for Water Retaining Structures (Ref. 12) and van der Meer et al. (Ref. 13).

J-2. Wave Runup

Wave runup can be calculated using the lesser of the maximum wave height (1.67 x the significant wave height) and the maximum breaker height, in accordance with ANSI/ANS-2.8-1992 (Ref. 3) and the USACE CEM (Ref. 4). Wave runup models also can be used in addition to the calculation of overtopping rates when waves encounter a shoreline or embankment. The inputs include wave type, breaking criteria, wave height, wave period, structure slope, structure height, slope type, material used (e.g., riprap, rubble, tetrapods), and roughness coefficient. In calculating overtopping rates, the relative heights of the embankment and the estimated still-water level are important. For state-of-the-art solutions to estimating wave runup, the USACE Automated Coastal Engineering System (ACES) is available from the Coastal Engineering Design and Analysis System (CEDAS) interface (Ref. 14). Other models and methods used in the past include those of Goda (Ref. 11), the Technical Advisory Committee for Water Retaining Structures (Ref. 12) and van der Meer et al. (Ref. 13).

J-3. Drawdown (Low-Water Level)

Drawdown may be an issue when safety-related structures and equipment (e.g., the intake structures for a safety-related ultimate heat sink) depend on water sources whose availability may be affected by a storm surge or seiche (Ref. 12). Numerical models, such as Advanced Circulation Model (ADCIRC) and Sea, Lake, Overland Surge from Hurricanes (SLOSH), provide visual or quantitative estimates of low-water-level conditions. Thus, elevation data from storm-surge, seiche, or tsunami computer model simulations should be retained and used for a detailed analysis of low-flow conditions.

J-4. Hydrostatic and Hydrodynamic Forces

The hydrostatic and hydrodynamic forces should be determined when flood levels due to storm surge, seiche, or tsunami are predicted to impinge on flood protection features for SSCs that are important to safety. Thus, current velocity and wave and wind data from the computer model simulations for these flood-causing mechanisms should be retained and used for a detailed analysis of hydrostatic and hydrodynamic forces.

The USACE CEM provides examples of standard approaches to the evaluation and analysis of hydrostatic and hydrodynamic forces on coastal structures (Ref. 5), as does the American Society of Civil Engineers (Ref. 14). Applicants may wish to consult the World Association for Water Transport Infrastructure (Ref. 15) for industry-developed guidance on design matters not described in Ref. 14.

J-5. Debris and Water-Borne Projectiles

The effects of debris and waterborne projectiles should be determined when flood levels due to storm surge, seiche, or tsunami are predicted to impinge on flood protection features of SSCs that are important to safety. Thus, data on the dynamic loads due to debris and waterborne projectiles for these flood-causing mechanisms should be retained and used for a detailed analysis.

The USACE CEM provides guidance on the estimation of hydrodynamic forces for coastal structures (Ref. 5), as does the American Society of Civil Engineers (Ref. 14). Applicants may wish to consult the World Association for Water Transport Infrastructure (Ref. 15) for guidance on design matters not described in Ref. 14.

J-6. Effects of Sediment Erosion or Deposition

The impact of sediment erosion and deposition should be considered when storm surge or seiche flood levels are predicted to impinge on flood protection features, SSCs important to safety, and foundation materials. Thus, current velocity and wave and wind data from storm surge or seiche models should be retained and used for a detailed analysis of the effects of sediment erosion and deposition. In connection with any analysis of sediment erosion and deposition, it may be necessary to perform numerical modeling or even possibly scaled wave tank modeling to better understand these effects for a proposed power plant site and design. These modeling efforts should be informed by a review of the pertinent literature.

The USACE CEM provides guidance on the effects of sediment erosion and deposition for coastal structures (Ref. 5).

J-7. References

1. *U.S. Code of Federal Regulations* (CFR), "Domestic Licensing of Production and Utilization Facilities," Part 50, Chapter I, Title 10, "Energy".

2. U.S. Nuclear Regulatory Commission (NRC), "Flood Protection for Nuclear Power Plants," Regulatory Guide 1.102, Revision 1, September 1976 (ML003740308).

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9. Smith, J.M. and A.R Sherlock, "Full-Plane STWAVE with Bottom Friction: II, Model Overview, System-wide Water Resources Program Technical Note," USACE, Engineer Research and Development Center, Vicksburg, Mississippi, 2007.

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12. Technical Advisory Committee for Water Retaining Structures, "Wave Run-up and Wave Overtopping at Dikes," Technical Advisory Committee on Flood Defence in the Netherlands (TAW), Technical Report, Delft, The Netherlands, 2002.

13. Van der Meer, J.W., et al., "Manual on Wave Overtopping of Sea Defences and Related Structures. An Overtopping Manual Largely Based on European Research, but for Worldwide Application," EurOtop (Joint FCERM Research Programme/Environment Agency and Rijkswaterstaat—Water, Verkeer en Leefomgeving), EurOtop 2016 Pre-release Edition, October 2016. Available at https://www.overtopping-manual.com.

14. USACE, CEDAS—Coastal Engineering Design and Analysis System, USACE Coastal and Hydraulics Laboratory, available at https://www.erdc.usace.army.mil/Locations/CHL/Products/Fact-Sheet-View/Article/2582597/cedas/ (accessed June 26, 2023).

15. NRC, "Ultimate Heat Sink for Nuclear Power Plants," Regulatory Guide 1.27, Revision 2, January 1976, ML003739969.

16. American Society of Civil Engineers/Structural Engineering Institute, "Minimum Design Loads and Associated Criteria for Buildings and Other Structures," ASCE/SEI 7-2016, Reston, Virginia.

17. World Association for Waterborne Transport Infrastructure (PIANC), "Recommendations for the Design and Assessment of Marine Oil and Petrochemical Terminals," PIANC Report 153-2016, Brussels, Belgium, 2016.

APPENDIX K

CONSIDERATIONS FOR APPLYING GUIDANCE TO ADVANCED REACTORS AND SMALL MODULAR REACTORS

This appendix describes considerations for applicants using this guidance for advanced reactors and small modular reactors (SMRs), as defined initially by the Nuclear Energy Innovation and Modernization Act (Ref. 1) and in more detail by the Energy Act of 2020 (Ref. 2). This guidance also applies to non-light-water reactors and microreactors, although these categories are not currently defined in the statutes (i.e., Refs 1 and 2). The guidance is also acceptable for the design of nonpower production or utilization facilities, fuel cycle facilities, spent fuel storage facilities, and waste disposal facilities.

Regulatory Guide 1.247, "Acceptability of Probabilistic Risk Assessment Results for Non-Light-Water Reactor Risk-Informed Activities" (Ref. 3), outlines a process to evaluate non-light-water reactor design safety for both internal and external events. The staff believes that potential applicants have flexibility in how they intend to demonstrate compliance with the Commission's regulations, including in how they use probabilistic risk assessment (PRA) results. Appendix K is presented as an alternative to the guidance in Regulatory Guide 1.247.

K-1 Background on Advanced Reactor Designs and Guidance

The 2008 "Policy Statement on the Regulation of Advanced Reactors" (Ref. 4) identifies attributes that could help establish the acceptability or "licensability" of a proposed advanced reactor design, including reliable and less-complex shutdown heat removal systems; longer time constants before reaching safety system challenges; simplified safety systems that, where possible, reduce required operator actions; reduced potential for severe accidents; and considerations for safety and security requirements together in the design process.

Some advanced reactors and SMRs have modified the traditional design features relied upon to maintain fundamental safety functions, such as radioactive material retention, reactivity and power control, and heat removal. Such reactors are potentially more reliable and need less radioactive material based on reactor size. These and other considerations, such as site location, could allow for the use of a screening approach to evaluate flooding mechanisms for advanced reactors and SMRs. For example, some advanced reactor designs may not rely on external water supply sources as the ultimate heat sink to maintain the fundamental safety functions; they could therefore be located away from bodies of water that pose external flood hazards through certain flood-causing mechanisms. Also, some advanced reactor designs could be sited in locations not previously considered for large light-water reactors, away from large population centers, transportation corridors, or other manmade facilities. Some designs may be able to demonstrate that the fundamental safety functions are maintained even while the plant is flooded, or they may include adequate flood protection features to maintain fundamental safety functions. If an applicant can demonstrate that the fundamental safety functions can be maintained under external flood conditions or that credited flood protection features are in place to maintain the fundamental safety functions under such conditions, then the flood hazard evaluation can be simplified. Such a demonstration can be achieved through a PRA or comparable analysis.

The U.S. Nuclear Regulatory Commission (NRC) also recognizes that some advanced reactor designs use coolants such as liquid metallic sodium that could cause adverse reactions if they encounter liquid water. For such designs, consideration should be given to whether external flood hazards might prevent the performance and maintenance of the fundamental safety functions.

The following guidance on advanced reactors may also be considered as part of a design-basis flood hazard evaluation:

- Regulatory Guide 1.233, "Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors" (Ref. 5), which endorses Nuclear Energy Institute (NEI) 18-04, Revision 1, "Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development," issued August 2019 (Ref. 6).

- American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS) RA-S-1.4-2021, "Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants" (Ref. 7), which the NRC has not endorsed as of the date of this regulatory guide.

- American National Standards Institute (ANSI)/ANS-2.8-2019, "Probabilistic Evaluation of External Flood Hazards for Nuclear Facilities" (Ref. 8), which the NRC has not endorsed

- Regulatory Guide 4.26, "Volcanic Hazards Assessment for Proposed Nuclear Power Reactor Sites" (Ref. 9)

- SECY-15-0081, "Staff Evaluation of Applicability of Lessons Learned from the Fukushima Dai-ichi Accident to Facilities Other than Operating Power Reactors," dated June 9, 2015 (Ref. 10)

- Interim Staff Guidance DANU-ISG-2022-02, "Advanced Reactor Content of Application Project Chapter 2 - Site Information," issued May 2023, provides guidance on the contents of a risk-informed, performance-based, nonlight-water reactor (non-LWR) application for a construction permit or operating license under Title 10 of the Code of Federal Regulations (10 CFR) Part 50, "Domestic Licensing of Production and Utilization Facilities", or for a combined license, manufacturing license, standard design approval, or a design certification under 10 CFR Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants". The application guidance found in this ISG supports the development of the portion of non-LWR application associated with an applicant's "Site Information," and provides guidance to NRC staff on how to review such an application (Ref 11).

K-2 Specific Flood Hazard Considerations for Advanced Reactors and Small Modular Reactors

The NRC staff has determined that a flexible stepwise approach can be used in addition to or in lieu of the detailed flood hazard analysis described earlier in this regulatory guide. Figure K-1 illustrates a risk-informed approach for conducting a flood hazard assessment to support license applications for advanced reactors and SMRs. This risk-informed approach allows an applicant to leverage the results from both site characterization and a site- or design-specific PRA, if one is available. As shown in block 1 of figure K-1, an advanced reactor application would need to identify and describe the characteristics of the candidate site. This information can be used to determine the applicable flood hazard mechanism(s) and the bounding flood hazard(s) that may initiate a potential accident covered by a sequence analyzed in the PRA or other optional analysis. A PRA or other appropriate analysis, if available, should be sufficient to evaluate the performance of engineering safety barriers or systems and to demonstrate that the proposed reactor design can operate under a reasonable range of site-specific conditions without exceeding specified radiation exposure limits.

An advanced reactor applicant should use the information generated in block 1 to identify the potential flooding hazards for the proposed site and determine whether external flooding could affect the structures, systems, and components (SSCs) important to safety. If no impact is found, the analysis is complete, and the applicant should document the results. If the assessment performed for the step that is in block 2 shows that there are potential effects on one or more SSCs important to safety, the applicant should assess the flood mechanism to determine whether there may be any adverse impact to SSCs important to safety and whether the proposed engineering features for flood protection and mitigation are adequate, as shown in block 3.

In evaluating a flood-causing mechanism to determine the potential elevation of flood inundation, as called for in block 4, the results of site characterization may reveal that one or more existing flood hazard assessments may be generally applicable to the proposed site. Upon consideration of these existing assessments, the applicant may find them appropriate for use in evaluating the proposed site or design. If so, the applicant should justify their use and their applicability to the proposed site. For example, the applicant may analyze the proposed site or design using available flood hazard information for existing NRC-licensed facilities nearby, if the applicant explains why this information is suitable for use for the proposed site. In such a scenario, the review process in block 3 would be limited to evaluating the engineering features for the proposed design. The applicant should consider the elevation of flood inundation and its potential effects on the SSCs important to safety to determine whether the flood protection features are sufficient.

If the analysis performed under block 3 demonstrates that the engineering features of the advanced reactor design are adequate, then the analysis is complete, and the applicant should document the results. If the analysis demonstrates that the engineering features are not adequate, the applicant should proceed to the step that is in block 4 to evaluate the adequacy of proposed mitigation plans to be implemented in response to a notice of an impending external flooding event. Under block 4, the applicant should evaluate the adequacy of any manual operating actions and procedures described in the mitigation plan given the hazard identified. If the analysis demonstrates that the manual operating actions and procedures are adequate for that hazard, then the analysis is complete, and the applicant should document the results (block 5). If the analysis demonstrates that the manual operating actions and procedures are not adequate to mitigate the external flood hazard(s) given the current advanced reactor design, it may be necessary to reassess the engineering features or mitigation actions initially included as part of the reactor design, as shown in block 6. After doing this, the applicant would reassess the engineering features (block 3) and the mitigation plans (block 4). Additionally, while minor modifications to either proposed design features or mitigation actions may not affect the content of the PRA, in some cases the applicant may need to revise the initial PRA for the amended design (if available).

K-3 References

1. *Nuclear Energy Innovation and Modernization Act*, 115 U.S.C. § 439 (2019), available at https://www.congress.gov/115/plaws/publ439/PLAW-115publ439.pdf.

2. *Energy Act of 2020*, 116 U.S.C. § 68 (2020), available at https://rules.house.gov/sites/democrats.rules.house.gov/files/BILLS-116HR133SA-RCP-116-68.pdf.

3. U.S. Nuclear Regulatory Commission (NRC), "Acceptability of Probabilistic Risk Assessment Results for Non-Light-Water Reactor Risk-Informed Activities," Regulatory Guide 1.247, trial version, March 2002.

4. NRC, "Policy Statement on the Regulation of Advanced Reactors," *Federal Register*, Vol. 73, No. 199, October 14, 2008, pp. 60612–60616.

5. NRC, “Guidance for a Technology-Inclusive, Risk-Informed, and Performance-Based Methodology to Inform the Licensing Basis and Content of Applications for Licenses, Certifications, and Approvals for Non-Light-Water Reactors,” Regulatory Guide 1.233.

6. Nuclear Energy Institute (NEI), “Risk-Informed Performance-Based Technology Inclusive Guidance for Non-Light Water Reactor Licensing Basis Development,” NEI 18-04, Revision 1, Washington, DC, August 2019 (ML19241A472).

7. American Society of Mechanical Engineers (ASME)/American Nuclear Society (ANS), “Probabilistic Risk Assessment Standard for Advanced Non-Light Water Reactor Nuclear Power Plants,” ASME/ANS RA-S-1.4-2021, New York, New York.

8. American National Standards Institute (ANSI)/ANS, “Probabilistic Evaluation of External Flood Hazards for Nuclear Facilities,” ANSI/ANS-2.8-2019, La Grange Park, Illinois.

9. NRC, “Volcanic Hazards Assessment for Proposed Nuclear Power Reactor Sites,” Regulatory Guide 4.26.

10. NRC, “Staff Evaluation of Applicability of Lessons Learned from the Fukushima Dai-ichi Accident to Facilities Other than Operating Power Reactors,” SECY-15-0081, June 9, 2015, ML15050A066.

11. NRC, “Advanced Reactor Content of Application Project Chapter 2 - Site Information,” Interim Staff Guidance DANU-ISG-2022-02, ML22048B41.

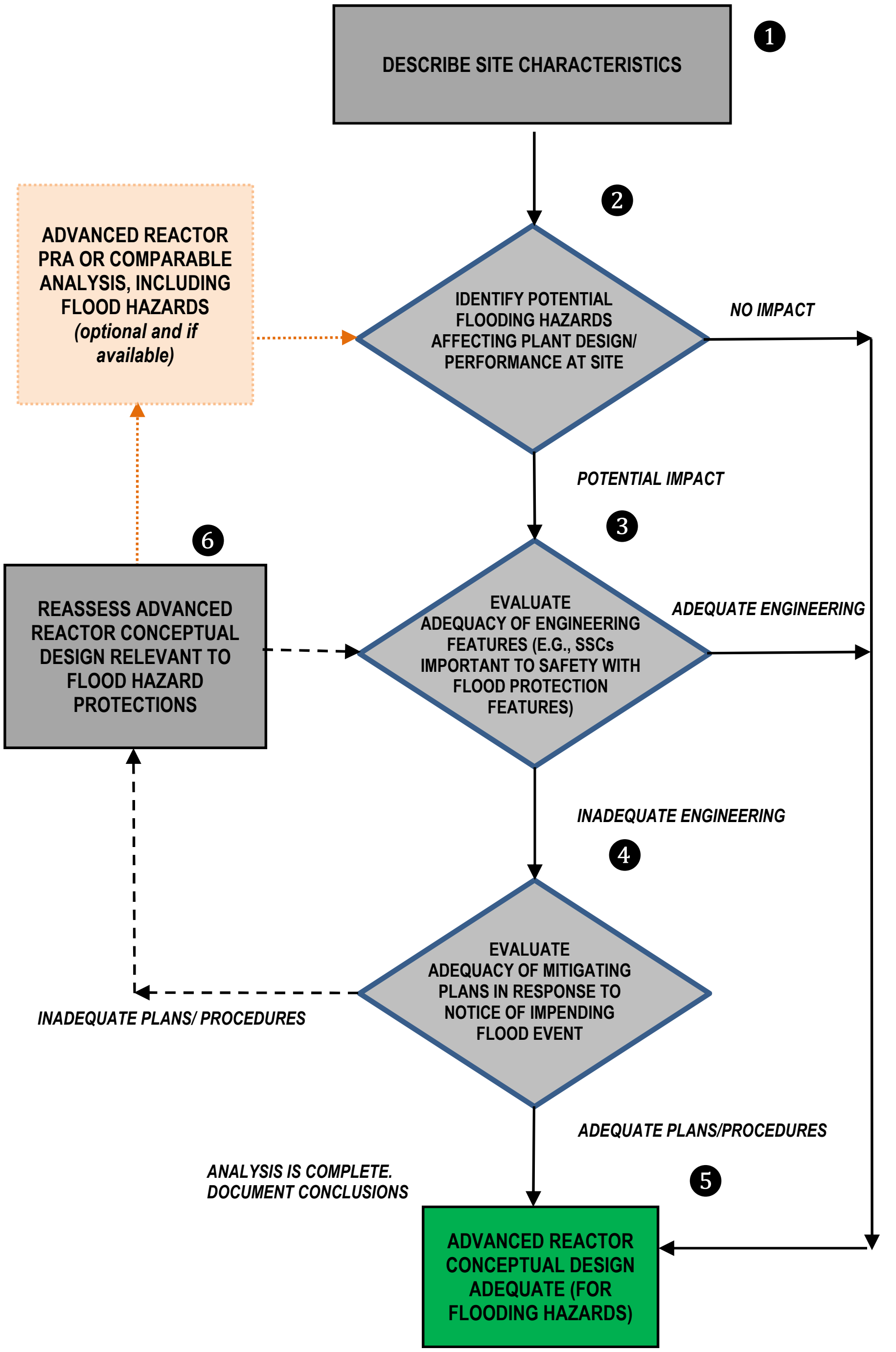

Figure K-1 Flowchart of flood hazard evaluation for advanced reactor and SMR applicants

APPENDIX L

ACRONYMS, ABBREVIATIONS, AND DEFINITIONS

This appendix provides lists of acronyms and abbreviations used throughout this regulatory guide and definitions for selected terms.

L-1. Acronyms and Abbreviations

AASHTO	American Association of State Highway and Transportation Officials
ACES	Automated Coastal Engineering System
ADAMS	Agencywide Documents Access and Management System
ADCIRC	Advanced Circulation Model
ANS	American Nuclear Society
ANSI	American National Standards Institute
ASCE	American Society of Civil Engineers
C	Celsius
CEDAS	Coastal Engineering Design and Analysis System
CEM	*Coastal Engineering Manual*
CFR	*Code of Federal Regulations*
COMCOT	Cornell Multi-grid Coupled Tsunami Model
COULWAVE	Cornell University Long and Intermediate Wave
EST	empirical simulation technique
ETSS	extratropical storm surge
F	Fahrenheit
FEMA	Federal Emergency Management Agency
FUNWAVE	Fully Nonlinear Boussinesq Wave
GDC	general design criterion
GIS	geographical information system
HDSC	Hydrometeorological Design Studies Center
HEC	Hydrologic Engineering Center

HHA	hierarchical hazard assessment
HMR	hydrometeorological report
HMS	Hydrologic Modeling System
IAEA	International Atomic Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISG	interim staff guidance
JPM	Joint Probability Method
JPM-OS	Joint Probability Method—Optimum Sampling
km/h	kilometer per hour
LIP	local intense precipitation
LMSL	local mean sea level
LWR	light-water reactor
MOST	Method of Splitting Tsunami
mph	miles per hour
NAD27	North American Datum of 1927
NAD83	North American Datum of 1983
NAVD88	North American Vertical Datum of 1988
NCAR	National Center for Atmospheric Research
NCEI	National Centers for Environmental Information
NCTR	National Center for Tsunami Research
NGS	National Geodetic Survey
NGVD29	National Geodetic Vertical Datum of 1929
NHC	National Hurricane Center
NHD	National Hydrography Dataset
NID	National Inventory of Dams
NOAA	National Oceanic and Atmospheric Administration
NOS	National Ocean Service

NPP	nuclear power plant
NRC	U.S. Nuclear Regulatory Commission
NTDE	National Tidal Datum Epoch
NWS	National Weather Service
OAR	Office of Oceanic and Atmospheric Research
OMB	Office of Management and Budget
PFHA	probabilistic flood hazard assessment
PIANC	World Association for Waterborne Transport Infrastructure
PMEL	Pacific Marine Environmental Laboratory
PMF	probable maximum flood
PMH	probable maximum hurricane
PMP	probable maximum precipitation
PMT	probable maximum tsunami
PRISM	Parameter-Elevation Regressions on Independent Slopes Model
RG	regulatory guide
SLOSH	Sea, Lake, Overland Surge from Hurricanes
SLR	sea-level rise
SPC	Storm Prediction Center
SSC	structure, system, or component
STWAVE	Steady-State Spectral Wave
SWAN	Simulating Waves Nearshore
SWE	snow water equivalent
TVA	Tennessee Valley Authority
USACE	U.S. Army Corps of Engineers
USBR	U.S. Bureau of Reclamation
USGCRP	U.S. Global Change Research Program
USGS	U.S. Geological Survey

VBS	vehicle barrier system
WIMS	Water Information Management Systems
WMO	World Meteorological Organization

L-2. Definitions

alternative conceptual model—The set of conceptualizations that describes how plausible hydrometeorological phenomena may result in flood events that can cause hazards at a site. The set should account for uncertainty in geohydrologic, hydraulic, geo-seismic, meteorologic, and structural characteristics that are relevant for the plausible phenomena.

antecedent precipitation—A precipitation event that precedes the main and usually larger storm.

astronomical tides—The tidal levels and character that would result from gravitational effects of the earth, sun, and moon without any atmospheric influences.

base flow—Ground water seepage into a stream channel.

bathymetry—The measurement of ocean depths in order to determine the topography of the sea floor.

caldera collapse—The collapse of land following a volcanic eruption that is usually triggered by the emptying of the magma chamber beneath the volcano.

catchment—See **drainage basin**.

catchment area—See **drainage basin**.

catchment basin—See **drainage basin**.

causative mechanism—Hydrometeorological, seismic, or other phenomenon that may cause a flood.

Code of Federal Regulations—A collection of general and permanent rules by executive departments and agencies of the Federal Government that are published in the *Federal Register*.

cyclone—See **tropical cyclone**.

dam breach—See **dam failure**.

dam failure—Any situation in which a dam cannot retain or control the water that is impounded behind it. Dam failure can result from several causes. It is also known as **dam breach**.

derecho—See **squall line**.

design-basis flood—The most severe flood conditions that can reasonably be anticipated to occur at a site.

design-basis load—The forces or stresses that a structure is designed to withstand without failing to perform its designed function.

drag—Forces arising from fluid resistance that act on a solid object in the direction of the relative fluid flow velocity.

drainage area—See **drainage basin.**

drainage basin—An area of land where surface water from precipitation (rain and melting snow or ice) converges to a single point (usually at the exit of the basin) where the waters join another water body. (In closed drainage basins, the water converges to a single point inside the basin, which may be a permanent lake, a dry lake, or a point where surface water is lost underground.) The drainage basin includes both the streams and rivers that convey the water and the land surfaces from which water drains into those channels; a drainage divide separates it from adjacent basins. Drainage basins drain into other drainage basins in a hierarchical pattern, with smaller subdrainage basins combining into larger drainage basins. Other terms for a drainage basin are **catchment**, **catchment area**, **catchment basin**, **drainage area**, **river basin**, and **watershed**.

early site permit—A permit issued by the U.S. Nuclear Regulatory Commission (NRC) under Subpart A, "Early Site Permits," of Title 10 of the *Code of Federal Regulations* (10 CFR) Part 52, "Licenses, Certifications, and Approvals for Nuclear Power Plants," through which one or more sites are approved as suitable for locating a nuclear power facility, independent of a specific plant design.

erosion—The process by which moving fluid (water in the context of this guide) removes materials from a surface and transports them to another location.

excess precipitation—The volume of water from precipitation that is available for direct runoff (e.g., the precipitation in excess of infiltration capacity, evaporation, transpiration, and other losses). Excess precipitation is the portion of storm precipitation that appears as streamflow during or shortly after a storm. It is also known as precipitation excess.

extratropical cyclone—A cyclonic-scale storm that is not a tropical cyclone; the term usually refers to the migratory frontal cyclones of the middle and high latitudes. It is sometimes called an **extratropical storm**.

extratropical storm—See **extratropical cyclone.**

extratropical transition—The process by which a decaying tropical cyclone evolves into a fast-moving and occasionally rapidly developing extratropical cyclone that produces intense rainfall, very large waves, and even hurricane-force winds.

fetch—The length of water over which a given wind has blown. It is often called the **fetch length**.

fetch length—See **fetch**.

final safety analysis report—A report prepared by an applicant for licensing of nuclear facilities that documents safety-related analyses and is submitted to the NRC as part of the licensing application.

flood—Any abnormally high-water stage or flow in a stream, floodway, lake, or coastal area that has significant detrimental effects.

flood hazards—Conditions to which nuclear power plant facilities may be exposed during a flood event, such as hydrostatic and hydrodynamic forces, debris accumulation, and impact forces, that should be considered in the design to prevent loss of functionality.

floodplain—The lowland that borders a river, which is usually dry but is subject to flooding.

general design criteria—General criteria listed in Appendix A, "General Design Criteria for Nuclear Power Plants," to 10 CFR Part 50, "Domestic Licensing of Production and Utilization Facilities," that establish minimum requirements for the design of facilities of a nuclear power plant.

grade elevation—Topographical elevation of the site near facilities of the nuclear power plant.

hierarchical hazard assessment—A progressively refined stepwise estimation of site-specific hazards that evaluates the safety of structures, systems, and components with the most conservative plausible assumptions consistent with available data.

hurricane—A tropical cyclone with winds that have reached a constant speed of 119 kilometers per hour (74 miles per hour) or more. See also **tropical cyclone**.

hydrodynamics—A branch of physics that deals with the motion of liquids and the forces exerted by liquids.

hydrometeorological report—A report prepared and published by the National Oceanic and Atmospheric Administration's National Weather Service to provide guidance for estimating probable maximum precipitation for a specific area of the United States.

hydrometeorology—A branch of meteorology that studies the transfer of water and energy between the land surface and the lower atmosphere.

hydrostatics—A branch of physics that deals with fluids at rest or the pressures they exert or transmit.

hyetograph—A plot of rainfall intensity versus time. It is often represented by a bar graph.

ice dam—See **ice jam**.

ice jam—An accumulation of ice forming where the slope of a river changes from steeper to milder, where moving ice meets an intact ice cover, or where there is some restriction of the channel. Water impounded behind the ice jam can cause local or regional flooding. Ice jams are also called **ice dams**.

maximum wave height—The highest individual wave height (measured crest to trough) that occurs over a given period.

levee—An elongated naturally occurring ridge or artificially constructed fill or wall that regulates water levels. It is usually earthen and often parallel to the course of a river in its floodplain or along low-lying coastlines.

local intense precipitation—Intense precipitation occurring at a specific site, often as the result of a convective storm.

paleo flood— A flooding event for which there is evidence in the geologic record but that occurred before observation and documentation in the historical record.

paleo tsunami — A tsunami for which there is evidence in the geologic record but that occurred before observation and documentation in the historical record.

precipitable water—The total atmospheric water vapor contained in a vertical column of unit cross-sectional area extending between any two specified levels. Precipitable water is commonly expressed in terms of the height to which that water substance would stand if it were completely condensed and collected in a vessel of the same unit cross section. The total precipitable water is the atmospheric water vapor contained in a column of unit cross section extending all the way from the Earth's surface to the "top" of the atmosphere.

precipitation loss—The portion of total precipitation that is lost to processes such as interception, depression storage, and evapotranspiration and, therefore, does not appear as runoff.

probable maximum event—A general concept used in hydrometeorological design that is thought to specify the physical limit of a natural event such as precipitation, a flood, a hurricane, or a tsunami, among others.

probable maximum flood—The hypothetical flood (i.e., peak discharge, volume, and hydrograph shape) that is considered to be the most severe reasonably possible flood, based on comprehensive hydrometeorological application of probable maximum precipitation and other hydrologic factors favorable for maximum flood runoff, such as sequential storms and snowmelt.

probable maximum hurricane—A hypothetical hurricane that has a combination of characteristics making it the most severe hurricane that can reasonably occur in the region of interest. The hurricane approaches the point under study along a critical path and at an optimum rate of movement that results in the most adverse flooding.

probable maximum precipitation—The greatest depth of precipitation for a given duration that is thought to be meteorologically possible over a given storm area size at a particular location and at a particular time of the year, with no allowance made for future long-term climatic trends.

probable maximum storm surge—A storm surge resulting from a probable maximum hurricane or probable maximum windstorm.

probable maximum tsunami—A hypothetical tsunami that is considered to be the most severe reasonably possible flood-based analysis of the best available scientific information to arrive at a set of scenarios reasonably expected to affect the nuclear power plant site. The analysis of the probable maximum tsunami accounts for (1) the most severe 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, (2) the appropriate combinations of the effects of normal and accident conditions with the effects of the natural phenomena, and (3) the importance of the safety functions to be performed.

probable maximum windstorm—A hypothetical extratropical cyclone that might result from the most severe combination of meteorological storm parameters considered physically possible in the region of interest. The windstorm approaches the point under study along a critical path and at an optimum rate of movement that will result in the most adverse flooding.

pyroclastic flow—A fluidized mixture of solid to semisolid fragments and hot, expanding gases that flows down the flank of a volcano during an eruption.

reach—A stream segment with fairly uniform size, shape, water surface slope, channel materials, and flow characteristics.

reservoir—A natural or artificial pond or lake used for the storage and regulation of water (i.e., the lake formed behind a dam).

river—See **stream**.

river basin—See **drainage basin**.

sedimentation—The process of deposition of a solid material from a state of suspension in a fluid (i.e., water, in the context of this guide).

seiche—An oscillation of a fluid body in response to a disturbing force having the same frequency as the natural frequency of the fluid system. In the Great Lakes area, a seiche is any sudden rise in the water of a harbor or a lake, whether or not it is oscillatory. (Although this usage of seiche is inaccurate in a strict sense, it is well established in the Great Lakes area.)

seismic— Pertaining to or caused by an earthquake or vibration of the Earth, due to either natural or artificial causes.

significant wave height—The average of the highest one-third of waves, measured from trough to crest, that occur over a given period.

snowpack—Layers of snow that accumulate in geographic regions and high altitudes where the climate includes cold weather for extended periods during the year.

snowmelt—Surface runoff produced from melting snow.

snow water equivalent—The amount of water contained within a snowpack. It can be thought of as the depth of water that would theoretically result if the entire snowpack instantaneously melted.

squall line—A line of severe thunderstorms and accompanying winds that can form along or ahead of a cold front. It is also called a **straight-line windstorm** or a **derecho.**

still-water level—The average water surface elevation at any instant, excluding local variations caused by waves and wave setup but including the effects of tides, storm surges, and long-period seiches.

storm surge—An abnormal rise in sea level accompanying a tropical cyclone or other intense storm. Its height is the difference between the observed level of the sea surface and the level that would have occurred in the absence of the storm.

straight line wind—See **squall line**.

stream—A general term for any body of water flowing with measurable velocity in a channel. Streams range in size from rills to brooks to creeks to rivers. (The use of these terms has no widely agreed-upon or strict quantitative boundaries.)

structures, systems, and components—Facilities of a nuclear power plant, some of which may be essential for safe operation and shutdown and for maintaining safe-shutdown conditions.

subaerial—Located or occurring on or near the surface of the Earth.

submarine—Occurring or situated below the surface of the sea.

time of concentration—The elapsed time for storm runoff to travel from the most distant part of a drainage basin to the outlet.

tributary—A stream that flows into a main stem (or parent) stream or a lake.

tropical cyclone—A warm-core, non-frontal, synoptic-scale cyclone that originates over tropical or subtropical waters with organized deep convection and a closed surface wind circulation about a well-defined low-pressure center. Depending on its location and strength, a tropical cyclone may be called a **tropical depression**, **tropical storm**, **hurricane**, **typhoon**, or simply **cyclone**.

tropical depression—See **tropical cyclone**.

tropical storm—A tropical cyclone in which the maximum 1-minute sustained surface wind ranges from 34 to 63 knots (39 to 73 miles per hour) inclusive. See also **tropical cyclone**.

tsunami—A series of impulsively generated water waves that propagate from the point of generation toward the shores of a water body. Typically, "tsunami" refers to an oceanic tsunami, but tsunamis or tsunami-like waves can also be generated in inland water bodies. The rapid, large-scale vertical displacement of a water column causes tsunamis.

tsunamigenic source—The geologic or seismic mechanism (typically an earthquake or landslide) that generates the rapid, large-scale vertical displacement of a water column that causes tsunamis.

typhoon—See **tropical cyclone**.

unit hydrograph—The direct runoff hydrograph for a given drainage basin from the unit depth of precipitation excess that occurs uniformly over the basin during a specified length of time.

watercourse—See stream.

watershed—See drainage basin.

wave climate—The long-term statistical characterization of the behavior of waves in a water body, typically at a particular ocean location.

wave runup—The maximum vertical extent of wave uprush on a beach or structure above the still-water level.

wave setup—The increase in the total still-water elevation within the surf zone (or against a barrier) caused by the transfer of wave-related momentum to the water column during wave breaking.