Applying Probabilistic Concepts in External Flooding Applications at Nuclear Power Plants

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ABSTRACT

Traditionally, flood hazard evaluations were completed using conservative deterministic analyses, which could result in costly mitigation/prevention strategies. When completing Probabilistic Flood Hazard Assessments (PFHA) and fragility curves, a key aspect is quantifying and understanding the uncertainty associated with model input parameters, and their potential impact on the results. This paper considers uncertainty with various input data sets and methods, and explores how uncertainty can be addressed through logic trees and Monte Carlo simulations for the development of hazard and fragility curves.

1. Introduction

A PFHA is a tool for quantifying the flood hazard potential necessary for risk based decision making and evaluation of mitigation strategies. Flood hazard curves are defined as graphs of peak flow and volume verses annual exceedance probabilities (1). Hazard curves can also be represented on graphs of flood levels verses their annual exceedance probabilities. The flood hazard results from the suggested probabilistic approach can be used in conjunction with applicable authority or regulatory body requirements such as the International Atomic Energy Agency (IAEA) to determine the design basis flood hazard for nuclear facility sites, or individual structures, systems and components (SSCs). They can also be used as input to external flood hazard Probabilistic Risk Assessments (PRAs) or Probabilistic Safety Analysis (PSA).

This Paper describes the main concepts of the PFHA and how it can be supplemented with a fragility analysis to determine the probability of failure based on flooding failure modes. This Paper also describes Monte Carlo simulations conducted to quantify runoff as an example step in the PFHA process, which is a step towards calculating the probability of the specified loads.

2. Process Overview

As part of the PFHA process, facilities are usually categorized into Flood Design Categories (FDC), which determine the level of detail required for the PFHA. The FDC is selected relative to the radiological hazard at a site or facility. The FDC level influences the level of details associated with the PFHA.

For this example, the likelihood of all credible external flood hazard sources that could impact the embankment are determined using a PFHA. Some of the PFHA characteristics associated with this specific study are:

- Data collection, identification of flood sources, screening out non-credible flood hazards and performance of the actual technical PFHA (i.e., hazard quantification);
- The PFHA quantifies and provides an understanding of the uncertainty associated with flooding model input parameters, and their potential impact on flood hazard evaluation;

- Probabilistic model selection describing the random nature of uncertainties including possible combination of different flood sources, identification and quantification of aleatory and epistemic uncertainties; and
- Peer review of the hazard quantification and documentation

A taxonomy of modeling uncertainties was defined as part of the PFHA process for this specific example. Generally, this is a labeling of uncertainties as aleatory or epistemic. Aleatory uncertainty includes those random events that can be described by a probability distribution function, and are often considered irreducible. Epistemic uncertainty includes those random events that can be reduced with further study and analysis. More simplistically, aleatory uncertainties can be assigned a return period and epistemic uncertainties cannot.

Determining the hazard curves for a flooding mechanism is an important step towards the development of fragility curves. A fragility curve indicates the probability of failure for some specified load (2). For the purposes of this paper, the failure of a flood protection embankment (or berm) is considered, and failure herein is defined using a serviceability requirement. That is, failure is considered a condition that the riprap protection of the embankment is unstable.

A preliminary step required to develop a fragility curve is to identify failure modes. For the flood protection provided by the embankments, failure modes include hydraulic, geohydraulic, global static, and other mechanisms (3). Defra/EA identifies failure modes of linear defense barriers as: overflow (overtopping), piping, sliding, and overturning. Overtopping and wave spillover are included in the category of hydraulic failure, piping in the category of geohydraulic failure, and slope instability and core sliding as global static failures (3).

It is apparent that there can be some flexibility in the definition of failure and the categorization of failure modes. The definition of failure could be influenced by risk, our understanding of underlying processes, our ability to quantify a stage of the failure event, and availability of data. It can also be influenced by the ease at which the event can be defined for numerical or analytical purposes. Similarly, the categorization of failure modes can be influenced by an underlying understanding of the processes, historical categorization, training, and convenience.

When the hazard quantification step is complete and the PFHA team has a family of hazard curves that are specific to the embankment, the fragility curves can be computed as follows:

1. Identify the loads and failure modes including load sources and failure measures. This typically includes the developing of hazard curves of the loads.
2. Collect data that describe the relationship between loads and failure.
3. Categorize uncertainties (aleatory and epistemic) as benefits the study.
4. List ranges for conditions used to determine loads.
5. Evaluate uncertainties:
    a. Determining or selecting Probability Density Functions (PDFs) for parameters
    b. Weight competing PDFs, models and parameters as necessary for the analysis
    c. Build logic tree
6. Determine fragility curves using Monte Carlo methods
7. Review to ascertain the reasonability of inputs and results.
8. Document.
9. Peer review and expert elicitation.

3. Illustrative Example

Following the process outlined above, the PFHA analysts evaluated all flooding sources and their probabilities. It was important to first identify all failure modes. The failure mode considered for this example is overtopping associated with static water levels and waves. In a broader sense, the loads associated with this failure modes are: significant wave height, wave period, and freeboard. For the purposes of this paper, the failure of the embankment is only considered from the perspective of erosion in order to illustrate the process.

Qualitative and quantitative screening evaluations were conducted to determine the applicable flooding hazards that can impact the levee under study. The screening evaluation concluded the river flooding is a source of concern and could cause a failure to the flood protection feature.

A probabilistic modeling approach for evaluating riverine flooding usually has the following components:

- Probabilistic model to evaluate rainfall or stream flow frequencies. The precipitation depths for rainfall events of various return periods and durations are then discretized into a hydrological rainfall-runoff model.
- Physically based hydrologic models to evaluate river flows for defined precipitation events that include the spatial and temporal pattern of precipitation, and watershed antecedent conditions, potential for ice jamming, temperature, performance of levee systems, etc.
- Hydraulic modeling to estimate flow depths and velocities for river flows of varying size, duration, etc., including the performance of levee systems.
- Probabilistic aleatory model to estimate the frequency of occurrence of flood levels, and
- Probabilistic model of the sources of epistemic uncertainty in the physically-based models and the uncertainty in implementing the aleatory model.

A flow chart showing the steps to calculate loads at the embankment is illustrated in Figure 3-1. This Paper focuses on the process indicated by boxes 1 through 3 of Figure 3-1. A previous paper (4) discusses the development of the fragility curves based on the loads and a future paper will discuss boxes 4 through 8 of Figure 3-1.

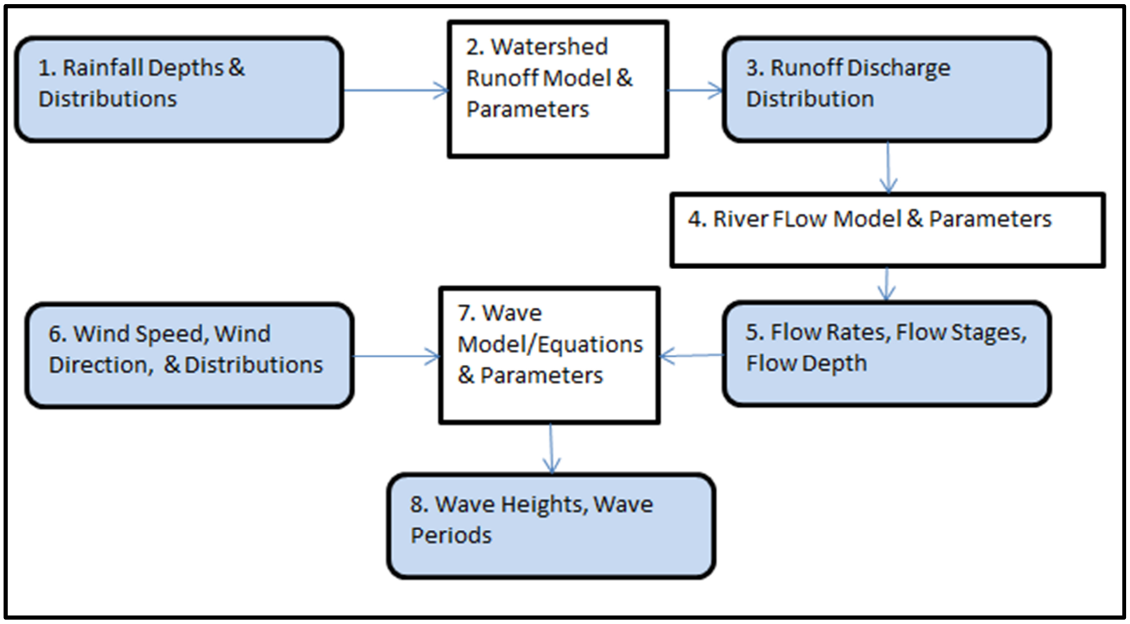

Figure 3-1. Flow Chart of Calculations

Note: Boxes are numbered for convenience of discussion.

A 1D or 2D models can be used to determine flood levels adjacent to the levee. A range of the available freeboard levels can then be evaluated using MCS techniques as one of the failure modes. Details for the results of the fragility analysis based on freeboard as a load are provide in an earlier paper (4). Note that the final objective of this analysis is the development of fragility curves for the levee based on the applicable loads such as freeboard, significant wave height and wave period. Monte Carlo simulations were used to calculate water levels adjacent to the levee, wave runup heights, runup depths, and runup flow velocities; which are compared to estimated stable riprap sizes (4). A Python (5) program is used to control the Monte Carlo simulations of runoff. The Python program selects parameter values based on the specified Probability Density Function (PDF) for each parameter, modifies the hydrologic model input files, calls the hydrologic program, and processes the model output files for the analysis. A branch of the logic tree for the Monte Carlo simulations is illustrated in Figure 3-2.

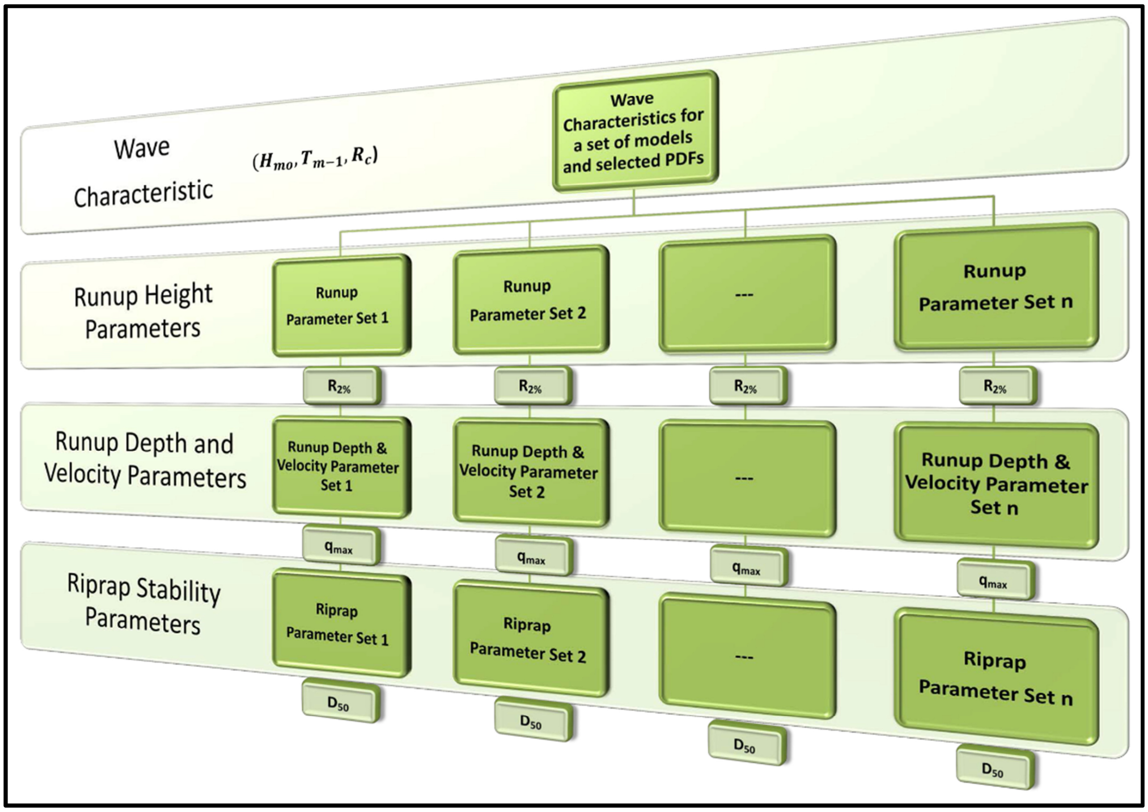

Figure 3-2. Small Branch of the Logic Tree

Notes: H_{mo} = significant wave height, $T_{m-1.0}$ = spectral wave period, R_c = freeboard height, $R_{2\%}$ = the run-up exceeded by two percent of the waves, q_{max} = flow rate per unit length of embankment, D_{50} = is the particle size for which 50 percent of the riprap sample is finer.

3.1 Rainfall Depths and Distribution

A PFHA resulting from precipitation external to the site (i.e., watershed precipitation) was one of flooding mechanisms evaluated as part of this analysis. The PFHA was derived from an evaluation of the frequency of the external flood hazard at the site and considerations of relevant historical data, relevant causative combinations of factors and characteristics of the watershed with consideration of reasonable concurrent events and projected impact of climate change during the lifetime of the unit to be evaluated.

For illustration purposes, the Atlas 14 (6) return periods are used with a specified return period and reported confidence interval in the Monte Carlo simulations. A normal probability distribution is assumed for rainfall depth with the standard deviations equal to the 90% confidence interval/1.645. Rainfall is assigned an SCS Type II Distribution as per TR-55 (7, Figure B-2). The rainfall time distributions are calculated using a Microsoft Excel ® spreadsheet (8).

One hundred simulations (or trails) are made for each combination of rainfall return period and duration (i.e., a box) of Atlas 14 data as part of the Monte Carlo simulations, a total of 19,000 simulations. Ten return periods (1, 2, 5, 10, 25, 50, 100, 200, 500, and 1000 year) and nineteen durations (5-min, 10-min, 15-min, 30-min, 60-min, 2-hr, 3-hr, 6-hr, 12-hr, 24-hr, 2-day, 3-day, 4-day, 7-day, 10-day, 20-day, 30-day, 45-day, and 60-day) are included in this illustrative analysis.

3.2 Hydrologic and Hydraulic Flow Model

For the purposes of this example, SITES (9) is used to calculate runoff using the Soil Conservation Services (SCS) method, which includes curve number (CN) and time of concentration (TOC) parameters. Table 1 shows the hydrologic parameters used in this analysis, their range, and PDF. A schematic for the hydrologic model setup is shown in Figure 3-3.

Component	Parameter	PDF	Mean	Min.	Max.	St.dev.
Basin1	CN	Normal	90	85	95	2.5
	TOC (hours)	Normal	0.82	0.2	1.6	0.4
Basin 2	CN	Normal	89	84	94	2.5
	TOC (hours)	Normal	0.5	0	1	0.25

Table 1: Hydrologic Programs used in the Runoff Calculations

Notes: CN = curve number, TOC= Time of Concentration, PDF = Probability Density Function. A normal distribution is not the only distribution that could be considered. It is used here for illustration purposes only. The range of values considered and the standard deviation represent uncertainty due to several unknowns include antecedent moisture conditions, accuracy of topography used in analysis, impact of roads and depressions, and Manning's roughness.

Admittedly, there is some potential uncertainty in the map data. Sources for this uncertainty might include: seasonal conditions (including agricultural conditions), atmospheric conditions, land development, and photographic errors and anomalies. These errors are site specific and may be difficult to quantify. There could also be errors (numerical or procedural) that could occur in processing the map data. Typical errors include those for overlapping and gaps between adjacent polygons used in the calculation of area weighted parameters using a Geographic Information System (GIS). The uncertainty associated with these potential sources of error are considered to be addressed through the uncertainty associated with parameters developed using the map data.

Topographic contours that are converted to a raster file using the tools of Spatial Analyst within ArcMap (10) are used in the watershed delineation and longest flow path selection. The watershed, subbasin boundaries, and longest flow paths are delineate using the resulting raster file and the procedures of ArcHydro (11).

3.3 River flooding and Wave Run-Up Analysis

As mentioned above a separate analysis was performed (4).

4. Results

Figure 4-1 shows the estimated mean runoff rates for the example site. Figure 4-2 shows the standard deviation of estimated runoff rates.

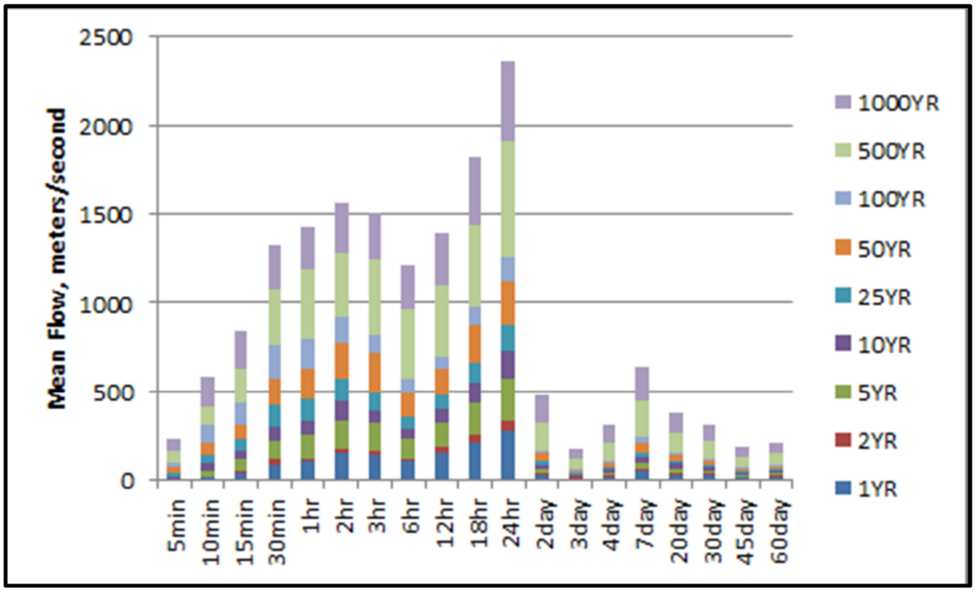

Figure 4.1: Mean Runoff Rates

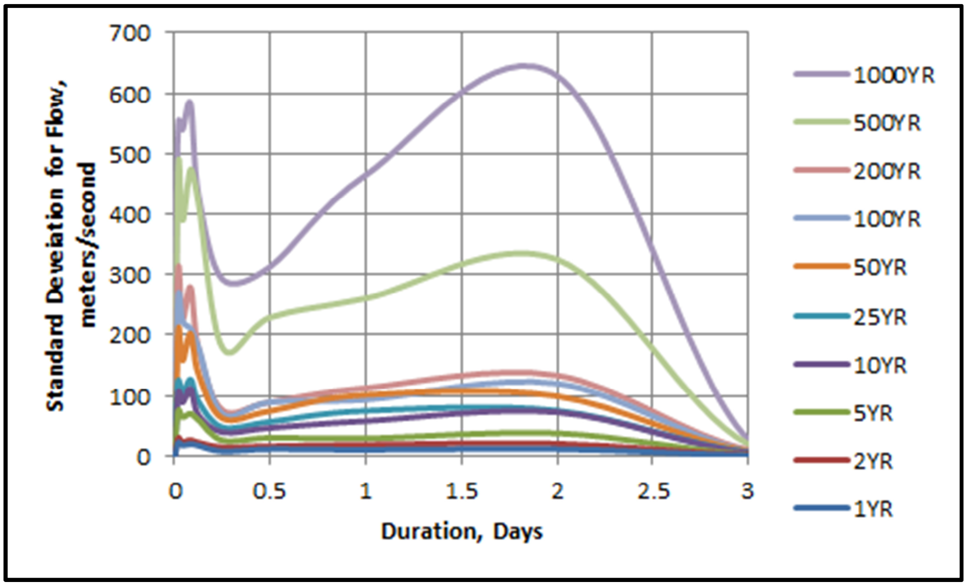

Figure 4.2: Standard Deviation of Flow

5. Conclusions

Probabilistic techniques can be divided into two broad categories:

1) Statistical methods that rely on extrapolation of historical data;
2) Detailed probabilistic analysis methods that integrate hydrologic and statistical models and the uncertainty associated therewith.

For the purposes of this illustrative example, we followed the second technique since it has few advantages over the purely statistical approach:

- Utilization of Monte Carlo Simulation (MCS) Techniques – By applying MCS, a PFHA can utilize a combination of stochastic and hydrologic models to develop probability of exceedance curves for hydrologic parameters such as peak discharge. Using MCS techniques, the climatic and storm-related input parameters can be allowed to vary as observed in nature (e.g., antecedant soil moisture may be represented as by a probability density function instead of a single value to account for natural variability in that parameter). It is important to note that that MCS schemes were assessed by suitable diagnostic checks to ensure that biases are minimized and results are consistent with either historical observations or physical reasoning.

- Accounting for coorelation in a Multivariate Analysis – The use of multiple variables in a hydrologic analysis (e.g., considering precipitation, watershed characteristics, and antecedent conditions as separate stochastic variables) leads to a more detailed analysis.

For this illustrative study, the Monte Carlo simulations used for development of the PFHA are not comprehensive. For example alternative models could be considered that might aid in verifying the range of parameters selected for this analysis. These alternative models could include 2D models, or alternatives to the SCS Curve Number methodology. Similar to the use of alternative PDFs, a weight can be applied to competing model results based on the estimated comparative adequacy of the models.

Other distributions could also be used to evaluate the rainfall data. The normal distribution was used in this example for simplicity. However, it is important to account for the uncertainty associated with any additional distributions. A representative weight factor for each distribution can be developed as part of the hazard curve development. For our study, the uncertainty in the Atlas rainfall data was accounted for as follows: Atlas 14 table has a mean, min and max. Standard deviations (σ) used in the Monte Carlo analysis are approximated from various sources, noting that approximately 95-percent of randomly selected values are expected to fall within the mean (μ) $\pm 2\sigma$ range.

A maximum return period of 1000-years is included in this analysis. However, a separated (1D and 2D) model simulation of the site specific Probable Maximum Precipitation (PMP) event was also made. The PMP event does not have a well-defined return period. Although the return period of the PMP is generally considered to greater than or equal to 1,000,000 years. Site and watershed specific evaluations of historical rainfall may be required to better define rainfalls with a return period greater than 1000-years for use in the PFHA analysis.

One-hundred trials of the Monte Carlo simulation were conducted for each box of rainfall return period and duration provided using Atlas 14. A sensitivity analysis to evaluate the need for a greater number of trails per box should be included in any future study of the site.

One of the intents of the PFHA methodology is to reduce conservativism generally inherent in deterministic evaluations. Future efforts to better define the most appropriate PDFs (including PDF parameters) and models for these analyses may further reduce the conservatism illustrated by the example. However, without that information, the PFHA studies will likely have significant conservatism.

In practice, the 2D runoff flow models may require significant computational effort that may exclude them from the Monte Carlo simulations. However, these models may provide valuable support to adjusting the distribution of parameters used in the Monte Carlo simulation.

The process illustrated through the example helps identify several points for consideration:

1. Deterministic modeling may be helpful for sensitivity tests and to evaluate suitability of parametric equations.
2. Available PDF selection may not provide full coverage of the range of values for parameters.

3. Potential selection of inappropriate PDFs may bias results
4. Assumed PDF for some parameters may require additional support.
5. Similar conclusions for PDF selection (items 2, 3, and 4) could be attributed to model selection.
6. Fragilities can be biased by limited or misleading values of parameter Minimum, maximum, mean, and standard deviations.

6. References

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