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A REVIEW OF AVAILABLE METHODS FOR THE PROBABILISTIC TREATMENT OF COINCIDENT AND CORRELATED FLOOD MECHANISMS

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ABSTRACT

This paper documents initial observations and findings from a research project sponsored by the U.S. Nuclear Regulatory Commission (NRC) and focused on development of the technical basis for guidance related to probabilistic assessment of multi-mechanism floods (MMFs). In particular, this paper summarizes outcomes of the first project task and provides a reconnaissance-level survey of the current state of concepts and methods for probabilistic assessment for MMFs. This paper introduces a generalized MMF assessment framework to describe the distinctions among various types of flood-forcing phenomena, flooding mechanisms, and flood severity metrics. It also outlines a path forward for future research activities under the project.

MOTIVATION AND CONTEXT

Critical infrastructures, such as nuclear facilities, may potentially be exposed to a range of flooding mechanisms such as local intense precipitation (LIP), flooding on streams and rivers, discharges from dam releases and failures, as well as coastal flooding phenomena such as storm surge, seiche, and tsunami. Hazards from these flooding mechanisms can be individually consequential to facilities. Moreover, multi-mechanism floods (MMFs) involving more than one of these flooding mechanisms can likewise be consequential. In fact, flood impacts on a facility from MMFs may be greater than the impacts of individual flooding mechanisms. To properly evaluate the hazards from MMFs, the hazards need to be analysed in a multivariate, probabilistic fashion. However, MMFs can be particularly challenging to characterize probabilistically. This arises due to the need to consider and assess the frequency of a range of possible combinations, including combinations in which one mechanism is of relatively low severity while the other is of relatively high severity (or vice versa) as well as combinations involving moderate severity events of each flooding mechanism. Moreover, it is necessary to understand and quantitatively characterize the dependence structure between these quantities.

This paper documents initial findings from the NRC-sponsored research project "Methods for Estimating Joint Probabilities of Coincident and Correlated Flooding Mechanisms for Nuclear Power Plant Flood Hazard Assessments." Overall, the project includes three main research components: (1) a survey of current concepts and methods used in assessing MMF hazards, (2) a critical assessment of selected approaches and methods for probabilistic modelling of MMF hazards, and (3) development of example cases to illustrate probabilistic MMF hazards modelling best practices. This paper summarizes the outcomes of Task 1, which provides a reconnaissance-level survey of the current state of concepts and methods for flood hazard assessment of MMFs. The paper also provides a generalized MMF assessment framework and outlines a path forward for research activities.

KEY TERMS AND CONCEPTS

Because of the wide variety of terminologies used in academic/scientific literature as well as other types of reports, regulatory guidance, and standards, we begin by setting up a semantic structure for discussing topics related to consideration of MMFs.[1] While this structure is helpful within the context of this paper, we envision this structure to be particularly important for future efforts under the aforementioned research project.

We use the term **flood-forcing phenomena** to describe the natural or man-made processes that create conditions that can ultimately lead to flooding at a site. Relevant flood-forcing phenomena include, but are not limited to, hydrometeorological forcings (e.g., tropical and extratropical cyclones, thunderstorms, snowpack accumulation, rapid wind or temperature changes), ground motion (e.g., earthquakes, landslides), operational factors (e.g., planned or unplanned releases from dams), equipment failure, and natural cyclic processes (e.g., tides).

Flood-forcing phenomena can then lead to site flooding through a variety of different **flooding mechanisms**; i.e., physical processes by which a natural or man-made flood-forcing phenomena can lead to inundation on or near a site. There are three primary categories (types) of flooding mechanisms:

- **Pluvial flooding mechanisms**: Pluvial flooding occurs when precipitation or snowmelt directly causes flooding of a site independent of the overflow of nearby river or water body. Pluvial flooding typically occurs when the volume or rate of precipitation or snowmelt exceeds infiltration capacity or the capacity of drainage or pumping systems (if available).
- **Fluvial flooding mechanisms**: Fluvial flooding is defined as flooding that occurs on a defined channel such as a river or stream. Fluvial flooding occurs when the cumulative surface runoff or snowmelt from upstream watersheds increase significantly and results in the exceedance of normal channel capacity.
- **Coastal flooding mechanisms**: Coastal flooding is associated with flooding of land adjacent to a sea, ocean, lake, or other open or semi-enclosed body of water.

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[1] It is noted that available literature uses a range of terms to refer to combinations of flooding mechanisms (which we refer to as MMFs). Terms that have been identified to describe these types of hazards include (but are not limited to): coincident, combined, concurrent, compound, joint, cascading, concomitant, simultaneous, and successive.

Finally, **flood severity metrics** refer to the quantities used to measure flood severity such as (1) water height or elevation of the flood, (2) flood volume, (3) peak discharge, (4) flood duration, and (5) associated effects.

MULTI-MECHANISM FLOOD HAZARD FRAMEWORK

Literature related to MMF assessment is wide-ranging in context, application, and terminology. To provide structure and consistency in describing the literature reviewed within this paper and broader project activities, we set up a framework and terminology for discussing combinations of flooding mechanisms. In particular, three classes of combinations are defined in conjunction with the conceptual diagrams in Figure 1. In this project, the term **coincident mechanisms** (see Figure 1a) refers to two (or more) flooding mechanisms that affect a facility at the same time but result from independent flood-forcing phenomena. An example is a fluvial flood caused by a seismically-induced dam failure that occurs coincident with rainfall-induced river flooding. The term **correlated mechanisms** refers to flooding mechanism combinations that are directly or indirectly driven by the same flood-forcing phenomena. This dependence takes two forms. The term **concurrent correlated mechanisms** (see Figure 1b) refers to flooding mechanisms that are generated by a common flood-forcing phenomena. For example, for sites located on estuaries or tidally influenced rivers, flooding mechanisms from both storm surge (coastal flooding mechanism type) and rainfall-induced river flooding (fluvial flooding mechanism type) can be caused by a single hurricane event. The term **induced correlated mechanisms** (see Figure 1c) refers to scenarios in which one flooding mechanism leads to (induces) another flooding mechanism. For example, rainfall-induced river flood may lead to (induce) a hydrologic dam failure and subsequent flood.

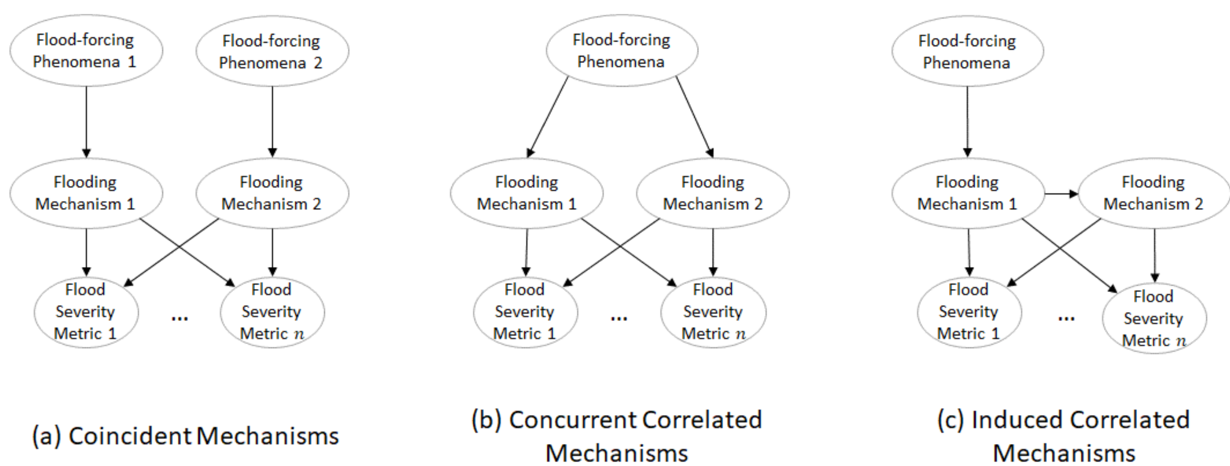

Figure 1: Categorization of combinations of flooding mechanisms.

METHODS FOR MULTI-MECHANISM FLOOD HAZARD ASSESSMENT

Two broad classes of approaches are used to assess flood hazards: deterministic flood hazard assessment (DFHA) and probabilistic flood hazard assessment (PFHA). DFHA considers a single scenario or a set of candidate scenarios intended to define a sufficiently severe flood hazard for consideration in a target application (e.g., design, analysis, or retrofit of a component or system). In particular, under DFHA, MMFs are typically addressed by considering a limited number of stylized scenarios that involve the occurrence of multiple flooding mechanisms (e.g., ANSI/ANS 1992). Flood severity metrics are then calculated under each of the limited number of assumed scenarios. The scenario that causes the most severe flood (among the scenarios considered) is selected for use in design or analysis. In such assessments, the flood hazard severity metric is often flood elevation, but may consider other metrics (e.g., flow velocity or inundation duration). Information regarding the frequency of exceedance associated with the resulting severity level is not explicitly calculated. As such, DFHA offers limited support for risk quantification and risk-informed decision-making.

In contrast, probabilistic methods enable quantitative estimation of flood hazard frequencies (and subsequently flood risk). Per USNRC (2014), "a truly risk-informed and performance-based approach requires quantitative probabilistic models for the flooding phenomena combined with probabilistic models for the fragility of flood protection features and reliability of flood protection or mitigation procedures." In general, a PFHA considers all (or nearly all) possible flooding scenarios of relevance to a site, the severity of hazard associated with each of those scenarios, and their joint likelihood of occurrence. In particular, PFHA is a systematic assessment of the likelihood that a specified flood severity metric or set of metrics will be exceeded at a site or in a region during a specified interval. The results of such an assessment are expressed as estimated probabilities (e.g., annual exceedance probability [AEP]) or frequencies. Results of a PFHA are often displayed as a hazard curve (or set of hazard curves), which include a flood severity metric on one axis and the probability of exceedance on the other axis.

The majority of work related to PFHA focuses on a single measure of flood severity. Most frequently, statistical analysis is performed using observations related to the severity metric of interest (e.g., river discharge) in conjunction with extreme value theory to estimate distributions of extrema associated with the severity metrics. These approaches do not, in general, distinguish whether the flood severity metric is the result of single or multiple flood-forcing phenomena as well as single or multiple flooding mechanisms.

When sufficient data are not available to support direct statistical analysis directly based on observations representing a flood severity metric at a particular location, a derived random variable approach (Der Kiureghian and Ditlevsen 2009) may be used. A derived random variable approach represents a flood severity metric as a function of quantifiable random variables representing the underlying flood-forcing phenomena or flooding mechanisms. For example storm surge may be estimated as a function of hurricane parameters. AEPs can then be estimated using the theorem of total probability or stochastic simulation based approaches. Derived random variable approaches can be readily extended to consider formulations that explicitly address multiple flood-forcing phenomena and flooding mechanisms.

EXISTING RESOURCES

While MMFs have been the focus of research studies (summarized below), there is limited guidance and experience regarding the application of MMF modelling frameworks. The current practice and guidance in PFHA generally focuses on single-mechanism flood hazard assessments, and while some documentation acknowledges multi-mechanism flood hazards, analytical frameworks and guidance for MMF assessment is generally not available. In addition, much of the existing guidance involving MMFs focuses on DFHA rather than PFHA. Consistent with this trend, the current guidance for flood hazard assessment used for siting of commercial nuclear power plants (NPPs) in the US remains primarily deterministic for the assessment of both individual and combinations of flooding mechanisms. More broadly, documents produced by the International Atomic Energy Agency (IAEA) emphasize the need to consider multi-hazard events, but do not provide explicit guidance for doing so. In 2015, the Electrical Power Research Institute (EPRI) released a review of the current state of nuclear industry practice for identification and screening of external hazards (EPRI 2015). While the EPRI report is broad in scope, it includes a section focused on multiple or combined hazards (including flooding and other hazards) and includes high-level summaries of methods used for screening or other treatment of combined events in France, Sweden, Finland, Germany and Switzerland. The report also summarizes other international experience, including outcomes of an IAEA-sponsored technical meeting in 2014, which noted some of the challenges related to assessment of combined hazards (e.g., lack of detailed guidance, the reliance on expert judgement, challenges associated with development of joint distributions, and need for practical guidance).

Academic and scientific literature related to the assessment of MMFs is wide-ranging in applications and focus. In general, coincident mechanisms (Figure 1a) are rarely addressed in the literature, as the independence of the mechanisms makes probabilistic assessment less challenging to address than the other groups. As such, literature focuses almost exclusively on concurrent flooding mechanisms, with concurrent correlated mechanisms (Figure 1b) being addressed more frequently than induced correlated mechanisms (Figure 1c).

A significant portion of available literature leverages statistical methods and focuses on (1) characterizing the correlation or dependence structure between parameters (e.g., flood severity metrics) associated with multiple flood mechanisms or (2) addressing the estimation of joint probability distributions of those metrics. A smaller portion of this statistical methods-focused literature extends the analysis to consider the effects of multiple mechanisms on the estimated probability or frequency of exceedance associated with one or more flood severity metrics. These statistical studies typically apply extreme values analysis methods (including multivariate extensions), copula-based approaches, and stochastic simulation.

A smaller portion of the literature focuses on modelling of physical processes. These modelling-focused studies do not typically address estimation of probabilities and risks. Nonetheless, they provide a set of tools that can be used in conjunction with derived random variable approaches to support probabilistic hazard assessments.

The MMF literature generally considers (1) MMFs that fall within a single flood type, or (2) MMFs that cut across flood types; e.g., the occurrence of river flooding (a fluvial flooding mechanism) concurrent with storm surge (a coastal flooding mechanism).

Literature addressing hazards within the *coastal flooding mechanism type* are addressed in works focused on topics such as interactions of coastal flooding mechanisms as well as models for capturing the concurrent occurrence of several flood severity metrics for hazards that result from a single coastal flooding mechanism. We found that most of these studies focus on modelling of processes and interactions and do not typically address probabilistic characterization or dependence structures. For example, several studies have explored the interactions between tides and tsunamis in computing water levels (e.g., Kowalik and Proshutinsky, 2010; Zhang et al. 2011). A number of coastal studies have explored the interaction of stillwater levels and wave effects or other wave characteristics during storm events (e.g., Hawkes et al. 2002; De Michele et al. 2007; and Masina et al. 2015). Research has also explored the effects of sea level rise (SLR) on estimated coastal hazards (e.g., Tebaldi et al. 2012; Vitousek et al. 2017).

Literature addressing hazards within the *fluvial flooding mechanism type* considers hazards from the occurrence of multiple fluvial flooding mechanisms, characterization of multiple severity metrics from a single fluvial flooding mechanism, as well as more targeted applications such as assessment of fluvial hazards at river confluences. For example, Sui and Koehler (2001) investigated the joint occurrence of precipitation on snow and snow melt. Several authors have addressed flooding at the confluence of two rivers and in multiple tributary systems (e.g., Wang et al. 2009; Wang 2016; Kao and Chang 2012; Bender et al. 2016; Gilja et al. 2018). Research has also been performed looking at several flood severity metrics associated with a single fluvial mechanism; e.g., to address flood peak and volumes or volumes and duration (e.g., Bastian et al. 2010; Papaioannou et al. 2016; Yue et al. 1999; Zhang and Singh 2006) or magnitudes and dates (e.g., Lu et al. 2012).

There is a substantial body of MMF literature involving *joint coastal and fluvial flooding types* (typically hurricane-induced storm surge with concurrent river flooding caused by hurricane-induced precipitation). A subset of such literature investigates the degree of correlation or dependence structure between coastal and fluvial flooding mechanisms. This group of literature focuses on characterization of this dependence structure but does not typically include estimation of probabilistic hazard measures (e.g., probabilities or frequencies of exceedance). Examples of such studies include those by Svensson and Jones (2002) and Svensson and Jones (2004), which were extended in a "best practices" guide in Hawkes (2006) and summaries in Hawkes and Svensson (2006) and Svensson and Jones (2006).

Other joint coastal and fluvial studies addressing simultaneous occurrence of storm surge and river discharge include Kew et al. (2013), Klerk et al. (2015), and Ward et al. (2018). Lian et al. (2012) (and the extension in Xu et al. 2014) investigated the joint effects of rainfall and tidal level. Petroliagkis (2018) and the associated technical report (Petroliagkis et al. 2016) investigated the dependence structure between surge and wave height in a variety of coastal environments along European riverine and estuary areas.

Going beyond the studies that investigate the dependence or dependence structure for coastal and fluvial mechanisms, several references seek to estimate the frequency of exceedance of water levels or inundation probabilities when considering combinations of flooding mechanisms (e.g., Zhong et al. 2013; Zheng et al. 2014; Moftakhari et al. 2017; and Bevacqua et al. 2017). While not focusing specifically on probabilistic characterization, several studies address the modelling of events involving the joint occurrence of coastal and fluvial flooding mechanisms (e.g., Bunya et al. 2010; Chen and Liu 2014; and Bass and Bedient 2018). These studies do not seek to characterize the dependence structure or compute probabilities; rather they focus on numerical modelling tools.

We also found MMF literature related to flooding hazards involving *joint coastal and pluvial flooding types*. This also includes works addressing coastal flooding mechanisms and precipitation in general (e.g., precipitation quantity, intensity) even when there is not an explicit link to subsequent pluvial or fluvial flooding. These works generally focus on investigating the degree of correlation or dependence structures, such as exploring the dependence between large rainfall and storm surge (e.g., Zheng et al. 2013; Engineers Australia 2015; Wahl et al. 2015; van den Hurk et al. 2015; and Archetti et al. 2011). Moreover, while not focusing specifically on probabilistic characterization or dependence structures, several studies address the modelling of events involving the joint occurrence of coastal and precipitation events (e.g., Lin et al. 2010; Lu et al. 2018). In addition to literature that focuses directly on consideration of coastal hazards and pluvial hazards (or precipitation), additional literature is available that provides "building blocks" for further evaluation involving multiple mechanisms. These studies focus on improving the capabilities for modelling tropical cyclone induced precipitation (e.g., Lonfat et al. 2007).

SUMMARY AND NEXT STEPS

This paper summarizes the initial findings of the first of multiple tasks to be performed under an NRC-funded PFHA research project intended to assist the NRC in establishing the technical basis for guidance on developing flood hazard curves for MMFs. The task summarized herein was designed to be a wide-ranging survey of approaches and methods that have been applied to understand and assess flood hazards due to MMFs.

To provide structure and context for the research project, this paper began by describing a hierarchy of relevant terminology as well as a general framework for consideration of MMFs. The remainder of the paper summarizes the concepts and methods currently used in practice and research for assessing hazards due to MMFs. Existing literature addresses MMFs from several different perspectives. The majority of identified literature focuses on characterizing the correlation or dependence structure between parameters related to MMFs (e.g., flood severity metrics) or estimating the joint probability distributions of those parameters. A smaller portion of the literature further considers the effects of MMFs on the estimated probability or frequency of exceedance associated with one or more flood severity metrics. Finally, a subset of studies focuses exclusively on understanding the physical interactions between mechanisms or the modelling of multiple flood mechanisms using coupled or integrated modelling tools.

In subsequent project activities under Task 2, the project team will perform a critical review of the approaches and methods identified in Task 1. The project team will identify a subset of available methods that appear to be sufficiently general or flexible for application to the range of flooding phenomena expected at NPPs in the United States. Finally, under Task 3, the research team will develop a set of illustrative examples for the approaches identified under Task 2.

DISCLAIMER

This paper was prepared as an account of work sponsored by an agency of the U.S. Government. The views expressed in this paper are not necessarily those of the U.S. Nuclear Regulatory Commission.

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