Appendix 11
Uncertainty Analysis

Introduction

One of the objectives of the New Orleans (NO) hurricane protection system (HPS) risk analysis is to quantitatively assess the uncertainties associated with the estimated levels of basin inundation due to hurricane events, which includes an evaluation of the uncertainty in the rate of future hurricane occurrences, the estimated storm surge and wave elevations, and the performance (reliability) of the HPS (levees and floodwalls). The subject of this appendix is the evaluation of epistemic uncertainties in the assessment of system performance and the 100-year inundation levels.

The risk analysis that is the basis for the inundation maps presented in Appendix 13 is based on a best-estimate analysis of the frequency of hurricane events and storm surge, levee and flood wall reliability, and the inundation that results from system overtopping and/or breaching. The subject of this appendix is twofold. The first is to estimate the uncertainty in the HPS risk and reliability analysis to estimate the level of uncertainty in the analysis results and to assess the factors that are the primary contributors to uncertainty. The second focus of the analysis is to estimate the level of uncertainty in the estimated 100-year flood levels.

This appendix describes the analysis of epistemic uncertainties in the hurricane frequency and surge/wave analysis and the levee/floodwall reliability analysis, the estimate of the levels of inundation that would occur as a result of HPS overtopping and/or breaching, and the propagation of the uncertainty in these parts of the analysis to derive an estimate of the uncertainty in the inundation of protected areas in New Orleans.

The following sections describe a taxonomy of the types of uncertainties that are addressed in the risk analysis and the approach to evaluate uncertainties in the level of inundation is described. The remainder of this appendix presents the evaluation of uncertainties in the hurricane hazard and fragility analysis, and the propagation of these uncertainties in the assessment of HPS reliability and inundation.

Taxonomy of Uncertainties

For the purpose of evaluating uncertainties in the HPS risk analysis it is useful to establish a taxonomy or framework within which different types of uncertainty can be identified and evaluated. In this analysis, two types of uncertainty are defined: aleatory and epistemic uncertainty. The first is attributed to the inherent randomness of events, manifesting as variability over time for phenomena that take place at a single location (temporal variability), or variability over space for phenomena that take occur at different locations but at a single time (spatial variability), or as variability over both time and space. These events are predicted in terms of their frequency of occurrence (for example, the frequency of occurrence per year of hurricane events, or per trial in the case of a levee reach that is impacted by a given surge event). Aleatory uncertainty is, in principle, irreducible.

Epistemic or knowledge-based uncertainty is attributed to our lack of knowledge and/or information (data) about events, or lack of understanding of physical processes that limits our ability to model natural phenomena (hurricane surges) or other events of interest (levee performance). For example, limitations in available data sets (length of record, data quality) impact the assessment of model parameters (shear strength of soils) or the likelihood of an event such as the annual frequency of hurricane occurrences. When limited data are available, parameter estimates may be quite uncertain (i.e., statistical confidence intervals on parameter estimates can be large). A second type of knowledge uncertainty is attributed to a lack of understanding or knowledge about physical processes that must be modeled (i.e., the meteorological processes that generate hurricane events, the hydrodynamic response of the ocean to the wind and pressure effects of hurricanes, etc.). In these instances model comparisons to measured events or expert evaluations are often required to assess the current state-of-knowledge and to quantitatively evaluate the level of uncertainty.

These uncertainties impact the assessment of each element of the HPS risk and reliability analysis: the hurricane and surge analysis, reliability analysis of the HPS, the assessment of flooding/inundation, and the analysis of consequences. To assess or model uncertainties a characterization of aleatory and epistemic of uncertainties can be made (partitioned) in terms of their effect on models and estimates of model parameters. Modeling uncertainty represents differences between a physical process (hurricane surge, embankment failure) and prediction models. Modeling uncertainty can be estimated by comparing model predictions to observed events/performance. Parameter uncertainty is the uncertainty in the estimates of model parameters. Parametric uncertainty is quantified by observing the variation in parameters inferred (either in a direct or indirect manner). This taxonomy is summarized in Table 1.

Table 1. Taxonomy/Partitioning of Uncertainties

	Risk Analysis	
	Epistemic	**Aleatory**
Modeling	Uncertainty about a model and the degree to which it can predict events (i.e., to what extent a model has a tendency to over- or under-predict observations).	Aleatory modeling variability is the variability that is not explained (observations) by a model. For instance, is variability that is attributed to elements of the physical process that are not modeled and, therefore, represent a variability (random differences) between model predictions and observations.
Parametric	Parametric epistemic uncertainty is associated with the estimates of model parameters given available data, indirect measurements, etc.	This uncertainty is similar to aleatory modeling uncertainty. This is variability that may be due to systematic, but random variations associated with parameters of a model. For instance, there may be storm-to-storm variation in hurricanes with the same parameters, but which differ due to details of the storms that are not modeled, but have a systematic effect. This is an aleatory, inter-event, variability that may be considered independent from event to event.

The distinction between aleatory and epistemic uncertainty can be difficult and is model dependent. For example, a simple engineering model of an event (levee performance) may have higher model aleatory variability (see Table 1) than a more complex model that addresses more details of a physical process. At the same time, the more complex model may have larger parametric epistemic uncertainty. Thus, the characterization of uncertainties is model dependent, making the distinction between different types of uncertainty difficult. Nonetheless, making a distinction between the sources of uncertainty in a logical manner helps insure that all uncertainties are identified and quantified. In principle, epistemic uncertainties are reducible with the collection of additional data or the use/development of improved models.

As part of the HPS risk and reliability analysis and the estimates of inundation presented in this report, only sources of aleatory uncertainty (e.g., randomness in hurricane occurrences, rainfall volumes, variability in levee performance, levee overtopping weir coefficients, and in the operation of closure gates) were considered. Sources of epistemic uncertainty were not addressed in the model used to predict response of the HPS to storm surges and waves. The subject of this appendix is to evaluate the primary sources of epistemic uncertainty.

Approach

The risk analysis of the HPS during hurricane events and the inundation that could occur as a result of rainfall, levee overtopping, and levee failure was evaluated using mean or best estimate models and parameters. The analysis quantifies the aleatory component of uncertainty and is the basis for the inundation maps that are presented in the risk analysis volume. The focus of the uncertainty analysis is to estimate the uncertainty in the HPS risk and reliability and to estimate the uncertainty in the 100-year depth of inundation. This result is illustrated (schematically) in Figure 1.

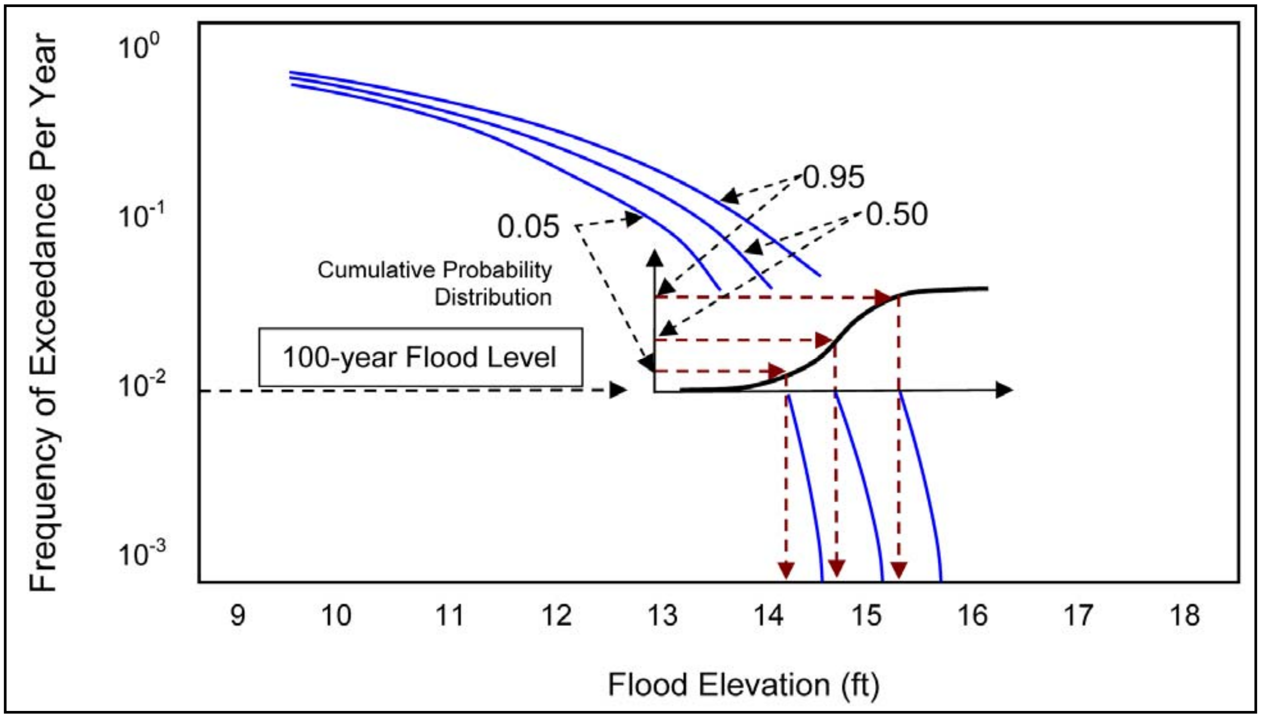

Figure 1. Schematic illustration of the epistemic uncertainty in the 100-year depth of flooding in a basin.

In principle, an analysis of the epistemic uncertainty would address each of the models and parameters in the risk analysis and propagate them through to the estimate of system performance and basin inundation. The risk model was not set up to propagate epistemic uncertainties through the analysis. Therefore, to conduct the uncertainty analysis an alternative approach was taken that focused on the primary sources of epistemic uncertainty; the uncertainty in the hurricane analysis (uncertainty in the frequency of occurrence of hurricane events and in the magnitude of surges/waves) and the assessment of the reliability of HPS levee and floodwall performance during hurricane events. It was judged these uncertainties are the dominant contributors to the uncertainty in the 100-year inundation levels. Considering the New Orleans basins are essentially enclosed, well-defined areas, it was judged the epistemic uncertainty in the volume-stage relationships is low and thus is not considered.

The contribution of rainfall to the inundation volumes in a basin was also not considered in the uncertainty analysis. The mean (best) estimate risk analysis results suggest the contribution of rainfall to 100-year inundation levels is small. However, studies have shown that rainfall is a significant contributor to the 50-year inundation levels. For this reason, the uncertainty in the 50-year inundation level is not addressed in this analysis.

Methodology

The elements of the HPS risk analysis are:

- Hurricane Hazard Analysis
- Levee Systems Model

- Levee and Flood Wall Fragility
- Inundation Analysis
- Consequence Analysis
- Risk Quantification

As described in the previous section the analysis of uncertainties focused on the uncertainty in the hurricane analysis and the HPS levee and floodwall reliability analysis. A summary of these elements of the analysis are presented here.

Hurricane Hazard Analysis

The hurricane hazard analysis estimates the frequency of occurrence of hurricane events and the temporal-spatial field of water elevations (storm surge and wave elevations) in the New Orleans region (see Appendix 8). In the analysis, a hurricane was defined in terms of five parameters:

- Central pressure deficit
- Radius to maximum winds
- Translational velocity at landfall
- Storm location at landfall
- Azimuthal direction of the storm motion at landfall

In the best-estimate risk analysis 76 hurricanes, each based on a combination of these parameters and an associated frequency of occurrence, were used. For each hurricane the temporal (hydrographs) and spatial field of surge and wave actions were estimated using the ADCIRC and STWAVE codes (see Appendix 8). The uncertainty in the frequency of occurrence of the 76 hurricane events (used in the best-estimate analysis), as well as the uncertainty in the estimated storm surge predictions, are evaluated.

Systems Model

An event tree model was developed for each basin/sub-basin in the NO HPS. The event tree was set up to capture the sequences of events that could lead to sub-basin and basin flooding due to levee/floodwall overtopping and/or levee/floodwall failure (breaching as a result of levee/floodwall instability or overtopping). Top events in the event tree model the occurrence of non-overtopping (embankment or wall instability) failures in each sub-basin and breaching due to overtopping. Following each branch through the event tree to its termination, defines a sequence of events (combinations of reach failures/non-failures due to overtopping or non-overtopping failure modes) that could occur for a hurricane. The set of sequences in the event tree considers all the combinations of levee reach performance failures/non-failures associated with instability or overtopping, and flooding due to levee overtopping. Individually, each sequence in the event tree corresponds to a possible combination of levee failures/non-failures and overtopping events. For a hurricane event, the conditional probability of a sequence occurring (given the event and the surge/wave elevations produced at each levee reach location for that event) is determined from the levee/floodwall fragility curves. The sequences in the event tree define an exhaustive set of the possible combinations of levee/floodwall reach performance states.

Levee and Floodwall Fragility

The reliability analysis of levees and floodwalls that comprise the NO HPS was evaluated to determine the conditional probability of failure as a function of peak-water surface elevation. The analysis, described in Appendix 10, addressed both overtopping and non-overtopping failure modes. As part of the uncertainty analysis, an estimate of the uncertainty in the conditional probability of failure is made, accounting for the uncertainty in engineering models and the uncertainty in estimating model parameters.

Inundation Analysis

For each hurricane event and sequence in the event tree, the volume of water that enters a basin due to a levee or floodwall breach or as a result of overtopping is estimated. Flood elevations for each occurrence are estimated from the basin volume-elevation relationships. As discussed above, it is judged that the uncertainty in the inundation analysis is small in comparison to the uncertainty in the hurricane and levee performance assessments and thus is not considered in this analysis. Other factors that influence flooding within the subbasins such as: open gates, failure of transitions, performance of the pumping system, rainfall volumes and overtopping due to wave runup were not included in the uncertainty water volume calculations. These factors were included in the risk model, however they were considered to not contribute significantly to the uncertainty analysis.

Quantification

The epistemic uncertainty in the hurricane hazard and levee/floodwall fragility parts of the risk analysis are combined to estimate the uncertainty in the frequency of levee failure of the hurricane protection system for each basin and the frequency distribution of basin inundation, and the uncertainty in the 100-year depth of inundation.

Hurricane Analysis Uncertainty

A principle source of epistemic uncertainty in the NO HPS risk analysis is the uncertainty associated with the occurrence and size[1] of hurricane events and the water elevations that occur onshore due to storm surge and wave action. These epistemic uncertainties are due to limitations of numerical models to model hurricane events and the hydrodynamic response of the ocean and wave action near-shore (model uncertainty), and limited observational data to estimate model parameters and to verify numerical models (parameter uncertainty). In addition, there are uncertainties associated in modeling the temporal and spatial frequency of occurrence of

[1] The term size is used here in a general sense to simply denote the joint characteristics of a hurricane event that generate large surges and wave events onshore.

hurricanes of different sizes that may approach New Orleans. The epistemic uncertainties associated with each of these parts of the hurricane analysis are considered.

Hurricane Hazard Analysis Aleatory Model

The IPET hurricane analysis used a response-surface approach to define a set of hurricane events that serve as input to the risk analysis (see Appendix 8). The taxonomy of uncertainties considered in the hurricane uncertainty analysis is summarized in Table 2. For each event, a joint probability method was used to estimate the frequency of occurrence of the events that were modeled. The results of this analysis can be denoted:

$$\{\nu_i, h_i\} \tag{1}$$

where,

ν_I = frequency of occurrence of hurricane event i
h_i = hurricane event i

A hurricane, h_i, is modeled by the following parameters:

ΔP = central pressure deficit at landfall (mb)
R_p = radius to maximum winds at landfall (nm)
X = longitudinal landfall location relative to downtown New Orleans (km)
θ = direction of storm motion at landfall (degrees)
v_f = storm translation speed at landfall (knots)
B = Holland radial pressure profile parameter at landfall (Holland 1980)

The frequency of occurrence of a hurricane event can be expressed as:

$$\nu_i = \nu_i(\Delta P, R_P, v_f, \theta_l, x) \tag{2}$$

The IPET hurricane analysis uses a joint probability method (see Appendix 8) to estimate the frequency of occurrence of hurricanes with a combination of properties that define the event. This is denoted:

$$\nu_i(\Delta P, R_P, v_f, \theta_l, x) = \Lambda_1 \Lambda_2 \Lambda_3 \Lambda_4 \Lambda_5 \tag{3}$$

where,

Λ_1 = probability of the hurricane central pressure deficit, ΔP
Λ_2 = conditional probability of storm radius, R_p, which is a function of the central pressure deficit
Λ_3 = probability of the hurricane forward velocity, v_f

Λ_4 = probability of the azimuthal approach/track direction at landfall, θ_l
Λ_5 = frequency of occurrence of storms per year along the Gulf coast

Table 2. Taxonomy of Hurricane Analysis Aleatory and Epistemic Uncertainties

Element	Epistemic	Aleatory
Model	Surge/Wave Modeling – 1) Uncertainty in the ADCIRC/wave analysis estimate of peak water elevations in New Orleans due to hurricane events. This uncertainty corresponds to the systematic error that may exist in predicted, mean peak surge/wave elevations at New Orleans HPS levee/floodwall reach locations.	Surge/Wave Modeling – Unexplained variability between model predictions and the estimate of peak surge/wave elevations observed for Hurricanes Katrina and Rita. Frequency Model – Randomness of hurricane occurrences and hurricane events with specific properties (i.e., C_p, R_p, etc.)
Parametric	Frequency Model – 1) Uncertain estimates in the mean rate of hurricane occurrences; 2) Uncertainty in the estimate of the parameters of models used in the joint probability analysis (e.g., GEV model parameters, R_p-C_p relationship).	Surge/Wave Modeling – Factors considered in this category include the effects of astronomical tides and Holland's B. Frequency Model – No aleatory parametric sources of variability were identified.

In the IPET hurricane analysis, the Holland B parameter was set to a fixed value (see Appendix 8) and thus not explicitly modeled as a random variable in estimating the occurrence of hurricane events.

In addition to the variables used to model the randomness of hurricane occurrences (eq. 3), other factors contribute to the randomness (aleatory uncertainty) of water-surface elevations. These include the Holland B parameter, astronomic tide, among others. The spatial, random field of hurricane surge and wave elevations that occur for a hurricane event can be expressed by:

$$s_i(\underline{x},t) = S(h_i, \underline{x}, t) + \varepsilon \qquad (4)$$

where,

$S(h_i, \underline{x}, t)$ = spatial hydrographs of water-surface elevations for hurricane i
ε = random term with zero mean and variance, σ^2

As described in Appendix 8, the ADCIRC and STWAVE models are used to model the hydrodynamic response to hurricane events. These models are denoted by $S(h_i, \underline{x}, t)$ in Equation 4. Equations 3 and 4 define the aleatory (frequency) model for hurricane occurrences.

The randomness of water-surface elevations, ε, models the randomness in water-surfaces that may occur as a result of factors that are not explicitly modeled in the analysis. Appendix 8 identifies the following factors as contributors to the aleatory variability in estimating water-surface levels resulting from hurricanes. These are:

- Holland B parameter.
- Astronomical tides.

- Unexplained variability associated with differences in model predictions and observed high-water marks from hurricane events.
- Factors associated with the hurricane event or the hydrodynamic model (grids, bathymetry, hydraulic parameters, etc.) that are not explicitly modeled and, thus, contribute to random deviations between model estimates and observations.

These sources of aleatory variability, randomness, can be defined in terms of the taxonomy of uncertainties summarized in Table 1 which distinguishes between model and parametric sources of aleatory variability. The distinction between model and parametric sources of variability has important implications to the spatial characterization of the water-surface elevations and the assessment of HPS risks. On one hand, parametric sources of aleatory variability have a random, but systematic effect (i.e., all locations are effected in a similar manner) on the estimated water-surface levels. One example of a factor that has a random, but systematic effect on water-surface elevations that occur is astronomical tides. If a hurricane makes landfall at high tide, water-surface elevations throughout New Orleans will be systematically higher everywhere. Conversely, if the same hurricane were to randomly arrive during low tide, water-surface elevations will be lower. Depending on the time of day that a hurricane makes landfall, the resulting storm surge will be systematically higher/lower. Thus, tides introduce a random, but systematic effect on water-surface elevations. Parametric, aleatory variability models the randomness between hurricane events (surges) (inter-event variability) that are attributable to differences between events that are modeled.

Alternatively, the effect of other factors is to introduce a randomness that is independent from one event to the next and from location to another for the same event. These factors are modeling sources of aleatory variability (see Table 1).

Given the distinction between the effects of different types of aleatory variability, ε (see Equation 4) can be defined as,

$$\varepsilon = \tau + \phi \tag{5}$$

where,

ε = total aleatory variability
τ = random variable that models the parametric aleatory variability
ϕ = random variable that models the modeling aleatory variability

Sources of Parametric Aleatory Variability (contributors to τ) – Three sources of parametric aleatory variability are modeled. They are:

- Holland B parameter
- Astronomical tides
- Hurricane model parameterization

In the IPET hurricane analysis, a fixed value of the Holland B parameter of 1.27 was used. In fact, individual hurricanes will have different Holland B values and this difference has a direct and systematic impact on surge levels. Appendix 8 suggests a value of 1.27 is the mean for the Holland B and thus estimated water-surface elevations will be unbiased. However, the effect of the Holland B varies with surge levels. Appendix 8 indicates this effect can be ±10 to 20 percent of the estimated peak surge height. Niedoroda et al. (2007) recommends a standard deviation of 0.15 × peak surge height. In this analysis, the randomness associated with the Holland B is assumed to be lognormally distributed with a median of 1.0 and a logarithmic standard deviation of 0.15.

A second source of systematic aleatory variability are astronomical tides. This randomness is modeled by a Normal distribution with zero mean and a standard deviation of 0.66 feet (Niedoroda et al. 2007).

The final source of parametric aleatory variability is attributed to the differences between modeled hurricane events and actual events. These differences and their impact on predicted hurricanes and surges have been estimated based on comparisons between tailored or customized model comparisons with actual events and 'standard' (non-customized) model predictions. These differences, which are systematic from one event to the next, were estimated by Niedoroda et al. (2007) to have a standard deviation of 1.18 feet. In this analysis, this source of variability is assumed to be Normally distributed with zero mean and a standard deviation of 1.18 feet.

Sources of Modeling Aleatory Variability (contributors to ϕ) – Aleatory modeling variability is attributed to the limitations in prediction models (ADCIRC and STWAVE) to model the details of the hurricane events (i.e., wind fields, translational tracks and speed, etc.), the details of near-shore bathymetry, hydrodynamics of the ocean, etc. Other factors include the numerical resolution of the modeling such as grid spacing/nodal density, time step, etc. These factors introduce differences between model predictions and observed high-water marks. This variability, unexplained by the model, exists even when comparisons are made for events where the modeling has been customized (calibrated) to the details of the hurricane wind field, etc. Figure 2 shows a comparison of high-water marks from Katrina and model predictions. While the modeling is, on average, essentially unbiased there is considerable variability about the 1:1 line. Analysis of this data suggests a standard deviation of this variability is approximately 0.75 feet. Niedoroda et al. (2007) recommends a similar value. In this analysis, the modeling aleatory variability is assumed to be Normally distributed with zero mean and a standard deviation of 0.75 feet. This variability is independent from one hurricane to the next, and it is assumed to be spatially independent (from one reach to the next for a given event).

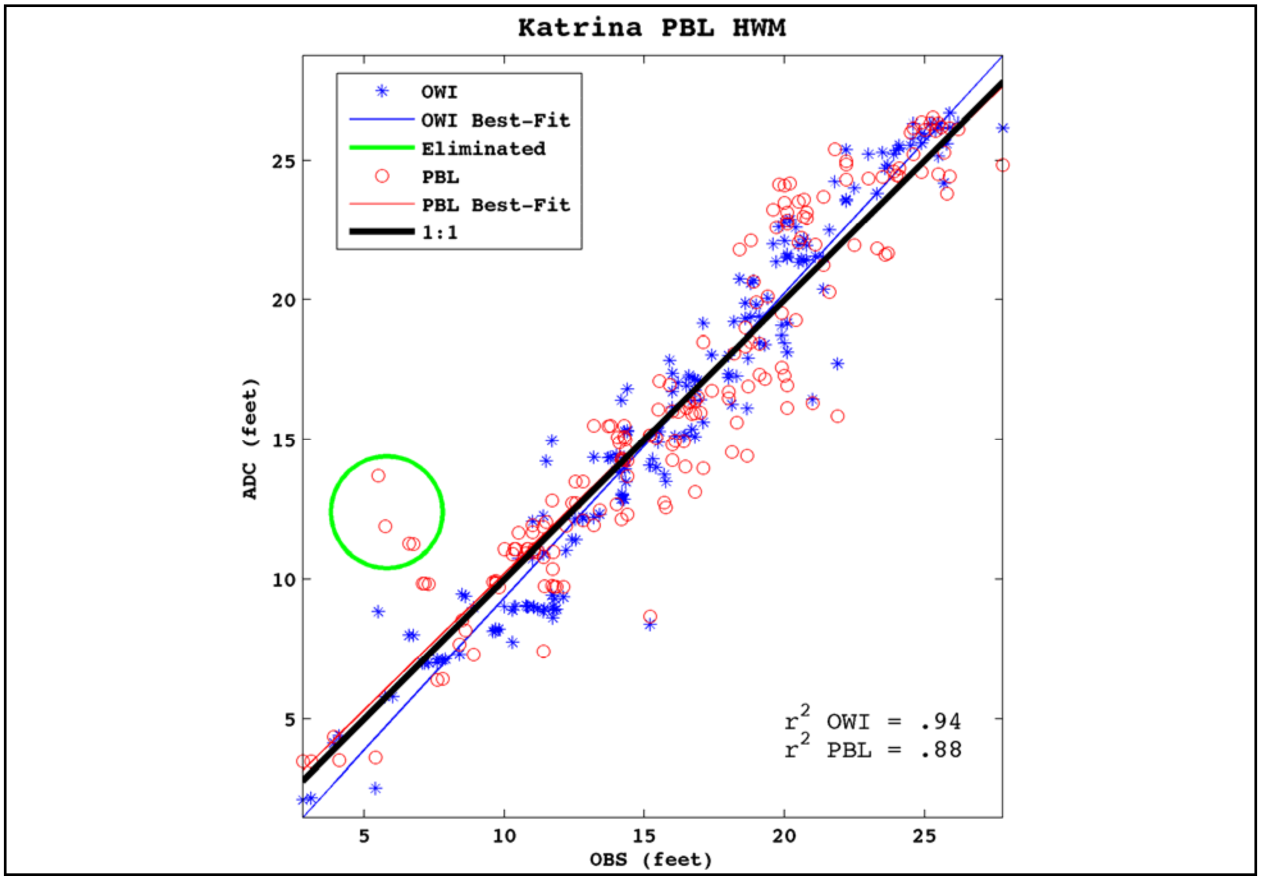

Figure 2. Comparison of predicted and observed high water marks for Hurricane Katrina.

Frequency of Exceedance Distribution of Storm Surges - The frequency of exceedance of storm surges at a location x_j can be determined by,

$$\lambda(s_p(x_j) > s) = \sum_i v_i P(S_p(h_i, x_j) + \varepsilon > s \mid h_i) \tag{6}$$

where the summation is over the discrete set of hurricane events,

v_i = the frequency of hurricane event i as defined in Equation 2
$P(S_P(h_i, x_j) > s|h_i)$ = probability that a peak surge S_P at a location x_j, given hurricane event h_i, exceeds a level s
ε = total aleatory variability (see Equation 5)

As part of the risk analysis methodology, the aleatory variability in water-surface elevations is taken into account in the best estimate of New Orleans flooding.

Hurricane Hazard Analysis Epistemic Uncertainties

The analysis of epistemic uncertainties in the hurricane hazard analysis builds on the analysis performed for the best-estimate risk analysis described in the main report and Appendix 8. The best-estimate hazard analysis considered the aleatory sources of variability associated with hurricane occurrences and estimates of storm surge, etc. The taxonomy of uncertainties considered in the hurricane uncertainty analysis is summarized in Table 2. As described previously, the taxonomy addresses the uncertainties associated with the estimate of the frequency of hurricane events (Equation 3) and in the numerical modeling of hurricanes and the estimate of water-surface elevations.

To model the epistemic uncertainty in the hurricane hazard analysis, a logic tree was constructed that models the principle sources of uncertainty (see Figure 3). The models/parameters in the logic tree are:

- Hurricane surge/wave model uncertainty
- Rate of hurricane occurrences in the Gulf
- Parameters of the Gumbel extreme value distribution (GEV) on central pressure
- Parameters of the radius to maximum winds-central pressure relationship

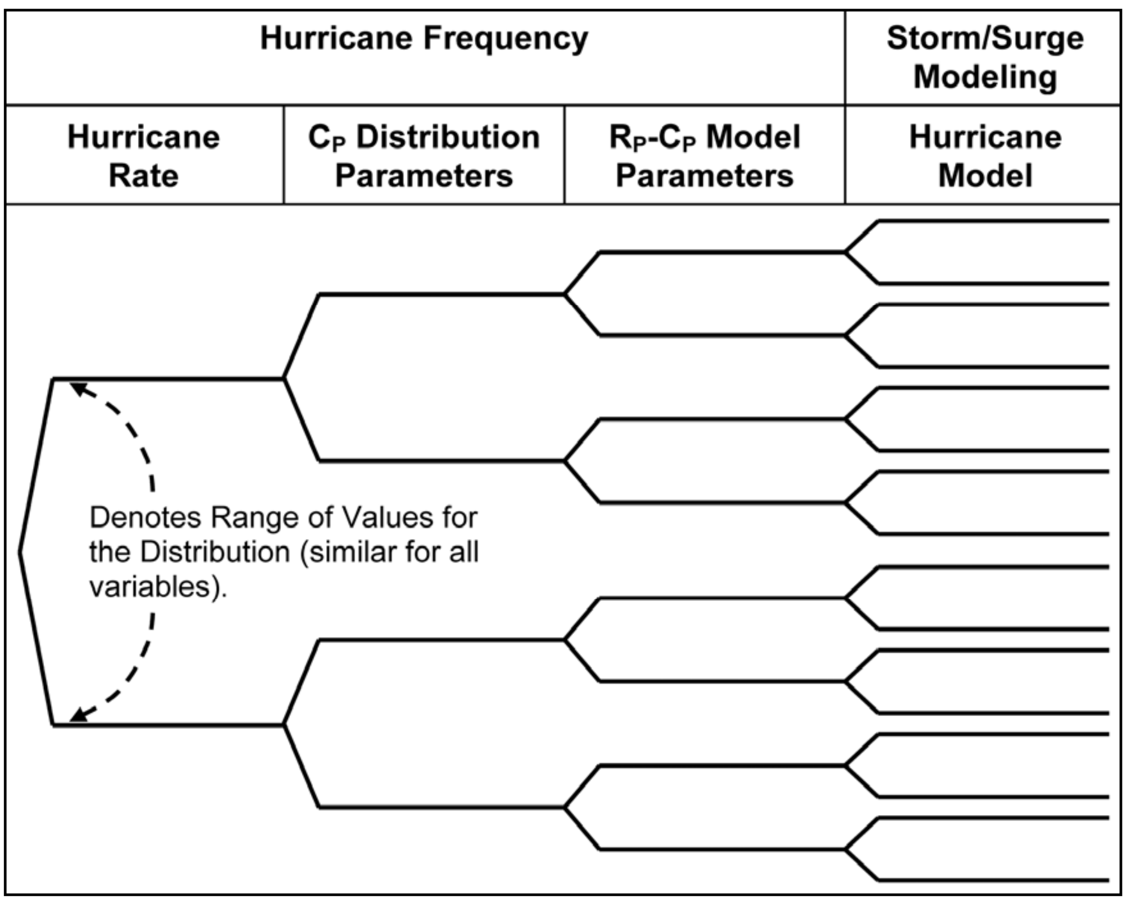

Figure 3. Logic tree for modeling the uncertainty in the hurricane hazard analysis.

The epistemic uncertainty in other parameters in the hurricane frequency model (see Equation 2) is not considered in this analysis. The following discussion describes each source of uncertainty and their estimate.

Model Epistemic Uncertainty - The model epistemic uncertainty in the hurricane modeling can be measured in terms of the standard error in the comparison of predicted and observed HWM (see Figure 2). Unfortunately there is limited quantitative information beyond the comparisons that have been done for Katrina and Rita in New Orleans to estimate the model error in hurricane surge and wave predictions. For this analysis, the IPET hydrodynamic analysts were consulted to assess the modeling uncertainty in the ADCIRC and wave calculations (Resio 2008). As suggested above, for Katrina, the model estimates tended to be unbiased. Resio (2008) suggests the standard modeling error for estimating hurricane surge elevations in New Orleans is 10 percent. In the uncertainty analysis, the modeling epistemic uncertainty in the hurricane and hydrodynamic analysis is assumed to be lognormally distributed with a median of 1.0 and a logarithmic standard deviation of 0.10.

Parametric Epistemic Uncertainty – Sources of parametric uncertainty considered are the annual rate of hurricane occurrences, the parameters of the Gumbel extreme value distribution, and the parameters of the radius to maximum winds model.

Parametric Uncertainty for the Gumbel Extreme Value (GEV) Distribution on C_p (Λ_1) – To estimate the uncertainty in the parameters of the C_p, a bootstrap simulation approach was used (Efron 1982). The approach involves re-sampling the historic record of storms used in the IPET hurricane analysis (see Appendix 8). For each re-sample of the catalog of hurricane events, the sampled data are used to estimate the parameters of the GEV distribution. The result is a sample estimate of the GEV parameters that is used to estimate the uncertainty in the GEV distribution parameters. Combined with the uncertainty in the annual rate of hurricane occurrences (discussed below), the uncertainty in the frequency distribution on C_p is determined (see Figure 4).

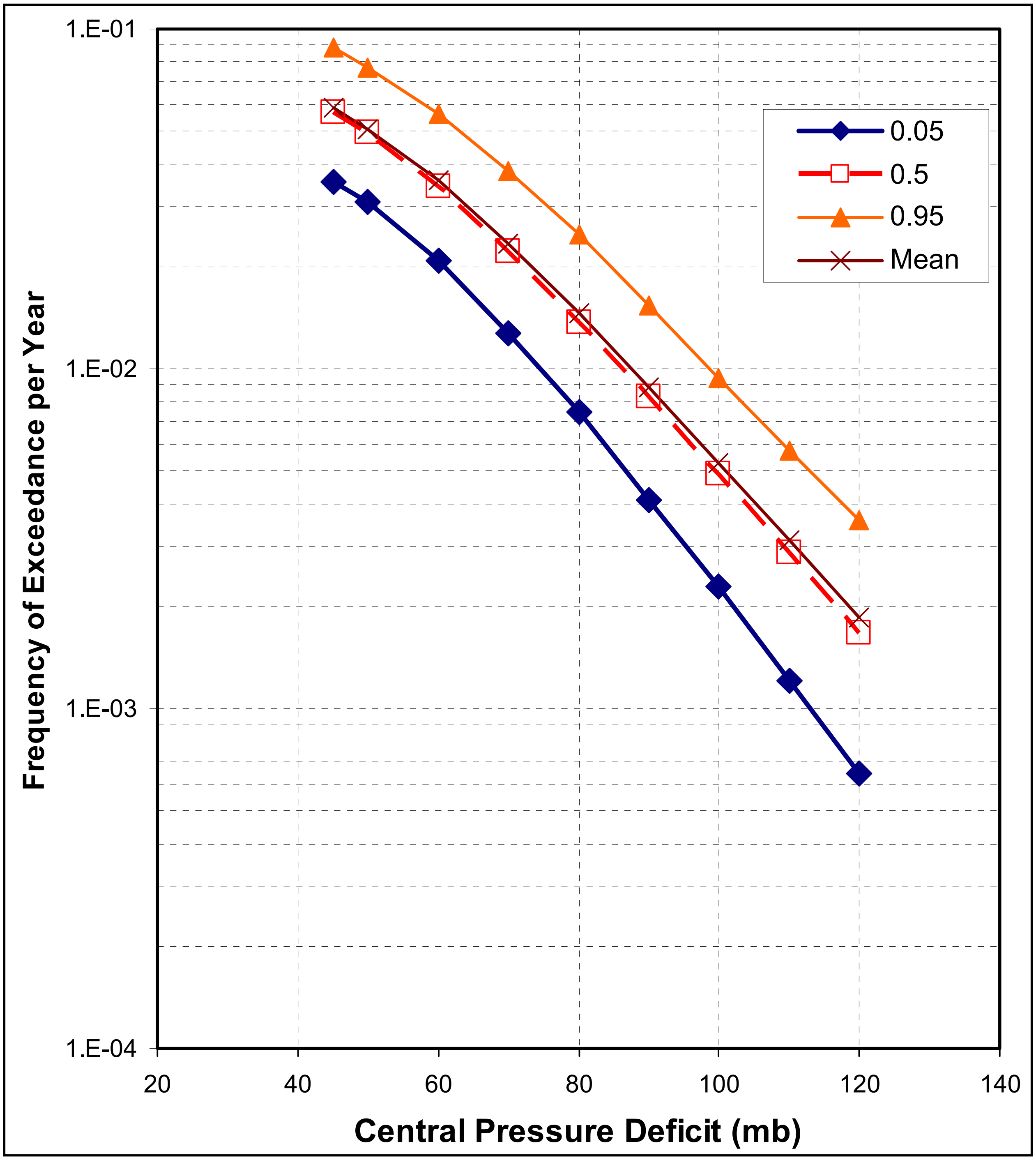

Figure 4. Uncertainty in the distribution on hurricane central pressure, C_p.

Radius to Maximum Winds (Λ_2) – There is considerable uncertainty in the estimate of the radius to maximum winds as illustrated by the data shown in Figure 5 (this is the same data shown in Figure 8a of Appendix 8-2). As discussed in Appendix 8-2, various models have been developed for the Gulf of Mexico and the Atlantic Ocean that relate the radius to maximum winds to the central pressure deficit.

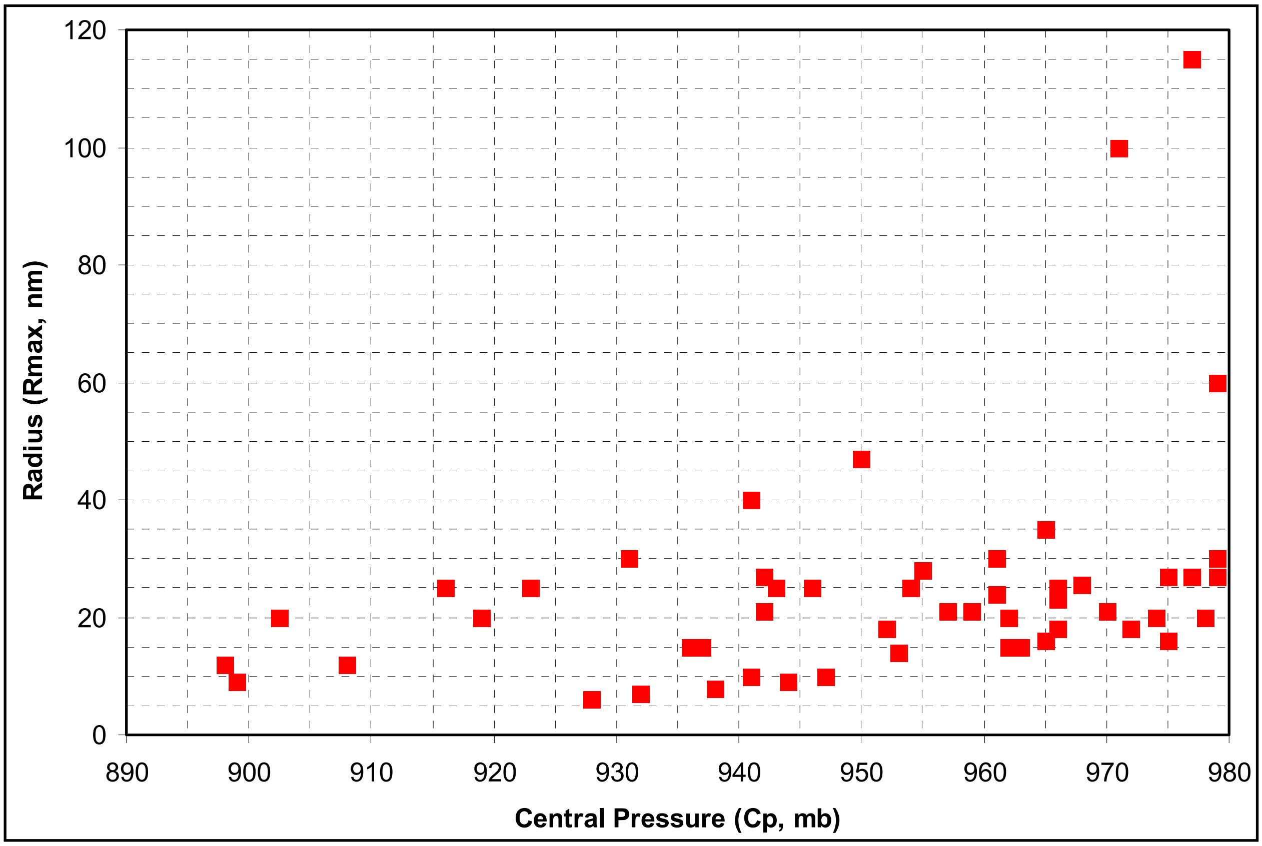

Figure 5. Data used in the hurricane hazard analysis to relate the radius to maximum winds (R_p) to the hurricane central pressure (C_p) (data are the same as those shown in Figure 8a of Appendix 8-2).

In the IPET hurricane frequency analysis, a relationship between C_p and R_p was developed from the data in Figure 5. There is, however, considerable scatter in the model and uncertainty in the estimate of model parameters. In this analysis, the uncertainty in the estimate of the relationship between the R_p and C_p parameters of (as derived from the data in Figure 5) was evaluated. As described in Appendix 8-2, a linear relationship between R_p and C_p was developed. Here, the uncertainty in the parameters of the R_p-C_p model was estimated by evaluating the log-likelihood function and developing a probability mass function on the range of estimates for the model parameters (intercept and slope). Figure 6 shows the distribution of intercept (a-value) and slope (b-value). Figure 7 shows the uncertainty in the R_p-C_p relationship.

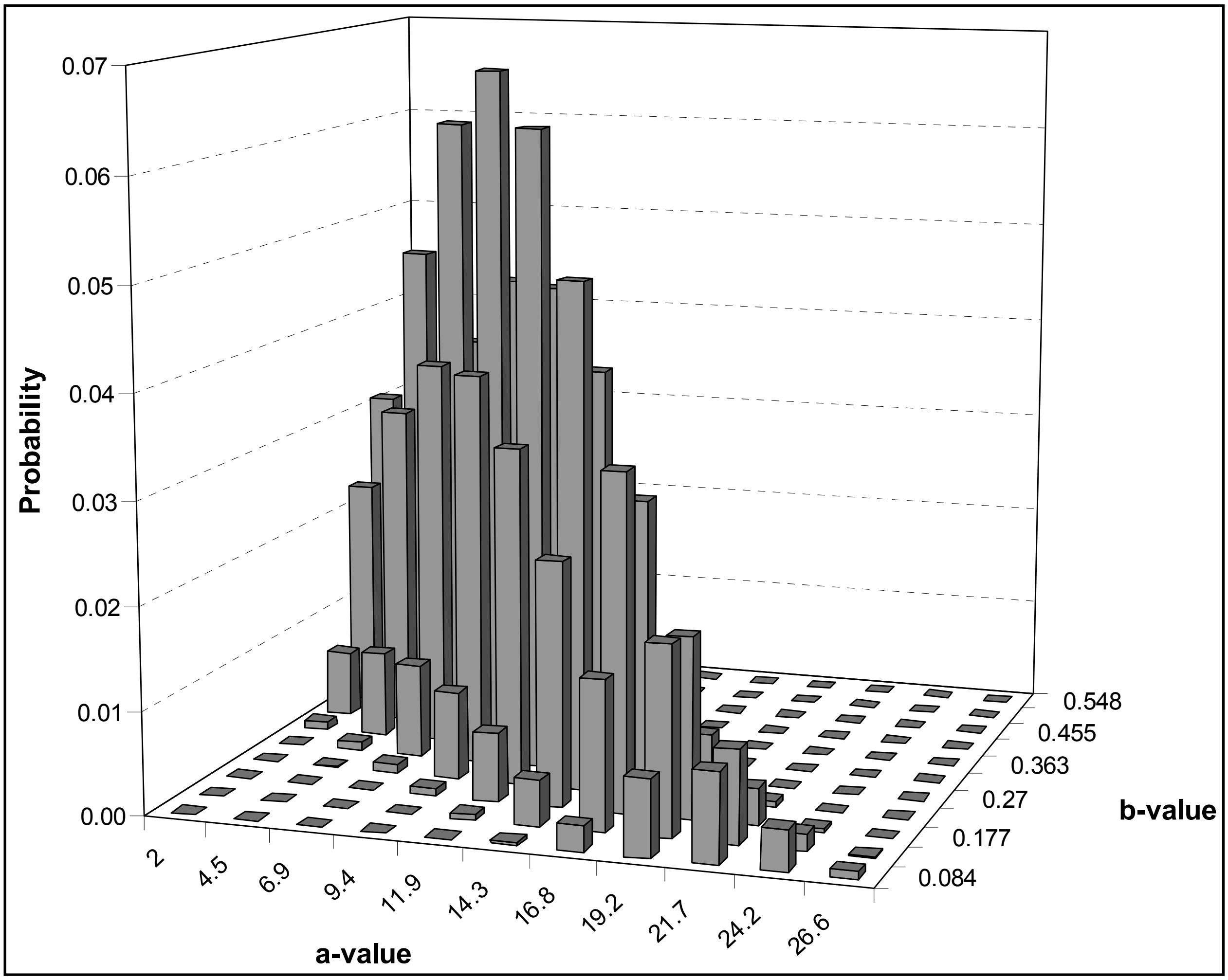

Figure 6. Distribution on the intercept (a-value) and slope (b-value) of the R_p and C_p relationship.

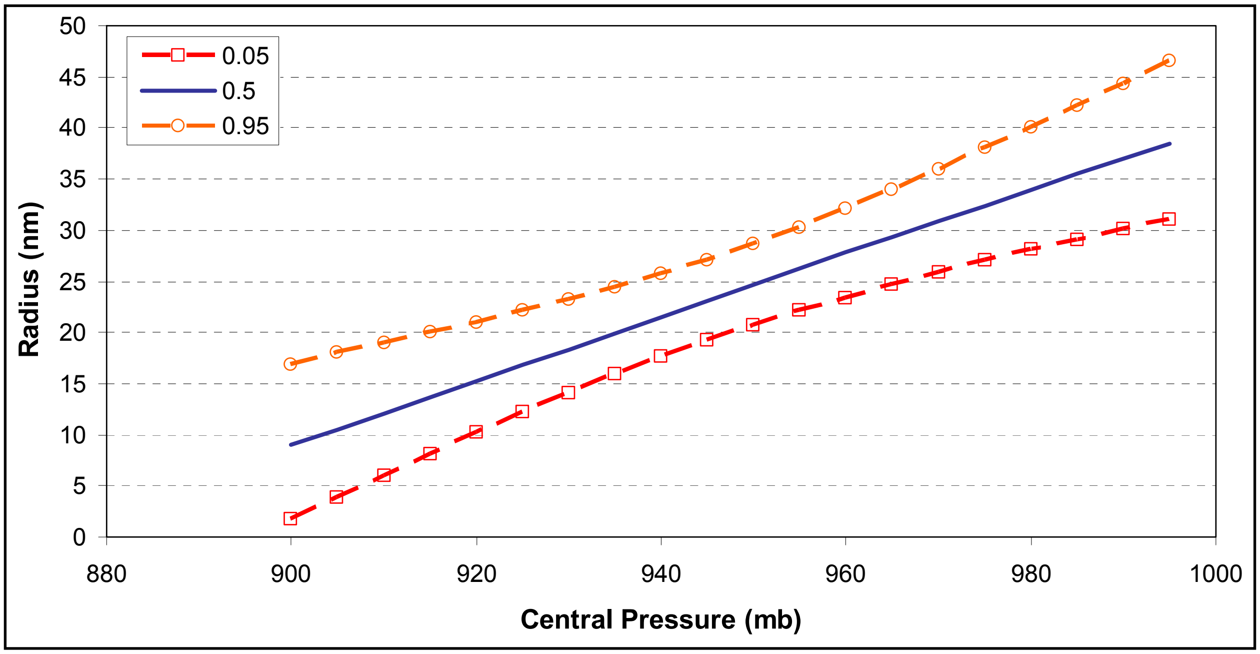

Figure 7. Uncertainty in the R_p and C_p relationship based on the statistical uncertainty in the estimate of the model parameters.

Annual Rate of Hurricane Occurrences (Λ_5) – Hurricane rates are uncertain due to the limited historical sample size and the uncertain near-future hurricane activity due to fluctuations and trends associated with climate changes and multi-decadal cycles. A first-order assessment is conducted to estimate the statistical uncertainty in the rate hurricane. As part of the hurricane analysis, an estimate of the hurricane rates did take into account effects of global warming and other shorter-term climatic fluctuations in the North Atlantic, however the epistemic uncertainty in these factors was not evaluated.

Toro, et al. (2007) estimate the annual rate of hurricane occurrences in the Gulf of Mexico, based on an analysis for Mississippi, has a coefficient of variation of 0.30. In this analysis, the uncertainty in the annual rate of occurrence of hurricanes is modeled by a lognormal distribution with a logarithmic standard deviation of 0.29.

Hurricane Hazard Estimates for New Orleans

The sources of aleatory and epistemic uncertainty in the hurricane hazard analysis are combined to estimate the uncertainty in the frequency of hurricane events, and the aleatory and epistemic uncertainty in hurricane surge level. Table 3 lists the parameters for each hurricane used in the hurricane analysis. A Latin Hypercube Simulation (LHS) approach was used to combine the sources of epistemic uncertainty and to generate a dataset of event frequencies and sets of maps of water-surface elevations in New Orleans. The results can be displayed to show the frequency of exceedance of water-surface elevations at reach locations throughout the system. For example, Figure 8 shows a photograph and a map of the St. Charles basin and levee reach locations. Figure 9 shows the hurricane hazard results for St. Charles - Reach 2. The hazard curve results are shown in terms of the 0.05, 0.15, 0.50, 0.85 and 0.95 fractile hazard curves and the mean. The fractile hazard curves quantify the uncertainty in the frequency of exceedance of water-surface elevations. Figure 10 shows the mean hazard curves for each St. Charles reach.

Table 3. Hurricane Storm Parameters

No.	P_0 (mb)	Rp (nm)	Vf	Angle	Track	LAT 1	LON
1	960	11	11	0	1	24.43	-79.1
2	960	21	11	0	1	24.43	-79.1
3	960	35.6	11	0	1	24.43	-79.1
4	930	8	11	0	1	24.43	-79.1
5	930	17.7	11	0	1	24.43	-79.1
6	930	25.8	11	0	1	24.43	-79.1
7	900	6	11	0	1	24.43	-79.1
8	900	14.9	11	0	1	24.43	-79.1
9	900	21.8	11	0	1	24.43	-79.1
10	960	11	11	0	2	24.42	-78.6
11	960	21	11	0	2	24.42	-78.6
12	960	35.6	11	0	2	24.42	-78.6
13	930	8	11	0	2	24.42	-78.6
14	930	17.7	11	0	2	24.42	-78.6
15	930	25.8	11	0	2	24.42	-78.6
16	900	6	11	0	2	24.42	-78.6
17	900	14.9	11	0	2	24.42	-78.6
18	900	21.8	11	0	2	24.42	-78.6
19	960	11	11	0	3	24.42	-78.5
20	960	21	11	0	3	24.42	-78.5
21	960	35.6	11	0	3	24.42	-78.5
22	930	8	11	0	3	24.42	-78.5
23	930	17.7	11	0	3	24.42	-78.5
24	930	25.8	11	0	3	24.42	-78.5
25	900	6	11	0	3	24.42	-78.5
26	900	14.9	11	0	3	24.42	-78.5
27	900	21.8	11	0	3	24.42	-78.5
28	960	11	11	0	4	24.4	-77.9
29	960	21	11	0	4	24.4	-77.9
30	960	35.6	11	0	4	24.4	-77.9
31	930	8	11	0	4	24.4	-77.9
32	930	17.7	11	0	4	24.4	-77.9
33	930	25.8	11	0	4	24.4	-77.9
34	900	6	11	0	4	24.4	-77.9
35	900	14.9	11	0	4	24.4	-77.9
36	900	21.8	11	0	4	24.4	-77.9
37	960	11	11	0	5	24.43	-78.9
38	960	21	11	0	5	24.43	-78.9
39	960	35.6	11	0	5	24.43	-78.9
40	930	8	11	0	5	24.43	-78.9
41	930	17.7	11	0	5	24.43	-78.9
42	930	25.8	11	0	5	24.43	-78.9

No.	P_0 (mb)	Rp (nm)	Vf	Angle	Track	LAT 1	LON
43	900	6	11	0	5	24.43	-78.9
44	900	14.9	11	0	5	24.43	-78.9
45	900	21.8	11	0	5	24.43	-78.9
46	960	18.2	11	-45	1	24.54	-80.9
47	960	24.6	11	-45	1	24.54	-80.9
48	900	12.5	11	-45	1	24.54	-80.9
49	900	18.4	11	-45	1	24.54	-80.9
50	960	18.2	11	-45	2	24.83	-80.8
51	960	24.6	11	-45	2	24.83	-80.8
52	900	12.5	11	-45	2	24.83	-80.8
53	900	18.4	11	-45	2	24.83	-80.8
54	960	18.2	11	-45	3	25.38	-80.8
55	960	24.6	11	-45	3	25.38	-80.8
56	900	12.5	11	-45	3	25.38	-80.8
57	900	18.4	11	-45	3	25.38	-80.8
58	960	18.2	11	-45	4.1	26.08	-80.8
59	960	24.6	11	-45	4.1	26.08	-80.8
60	900	12.5	11	-45	4.1	26.08	-80.8
61	900	18.4	11	-45	4.1	26.08	-80.8
62	960	24.6	11	45	1	21.28	-90.0
63	900	12.5	11	45	1	21.28	-90.0
64	900	18.4	11	45	1	21.28	-90.0
65	960	18.2	11	45	2	21.3	-90.0
66	960	24.6	11	45	2	21.3	-90.0
67	900	12.5	11	45	2	21.3	-90.0
68	900	18.4	11	45	2	21.3	-90.0
69	960	18.2	11	45	3	21.27	-90.1
70	960	24.6	11	45	3	21.27	-90.1
71	900	12.5	11	45	3	21.27	-90.1
72	900	18.4	11	45	3	21.27	-90.1
73	960	18.2	11	45	4	21.28	-90.0
74	960	24.6	11	45	4	21.28	-90.0
75	900	12.5	11	45	4	21.28	-90.0
76	900	18.4	11	45	4	21.28	-90.0

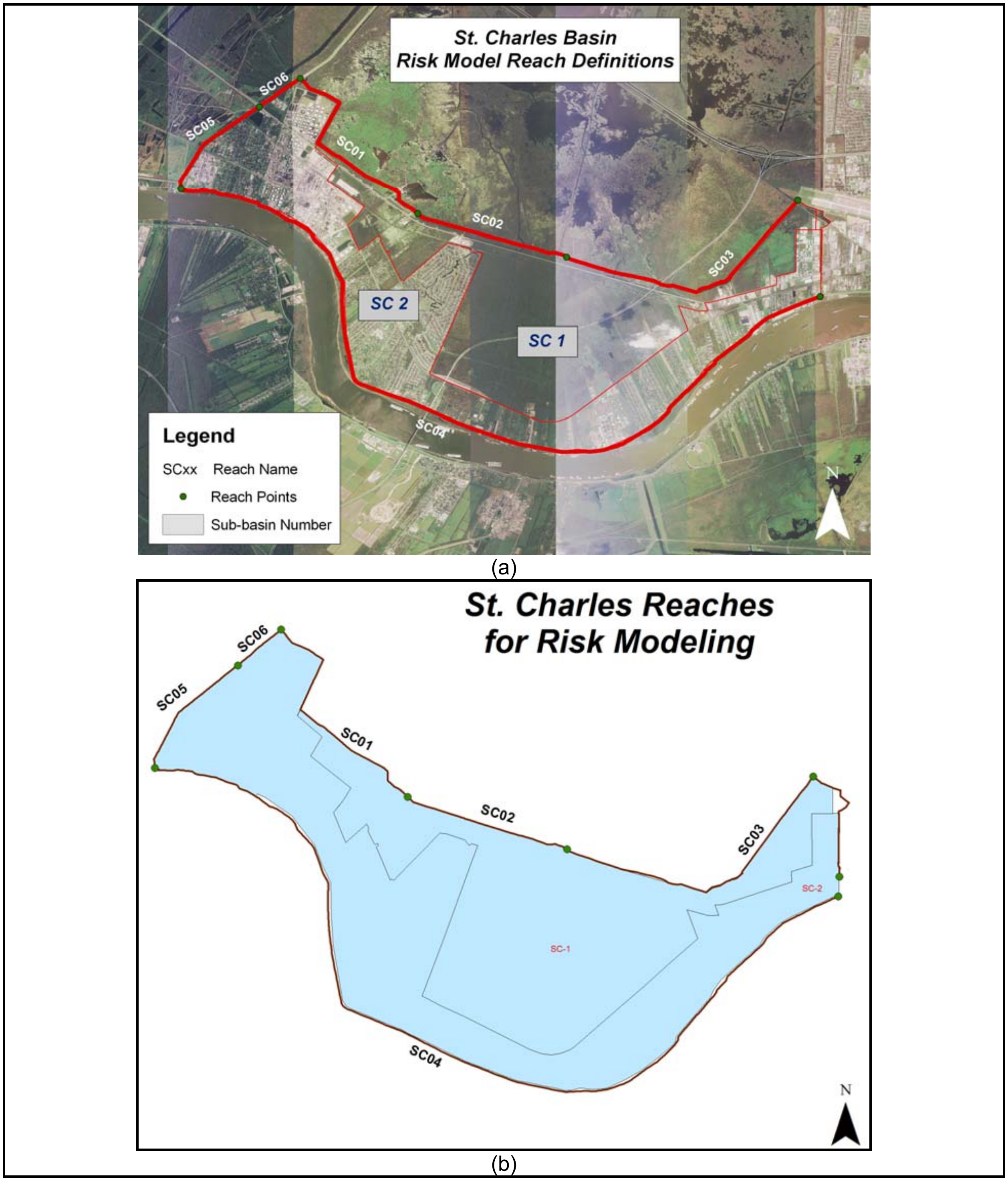

Figure 8. St. Charles Basin reach (SC01 – SC06) and sub-basin (SC 1 and SC 2) definition shown in (a) an areal photograph, and (b) schematically, for use in the risk model.

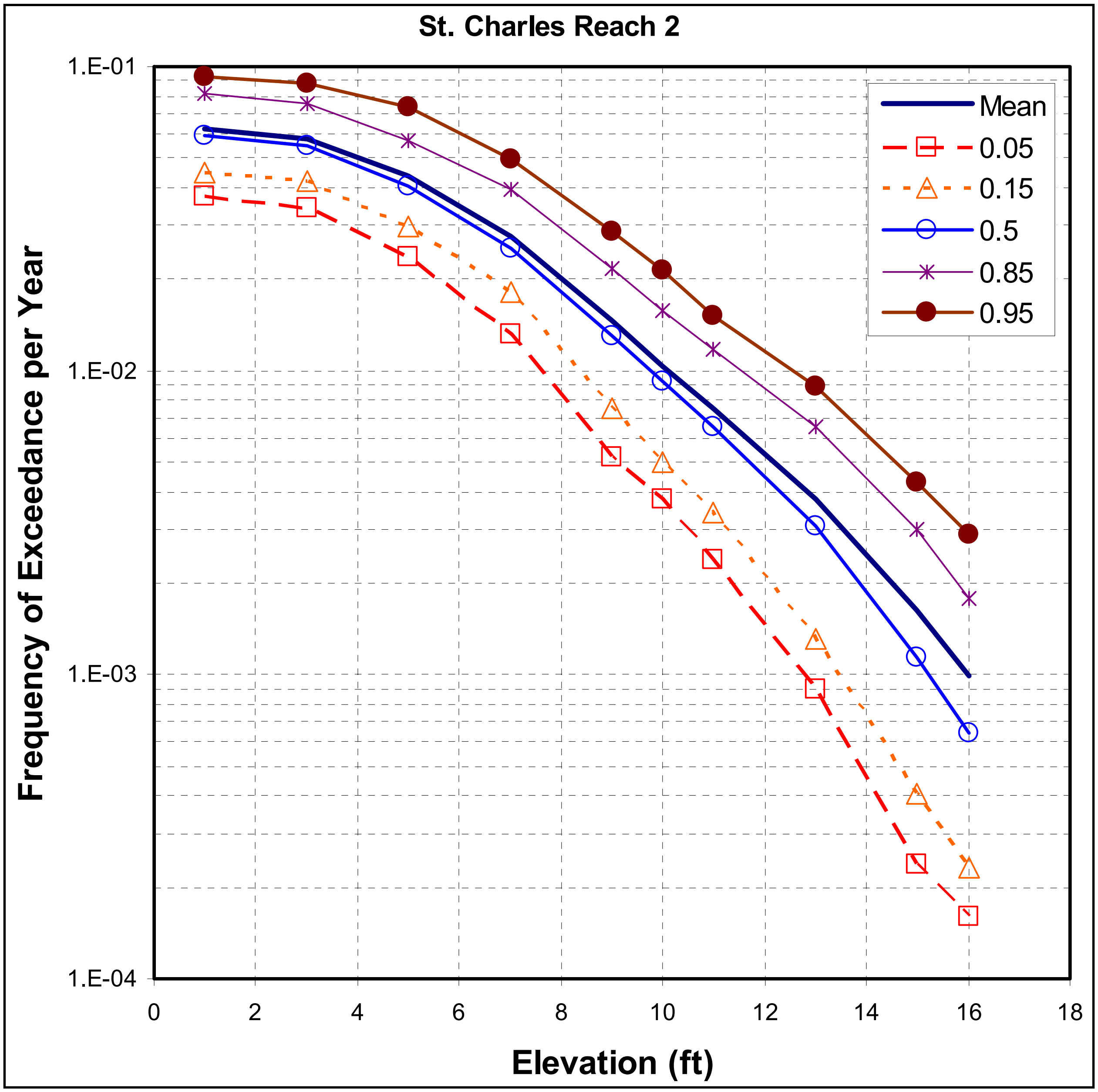

Figure 9. Hurricane hazard curves for St. Charles – Reach 2. The fractile hazard curves quantify the epistemic uncertainty in the frequency of exceedance of water-surface elevations exterior or water-side of the levee.

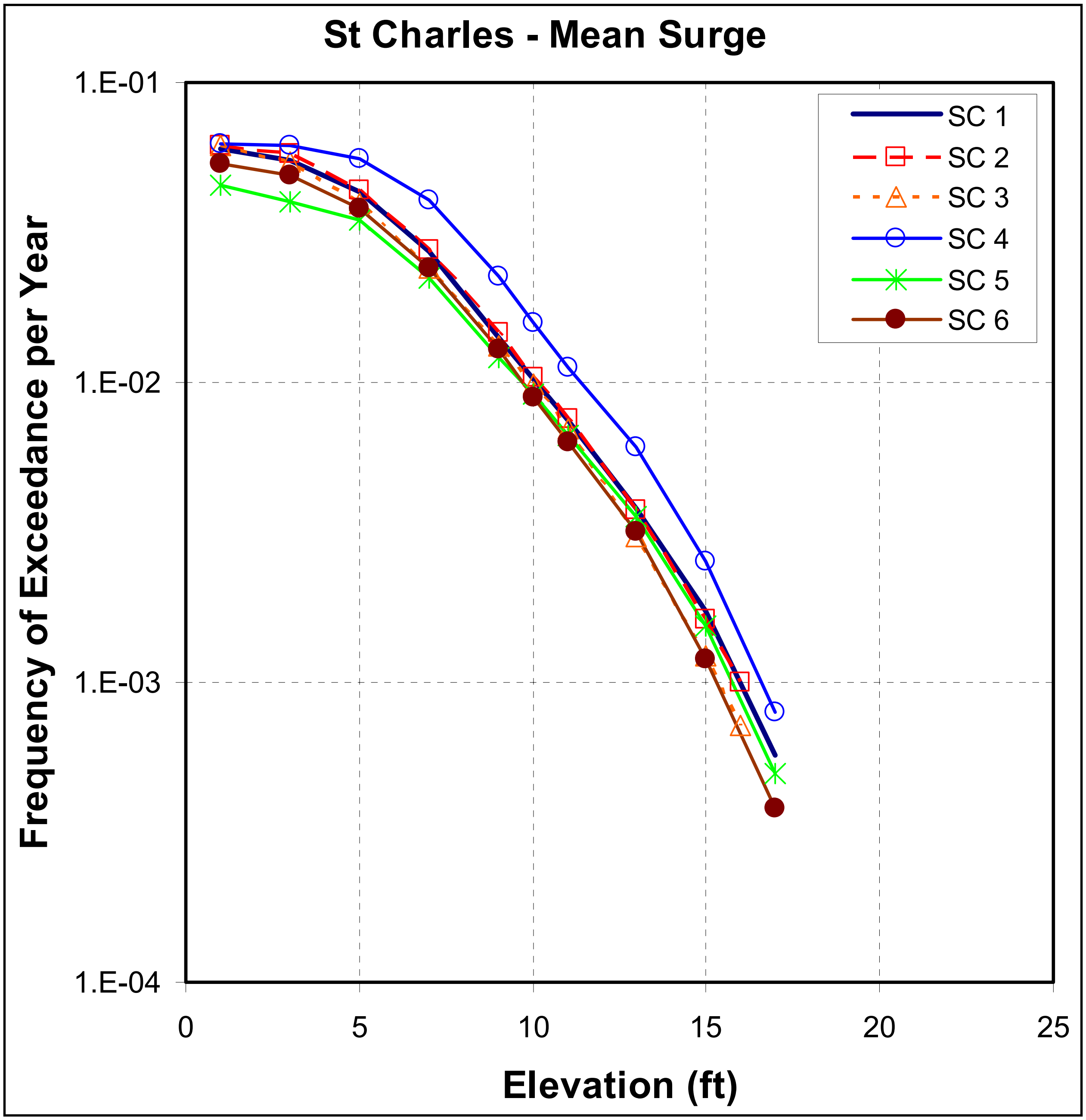

Figure 10. Mean hurricane hazard curves for each St. Charles reach.

Appendix A presents the hurricane hazard results for selected reaches in each of the New Orleans basins.

A summary of the hurricane hazard analysis is provided in Figure 11 which shows the mean water-surface levels corresponding to annual frequencies of exceedance of 0.05, 0.01 and 0.002. Also shown on the figure is the levee crest elevation for the Pre-Katrina system.

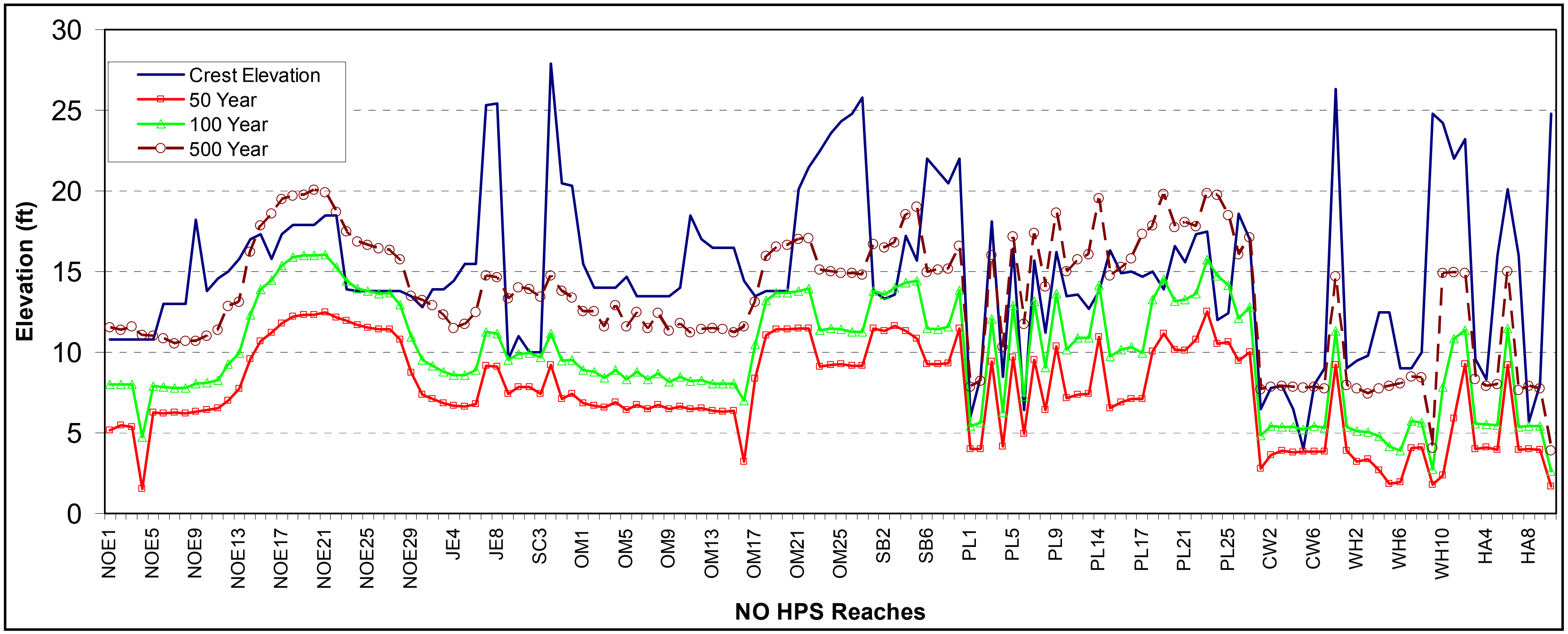

Figure 11. Plot showing the mean water-surface elevation corresponding to the 0.02, 0.01, 0.002 annual frequency of exceedance and the levee crest elevations for the Pre-Katrina system and the reaches modeled in the NO HPS risk analysis (see Appendix 14 for a description of the risk model).

Levee and Floodwall Fragility

Appendix 10 to this volume describes the assessment of levee and floodwall fragility and the analysis of aleatory and epistemic uncertainties. A summary of the fragility analysis and the estimate of epistemic uncertainties is presented here. Levee and floodwall fragility curves were developed for each reach modeled in the risk analysis (see Appendix 14). The fragility analysis considered the range of failure modes that could lead to a breach including instability, seepage/piping, overtopping, etc. (see Appendix 10 for a discussion of the failure modes that were evaluated).

The levee fragility curves were evaluated in two parts: the first part of the curve represents low water levels up to the top of the levee or flood wall, and the second part of the curve represents water levels greater than the top of levee or wall to three (3) feet above the top. The fragility calculation involved:

a. For the first part, the fragility was based on limiting-equilibrium stability analysis using the method of planes of the New Orleans District (MVN), and

b. For the second part, the fragility was based on observations of levee/floodwall performance during Hurricane Katrina to estimate the fractional length of overtopped levee or wall sections that breached due to overtopping erosion.

The approach to evaluate the reliability of levees and floodwalls and the epistemic uncertainty for these two parts of the fragility is presented in detail in Appendix 10. A summary of the approach and the estimates of the epistemic uncertainty are presented here.

The epistemic uncertainty in the fragility analysis for the water levels up to the top-of-levee or top-of-wall evaluated the uncertainties in the estimated mean and variance in the factor of safety (FS) for the levee and floodwall design methodology. Factors considered in the analysis were:

a. Bias in the method of planes calculation of the factor of safety (FS) compared to more accurate methods. The mean bias was taken to be about +20% based on comparative calculations performed by the IPET team "Performance – Levees and Floodwalls" (See Volume V).

b. Statistical estimate of the error in the mean soil property due to the limited numbers of measurements.

c. Conservative bias associated with using the undrained strength at the 1/3-point of the test results.

d. Epistemic (bias) uncertainties in the variance of the FS occur as a measurement noise in the soil properties that should be removed before calculating the variance above. Soil property data, especially as measured in traditional USACE practice by the unconsolidated undrained (UU) test, is notoriously noisy. The fraction of the total variance attributable to measurement noise is estimated using statistical filtering techniques based on the autocorrelation function.

Another source of uncertainty was the length effect. The "characteristic length" of a failure section was taken to be 1000 feet. Each characteristic length was assumed to behave independently of its adjacent lengths, and the probability of at least one failure in a reach of *n* lengths was approximated as $P=[1-(1-p)^n]$, in which *p* is the probability of failure of the characteristic length. The characteristic length was estimated from the autocorrelation structure of the soil properties and from observations of failure lengths during Katrina. It is thought that the length could range from 500 ft to 2000 ft, although there is much uncertainty about these numbers in the way they influence probability of system failure.

For failures that occur as a result of overtopping and levee erosion, the fragility was based on the observation experience during Hurricane Katrina. The epistemic uncertainty in these estimates is attributed to the limited number of observations available to estimate the fraction of levee or floodwall failures that occur as a function of water level.

The epistemic uncertainty in the levee and floodwall fragility was quantified in terms of a coefficient of variation in the estimate of the mean and variance of the FS or standard deviation in the probability of failure (see the Reliability Analysis section and Appendix 10) for a given water level in the case of overtopping.

Table 4 summarizes the sources of uncertainty in the levee fragility analysis.

Table 4. Sources of Uncertainty in the Levee Reliability Analysis

Element	Epistemic	Aleatory
Model	Levee Instability – Model uncertainty associated with the method of plains. Levee Overtopping – No model uncertainties were identified.	Levee Instability – Spatial variability of soil properties within a levee reach. Levee Overtopping – Variability in the performance of levee and floodwalls that were overtopped during Hurricane Katrina.
Parametric	Levee Instability – 1) Uncertainty in the estimate of mean soil properties due to with limited; 2) Uncertainty in the selection of soil properties used in the slope stability analysis. Levee Overtopping – Uncertainty in the estimate of the fraction of levee failures that occur due to depths of overtopping.	No sources of parametric aleatory variability were identified and modeled.

Levee Fragility Analysis Results

The uncertainty in the levee and floodwall fragility for a reach is represented by a series of discrete (individual) fragility curves. The estimate of the epistemic uncertainty standard deviation for overtopping and non-overtopping failure modes was used to determine a set of discrete fragility curves with probability weights for each levee/floodwall reach. The discrete curves, illustrated schematically in Figure 12, are defined at the 0.05, 0.50 and 0.95 fractile levels of the uncertainty distribution. The probability weights associated with these curves are 0.185, 0.63 and 0.185 respectively, based on the Pearson-Tukey (1965) approximation for using a probability mass function to represent a probability density function (PDF). This discrete representation preserves the moments of the PDF and its monotonic transformations and at the same time captures the range of the original density function.

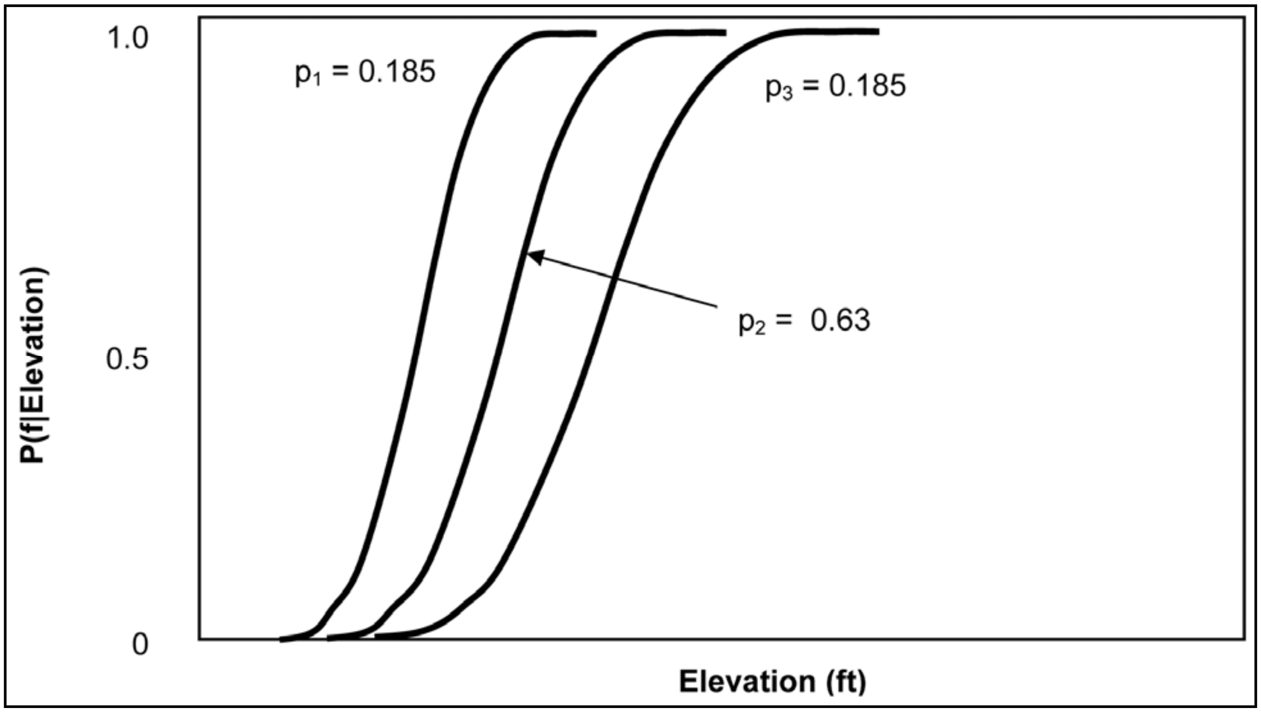

Figure 12. Schematic illustration of the discrete representation of the uncertainty in levee and floodwall fragility curves. The probability weights associated with each curve, which correspond to the 0.05, 0.50, and 0.95 fractile levels of the uncertainty distribution, are 0.185, 0.63, and 0.185, respectively.

Pre-Katrina Levee Fragility – Estimates of the uncertainty in the levee fragility are illustrated for selected reaches in Orleans Main in Figure 13. The curves shown provide examples of levee/floodwall fragility (OM2) and levee fragility (OM12). For elevations above the top-of-levee or top-of-wall, the fragility corresponds to overtopping failures, whereas for lower elevations, the fragility corresponds to stability failures.

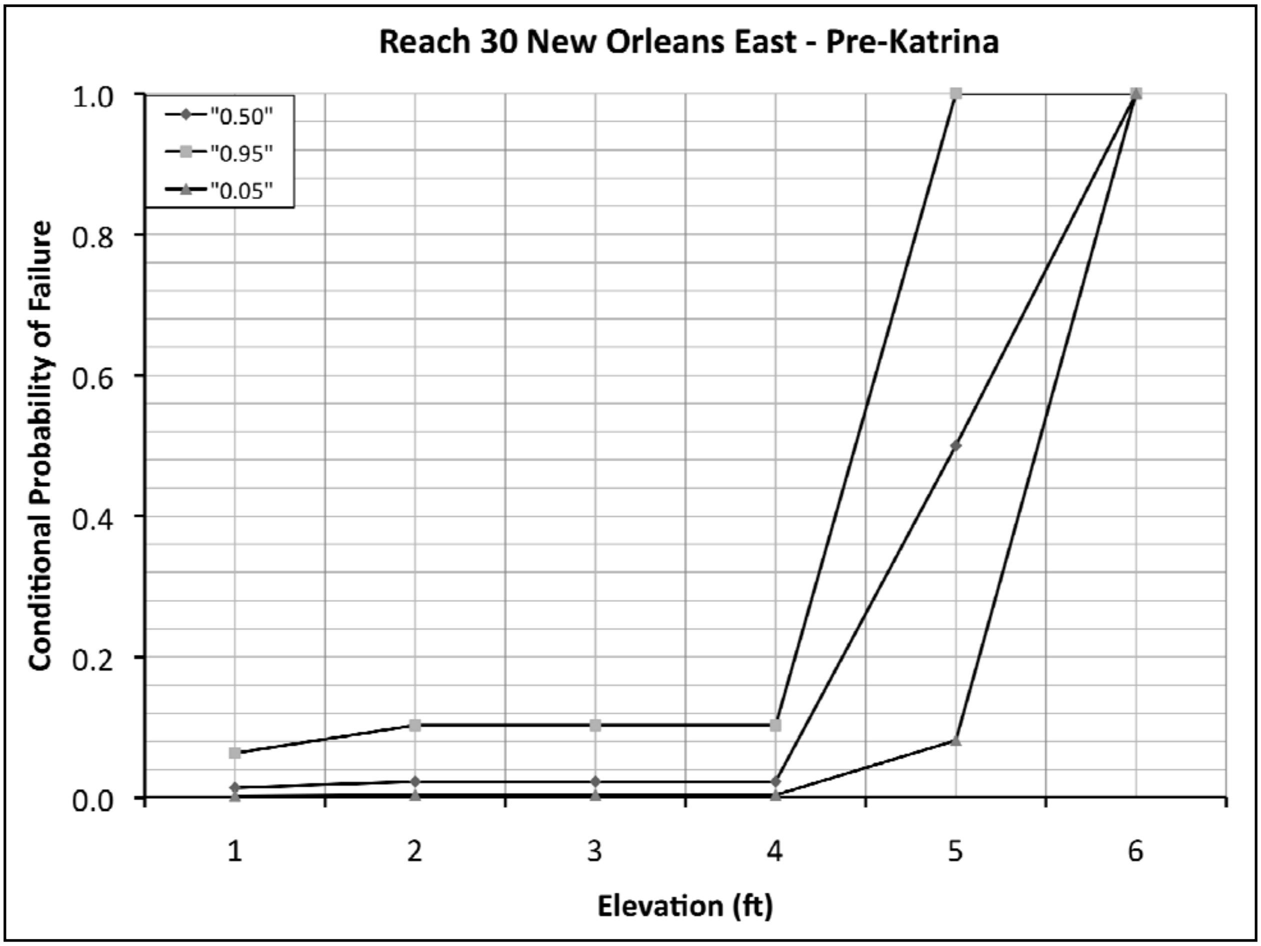

Figure 13. Example of the epistemic uncertainty in the pre-Katrina levee/floodwall fragility curves for levee section reach 30 in New Orleans East, pre-Katrina.

Figure 14 shows the best-estimate (median) fragility curves for the reaches that protect St. Charles. The figure shows the range of vulnerability in this basin. For three of the reaches (SC4, 5 and 6) the potential for failure is very low. These reaches are Mississippi River levee reaches which are typically very robust. For the other reaches (SC1, 2, and 3) there is a considerably higher chance of failure due to levee instability and overtopping.

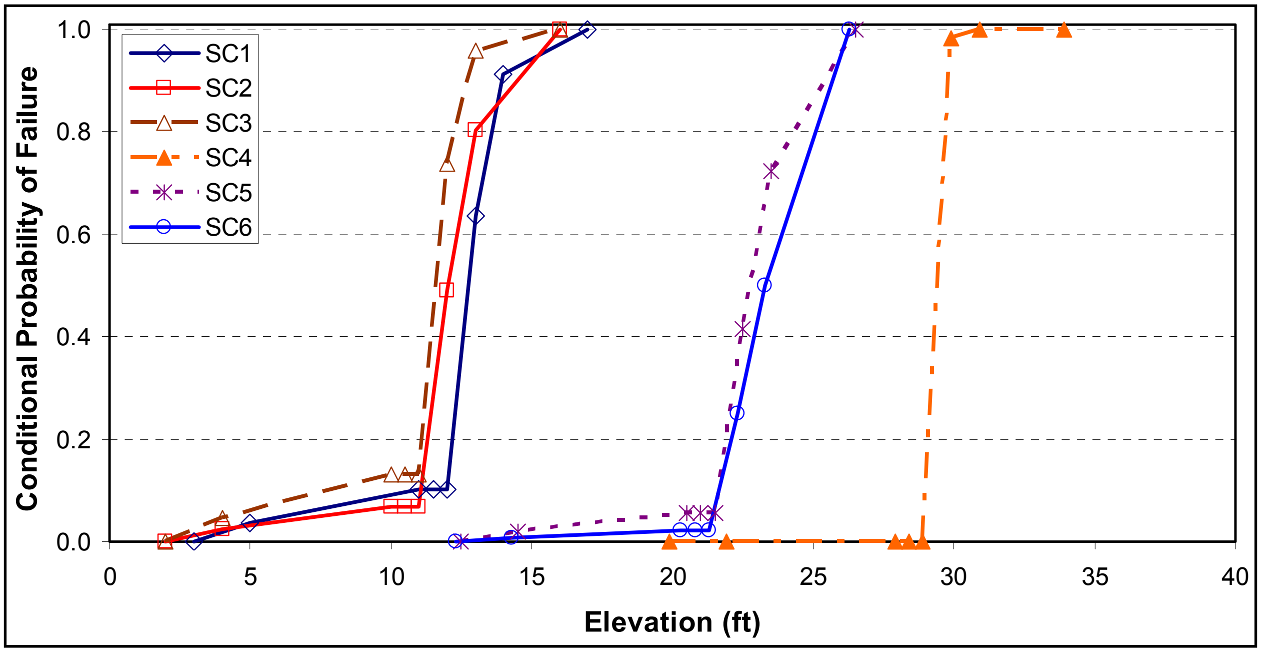

Figure 14. Median or best-estimate pre-Katrina levee fragility curves for St. Charles.

The results of the pre-Katrina fragility uncertainty analysis for each levee and floodwall reach in the HPS model are provided in Appendix B.

2007 HPS Levee Fragility – The uncertainty in the levee fragility has also been estimated for the 2007 HPS. Figure 15 shows the uncertainty in the 2007 levee fragility for reaches in Orleans Main (the same reaches as those used in Figure 13 are shown). Figure 16 shows the best-estimate (median) fragility curves for the reaches that protect St. Charles for the 2007 HPS (see also Figure 14).

The results of the 2007 levee fragility uncertainty analysis for reaches in the HPS model are provided in Appendix B.

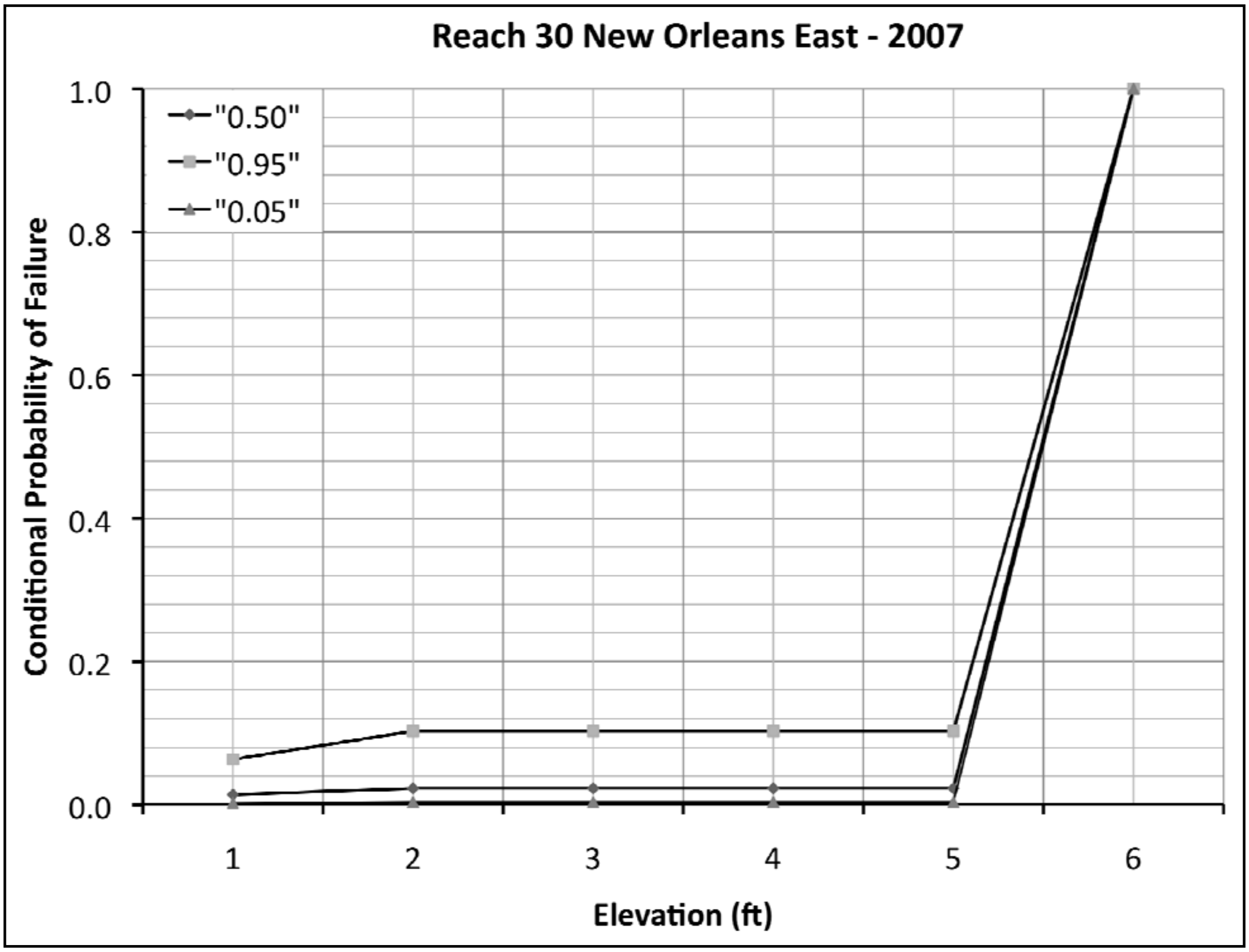

Figure 15. Example of the epistemic uncertainty in the 2007 levee fragility curves for levee sections reach 30 in New Orleans East, post-Katrina (2007).

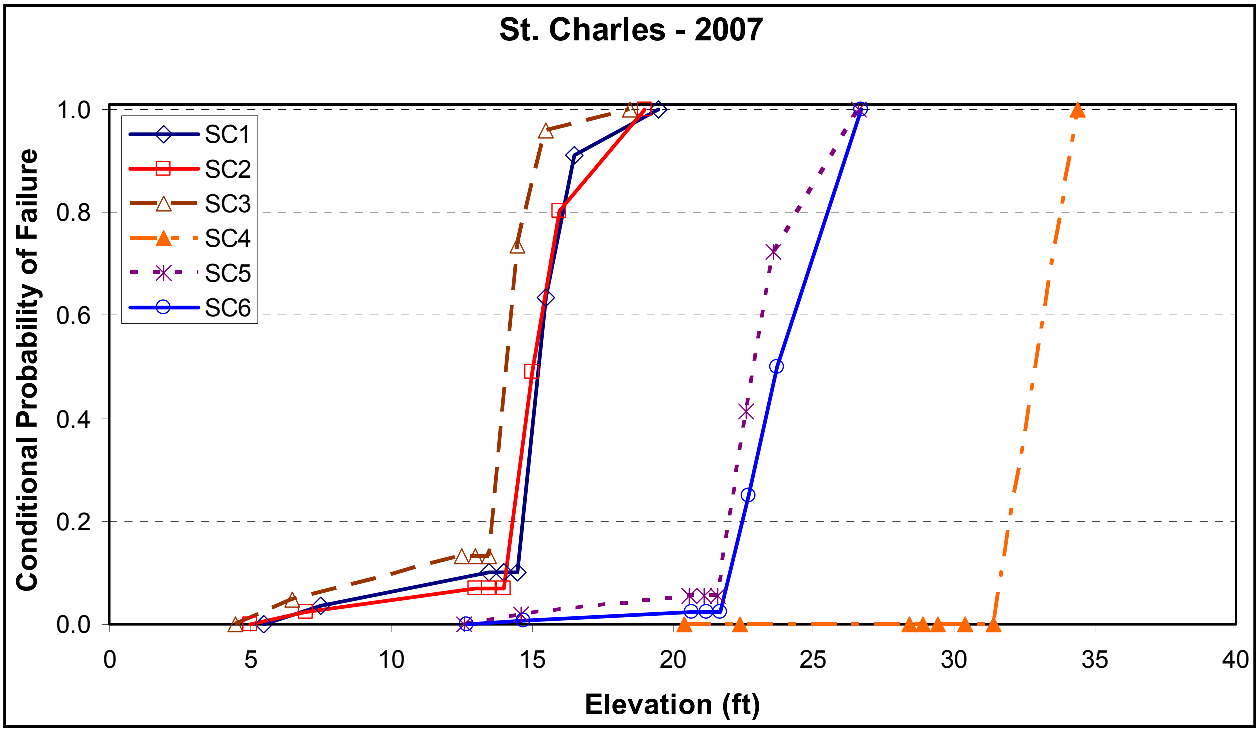

Figure 16. Median or best-estimate 2007 HPS levee fragility curves for St. Charles.

Pre-Katrina – 2007 HPS Levee Fragility Comparison – The improvement in the HPS levees can be observed by comparing the pre-Katrina and 2007 levee fragility curves. Figure 17 shows the median fragility curves for the pre-Katrina and 2007 HPS for St. Charles. With the exception of reaches SC5 and SC6, there is considerable improvement in the fragility of the St. Charles fragility curves (i.e., lower conditional probabilities of failure). The central and upper part of the fragility curves, the part associated with overtopping failures, are shifted to the right approximately 3 feet, reflecting the greater surge elevations required to produce overtopping and potential breach failures.

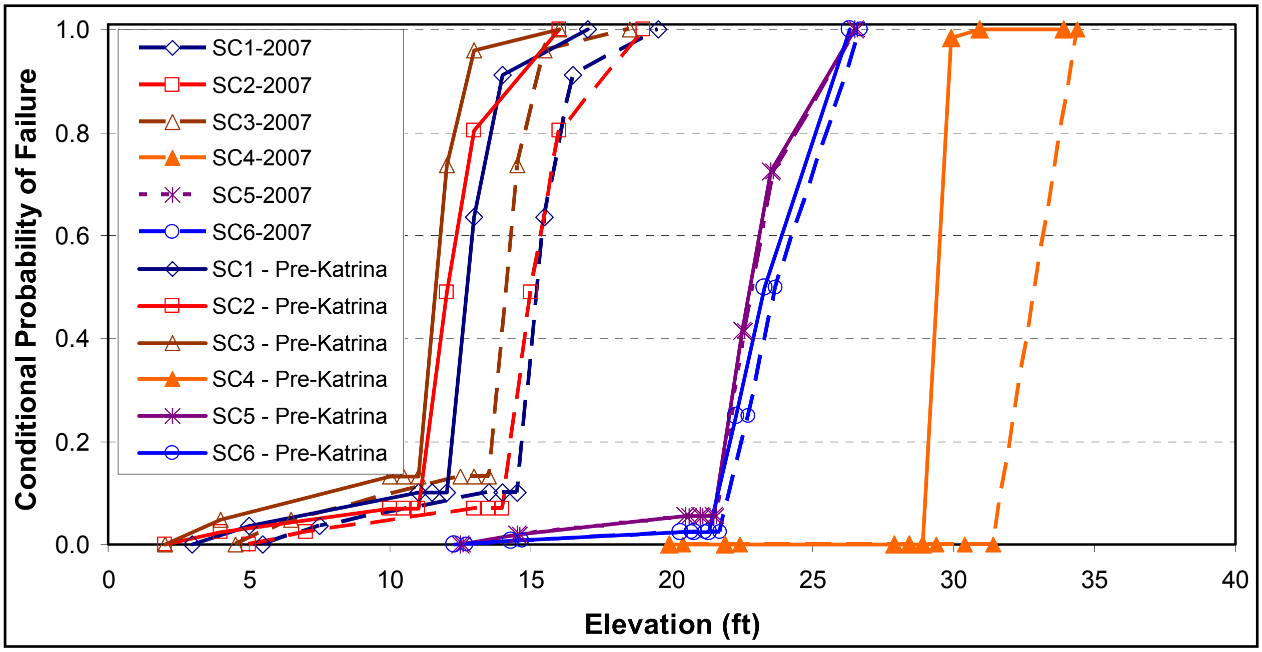

Figure 17. Comparison of the median or best-estimate for the pre-Katrina and 2007 HPS levee fragility curves for St. Charles.

Flood Inundation Level for Basins and Sub-basins

Only primary sources of floodwaters were considered in determining the uncertainty in the flood inundation levels estimated for each of the sub-basins and basins in the HPS. The primary mechanisms for floodwaters entering a basin were overtopping, breaching during overtopping due to erosion and non-overtopping stability failures. Flood inundation was evaluated only for levees and reaches. Other factors that influence flooding within the subbasins such as: open gates, failure of transitions, performance of the pumping system, rainfall volumes and overtopping due to wave runup was not included in the uncertainty water volume calculations. These factors were included in the risk model, however they were considered to not contribute significantly to the uncertainty analysis.

Estimating Basin Water Volumes due to Overtopping and Erosional Breach Events - To estimate flood inundation levels in HPS basins, the volume of water due to overtopping of levees and floodwalls and erosional breaching of levees was calculated using a weir equation, where

$$Q(t) = C_w \, L \, H(t)^{3/2} \text{ (cfs)} \tag{7}$$

$$\text{Water Volume} = \int Q(t)\, dt \tag{8}$$

where,

$Q(t)$ = Flow rate of water over a weir (i.e., levee or floodwall) (cfs)

C_w = Weir coefficient
L = Weir length (ft)
H(t) = Height of water over the weir as a function of time (ft)

For each storm, the surge elevation data was estimated at each reach every 1800 s (30 min) over approximately 4 days. The water volume integral was computed using a summation approach, where the hydrograph data was summed over all Δt as follows:

$$\begin{aligned} \text{Water Volume} &= \sum Q(\Delta t)\,\Delta t \\ &= Cw\, L \sum H(\Delta t)^{3/2}\,\Delta t \\ &= Cw\,\Delta t \sum L\, H(\Delta t)^{3/2} \end{aligned} \tag{9}$$

where Δt = 1800 sec

For estimation of flood inundation levels in a basin due to overtopping, the height of water over the top of each reach was used to estimate the total volume of water that flowed into a basin as a function of time.

In the case when a levee reach fails by overtopping, the additional water volume due to erosional breaching was estimated using parameters in Table 5 (repeated here from Appendix 9). A breach width and depth were assumed based on the criteria in Table 5. The water volume flow rate increased at a breach location, as the water height above the top of the reach also included the breach depth. To avoid "double counting" of water volumes at erosional breach locations, the lengths for overtopping and erosional breach were computed for each reach and the resulting water volumes were calculated separately.

Table 5. Breach Given Overtopping (Erosional Breach)

		Reach Length < 1000 ft				Reach Length > 1000 ft			
Material	**Symbol**	**1<H<3 ft, Depth (ft)**	**H>3 ft, Depth (ft)**	**Breach Width/ Reach Length***	**Maximum Width Breach (ft)**	**1<H<3 ft, Depth (ft)**	**H>3 ft, Depth (ft)**	**Breach Width/ Reach Length***	**Min. Width Breach/L**
Hydraulic Fill	H	9	18	0.5	400	9	18	0.4	400
Clay	C	3	13	0.5	135	3	13	0.1	135
Unknown	U	6	17	0.5	290	6	17	0.3	290
Wall	W	0	17	0	0	0	17	0	315

The water volume over each reach was summed for each storm. Interflow between sub-basins was not considered in the uncertainty analysis. Instead, the computed water volume was averaged over the entire basin. This simplified approach was consistent with the simplified nature of estimating volumes for the uncertainty analysis. A stage storage curve for a basin was used to determine an average flood elevation level from the total volume of water accumulated.

Estimating Basin Water Volumes due to Non-Overtopping Stability Failure Events – To estimate flood inundation levels in HPS basins, the peak surge level was assumed to be equal to the water elevation achieved inside the basin when a breach due to a stability failure occurred during a non-overtopping event. All stability failures were considered to be a result of a structural or foundation failure and the breach depth was set equal to the lowest elevation of the levee or floodwall.

The peak surge level was not the same at each reach. Therefore, the reach for which a stability failure was most likely to occur was used to select the peak surge level for the sub-basin.

Uncertainty Quantification

The steps in the uncertainty analysis are shown in Figure 18. In the quantification, the uncertainty in the hurricane hazard and the levee fragility for a basin were sampled by LHS (see Figure 18). Each LHS sample from the hurricane hazard and levee fragility was combined to estimate the frequency of occurrence of each sequence in the basin event tree. This process was repeated until all combinations of the hurricane and fragility LHS samples were exhausted. The result for each sequence in the event tree is a discrete probability mass function on the frequency of occurrence.

The principal steps in the quantification are:

- Generate LHS samples of the hurricane hazard for the HPS.
- Generate LHS samples of the HPS levee fragility.
- Evaluate the basin system model to determine the levee system reliability (conditional probability of failure given a hurricane event) and the frequency of occurrence of each sequence of events in the basin event tree.
- For each sequence in the basin event tree and each hurricane, the conditional probability of occurrence of the sequence given the hurricane event and the hurricane event frequency of occurrence are combined (multiplied) to determine the sequence frequency of occurrence.
- For each sequence in the basin event tree and each hurricane event, the inundation in the basin (peak flood elevation) is determined. The volume of flooding into a basin depends on the events that occur in the sequence (i.e., levee reach breaches and/or levee overtopping) and the characteristics of the hurricane surge (surge levels, duration, etc.).
- The set of event tree sequence/hurricane frequencies of occurrence and the basin inundation that occurs (as determined in the previous two steps) is used to generate an inundation frequency distribution.
- The estimate of event tree sequence frequencies of occurrence and resulting inundation frequency distributions is repeated for the full set of hurricane and levee fragility LHS estimates (see above). The LHS sets of inundation frequency distributions are used to

generate a probability (uncertainty) distribution on the basin inundation frequency distribution which is used to determine the uncertainty in the 100-year flood levels.

Propagating the uncertainty in the hurricane hazard and the levee fragility produces a probability distribution on the frequency of basin inundation as illustrated in Figure 1. This result was used to determine the uncertainty in the 100-year flood level.

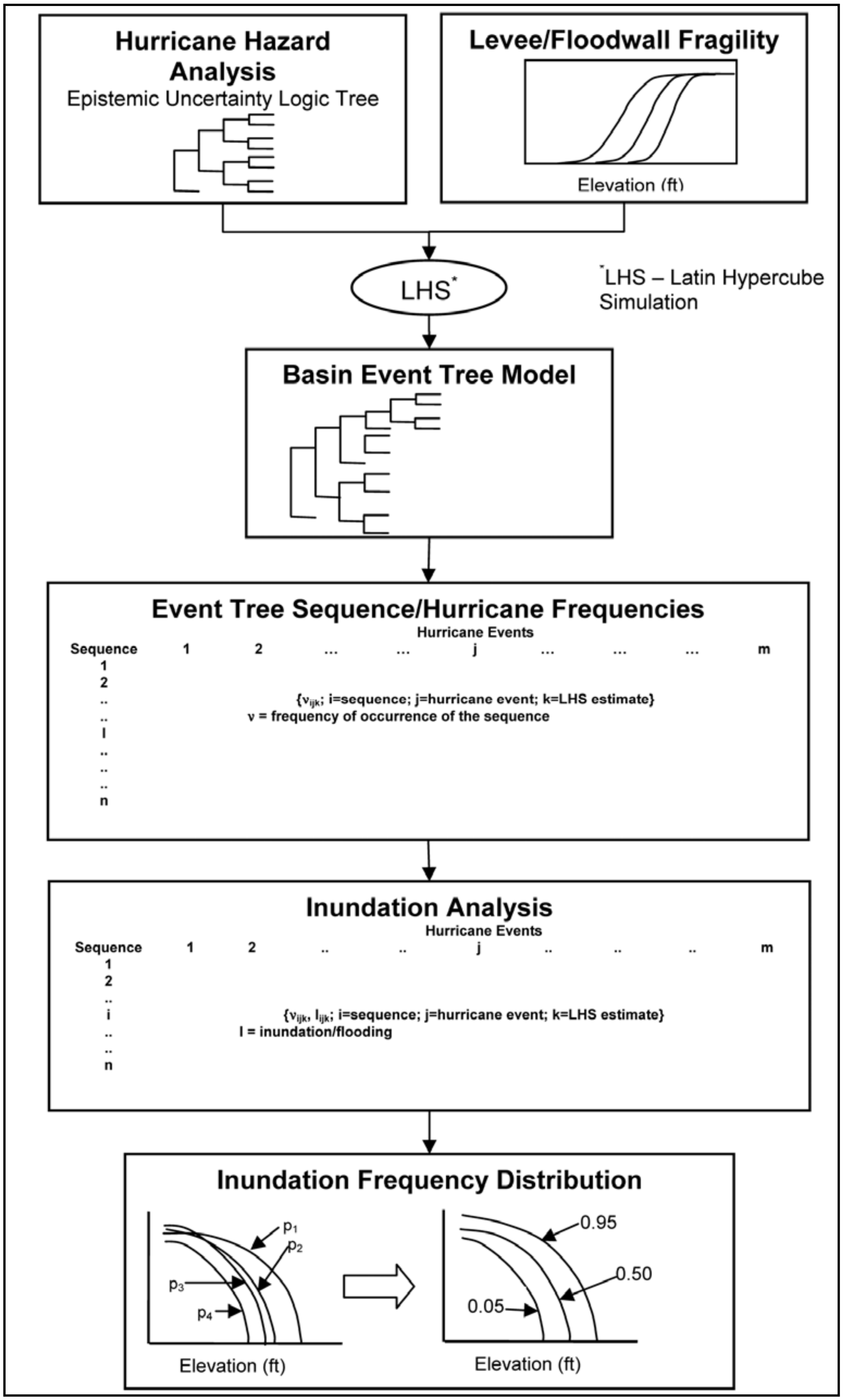

Figure 18. Steps in the epistemic uncertainty analysis for the New Orleans hurricane protection system.

Risk and Inundation Uncertainty

This section presents the results of the uncertainty quantification for the NO HPS. Each of the steps in the uncertainty analysis is carried out for the pre-Katrina system. For the 2007 system, the system reliability and the frequency of system failure only is evaluated.

This section presents the results of these steps to determine the uncertainty in the levee system reliability and frequency of system failure for each New Orleans basin. Estimates of the uncertainty in pre-Katrina 100-year estimate of basin flooding are evaluated for a selected set of the system basins.

Levee System Reliability

In the first step of the quantification process, the levee system model is evaluated to determine the conditional probability of system failure (the probability of one or more breaches in the system) for each hurricane event. The system fragility curve for a basin considers the potential for stability and overtopping failures and is estimated using the following relationship:

$$P(L_s \mid h_i) = 1.0 - [\prod_{j=1}^{n} \prod_{k=1}^{2} (1.0 - P(R_{jk} \mid h_i))] \tag{10}$$

where,

$P(L_s \mid h_i)$ = levee system fragility for hurricane event h_i

$P(R_{jk} \mid h_i)$ = levee reach fragility for reach j and failure mode k (stability, overtopping) for hurricane event h_i

n = number of levee reaches in a basin

Table 3 lists the hurricanes used in the analysis for which the levee system fragility curves were determined. The uncertainty in the individual levee reach fragility curves is propagated through the levee system fragility calculation using equation 10 to determine the uncertainty in the levee system fragility for a basin.

Pre-Katrina – Figure 19 shows the uncertainty results for the pre-Katrina levee system fragility for the New Orleans East basin. The results are presented in terms of the 0.05, 0.50 and 0.95 fractile fragility curves and as a function of storm (hurricane) number (see Table 5). For presentation purposes, the levee system reliability results are rank ordered with respect to the 0.50 fragility curve. As illustrated in the figure, there is considerable uncertainty in the levee system fragility estimates as the conditional probability of failure increases. For instance, referring to the 0.50 fragility curve, at the point where the curve corresponds to a 0.50 conditional probability of failure, the 0.05 to 0.95 range of estimates varies from 0.14 to 0.92. As the conditional probability of failure continues to increase to certainty (conditional probability of 1.0 of failure), the level of uncertainty decreases.

The pre-Katrina system level fragility results for the other basins are provided in Figures 20 to 27.

2007 HPS System – Figures 28 to 36 present the levee system fragility curves for the 2007 HPS system.

Pre-Katrina – 2007 Levee System Fragility Comparison - The improvement in the system is generally apparent in the shift to the right (larger storms are required to cause system failure) of the fragility curves. For example, Figure 37 shows a comparison of the median pre-Katrina and 2007 HPS fragility curves for St. Charles.

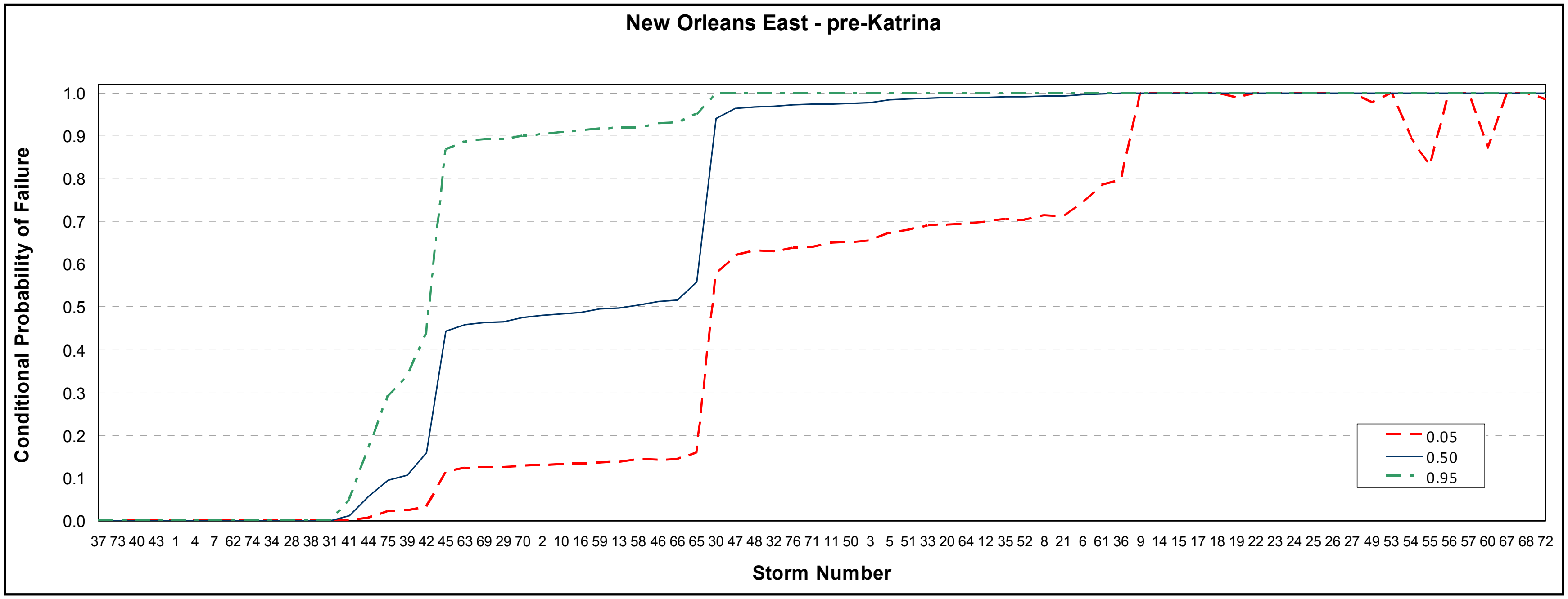

Figure 19. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for New Orleans East displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

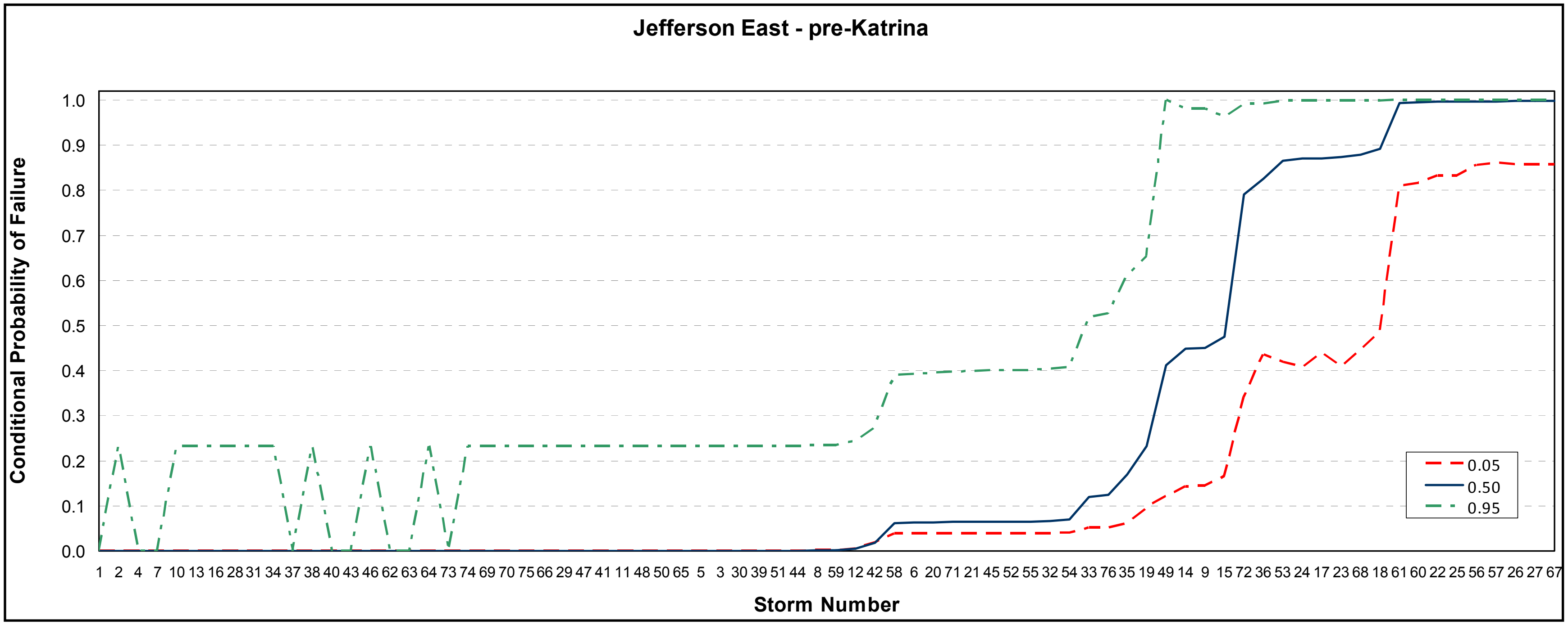

Figure 20. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for Jefferson East displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

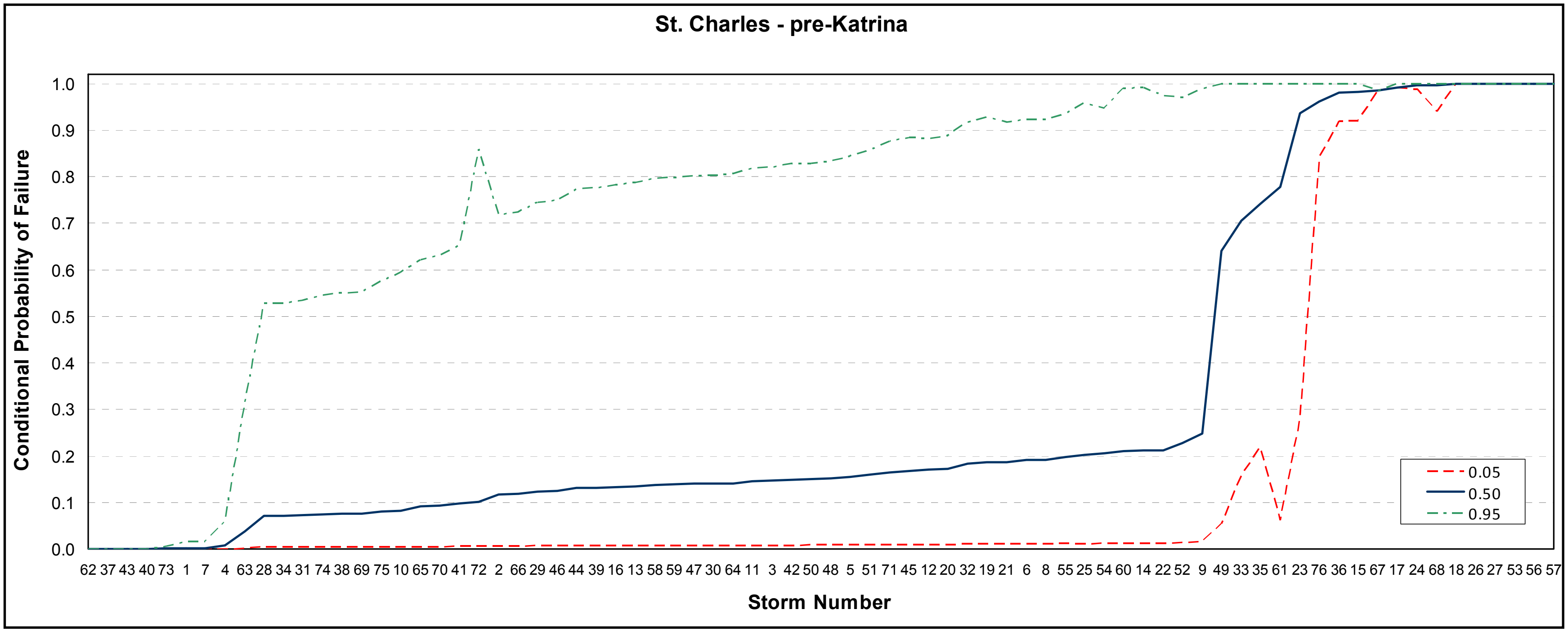

Figure 21. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for St. Charles displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

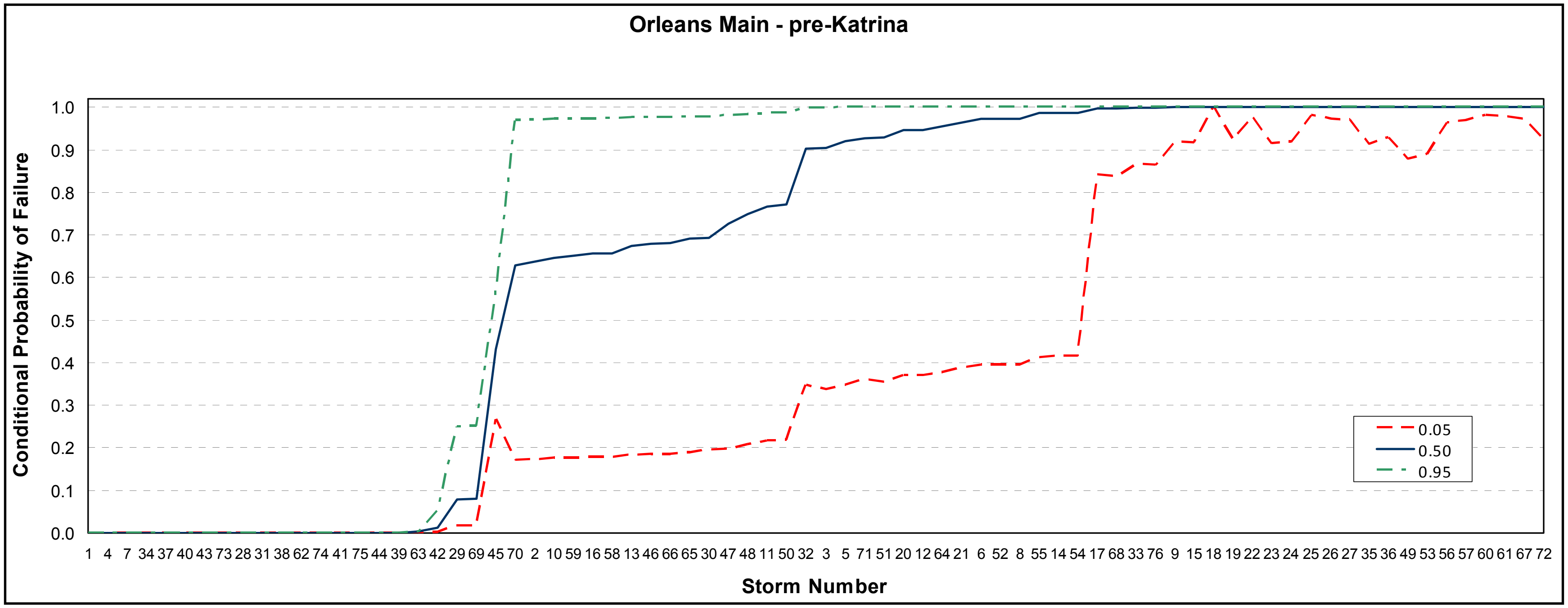

Figure 22. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for Orleans Main displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

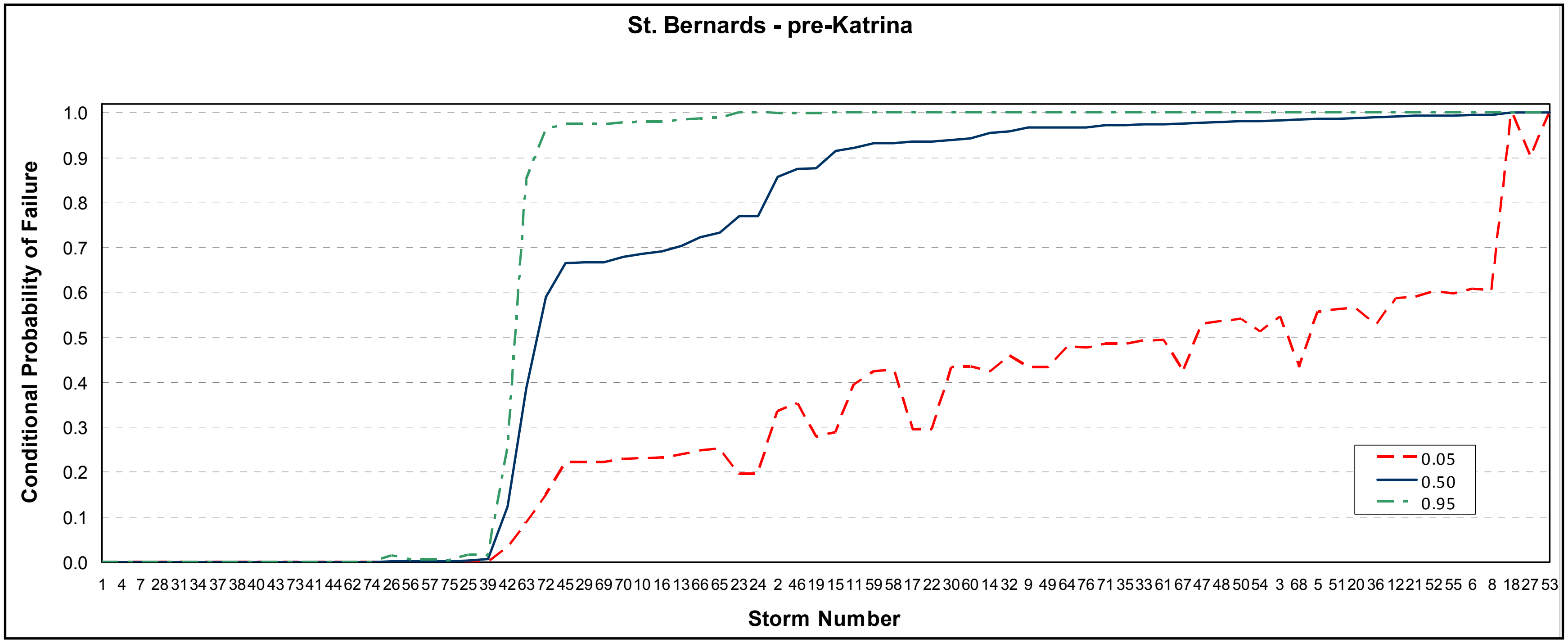

Figure 23. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for St. Bernard displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

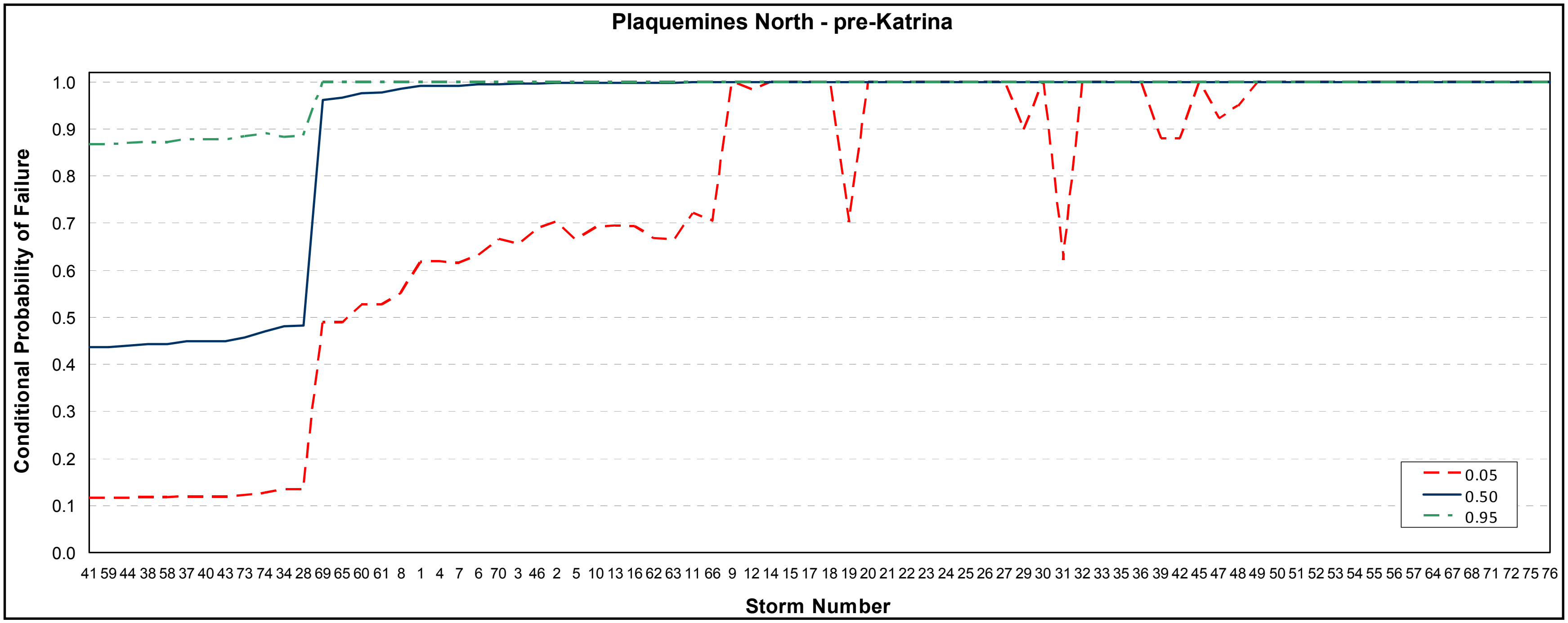

Figure 24. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for Plaquemines North displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

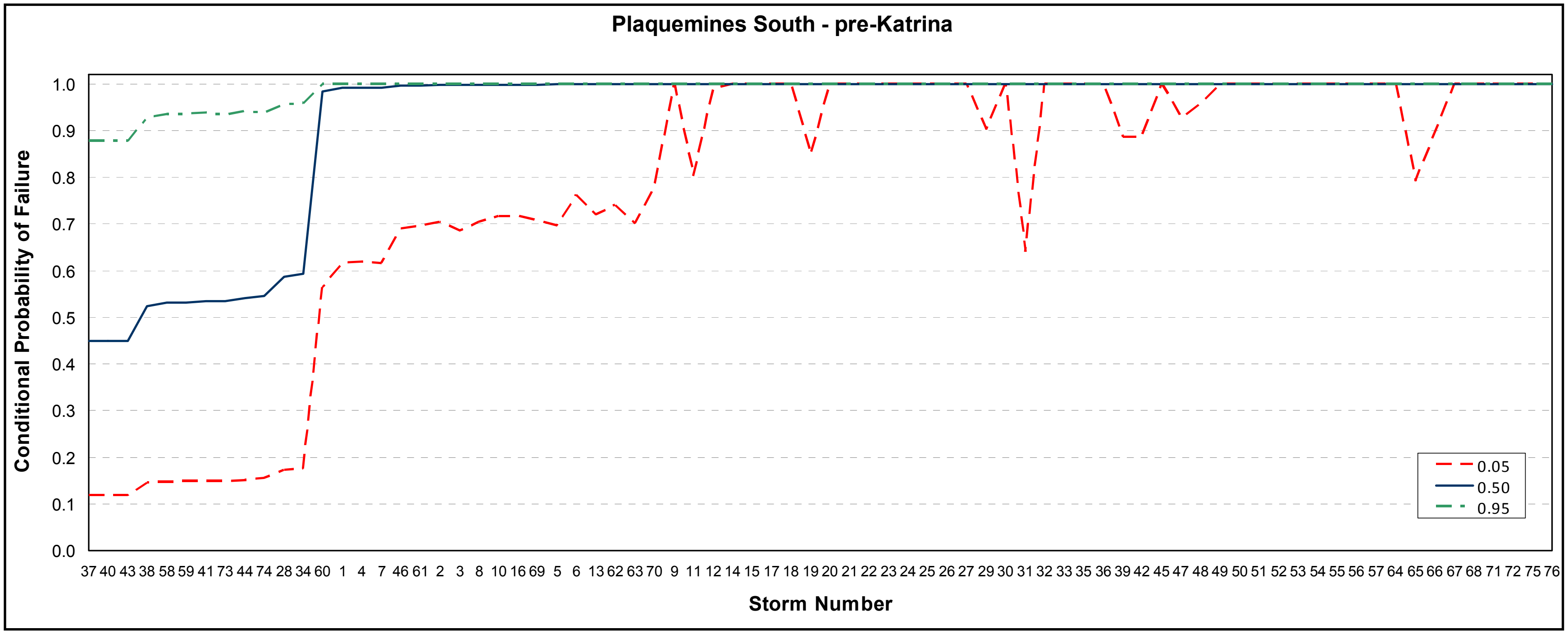

Figure 25. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for Plaquemines South displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

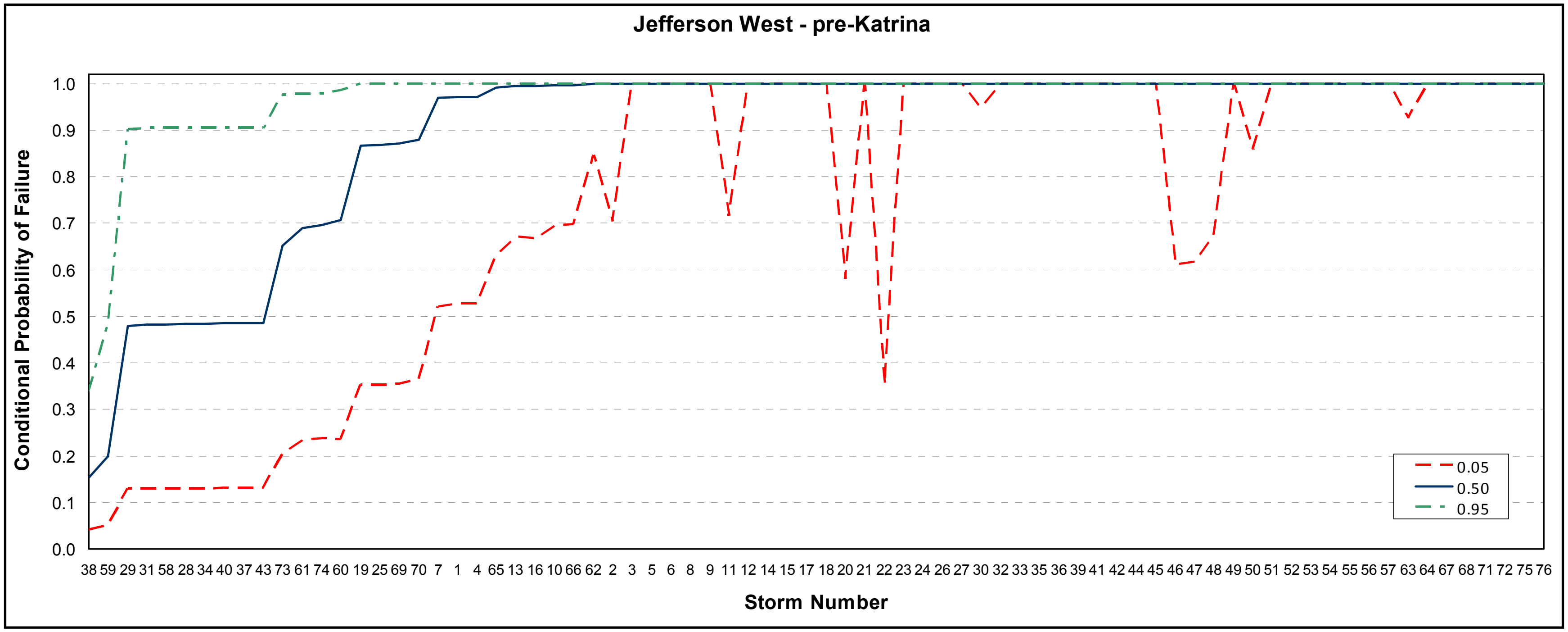

Figure 26. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for Jefferson West displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

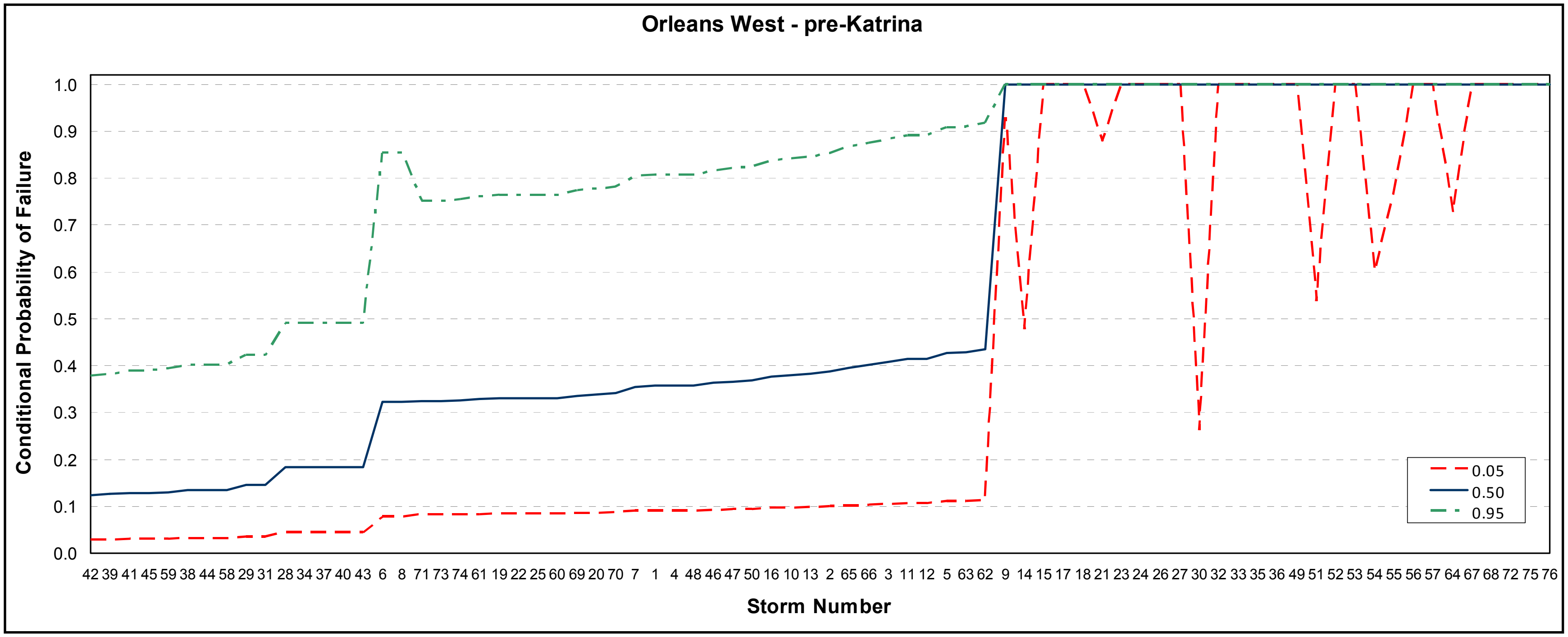

Figure 27. Uncertainty in the levee system fragility curves for the pre-Katrina HPS for Orleans West displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

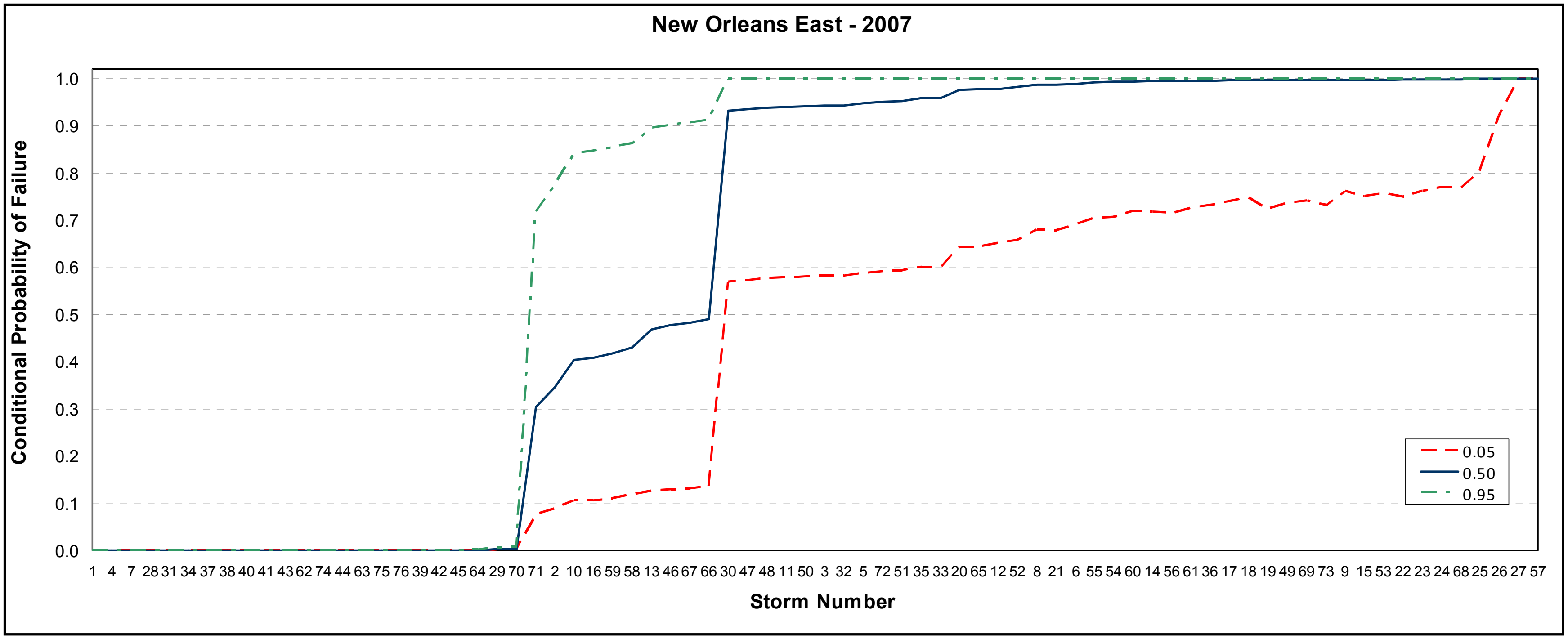

Figure 28. Uncertainty in the levee system fragility curves for the 2007 HPS for New Orleans East displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

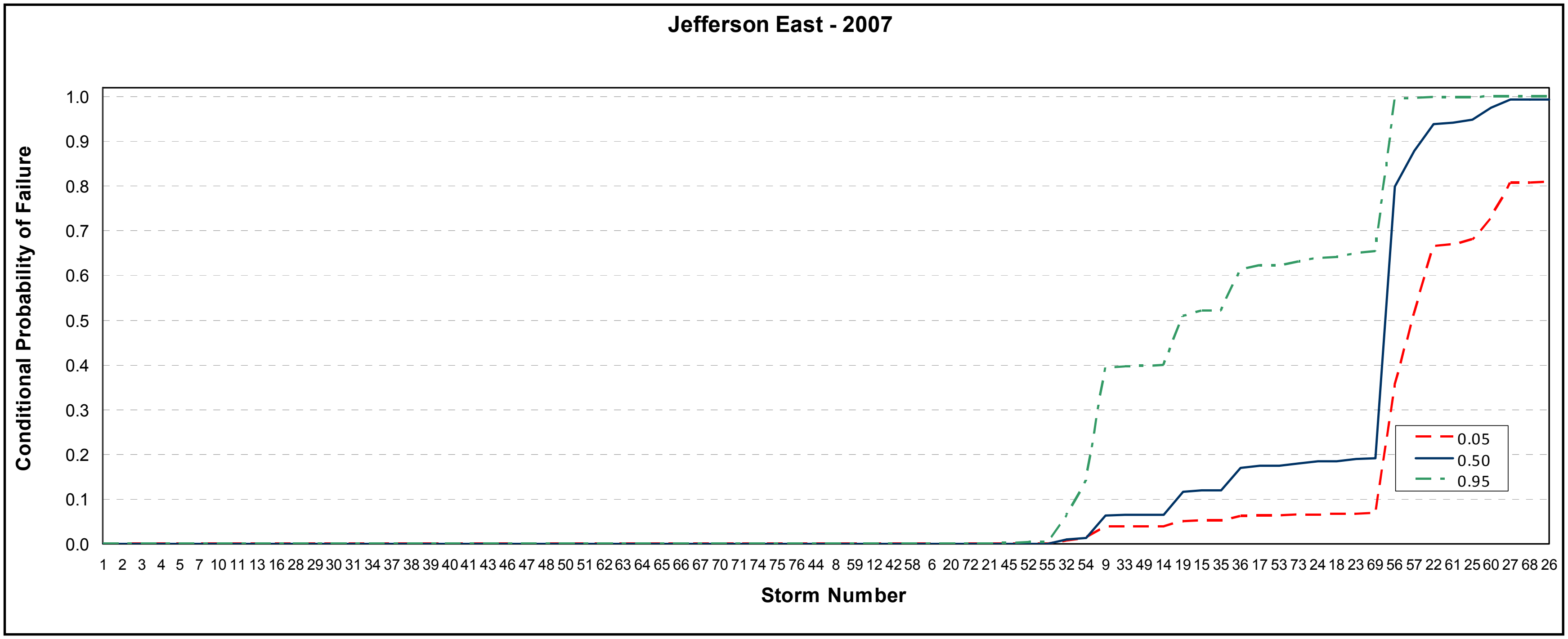

Figure 29. Uncertainty in the levee system fragility curves for the 2007 HPS for Jefferson East displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

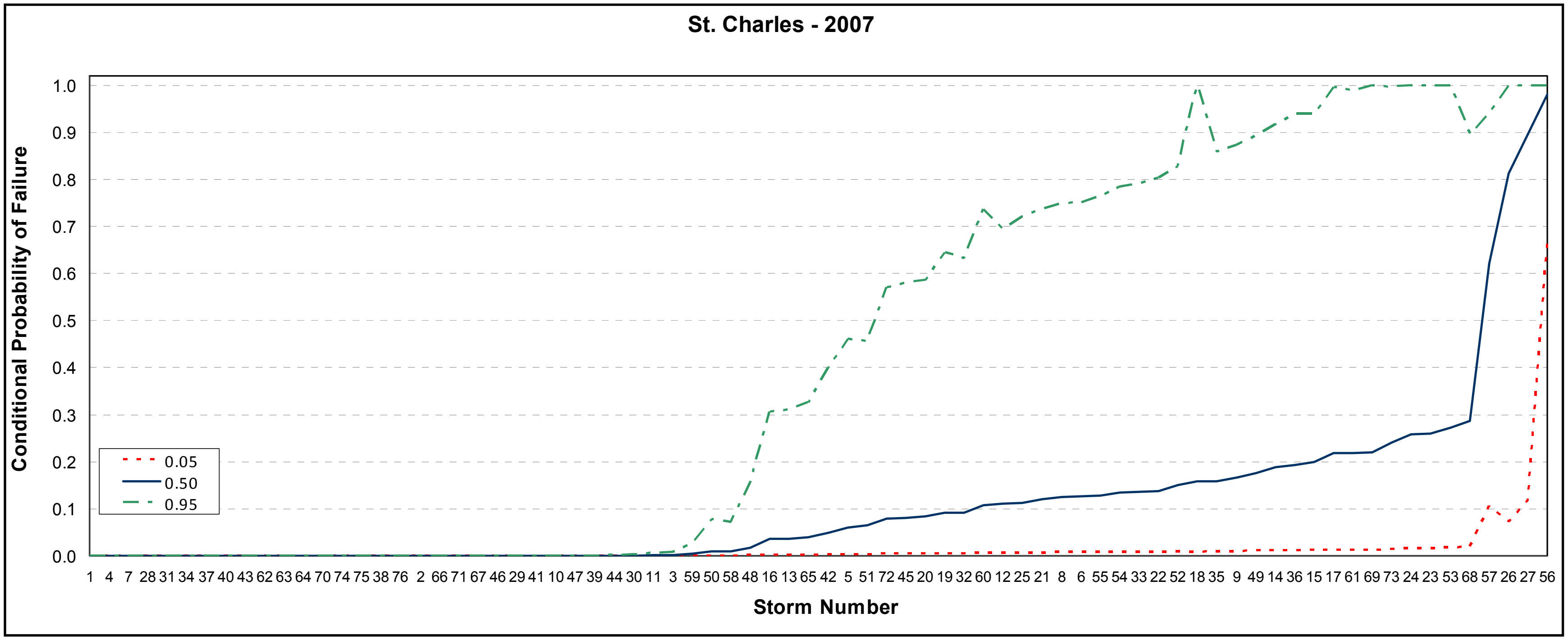

Figure 30. Uncertainty in the levee system fragility curves for the 2007 HPS for St. Charles displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

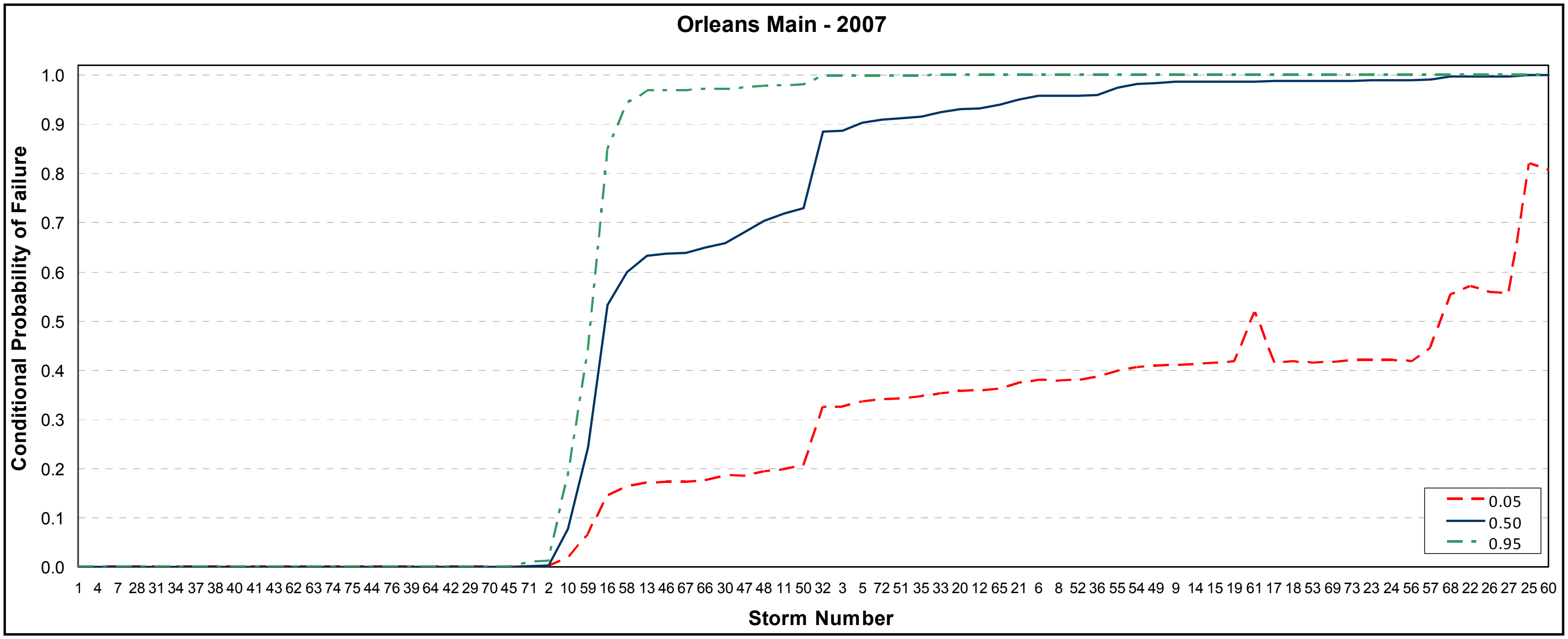

Figure 31. Uncertainty in the levee system fragility curves for the 2007 HPS for Orleans Main displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

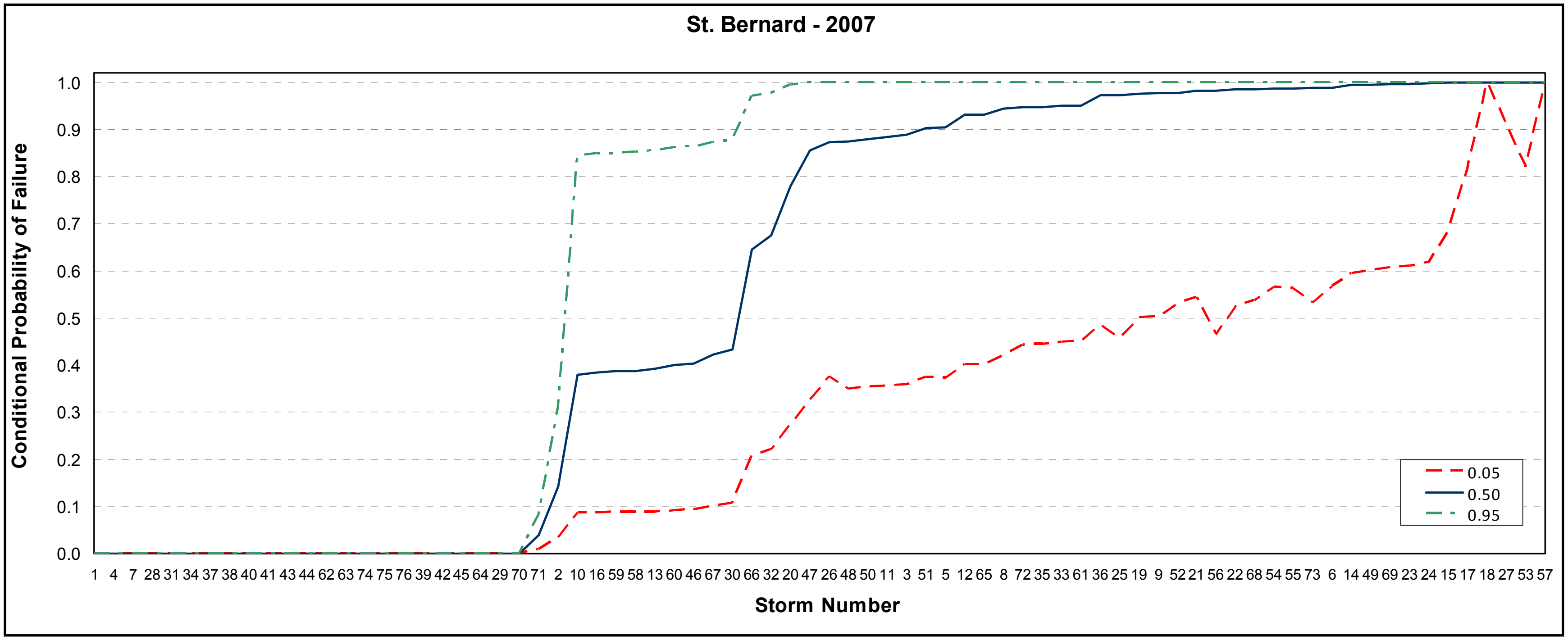

Figure 32. Uncertainty in the levee system fragility curves for the 2007 HPS for St. Bernard displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

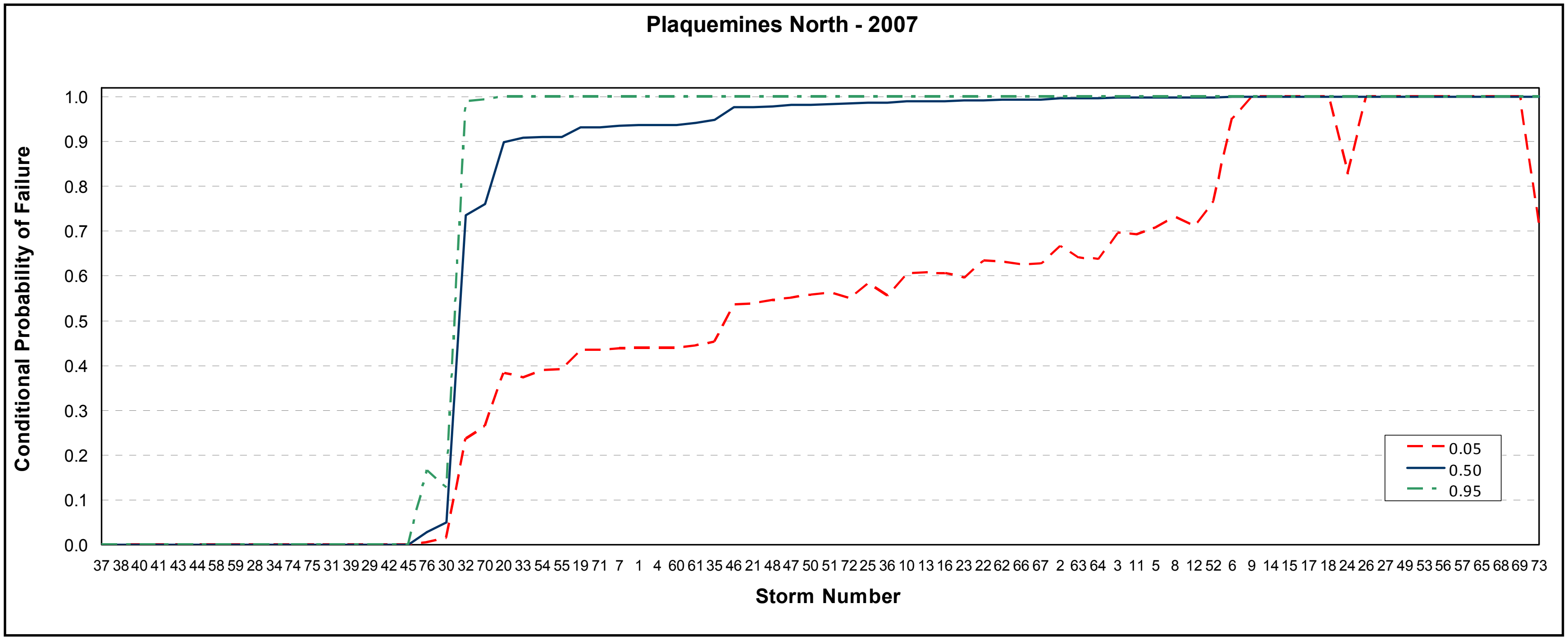

Figure 33. Uncertainty in the levee system fragility curves for the 2007 HPS for Plaquemines North displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

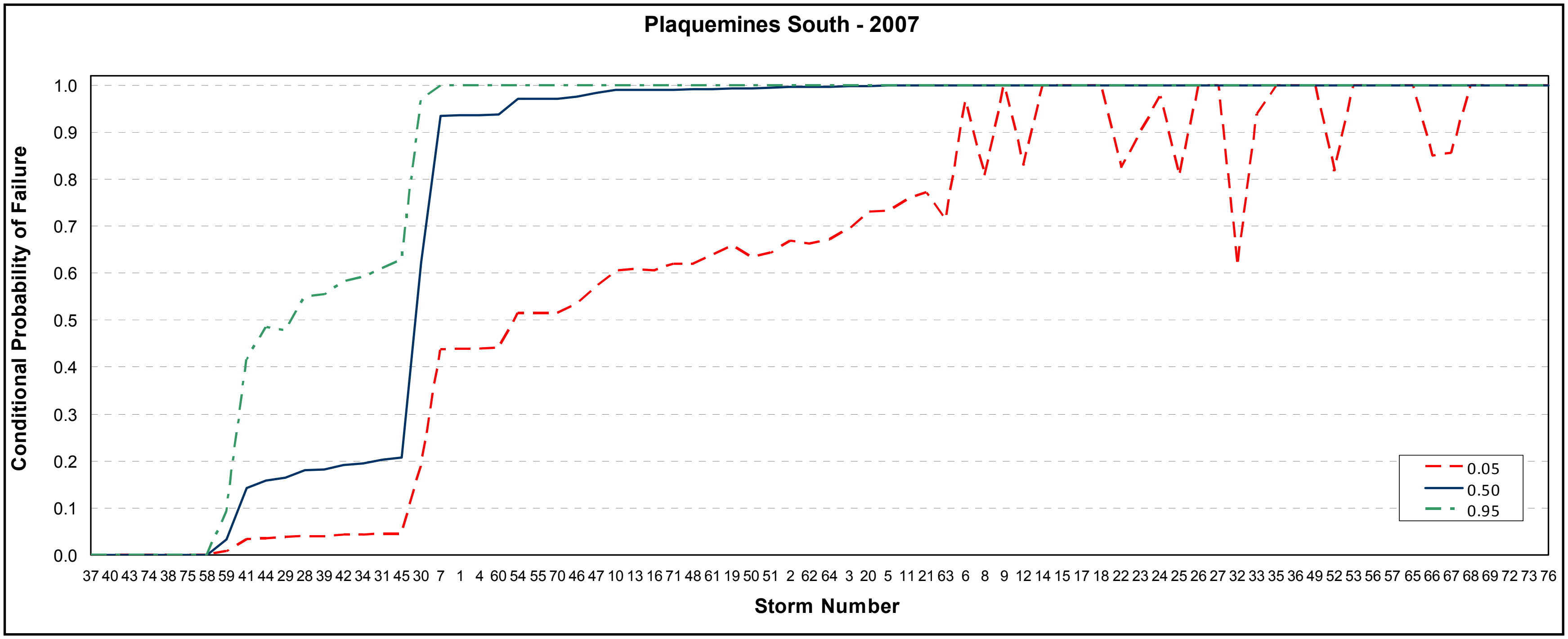

Figure 34. Uncertainty in the levee system fragility curves for the 2007 HPS for Plaquemines South displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

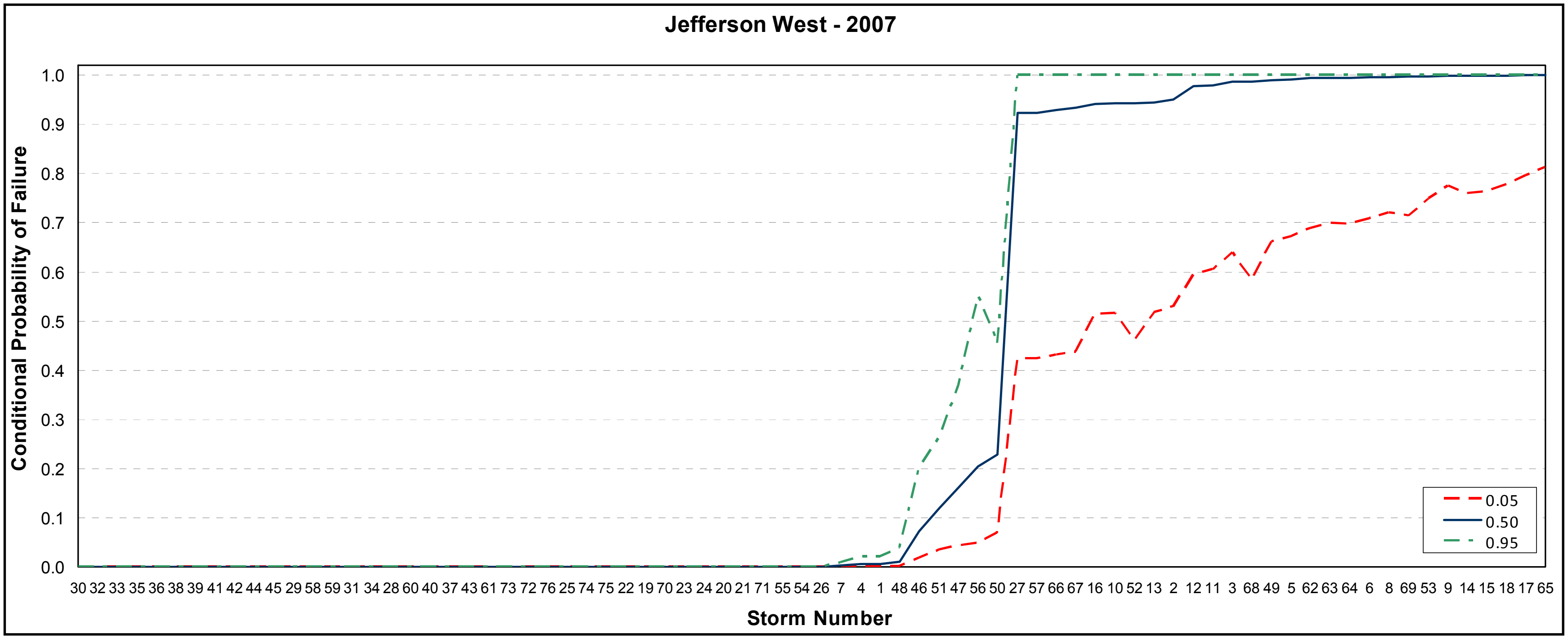

Figure 35. Uncertainty in the levee system fragility curves for the 2007 HPS for Jefferson West displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

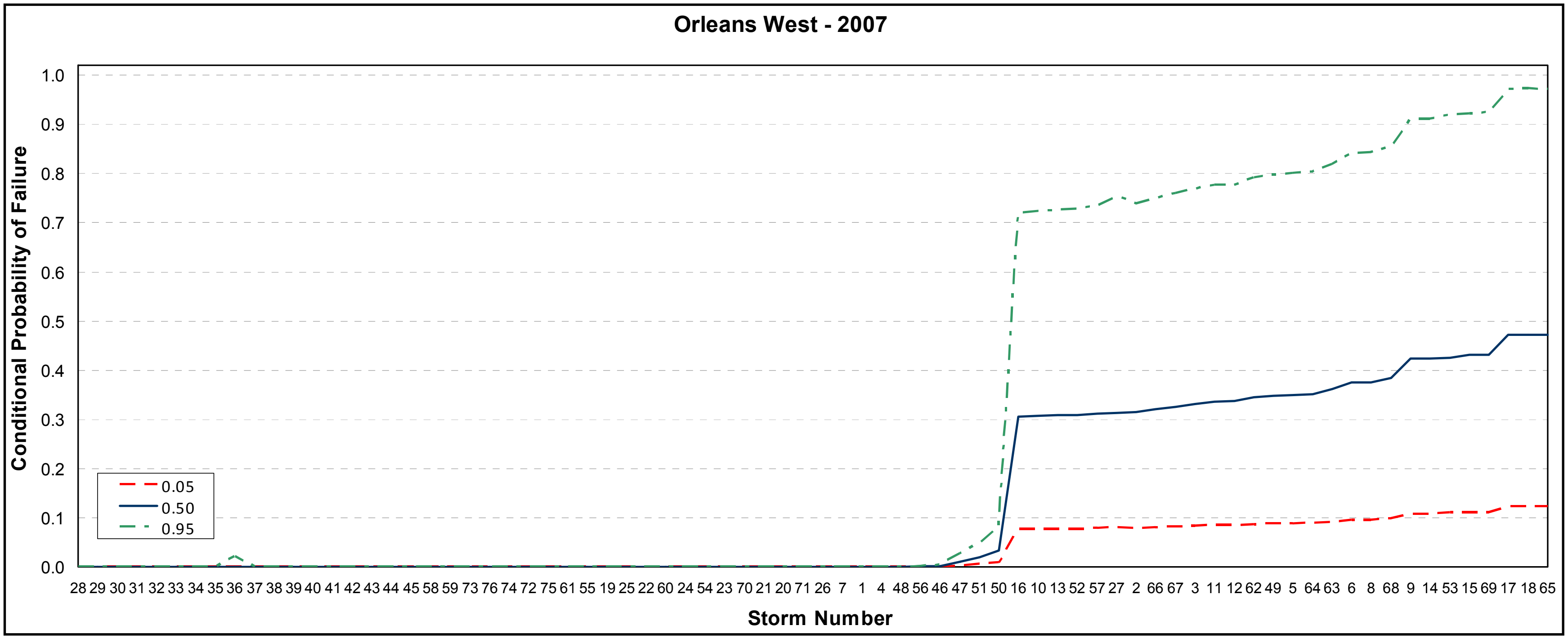

Figure 36. Uncertainty in the levee system fragility curves for the 2007 HPS for Orleans West displayed in terms of the 0.05, the 0.50 and the 0.95 fractile estimates of the conditional probability of failure as a function of the hurricane event. The fragility values are ranked with respect to the 0.50 fragility curve.

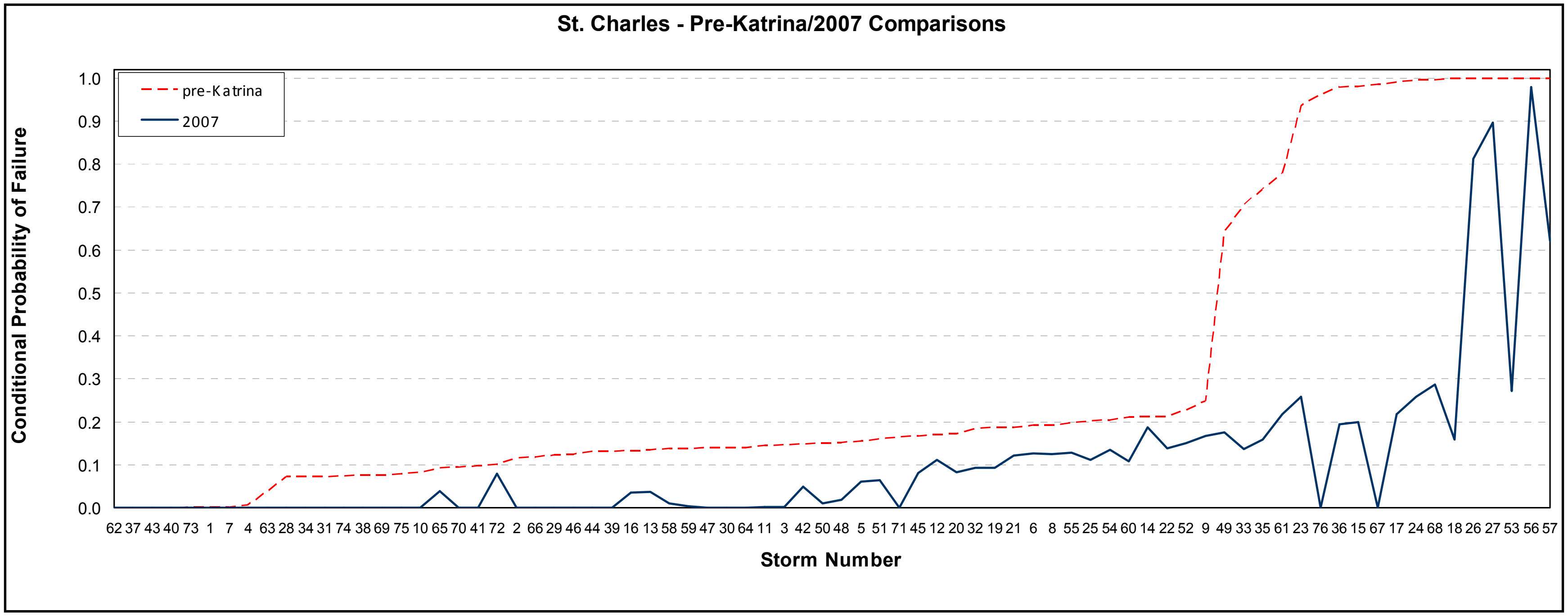

Figure 37. Comparison of the St. Charles levee system median fragility curve for the pre-Katrina and the 2007 system. The fragility values are ranked with respect to the pre-Katrina medina fragility curve.

Frequency of Levee System Failure

The hurricane hazard and levee system fragility results are combined to estimate the uncertainty in the frequency of system failure. The frequency of system failure is evaluated for the pre-Katrina and the 2007 NO HPS systems.

The frequency of levee system failure is estimated according to:

$$\nu_{Ls} = \sum_{i=1}^{m} P(L_s \mid h_i)\nu(h_i) \tag{11}$$

where,

$P(L_s \mid h_i)$ = levee system fragility for hurricane event h_i (see Equation 10)
$\nu(h_i)$ = frequency of occurrence of hurricane event i
m = number of hurricane events considered in the analysis

The probability distribution on the frequency of levee system failure is determined by applying Equation 11 for each of the LHS combinations of hurricane events and levee system fragility curves. The result is a set of levee system frequency of failure estimates (each with equal probability weight) that are used to generate the probability (uncertainty) distribution on the frequency of failure.

Pre-Katrina – Table 6 presents the results of the uncertainty analysis in estimating the frequency of system failure. For each basin the mean, standard deviation, ratio of the 0.95 to 0.05 levels of the uncertainty distribution and the 0.05, 0.15, 0.50, 0.85 and 0.95 levels are reported. Figure 38 shows the complimentary cumulative probability distribution on the frequency of levee system failure for each of the HPS basins.

Table 6. Pre-Katrina NO HPS Basin Frequency of Failure

Basin	Mean	Std Deviation	Ratio (0.95/0.05)	Fractiles				
				0.05	0.15	0.5	0.85	0.95
NOE	3.49E-02	1.27E-02	3.61	1.69E-02	2.24E-02	3.15E-02	4.64E-02	6.10E-02
JE	1.56E-02	7.82E-03	5.13	5.85E-03	9.04E-03	1.31E-02	2.43E-02	3.00E-02
SC	1.86E-02	1.45E-02	12.36	4.07E-03	6.52E-03	1.33E-02	3.29E-02	5.03E-02
OM	3.33E-02	1.28E-02	3.74	1.63E-02	2.04E-02	3.09E-02	4.46E-02	6.09E-02
SB	3.36E-02	1.37E-02	4.61	1.34E-02	1.86E-02	3.14E-02	4.65E-02	6.18E-02
PLN	5.47E-02	1.70E-02	2.79	3.02E-02	3.88E-02	5.19E-02	7.25E-02	8.44E-02
PLS	5.55E-02	1.71E-02	2.76	3.08E-02	3.96E-02	5.28E-02	7.39E-02	8.51E-02
JW	4.88E-02	1.58E-02	2.96	2.61E-02	3.36E-02	4.56E-02	6.45E-02	7.73E-02
OW	3.11E-02	1.42E-02	5.03	1.18E-02	1.73E-02	2.75E-02	4.57E-02	5.94E-02

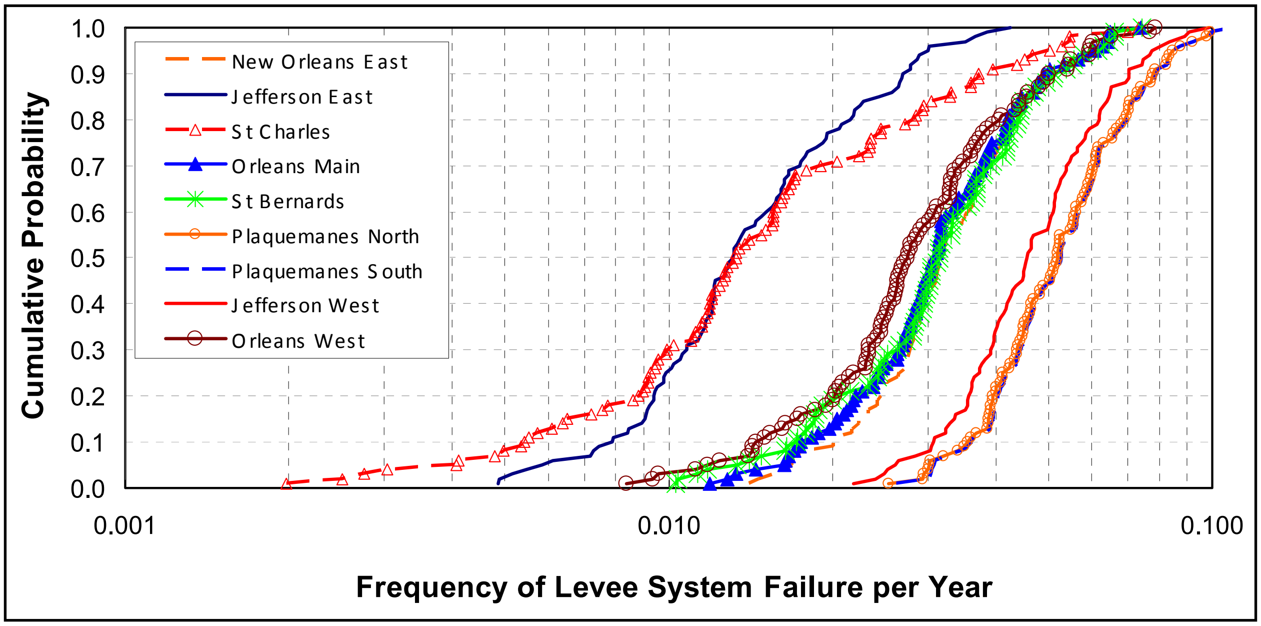

Figure 38. Probability distribution on the frequency of the pre-Katrina levee system failure for basins in New Orleans.

Referring to Table 6 the mean frequency of levee system failure for the NO HPS varies from 1.56×10^{-2} (Jefferson East) to 5.55×10^{-2} (Plaquemines South). Using the ratio of the 0.95 to 0.05 estimates of the frequency of failure as a measure of the range in the uncertainty in the frequency of failure estimates, results vary from approximately 2.8 to over 12 (St. Charles), with the majority of the results in the 2.8 to 5 range which is somewhat low. The wide range of the distribution for St. Charles is a function of a number of factors. For a system failure to occur, only one reach of the many that comprise a system must fail. For a given storm event, the performance of each levee reach provides an opportunity for the system to fail. As a result, with multiple reaches the conditional probability of failure rises sharply as the severity of storms increases. At the same time the uncertainty that the system might fail decreases. This can be seen in the case for NOE (see Figure 19). Once the median (0.50) fragility curve reaches a conditional probability of failure of 0.50, the uncertainty in the fragility begins to get smaller as the probability of system failure approaches 1.0; there is less uncertainty the system will fail. For St. Charles, there are only 3 reaches in the basin that have a significant conditional probability of failure (see Figure 14). The 3 reaches along the Mississippi River have a small chance of failure due to stability or as a result of overtopping (except at very high elevations) (see Figure 14). As a result there is considerable uncertainty in the levee system fragility (see Figure 21) over a large range of storms and thus large uncertainty in the conditional probability of failure and the frequency of failure (discussed later). This is also seen in the estimate of the relative contribution of the fragility uncertainty to the total uncertainty in the frequency of failure (discussed next).

The uncertainty results in Table 6 for the frequency of system failure provide a measure of the total uncertainty. Re-running the analysis using the mean estimate of the hurricane hazard and the uncertainty in the levee fragility only, provides a measure of the contribution of the uncertainty in the fragility to the uncertainty in frequency of failure. These results are presented in Table 7. The results in Tables 6 and 7 are combined to determine the relative contribution of the uncertainty in the levee fragility and the hurricane hazard to the total. The relative contributions are summarized in Table 8 for each basin.

Table 7. Pre-Katrina NO HPS Basin Frequency of Failure Results Considering Only the Uncertainty in Levee Fragility

Basin	Mean	Std Deviation	Ratio (0.95/0.05)	Fractiles				
				0.05	0.15	0.5	0.85	0.95
NOE	3.39E-02	4.25E-03	1.52	2.61E-02	2.61E-02	3.46E-02	3.97E-02	3.97E-02
JE	1.53E-02	4.24E-03	2.16	1.11E-02	1.11E-02	1.40E-02	2.40E-02	2.40E-02
SC	1.87E-02	1.17E-02	5.47	7.84E-03	7.84E-03	1.51E-02	4.29E-02	4.29E-02
OM	3.25E-02	5.30E-03	1.73	2.19E-02	2.19E-02	3.41E-02	3.78E-02	3.78E-02
SB	3.27E-02	7.44E-03	2.23	1.77E-02	1.77E-02	3.54E-02	3.94E-02	3.94E-02
PLN	5.47E-02	5.48E-03	1.37	4.37E-02	4.37E-02	5.66E-02	5.98E-02	5.98E-02
PLS	5.55E-02	5.26E-03	1.35	4.49E-02	4.49E-02	5.71E-02	6.06E-02	6.06E-02
JW	4.86E-02	5.45E-03	1.44	3.78E-02	3.78E-02	5.01E-02	5.44E-02	5.44E-02
OW	3.14E-02	8.60E-03	2.48	1.90E-02	1.90E-02	3.07E-02	4.71E-02	4.71E-02

Table 8. Pre-Katrina Fraction Contribution to the Total Uncertainty in the Frequency of Levee System Failure

Basin	Fragility	Hurricane
NOE	0.125	0.875
JE	0.330	0.670
SC	0.696	0.304
OM	0.190	0.810
SB	0.328	0.672
PLN	0.108	0.892
PLS	0.099	0.901
JW	0.125	0.875
OW	0.382	0.618

For each basin, with the exception of St. Charles, the uncertainty in the hurricane hazard is the primary contributor to the uncertainty in the frequency of levee system failure. For St. Charles the uncertainty in the levee fragility is a much greater contributor to the frequency of failure.

An additional insight to the contributors to levee system failure is the relative contribution of overtopping failure and stability (and other) failure modes to the frequency of failure. Table 9 summarizes for each basin the contribution of each mode of failure to the mean frequency of system failure. The contribution of different modes of failure is split into two groups. For 5 of the 9 basins, stability failures are the dominant contributors to the mean frequency of failure. For the remaining four basins, overtopping failures make the greatest contribution.

It was found that the Pre-Katrina levee system experienced overtopping and breach failures, not stability failures, during Hurricane Katrina. However, this was one event, while the data presented in Tables 8 and 9 represent the expected performance for many hurricane events.

However, the dominance of stability failures suggests that the fragility curves may benefit from further study and refinement, to ensure that they are reasonable.

Table 9. Pre-Katrina HPS – Contribution of Failure Modes to the Frequency of System Failure

Basin	Overtopping	Stability
NOE	0.407	0.593
JE	0.324	0.676
SC	0.452	0.548
OM	0.047	0.953
SB	0.102	0.898
PLN	0.580	0.420
PLS	0.571	0.429
JW	0.684	0.316
OW	0.550	0.450

2007 HPS System – Table 10 presents the results for the frequency of levee system failure for the 2007 HPS system. Figure 39 shows the associated complimentary cumulative probability distribution functions on the frequency of system failure for each basin.

Table 10. 2007 NO HPS Basin Frequency of Failure

Basin	Mean	Std Deviation	Ratio (0.95/0.05)	Fractiles				
				0.05	0.15	0.5	0.85	0.95
NOE	3.06E-02	1.17E-02	3.83	1.43E-02	1.87E-02	2.81E-02	4.15E-02	5.47E-02
JE	8.46E-03	4.57E-03	6.36	2.47E-03	4.57E-03	6.91E-03	1.36E-02	1.57E-02
SC	8.48E-03	8.41E-03	30.25	9.09E-04	2.14E-03	5.32E-03	1.58E-02	2.75E-02
OM	2.81E-02	1.23E-02	5.10	1.05E-02	1.42E-02	2.60E-02	4.04E-02	5.36E-02
SB	2.81E-02	1.21E-02	4.98	1.07E-02	1.58E-02	2.59E-02	4.01E-02	5.33E-02
PLN	3.90E-02	1.37E-02	3.21	2.05E-02	2.45E-02	3.62E-02	5.22E-02	6.58E-02
PLS	4.33E-02	1.47E-02	3.10	2.30E-02	2.86E-02	4.04E-02	5.71E-02	7.12E-02
JW	4.22E-02	1.51E-02	3.08	2.15E-02	2.51E-02	4.01E-02	5.80E-02	6.63E-02
OW	9.37E-03	6.48E-03	13.51	1.71E-03	2.74E-03	7.56E-03	1.56E-02	2.31E-02

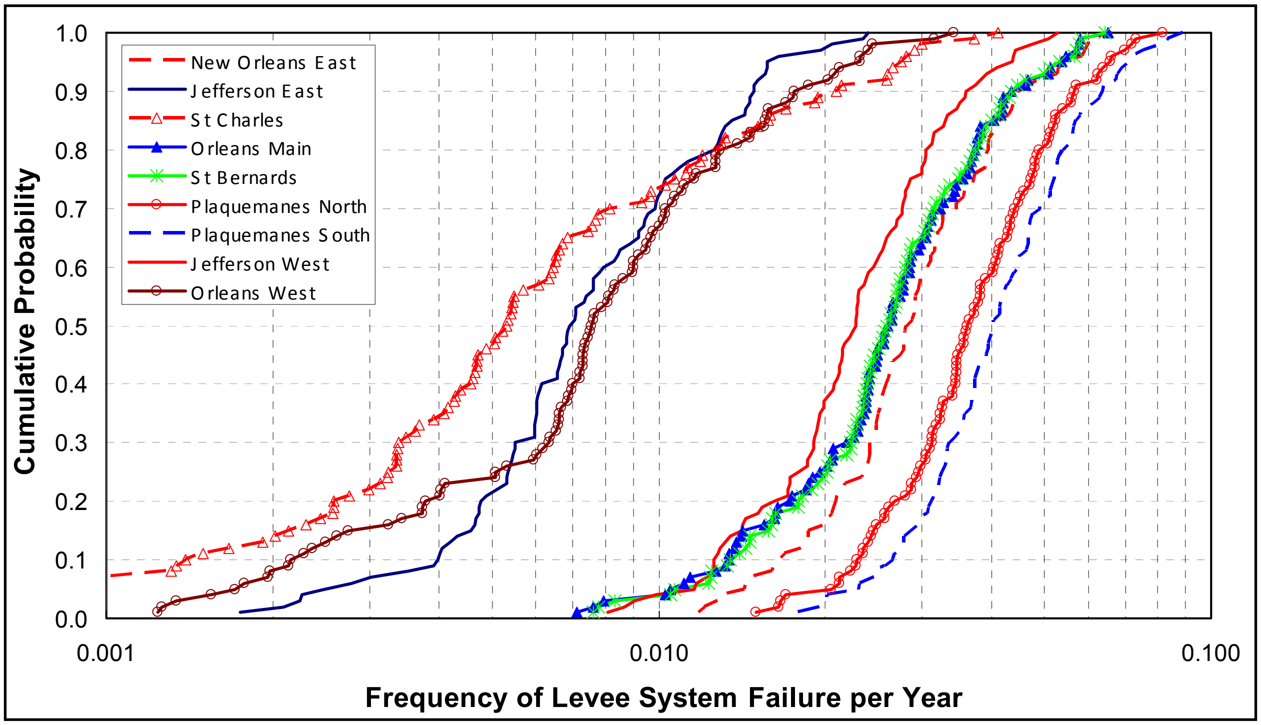

Figure 39. Probability distribution on the frequency of the 2007 levee system failure for basins in New Orleans.

To estimate the relative contribution of the fragility and hurricane hazard to the uncertainty in the frequency of system failure, the analysis was re-run using the mean estimate of the hurricane hazard and the uncertainty in the levee fragility only. These results are presented in Table 11. The results in Tables 10 and 11 are combined to determine the relative contribution of the uncertainty in the levee fragility and the hurricane hazard to the total. The relative contributions are summarized in Table 12 for each basin.

Table 11. 2007 NO HPS Basin Frequency of Failure Results Considering Only the Uncertainty in Levee Fragility

Basin	Mean	Std Deviation	Ratio (0.95/0.05)	Fractiles				
				0.05	0.15	0.5	0.85	0.95
NOE	3.07E-02	4.42E-03	1.62	2.21E-02	2.21E-02	3.19E-02	3.58E-02	3.58E-02
JE	8.35E-03	2.28E-03	2.36	5.39E-03	5.39E-03	7.99E-03	1.27E-02	1.27E-02
SC	8.23E-03	7.28E-03	12.79	1.83E-03	1.83E-03	5.82E-03	2.34E-02	2.34E-02
OM	2.78E-02	6.81E-03	2.41	1.40E-02	1.40E-02	3.02E-02	3.37E-02	3.37E-02
SB	2.80E-02	6.26E-03	2.21	1.57E-02	1.57E-02	2.98E-02	3.47E-02	3.47E-02
PLN	3.89E-02	6.10E-03	1.66	2.65E-02	2.65E-02	4.12E-02	4.39E-02	4.39E-02
PLS	4.32E-02	5.92E-03	1.58	3.16E-02	3.16E-02	4.48E-02	4.98E-02	4.98E-02
JW	4.20E-02	8.13E-03	1.95	2.61E-02	2.61E-02	4.43E-02	5.10E-02	5.10E-02
OW	9.23E-03	5.32E-03	8.43	2.30E-03	2.30E-03	8.40E-03	1.94E-02	1.94E-02

Table 12. 2007 Fraction Contribution to the Total Uncertainty in the Frequency of Levee System Failure

Basin	Fragility	Hurricane
NOE	0.150	0.850
JE	0.281	0.719
SC	0.844	0.156
OM	0.332	0.668
SB	0.287	0.713
PLN	0.209	0.791
PLS	0.171	0.829
JW	0.287	0.713
OW	0.734	0.266

As was the case for the pre-Katrina system, the uncertainty in the hurricane hazard is the primary contributor to the uncertainty in the frequency of levee system failure. However, for the upgraded system, the relative contribution of the uncertainty in the levee fragility is slightly higher than it was in the pre-Katrina case. In the case of St. Charles and Orleans West, the uncertainty in the levee fragility is the greater contributor to the uncertainty.

Table 13 shows the contribution of the different failure modes to the frequency of failure for the upgraded 2007 system. A review of the table shows that stability failures, compared with overtopping failures, are dominant for all basins. In addition, the relative contribution has increased as compared to the pre-Katrina case. The lowest relative contribution of stability failures is 0.72.

Table 13. 2007 HPS – Contribution of Failure Modes to the Frequency of Levee System Failure

Basin	Overtopping	Stability
NOE	0.231	0.769
JE	0.060	0.940
SC	0.267	0.733
OM	0.166	0.834
SB	0.219	0.781
PLN	0.233	0.767
PLS	0.279	0.721
JW	0.177	0.823
OW	0.047	0.953

Pre-Katrina – 2007 HPS Comparison – Table 14 shows a comparison of the levee system mean frequency of failure results for the pre-Katrina and 2007 systems. The frequency of failure has decreased for all basins. For New Orleans East the improvement is small, about 12 percent, while for Orleans West there is over a factor of 3 reduction in the frequency of failure. There is also considerable improvement (about a factor of 2 or more) for Jefferson East and St. Charles.

Table 14. Comparison Pre-Katrina and the 2007 HPS System Mean Frequency of Levee System Failure

Basin	Mean Frequency of Failure		Ratio (2007/Pre-K)
	Pre-Katrina	2007	
NOE	3.49E-02	3.06E-02	0.88
JE	1.56E-02	8.46E-03	0.54
SC	1.86E-02	8.48E-03	0.46
OM	3.33E-02	2.81E-02	0.84
SB	3.36E-02	2.81E-02	0.84
PLN	5.47E-02	3.90E-02	0.71
PLS	5.55E-02	4.33E-02	0.78
JW	4.88E-02	4.22E-02	0.87
OW	3.11E-02	9.37E-03	0.30

Table 15 compares the uncertainty in the frequency of failure estimates (in terms of the logarithmic standard deviation) and the relative contribution of the fragility and hurricane hazard uncertainty to the total uncertainty for the pre-Katrina and the 2007 levee systems. Accompanying the decrease in the frequency of failure (see Table 14) is an increase in the total uncertainty. Further, the increase in uncertainty is greatest for the basins that have the largest decrease in the mean frequency of failure (St. Charles and Orleans West). This consequence is attributed to the fact there is greater uncertainty in the hurricane hazard estimates for larger storms, higher surge elevations, which are required to cause levee failures for the upgraded system (see the hurricane hazard curves in Appendix A).

Table 15. Comparison Pre-Katrina and the 2007 HPS System Uncertainty in the Frequency of Levee System Failure

Basin	Logarithmic Standard Deviation on the Frequency of Failure		Contribution to the Total Uncertainty			
			Pre-Katrina		2007	
	Pre-Katrina	2007	Fragility	Hurricane	Fragility	Hurricane
NOE	0.353	0.369	0.125	0.875	0.150	0.850
JE	0.473	0.506	0.330	0.670	0.281	0.719
SC	0.689	0.828	0.696	0.304	0.844	0.156
OM	0.371	0.419	0.190	0.810	0.332	0.668
SB	0.392	0.412	0.328	0.672	0.287	0.713
PLN	0.304	0.341	0.108	0.892	0.209	0.791
PLS	0.301	0.330	0.099	0.901	0.171	0.829
JW	0.316	0.347	0.125	0.875	0.287	0.713
OW	0.435	0.625	0.382	0.618	0.734	0.266

Table 15 also shows the relative contribution of the fragility and hurricane hazard uncertainty to the total uncertainty in the estimate of the frequency of failure. Comparing the results for the two systems, the relative contribution of the levee fragility generally increases. The largest change is for Orleans West, where the levee fragility uncertainty is the primary contributor to the total uncertainty (similar to St. Charles for the pre-Katrina and 2007 systems). Orleans West also had the largest decrease in the mean frequency of failure (over a factor of 3) and the largest increase in the total uncertainty (a 44 percent increase in the logarithmic standard deviation).

New Orleans 100-Year Flooding Uncertainty

The assessment of the uncertainty in the 100-year flood elevation level for the pre-Katrina system was evaluated for four basins; Jefferson East, Orleans Main, St. Charles, and St. Bernard. For each sequence in a basin event tree the volume of water that enters a basin as a result of levee failure or overtopping as a result of each hurricane was determined. These results, along with the uncertainty in the hurricane events and the levee and floodwall fragility are combined to determine the frequency distribution on basin inundation. This result was then used to determine the one-standard deviation uncertainty in the estimated depth of the 100-year flooding level. Estimates of the flood inundation uncertainty are determined for the pre-Katrina system only. These results for the four basins analyzed are given in Table 16. The one standard deviation uncertainty ranges from approximately 3 to 6 feet. This uncertainty reflects:

- The uncertainty in the storm surge levels that result in levee failure, which can vary more than 2 feet at a given frequency of exceedance (i.e., annual frequency of exceedance of 10^{-2}; see Appendix A).
- Uncertainty in the frequency of occurrence of sequences (combinations of different levee reach breaches) that result in basin inundation.

Table 16. Uncertainty in the Estimate of the 100-year Flood Depth

Basin	Standard Deviation
Jefferson East	4.7
Orleans Main	4.7
St. Bernard	6.2
St. Charles	3.1

Observations

From the results of the uncertainty analysis of the performance of the hurricane protection system and basin inundation, the following observations are made:

- The uncertainty in the levee fragility and the hurricane hazard analysis contribute considerable uncertainty to the estimate of the 100-year basin flood depths determined using the event tree model developed for the uncertainty analysis.

- Estimates of the uncertainty in the 100-year basin flood depths vary from approximately 3 to 6 feet. The inundation levels in the actual risk model would be expected to have similar uncertainty.

- For most basins, the primary contributor to the uncertainty in the frequency of failure is the uncertainty in the hurricane hazard for the pre-Katrina and the 2007 levee systems.

- For the pre-Katrina system, the stability failure of levees and floodwalls is the primary contributor to system failure in 5 of the 9 basins. For the 2007 system, stability failures are the primary contributor to the frequency of failure for all basins.

- The 2007 HPS has improved reliability and a lower frequency of failure for all basins. Reductions in the frequency of failure vary from 12 percent to over a factor of 3.

- For 3 basins (Jefferson East, St. Charles, and Orleans West) the 2007 system provides slightly better than 100-year flood protection (the mean frequency of system failure due to levee or floodwall failure only) is less than 10^{-2} per year. This result does not take into account other factors that might contribute to system failure (i.e. gate closures, etc.) that were not considered in this analysis.

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DeGroot, D. (2006). "Analyzing spatial variability of in situ soil properties," *Uncertainty in the Geological Environment*, ASCE Congress, Madison v2, pp. 21-238.

Efron, B. (1982). *The Jacknife, the Bootstrap, and other Resampling Plans*, Society for Industrial and Applied Mathematics, Philadelphia.

Holland, G. J. (1980). "An analytic model of the wind and pressure profiles in hurricanes," *Monthly Weather Review*, v108, pp. 1212-1218.

Niedoroda, A., D. Resio, G. Toro, D. Divoky, H. Das, and C. Reed (2007). "Evaluation of the Storm Surge Hazard in Coastal Mississippi," *Proceedings of the 10th International Workshop on Wave Hindcasting and Forecasting and Coastal Hazards*, Honolulu, Hawaii.

Pearson and Tukey (1965). "Approximate Means and Standard Deviations Based on Distances between Percentage Points of Frequency Curves," *Biometrika*, Vol. 52, No. 3/4, pp. 533-546.

Resio, D. (2008). E-mail from D. Resio to M.W. McCann regarding the modeling error in hurricane surge predictions.

Appendix A
Hurricane Hazard Uncertainty Results

The following pages present results of the hurricane hazard uncertainty analysis for selected reaches for basins in New Orleans.

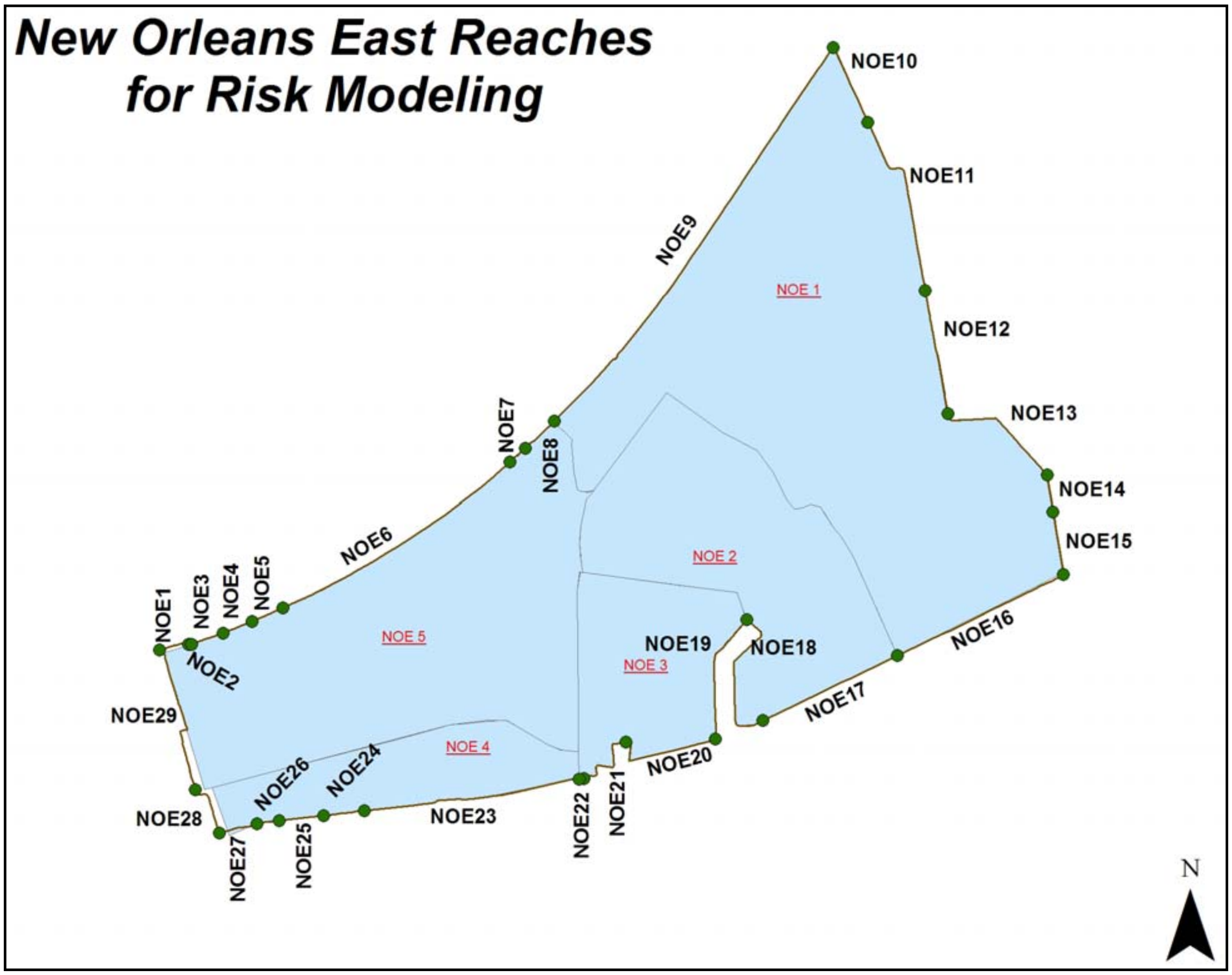

Figure A-1. Map showing the New Orleans reaches modeled in the risk analysis.

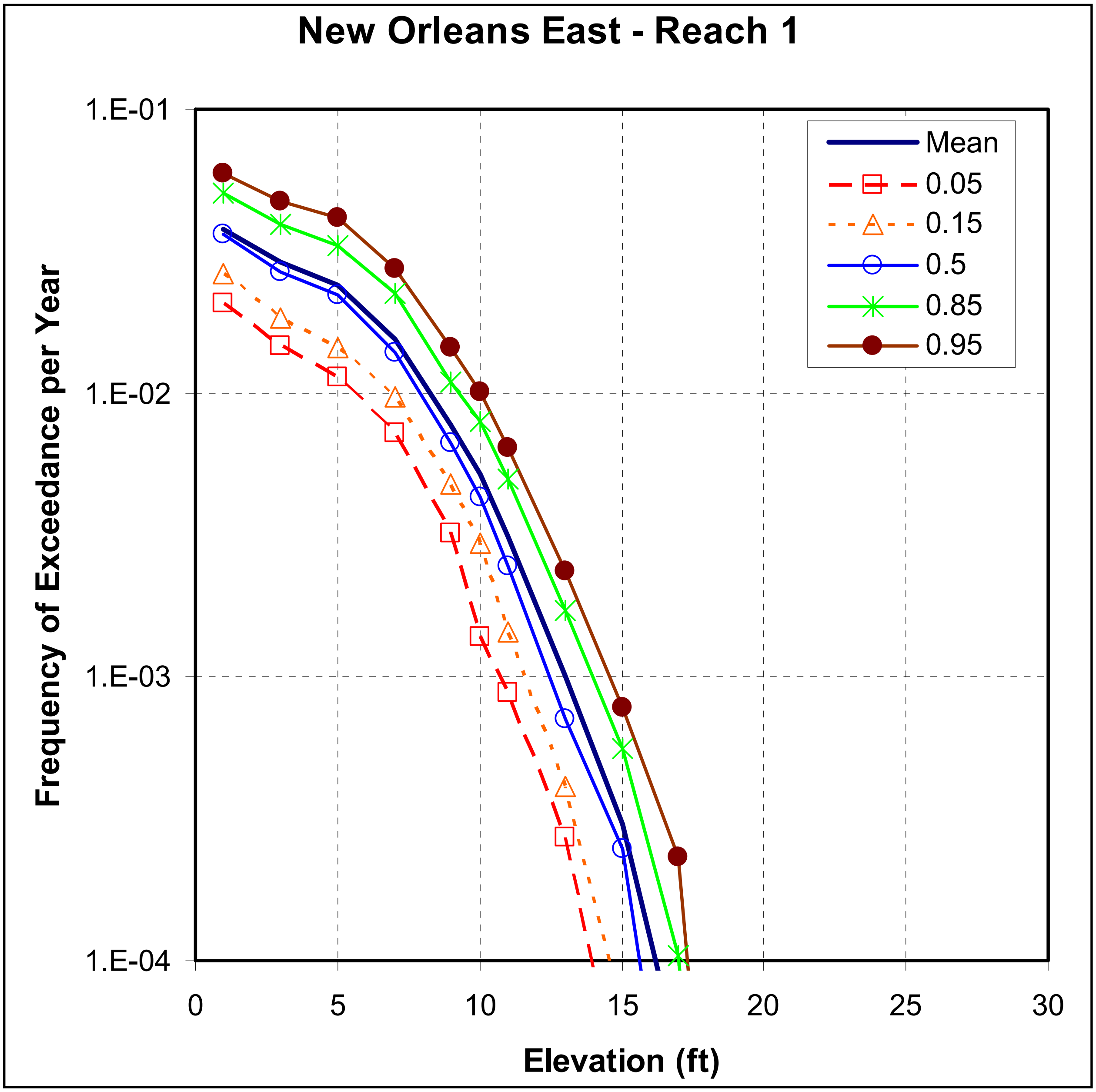

Figure A-2. Hurricane hazard curves for New Orleans reach 1.

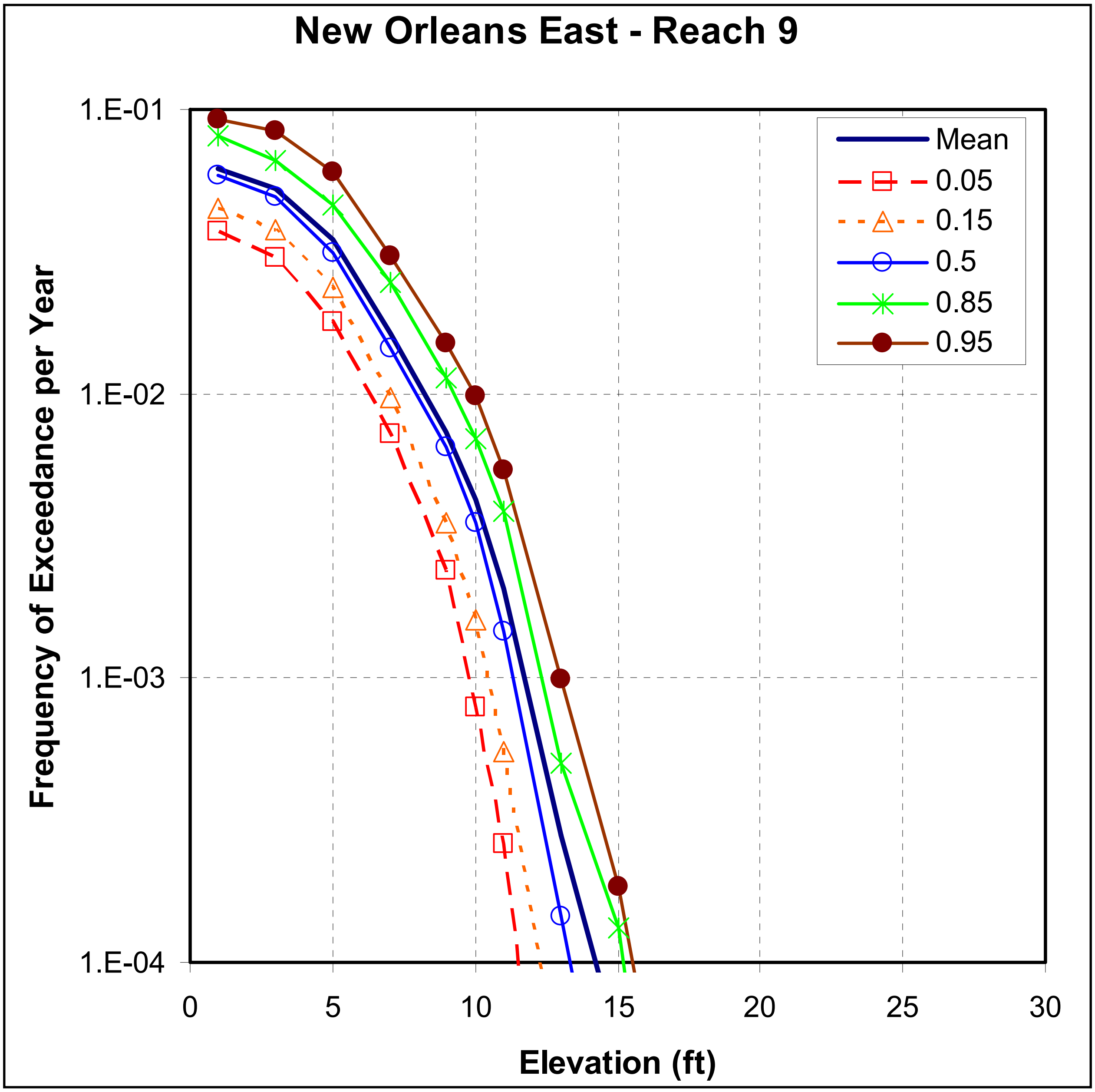

Figure A-3. Hurricane hazard curves for New Orleans reach 9.

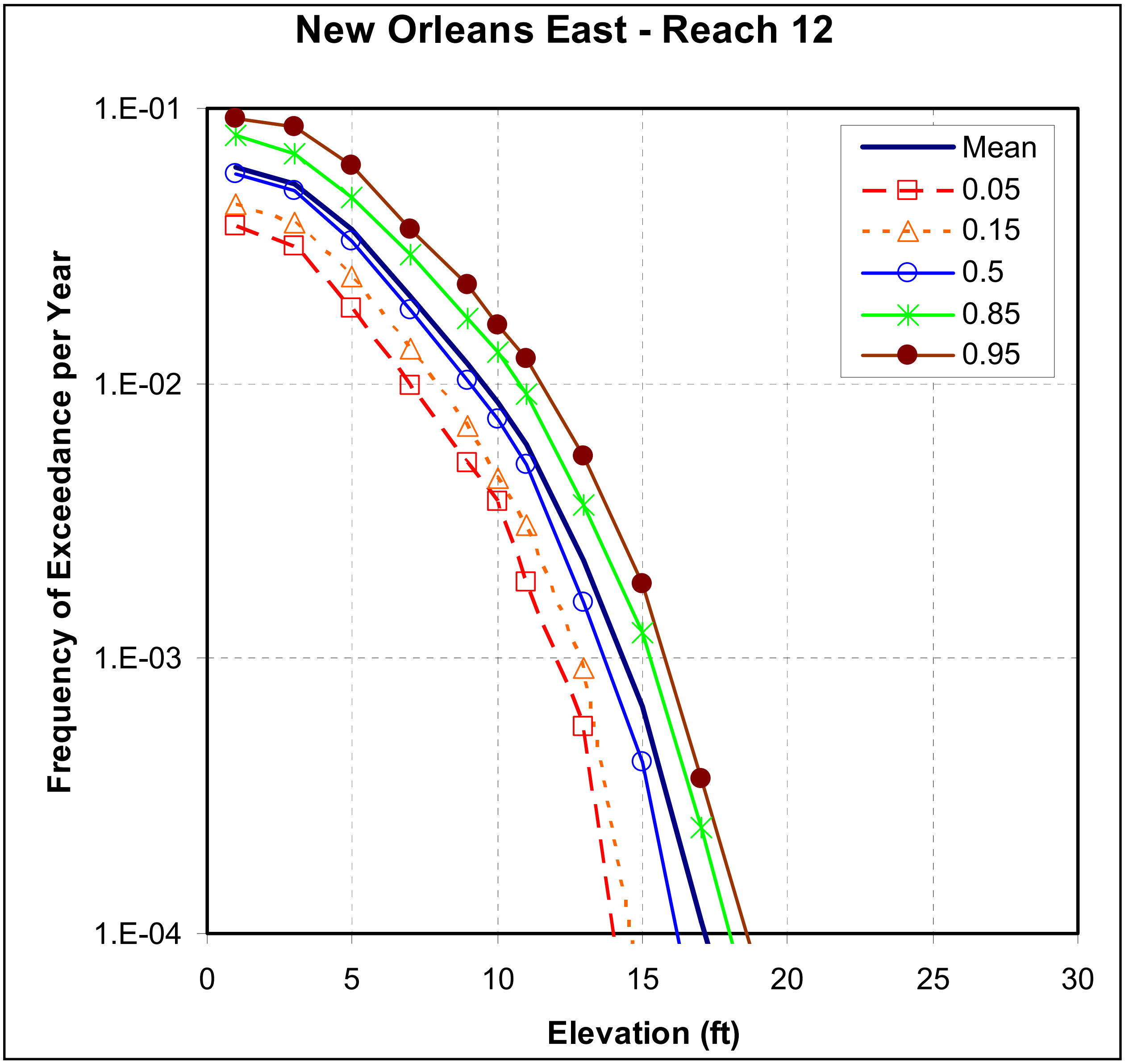

Figure A-4. Hurricane hazard curves for New Orleans reach 12.

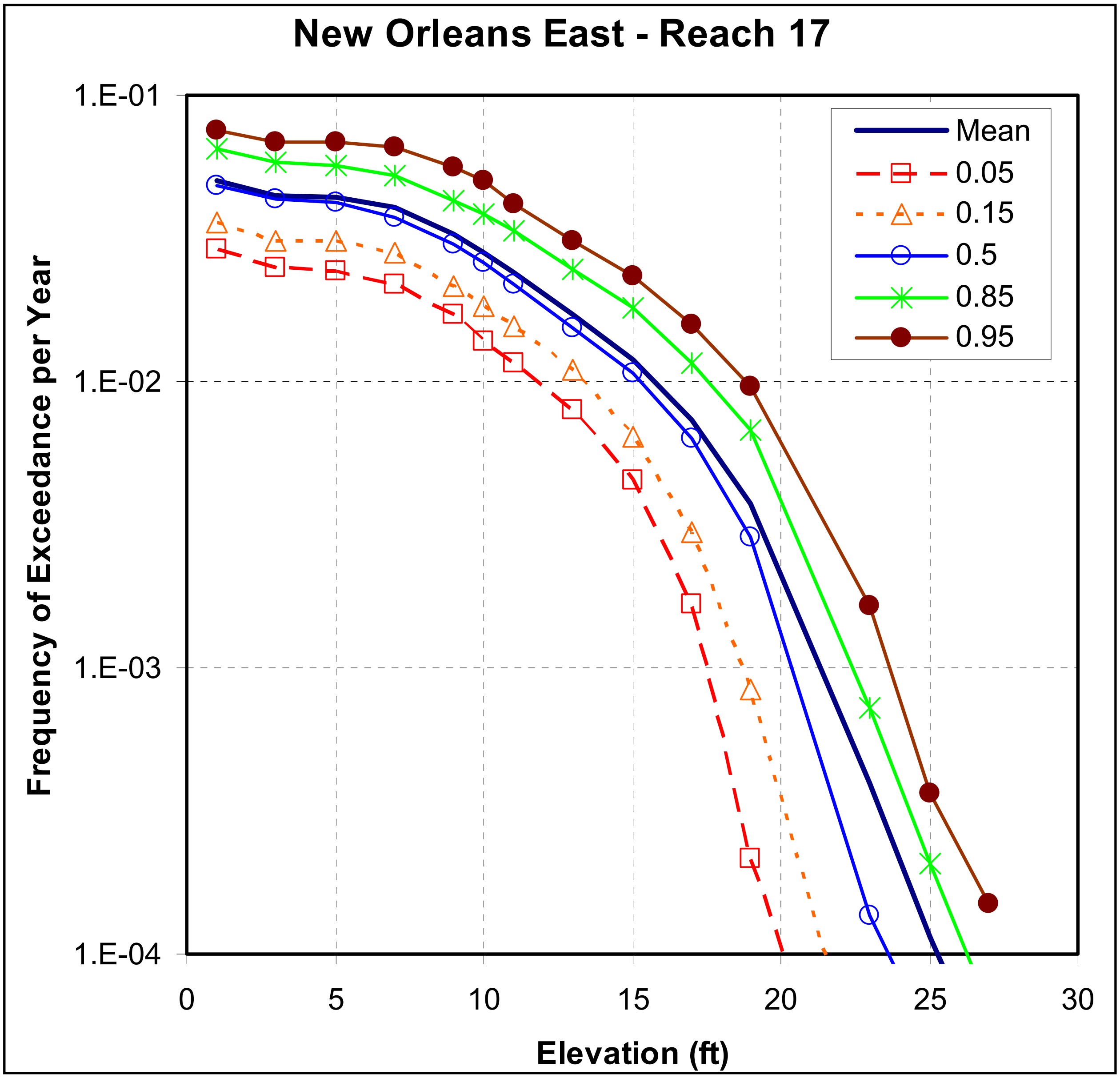

Figure A-5. Hurricane hazard curves for New Orleans reach 17.

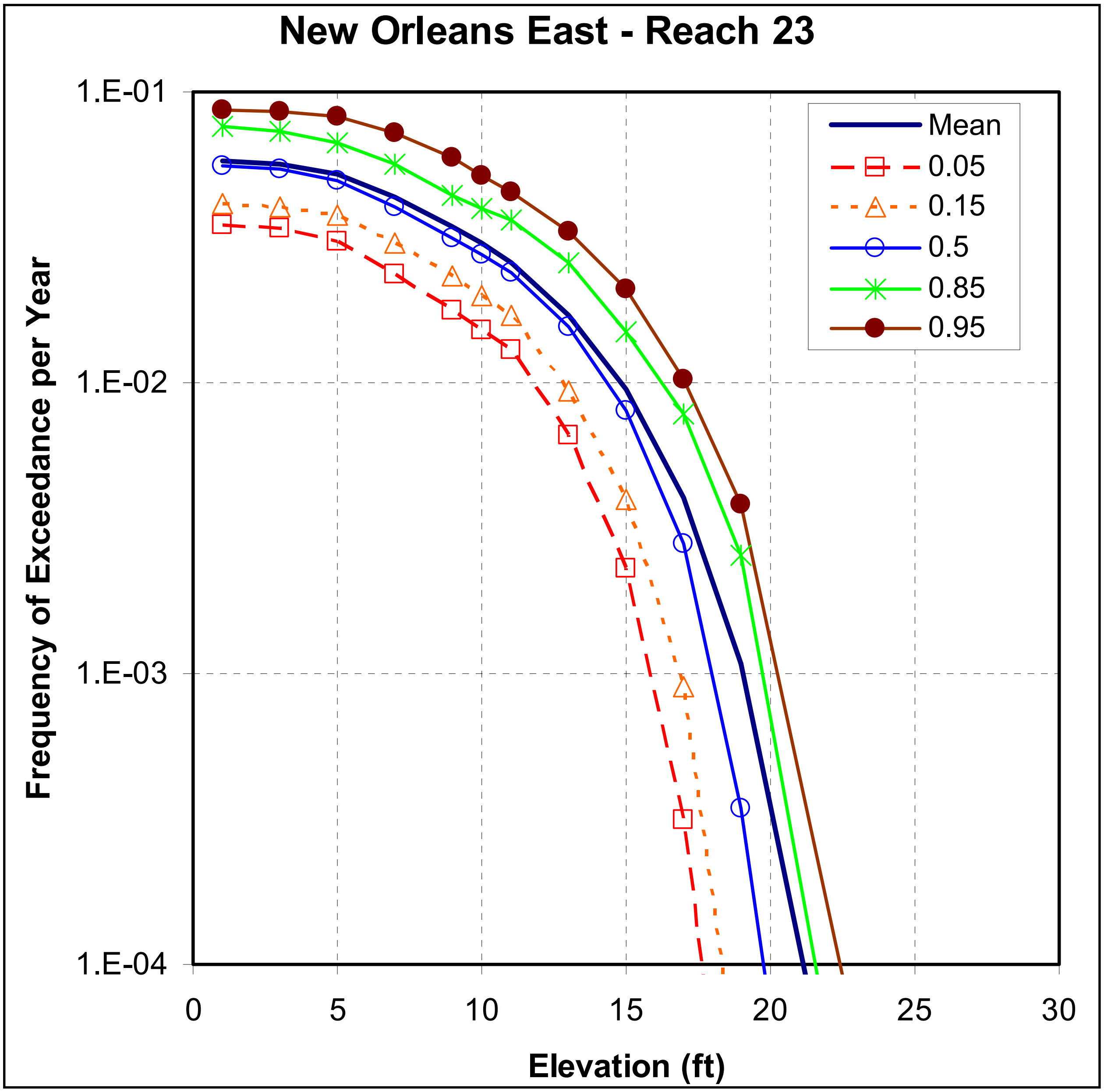

Figure A-6. Hurricane hazard curves for New Orleans reach 23.

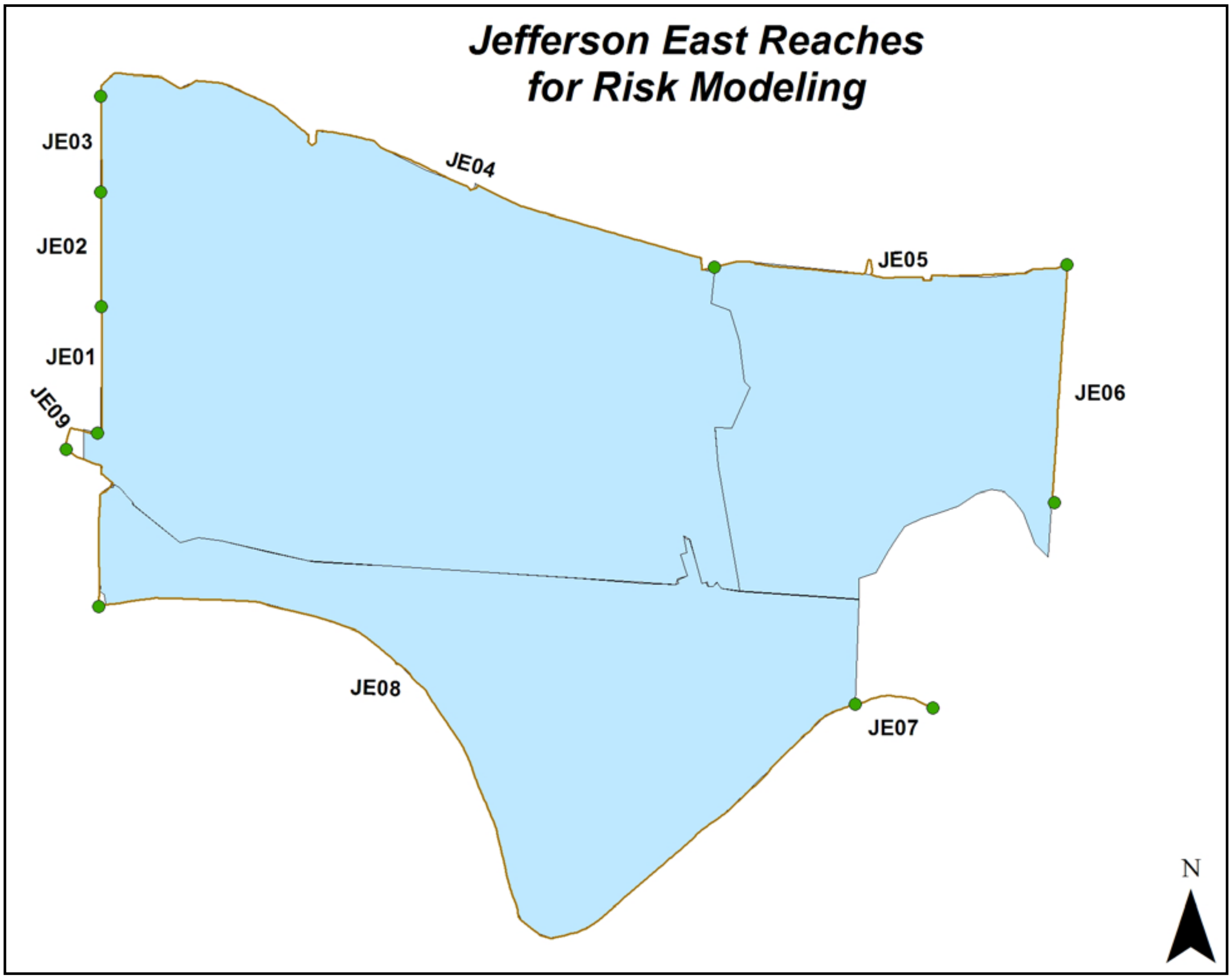

Figure A-7. Map showing the Jefferson East reaches modeled in the risk analysis.

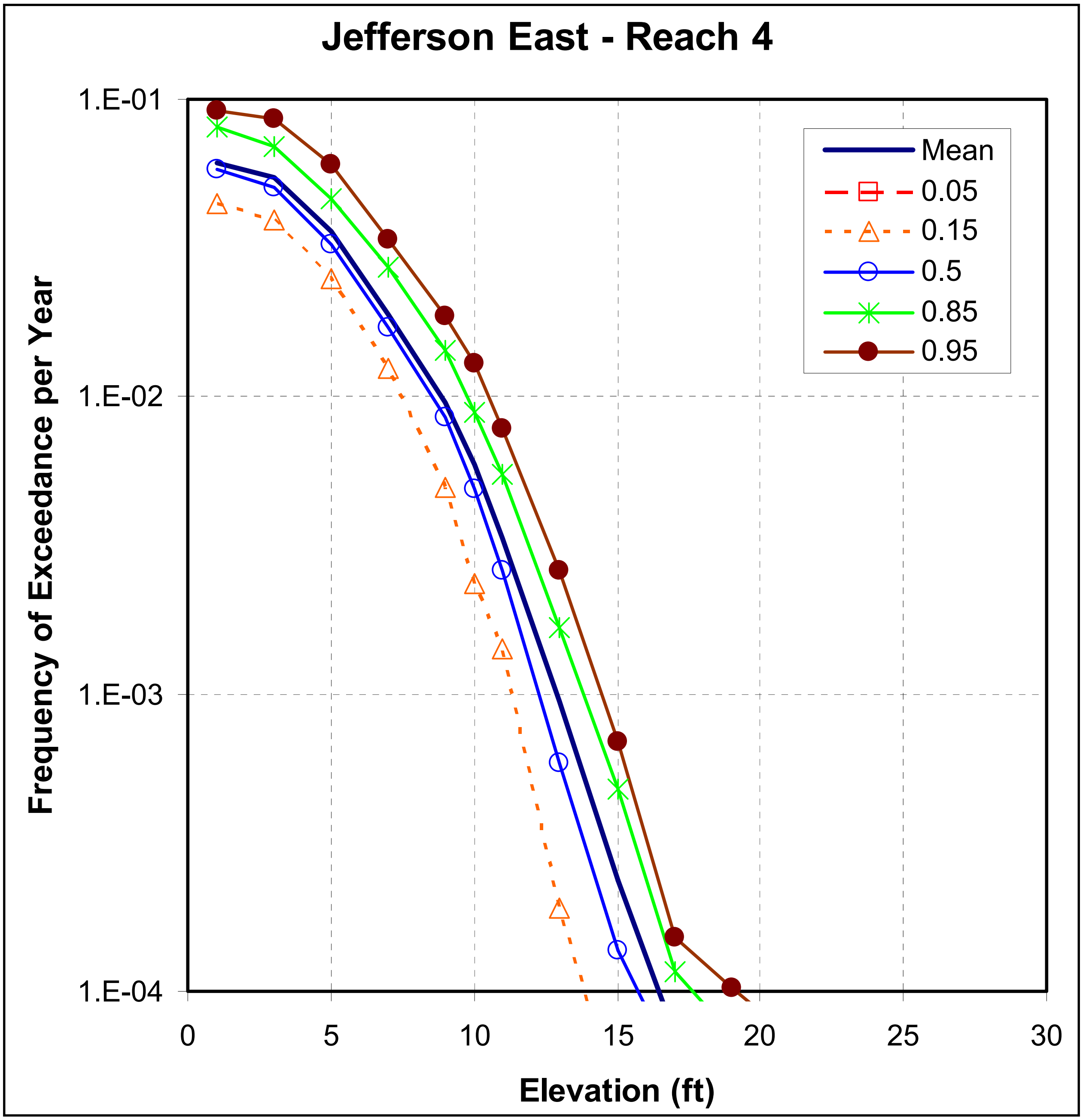

Figure A-8. Hurricane hazard curves for Jefferson East reach 4.

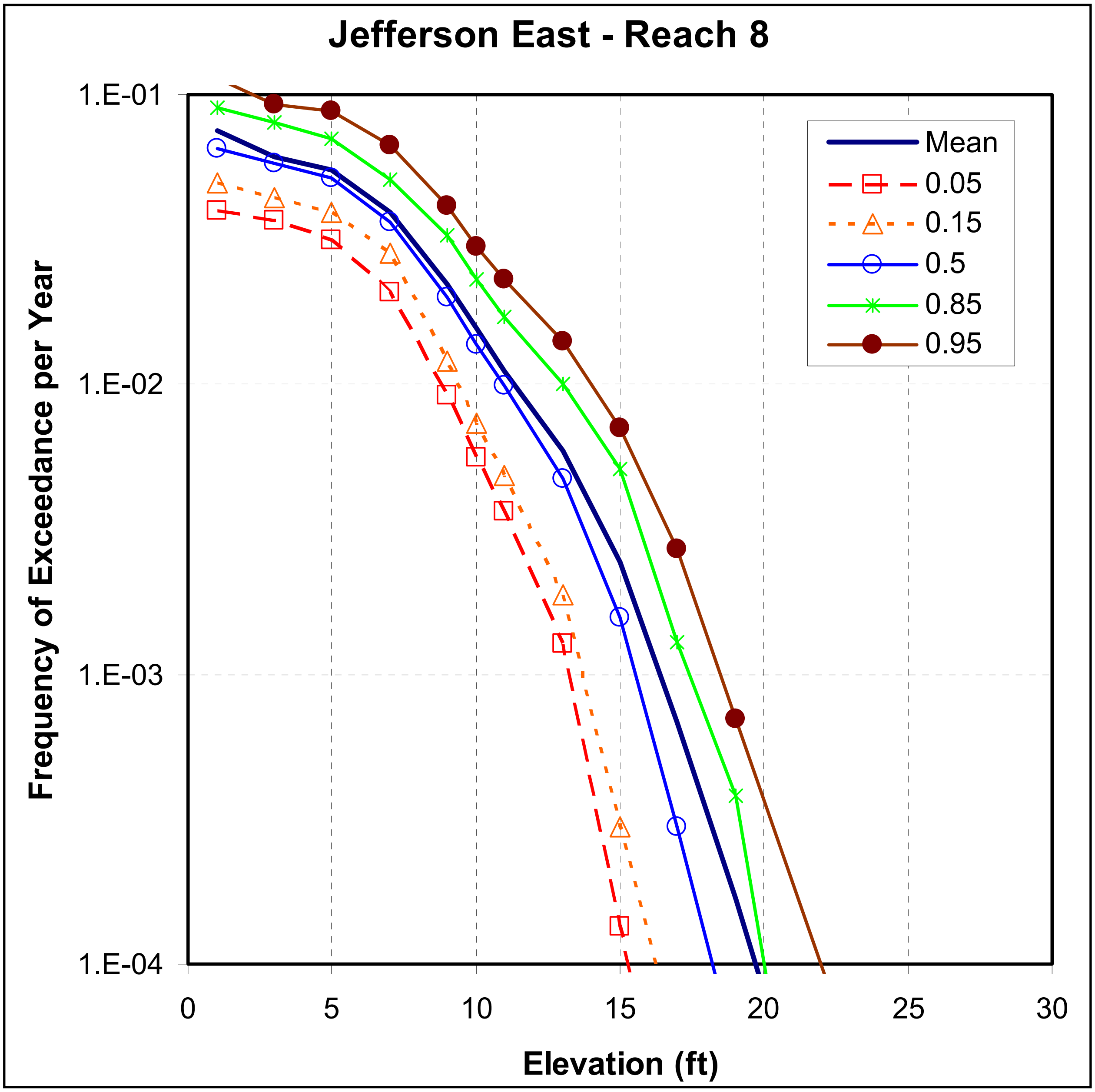

Figure A-9. Hurricane hazard curves for Jefferson East reach 8.

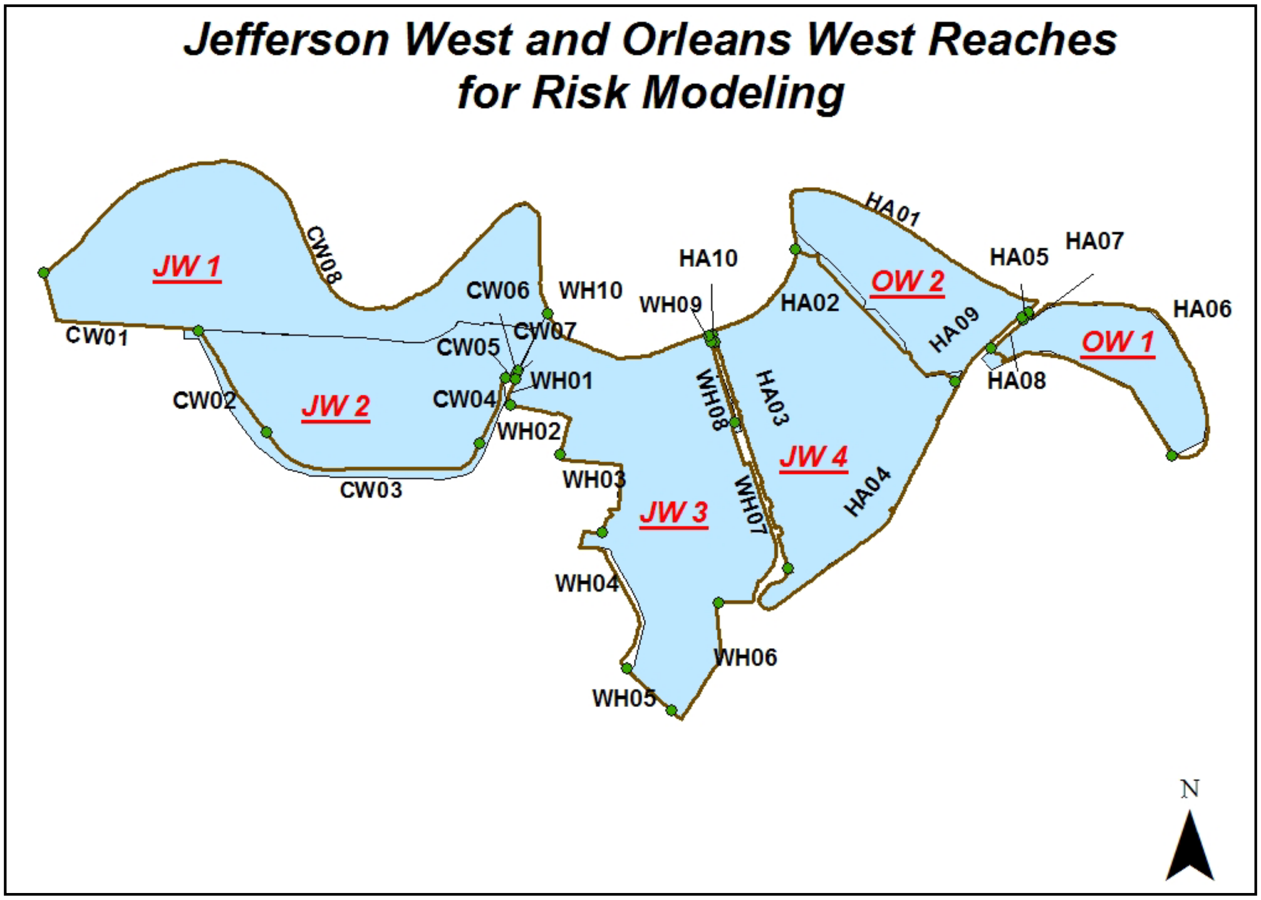

Figure A-10. Map showing the west bank reaches modeled in the risk analysis.

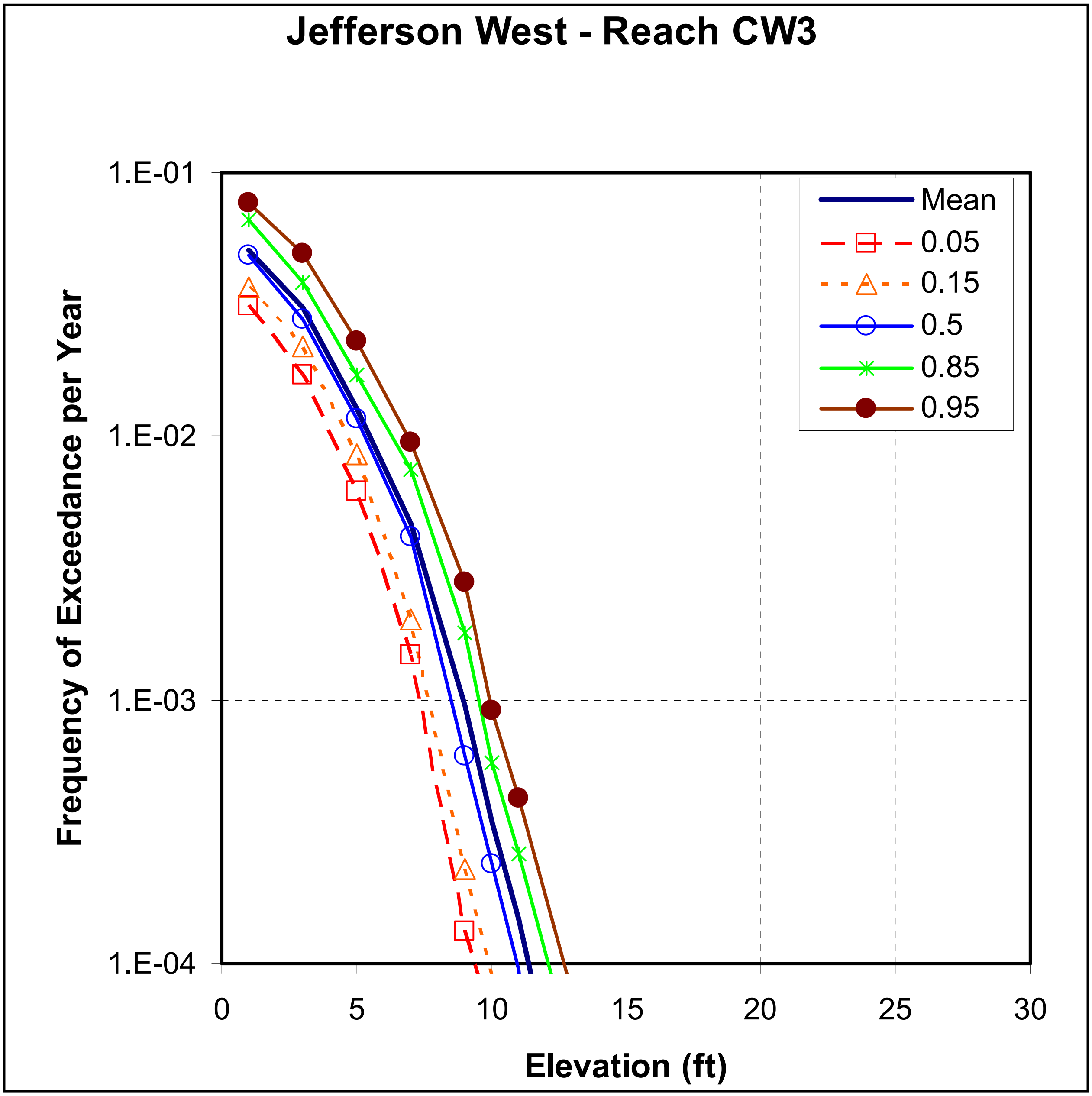

Figure A-11. Hurricane hazard curves for Jefferson West reach CW3.

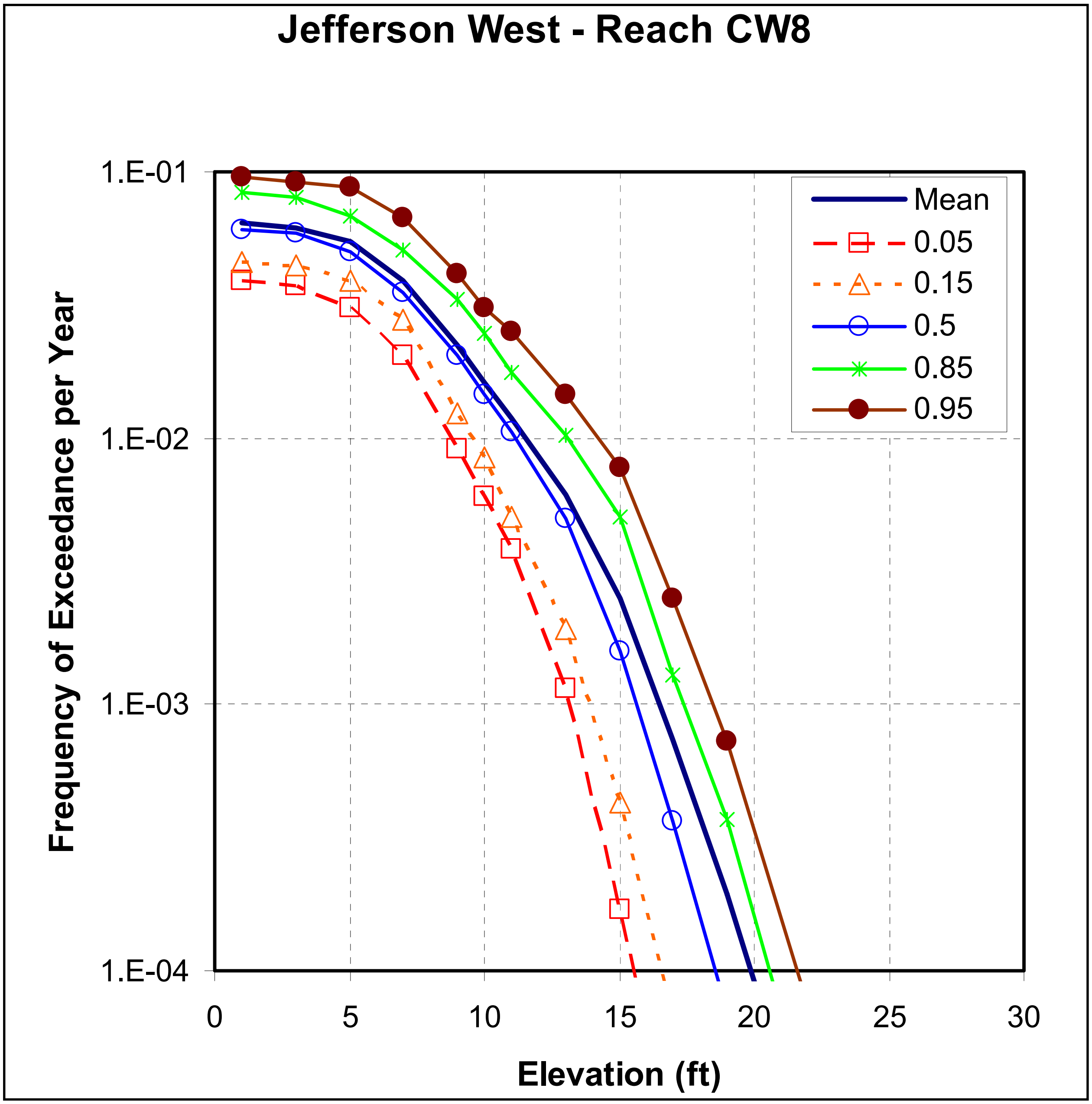

Figure A-12. Hurricane hazard curves for Jefferson West reach CW8.

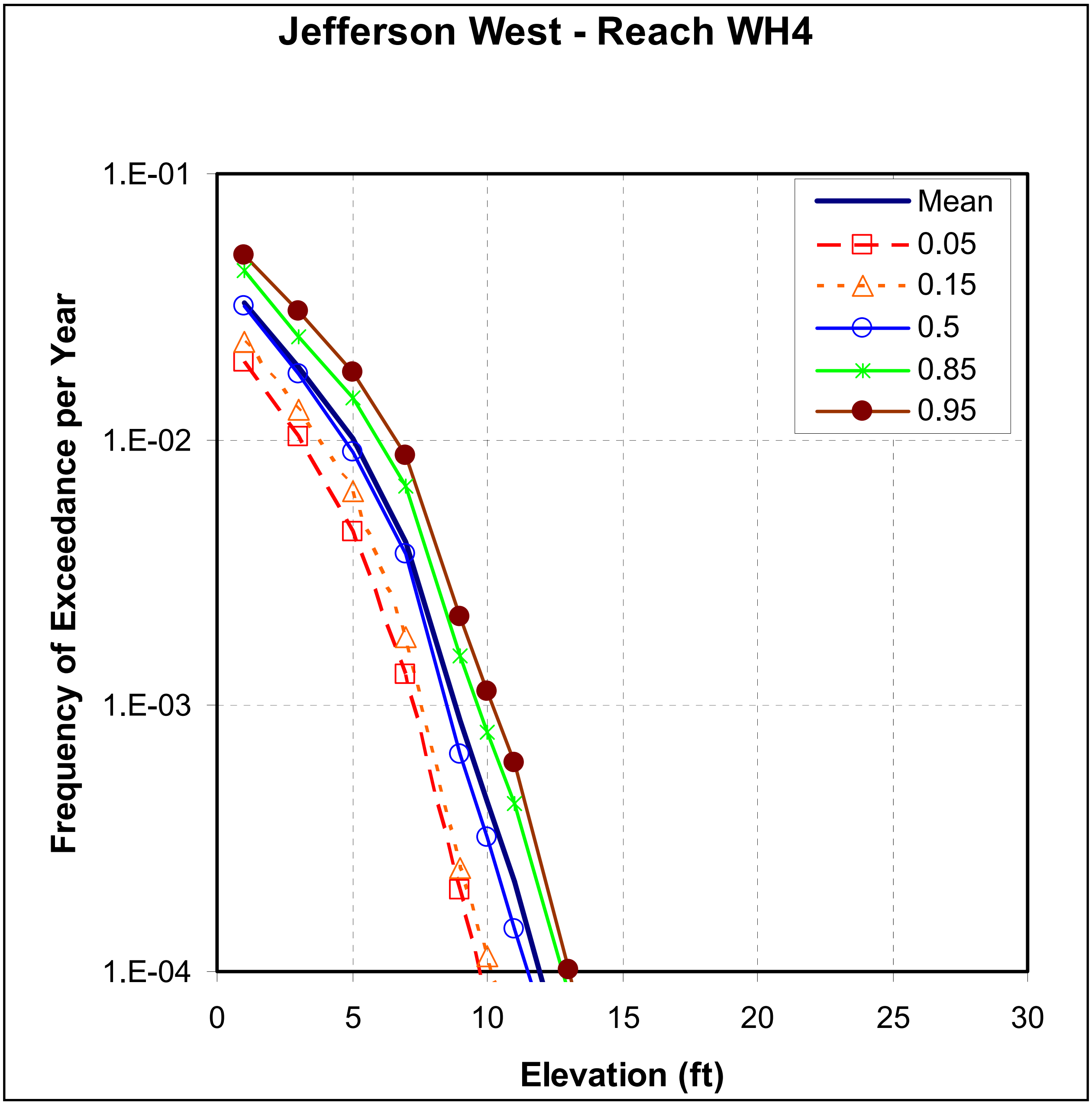

Figure A-13. Hurricane hazard curves for Jefferson West reach WH4.

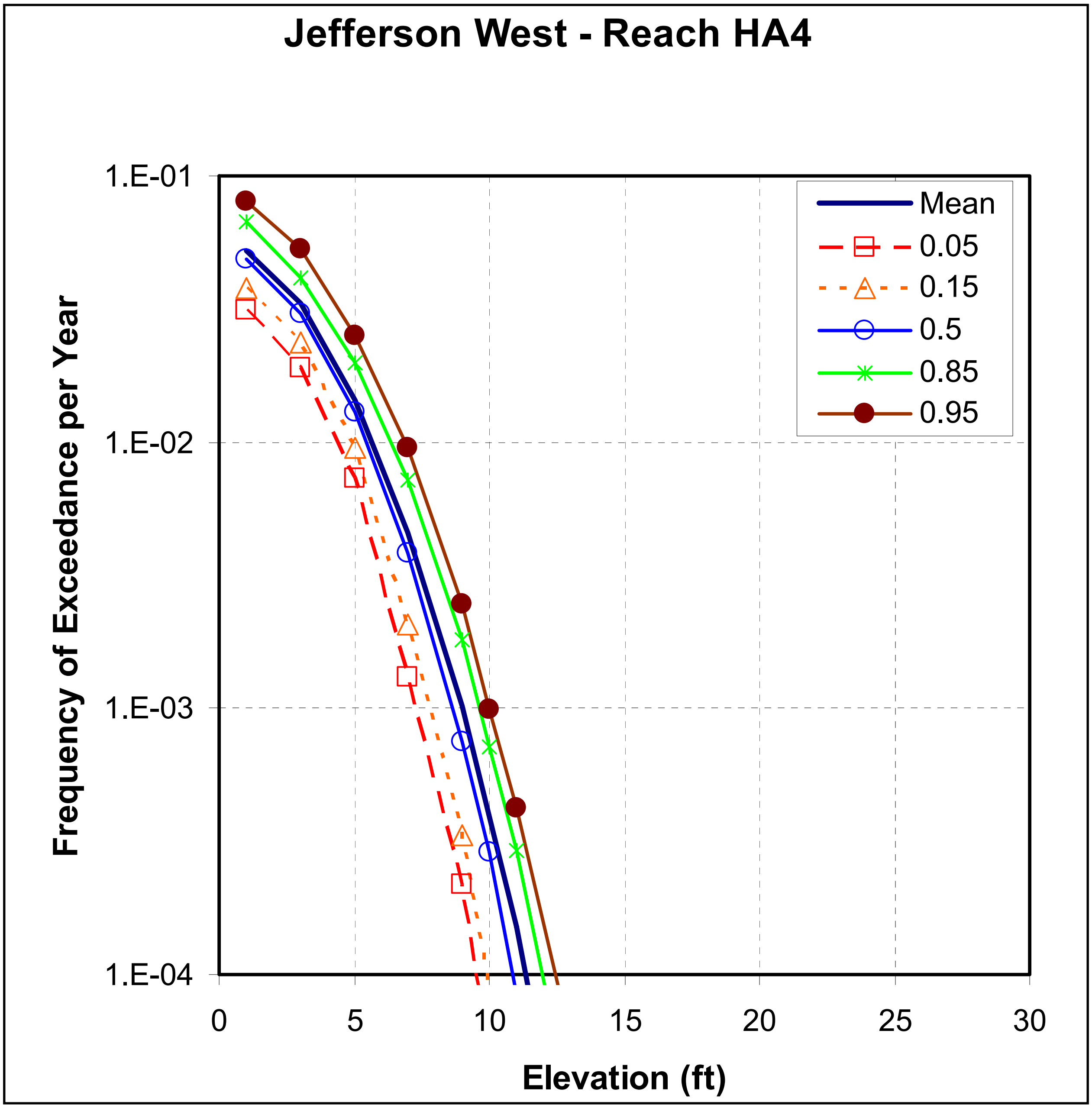

Figure A-14. Hurricane hazard curves for Jefferson West reach HA4.

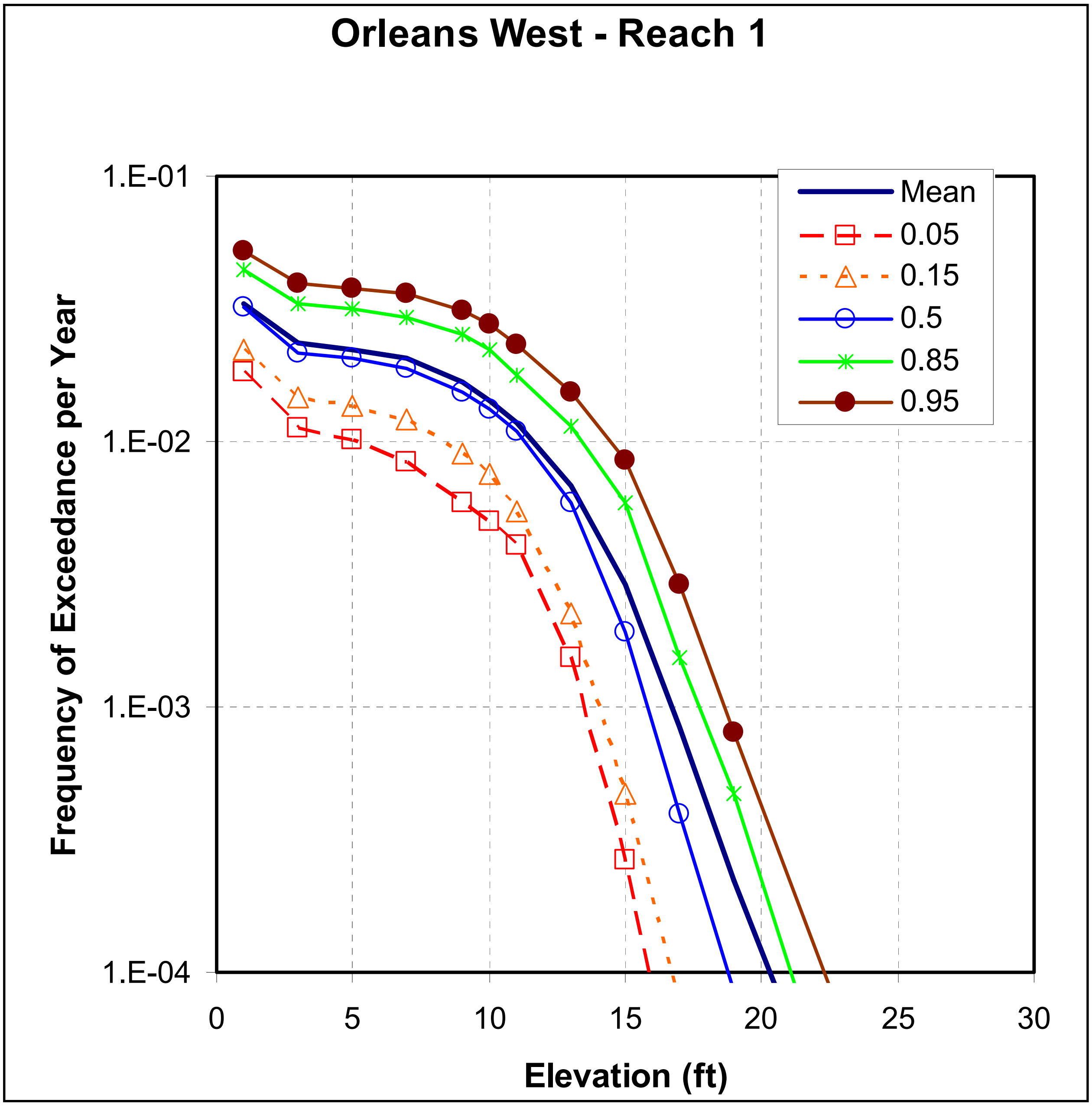

Figure A-15. Hurricane hazard curves for Orleans West reach 1.

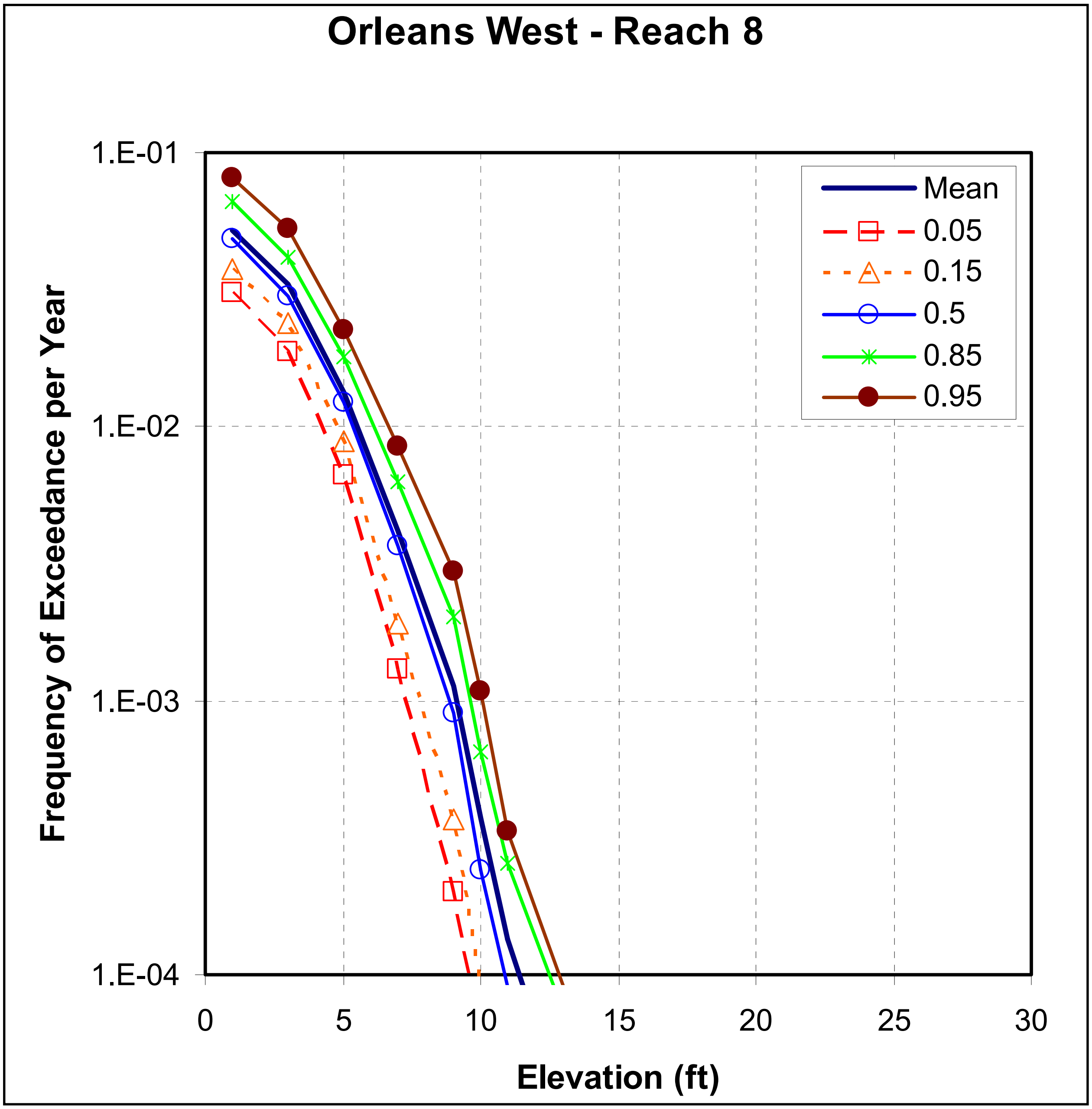

Figure A-16. Hurricane hazard curves for Orleans West reach 8.

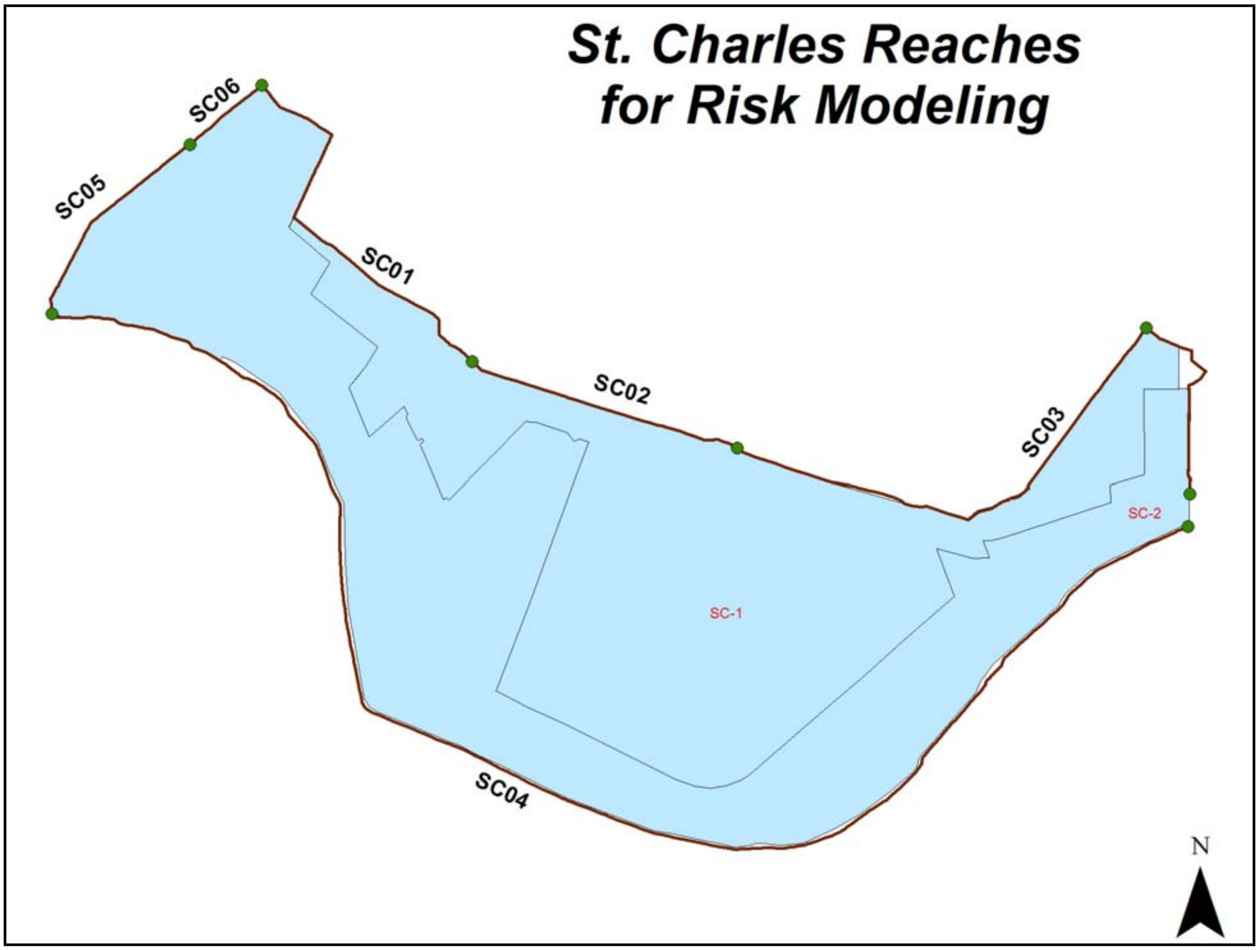

Figure A-17. Map showing the St. Charles reaches modeled in the risk analysis.

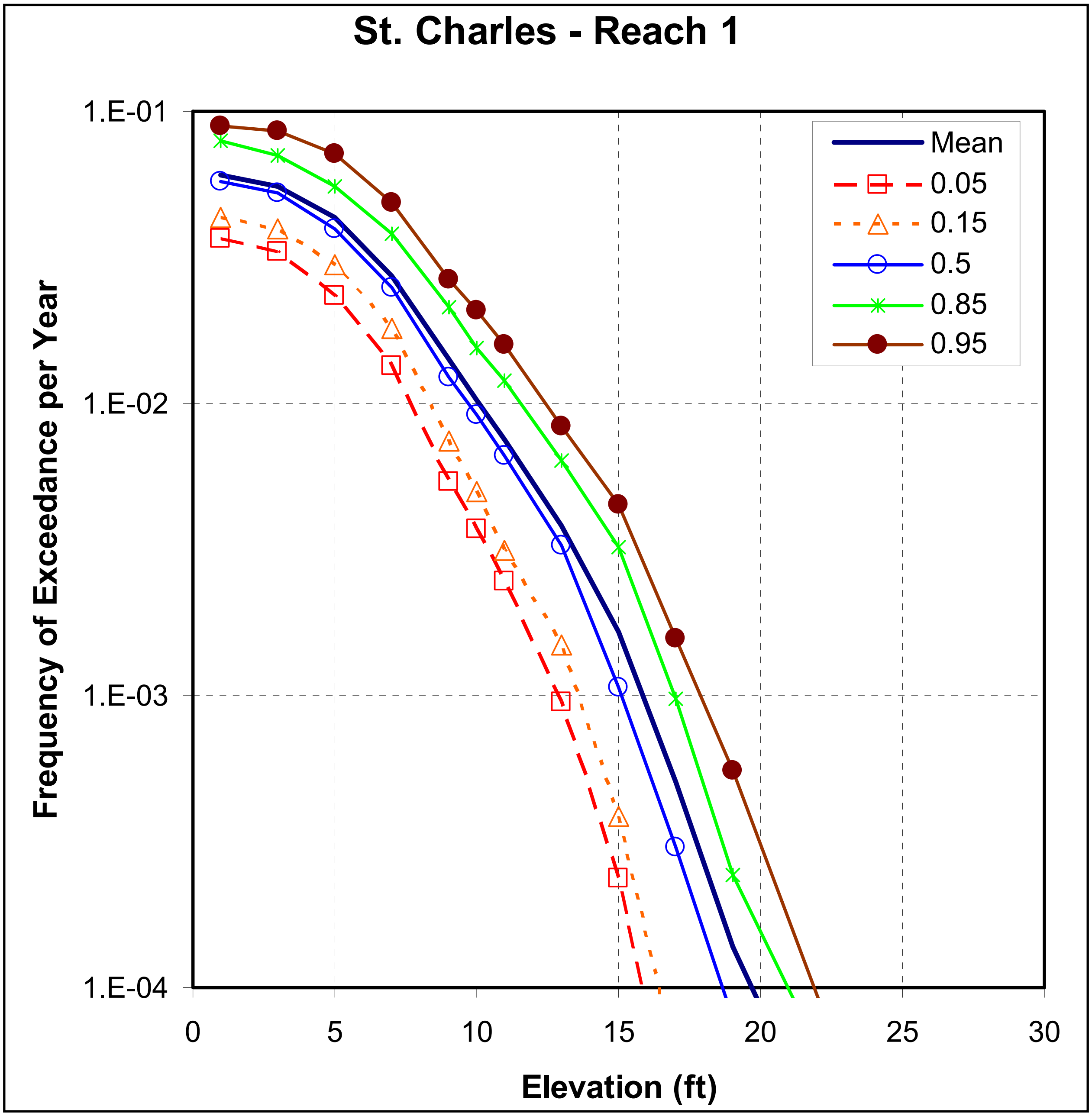

Figure A-18. Hurricane hazard curves for St. Charles reach 1.

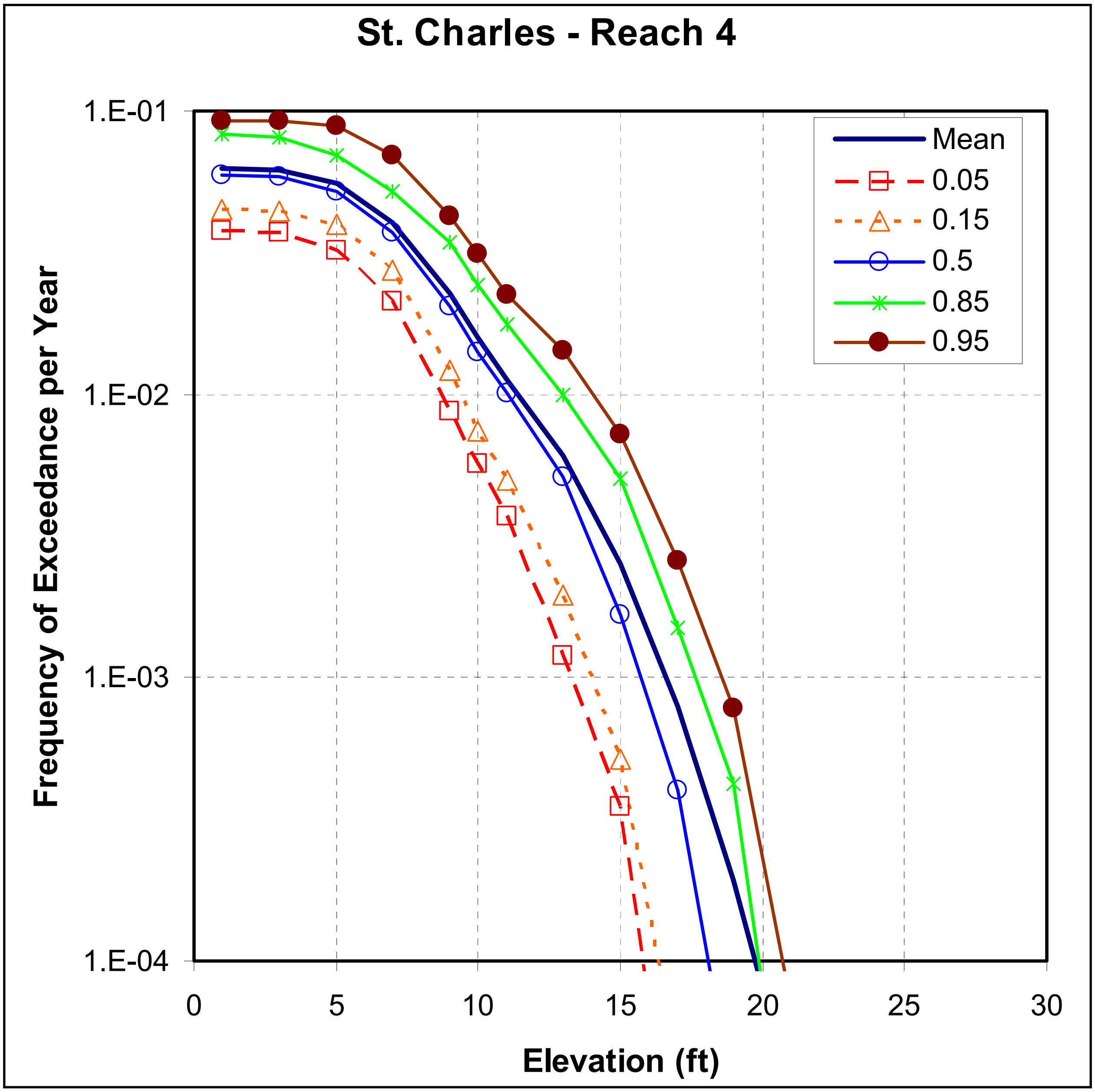

Figure A-19. Hurricane hazard curves for St. Charles reach 4.

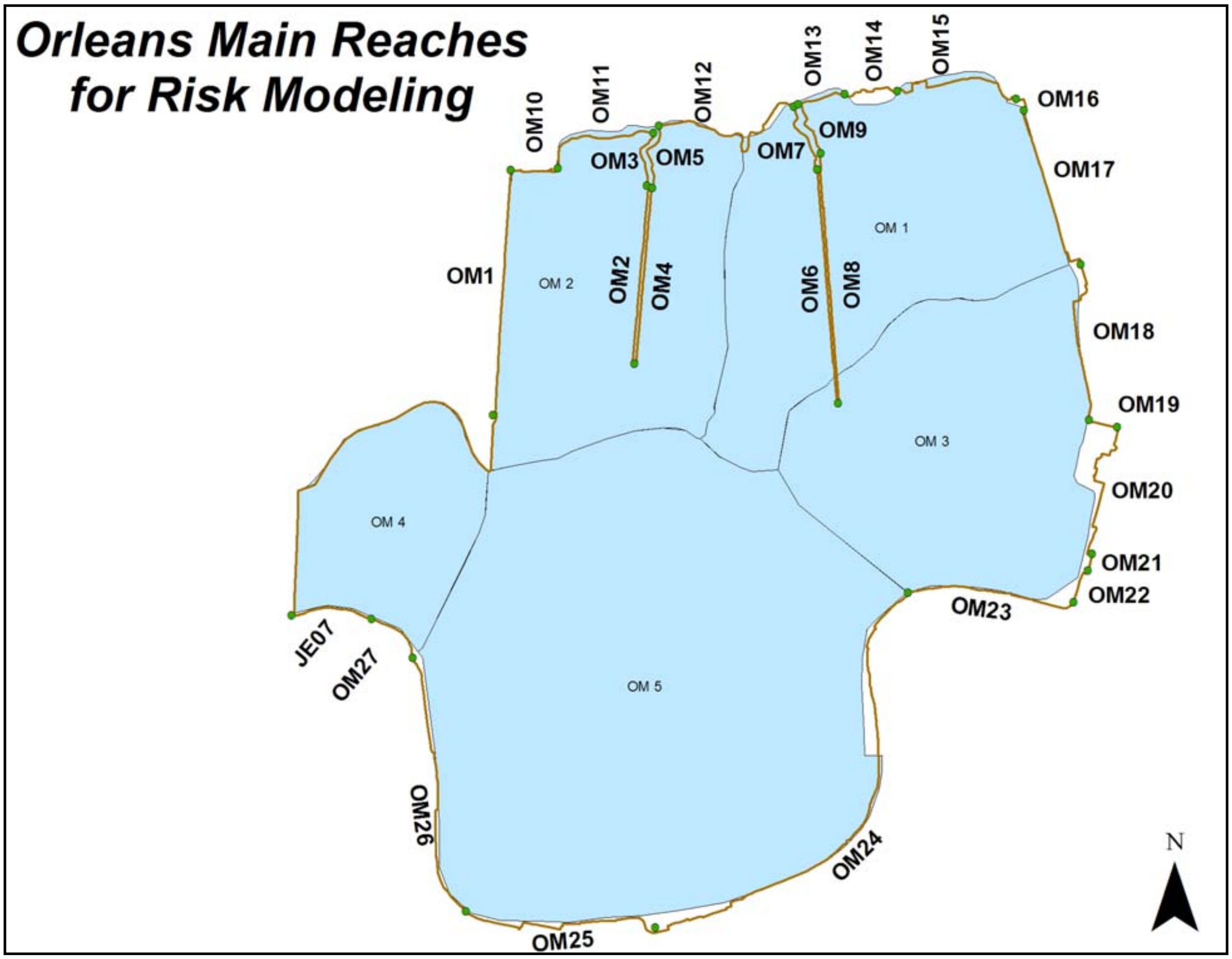

Figure A-20. Map showing the Orleans Main reaches modeled in the risk analysis.

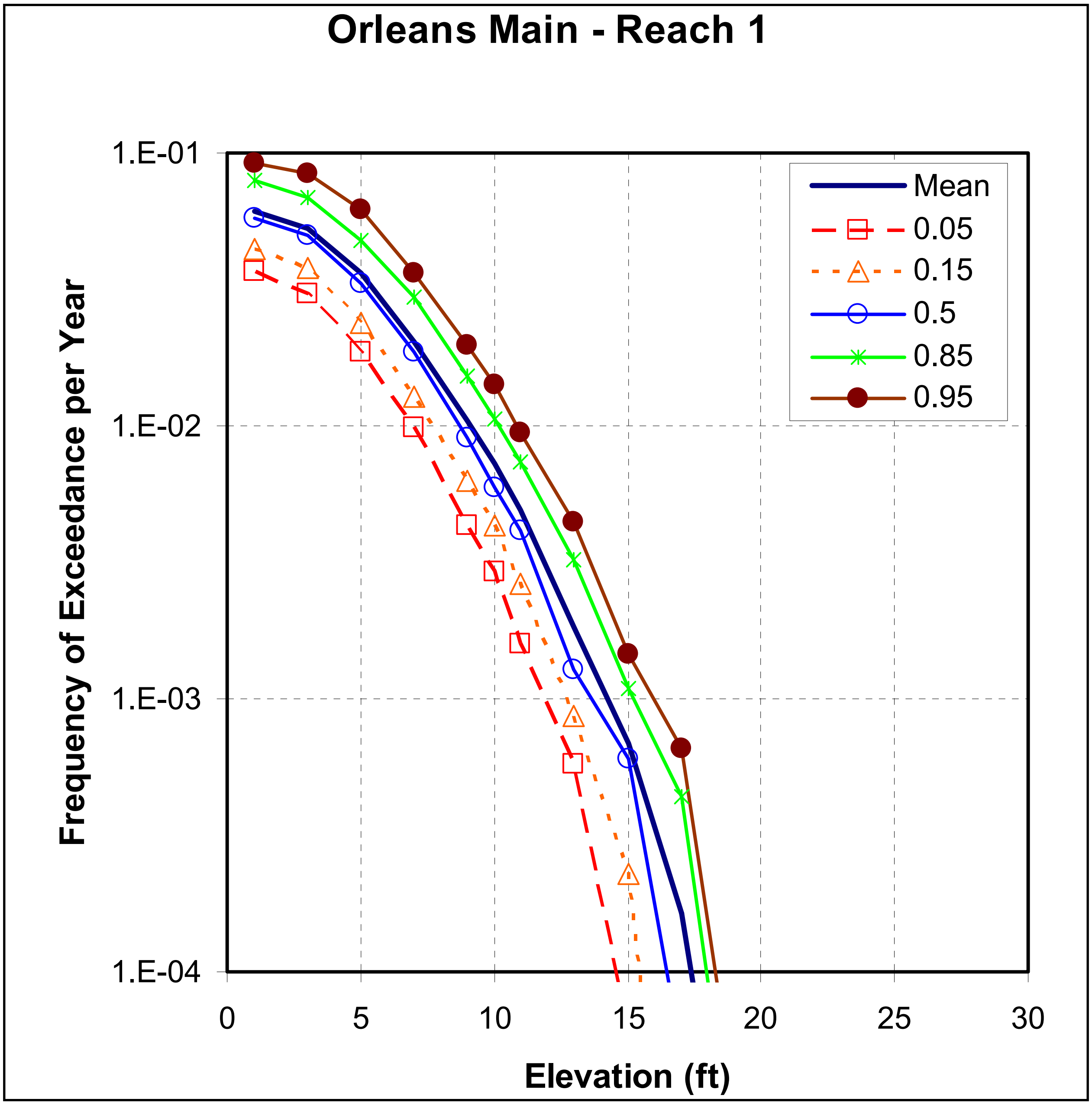

Figure A-21. Hurricane hazard curves for Orleans Main reach 1.

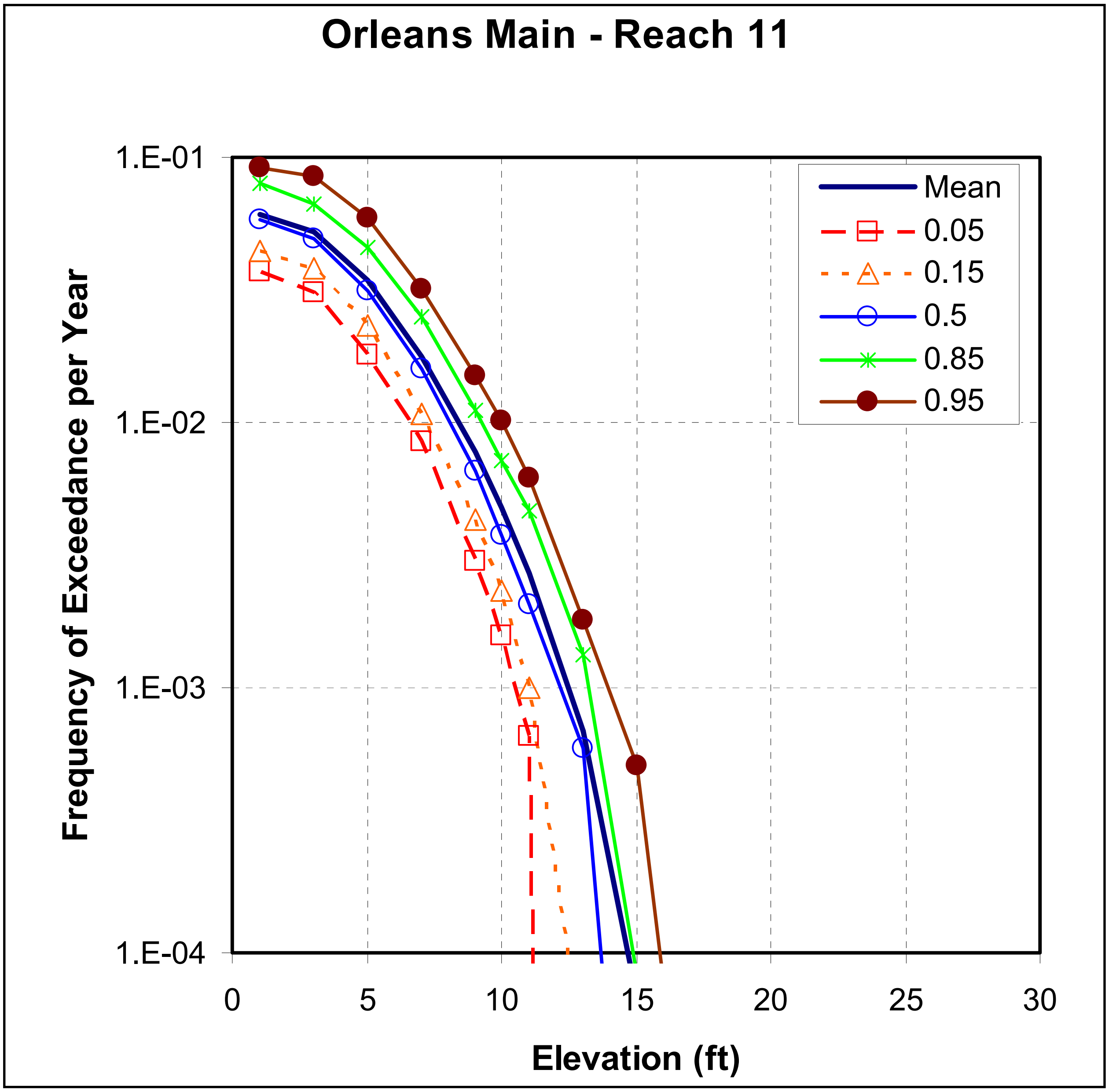

Figure A-22. Hurricane hazard curves for Orleans Main reach 11.

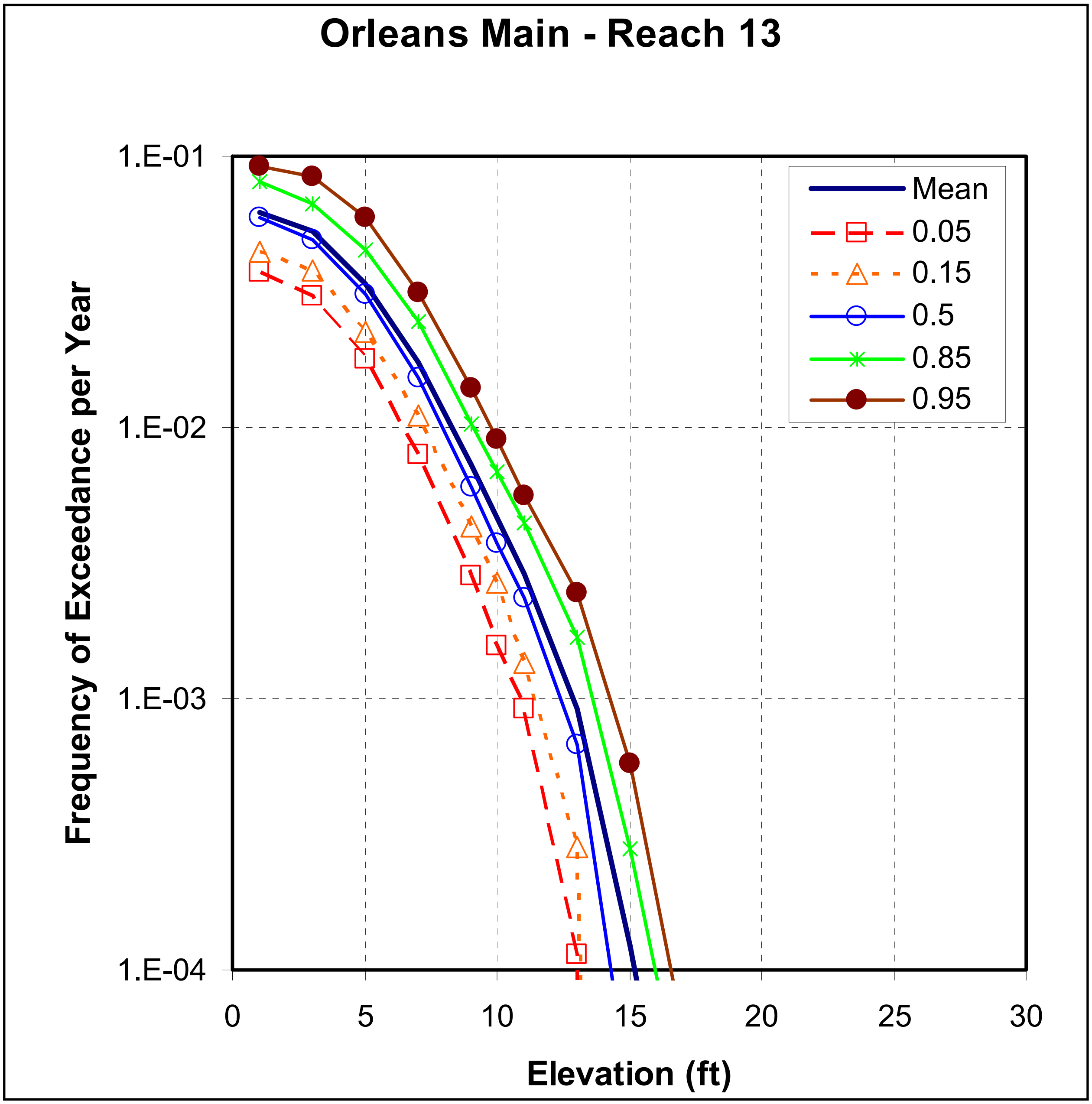

Figure A-23. Hurricane hazard curves for Orleans Main reach 13.

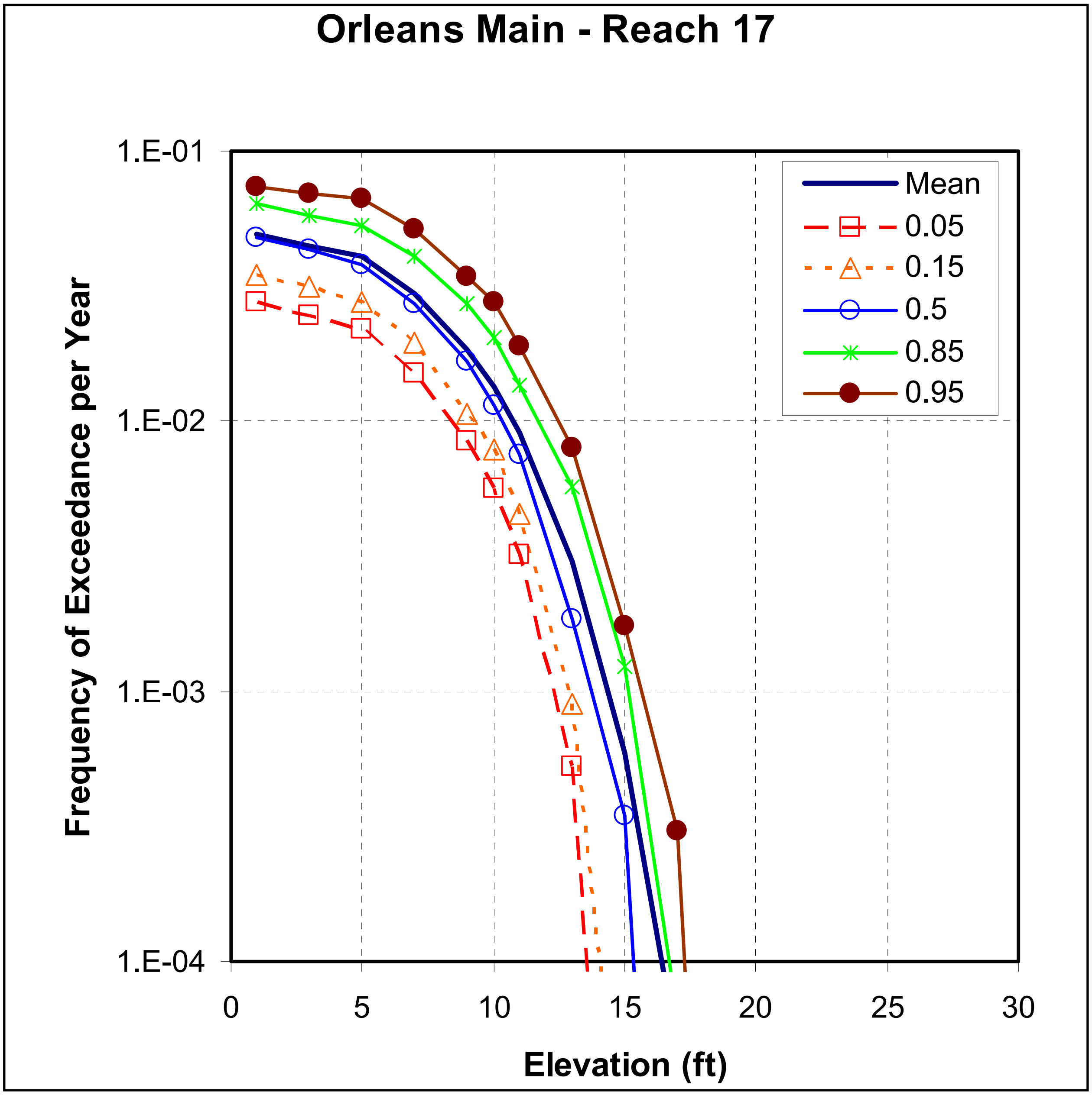

Figure A-24. Hurricane hazard curves for Orleans Main reach 17.

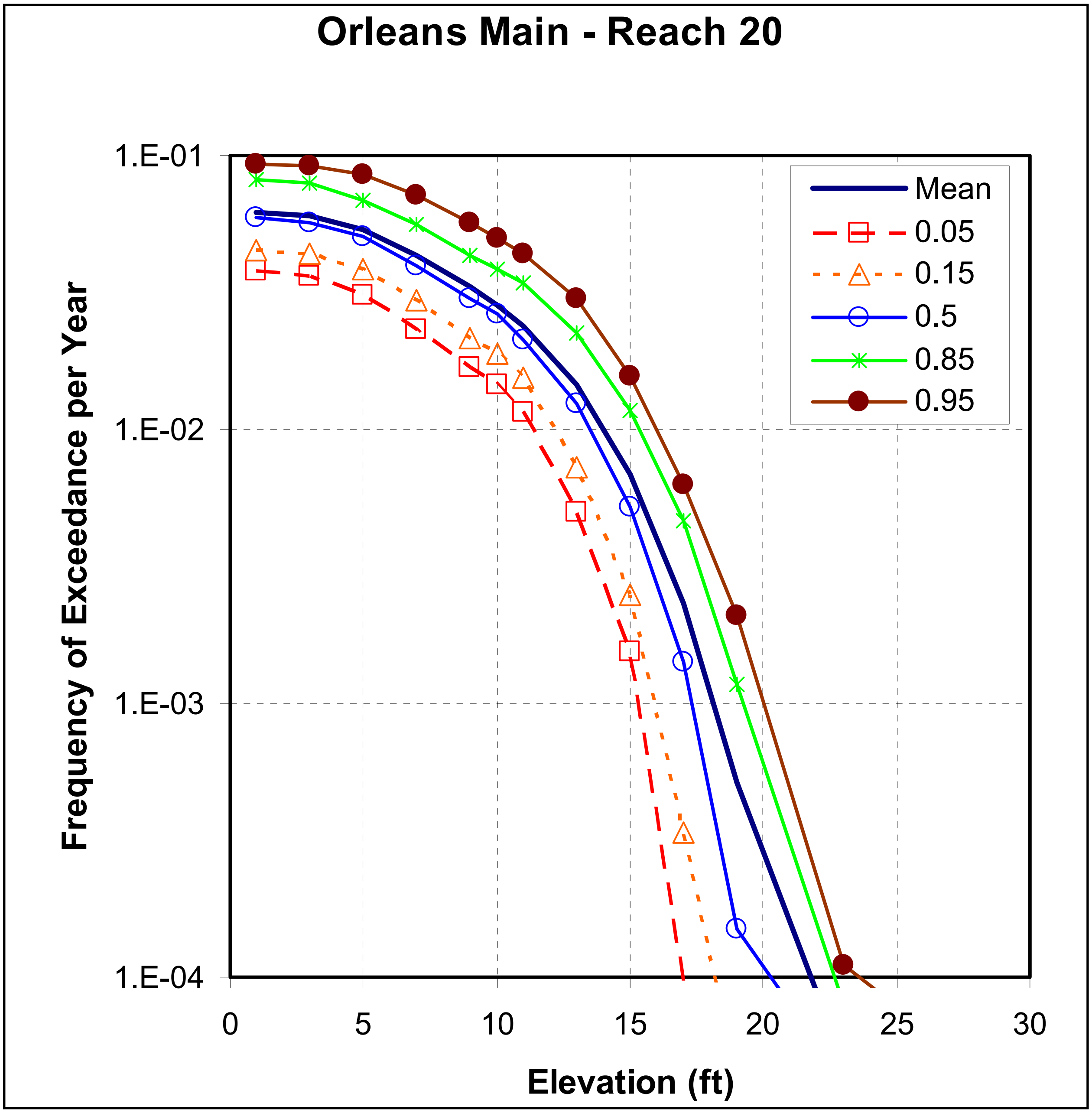

Figure A-25. Hurricane hazard curves for Orleans Main reach 20.

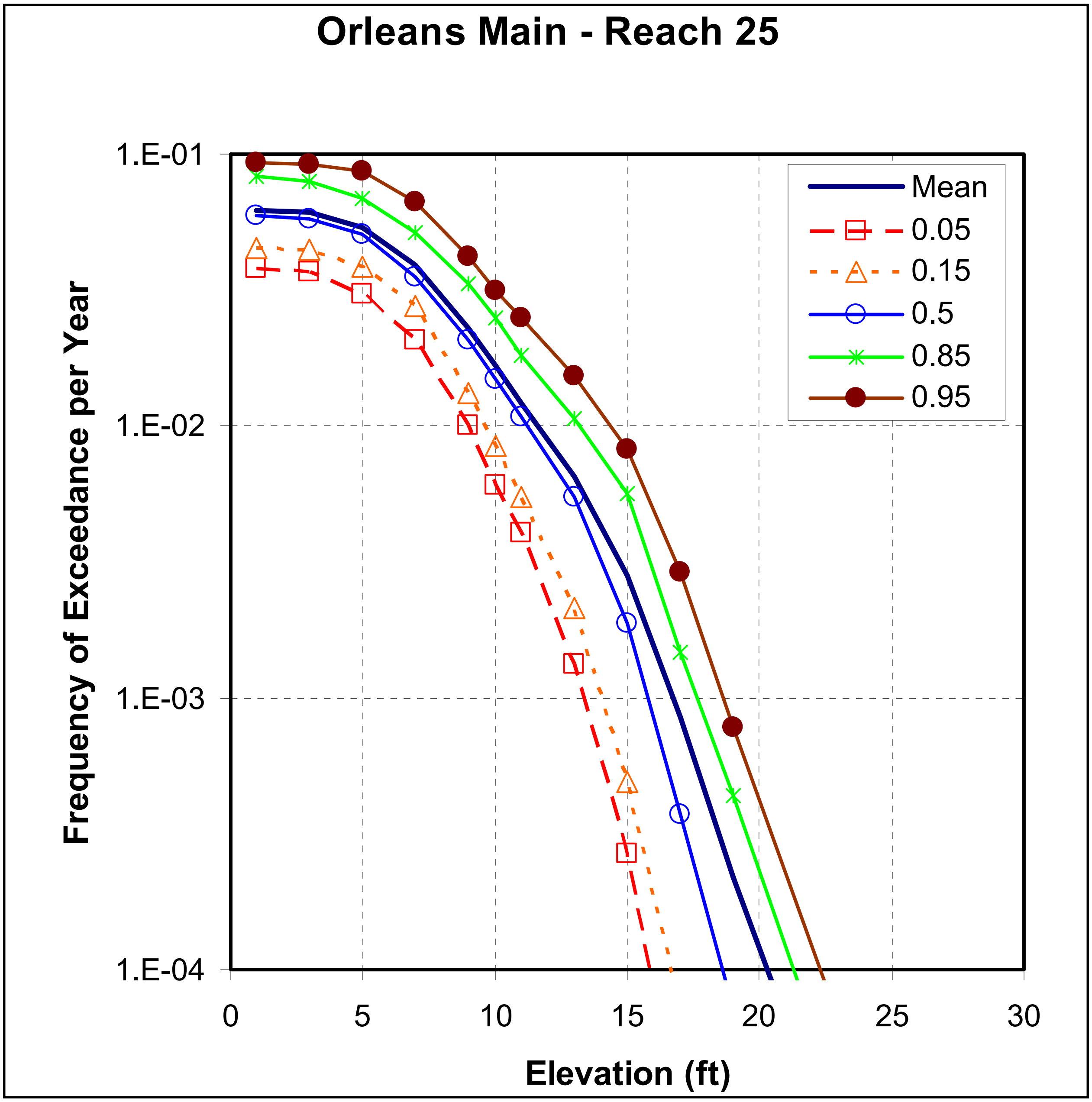

Figure A-26. Hurricane hazard curves for Orleans Main reach 25.

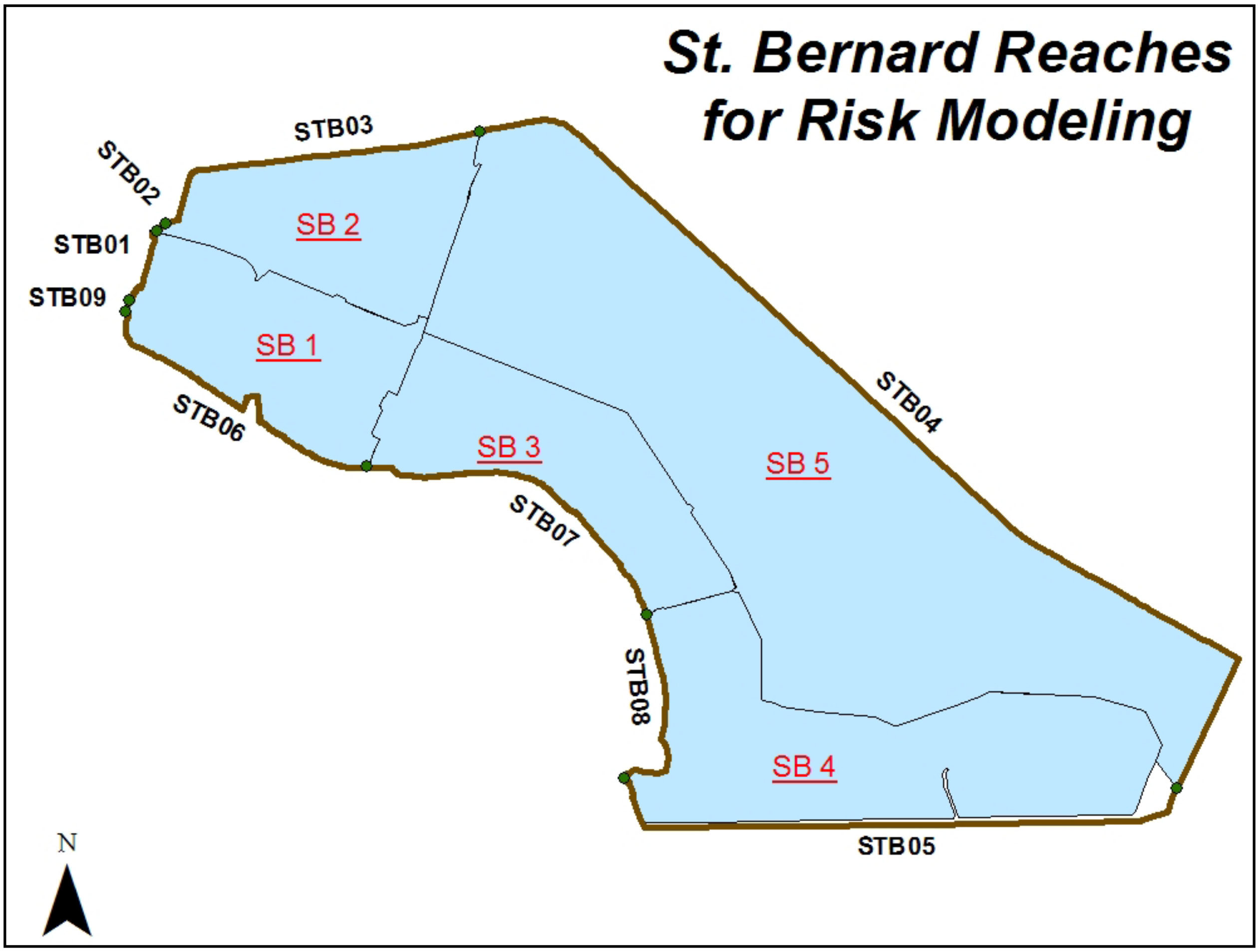

Figure A-27. Map showing the St. Bernard reaches modeled in the risk analysis.

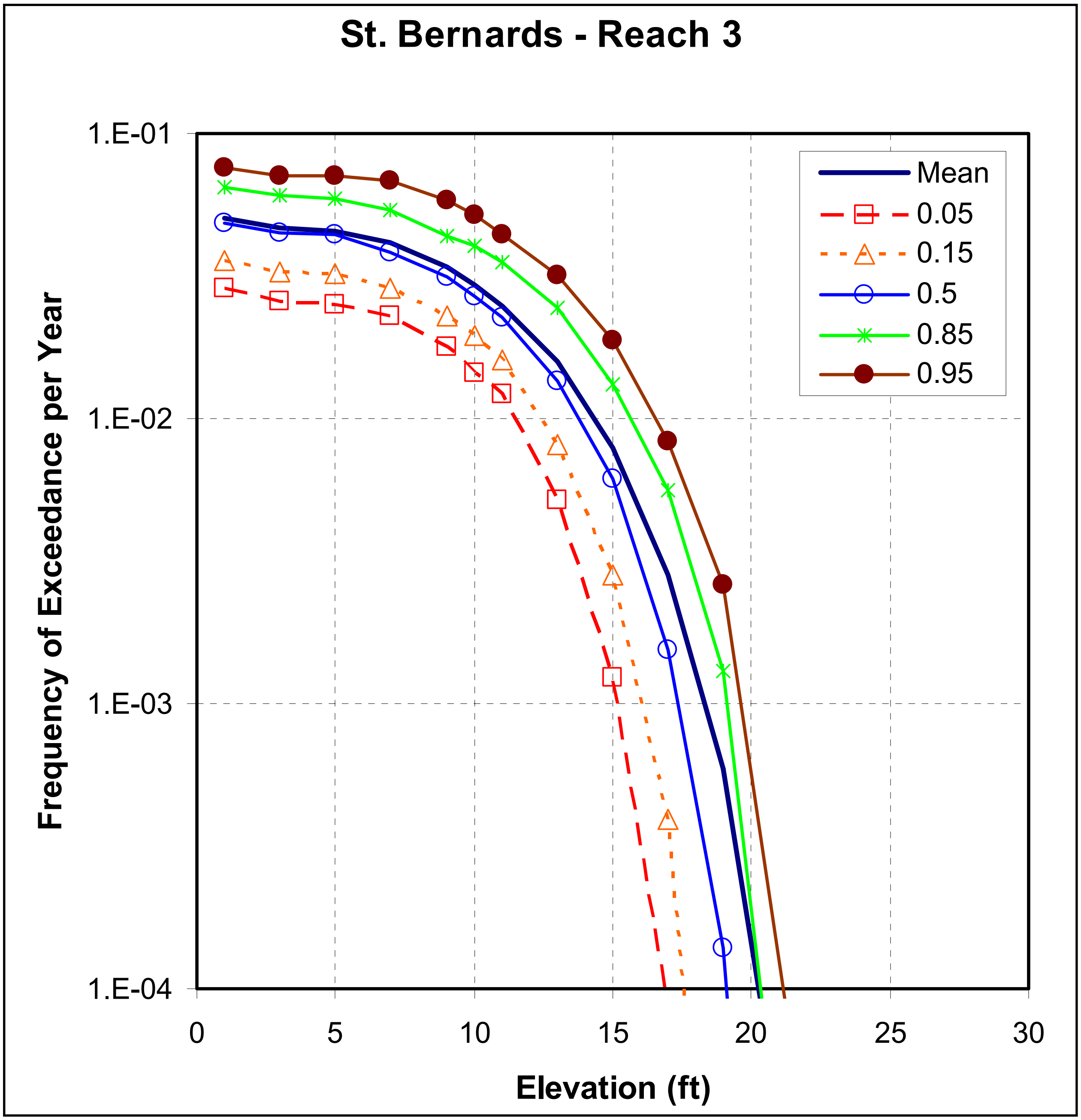

Figure A-28. Hurricane hazard curves for St. Bernard reach 3.

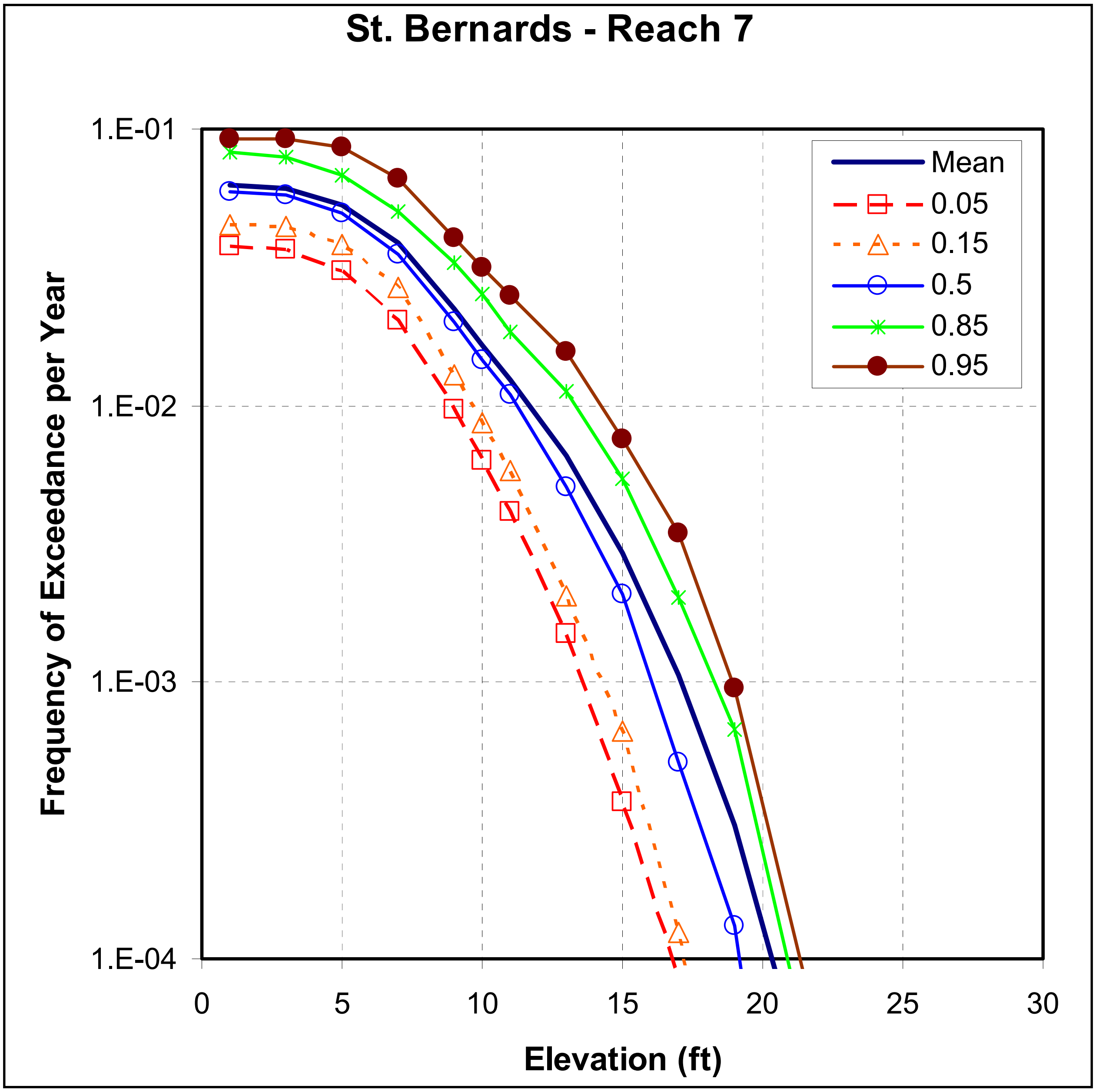

Figure A-29. Hurricane hazard curves for St. Bernards reach 7.

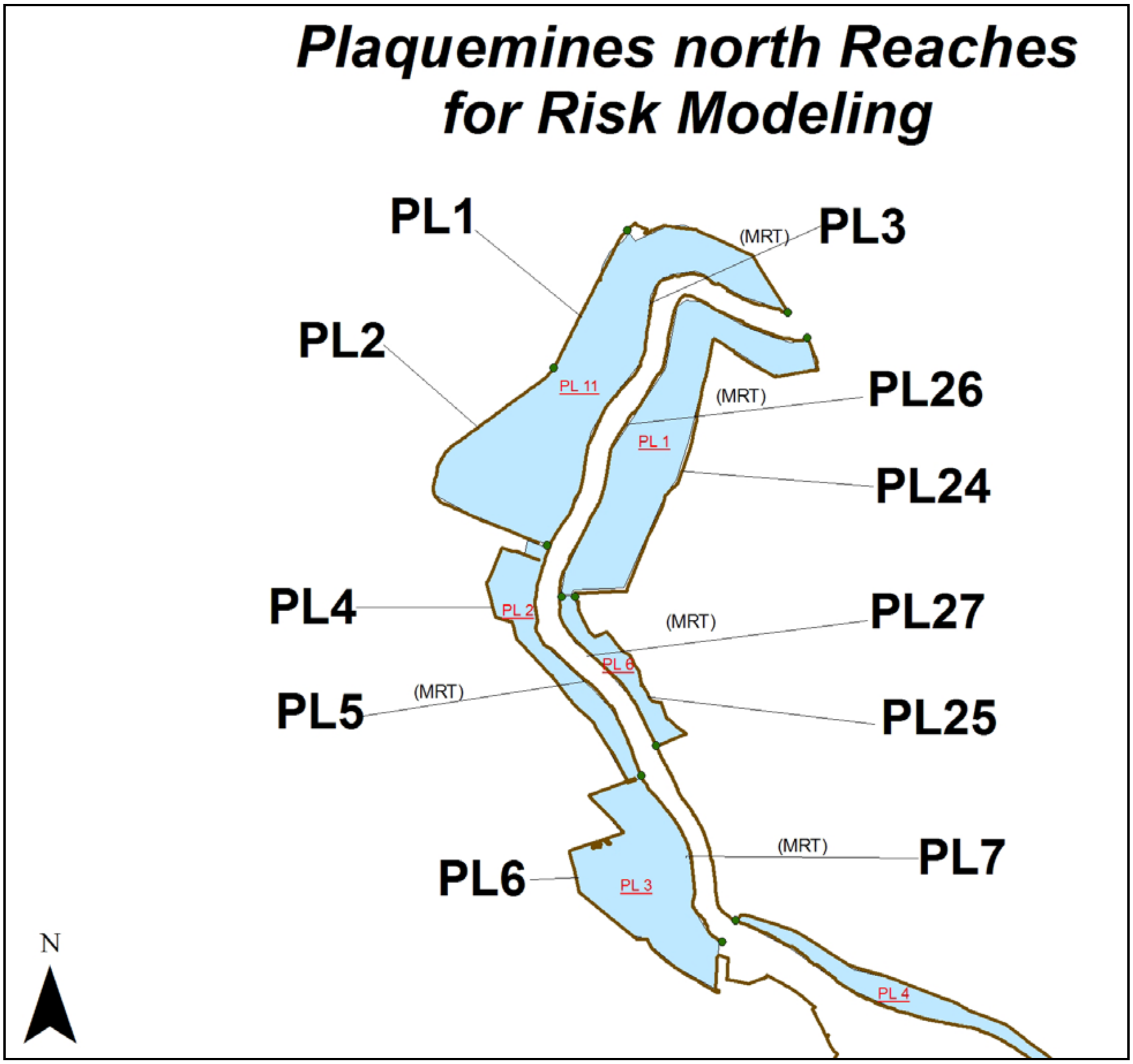

Figure A-30. Map showing the Plaquemines North reaches modeled in the risk analysis.

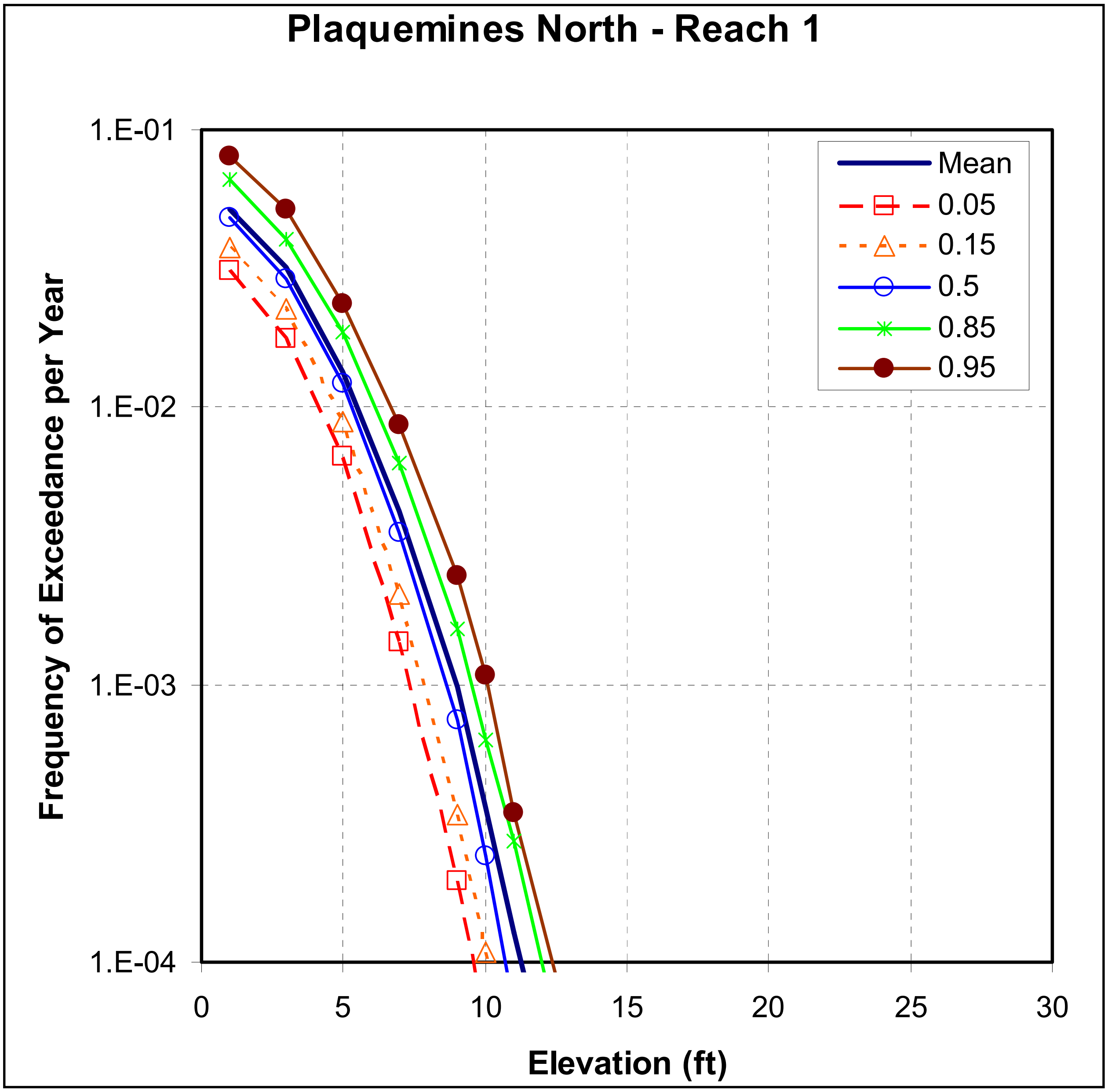

Figure A-31. Hurricane hazard curves for Plaquemines reach 1.

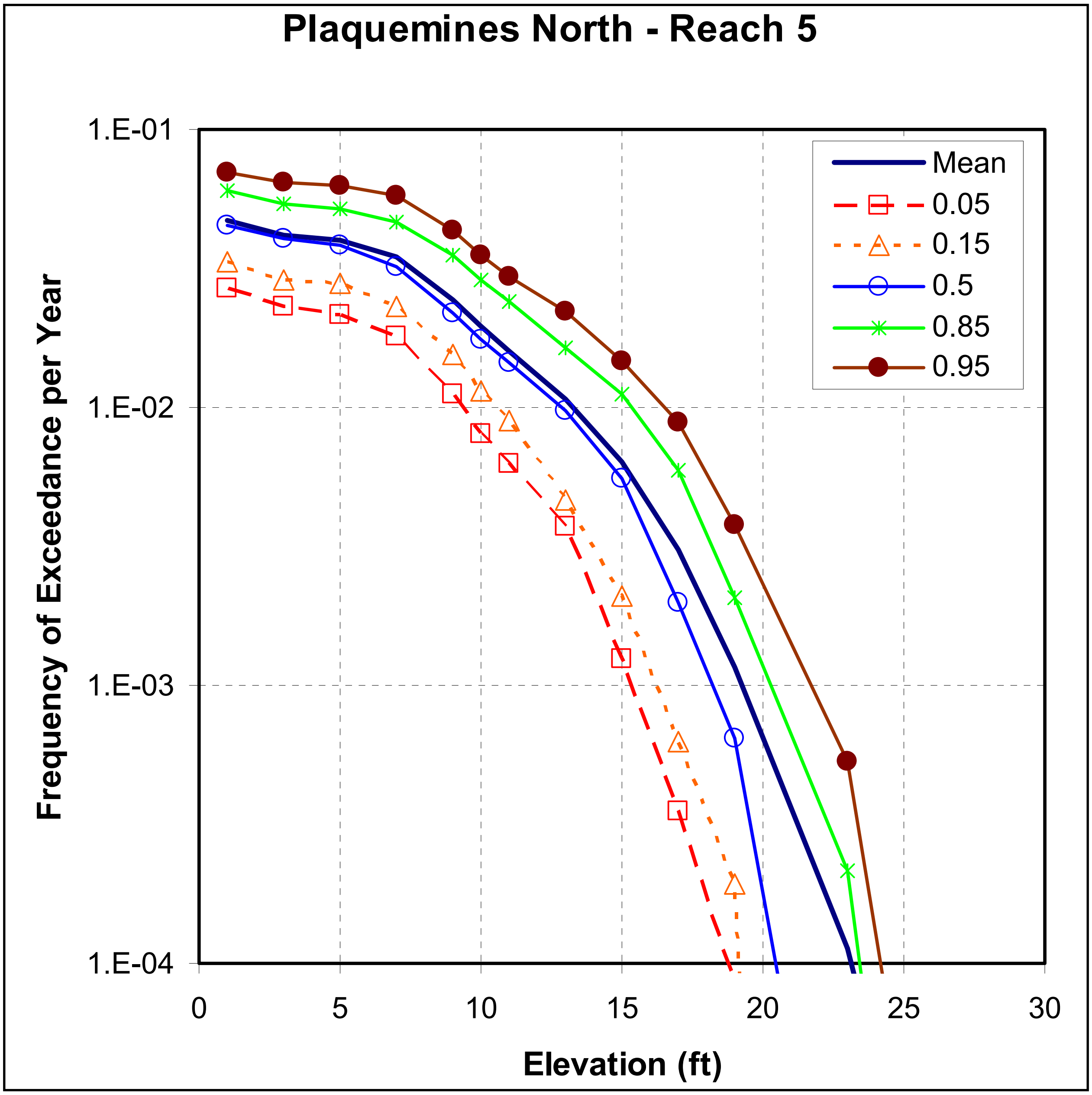

Figure A-32. Hurricane hazard curves for Plaquemines reach 5.

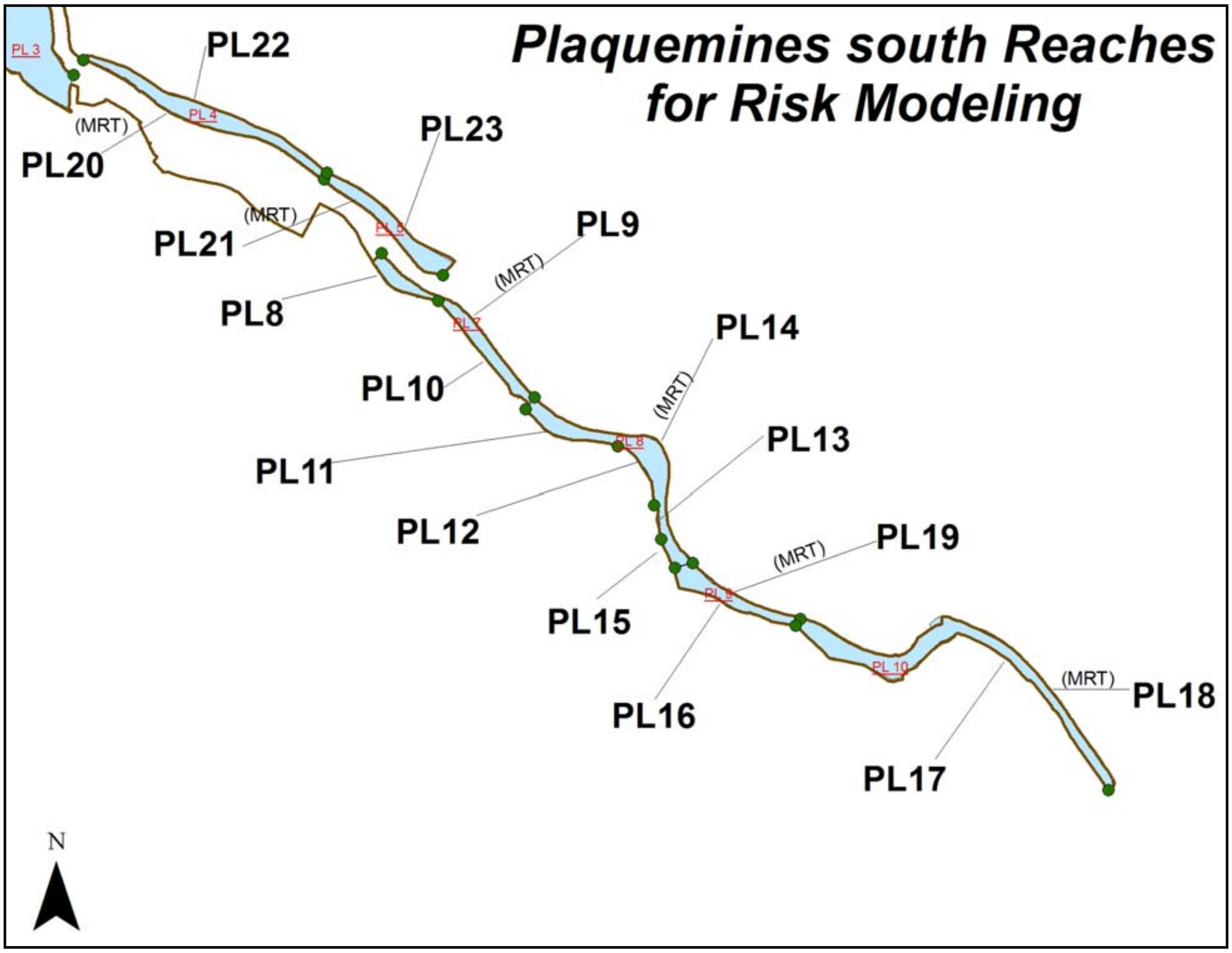

Figure A-33. Map showing the Plaquemines south reaches modeled in the risk analysis.

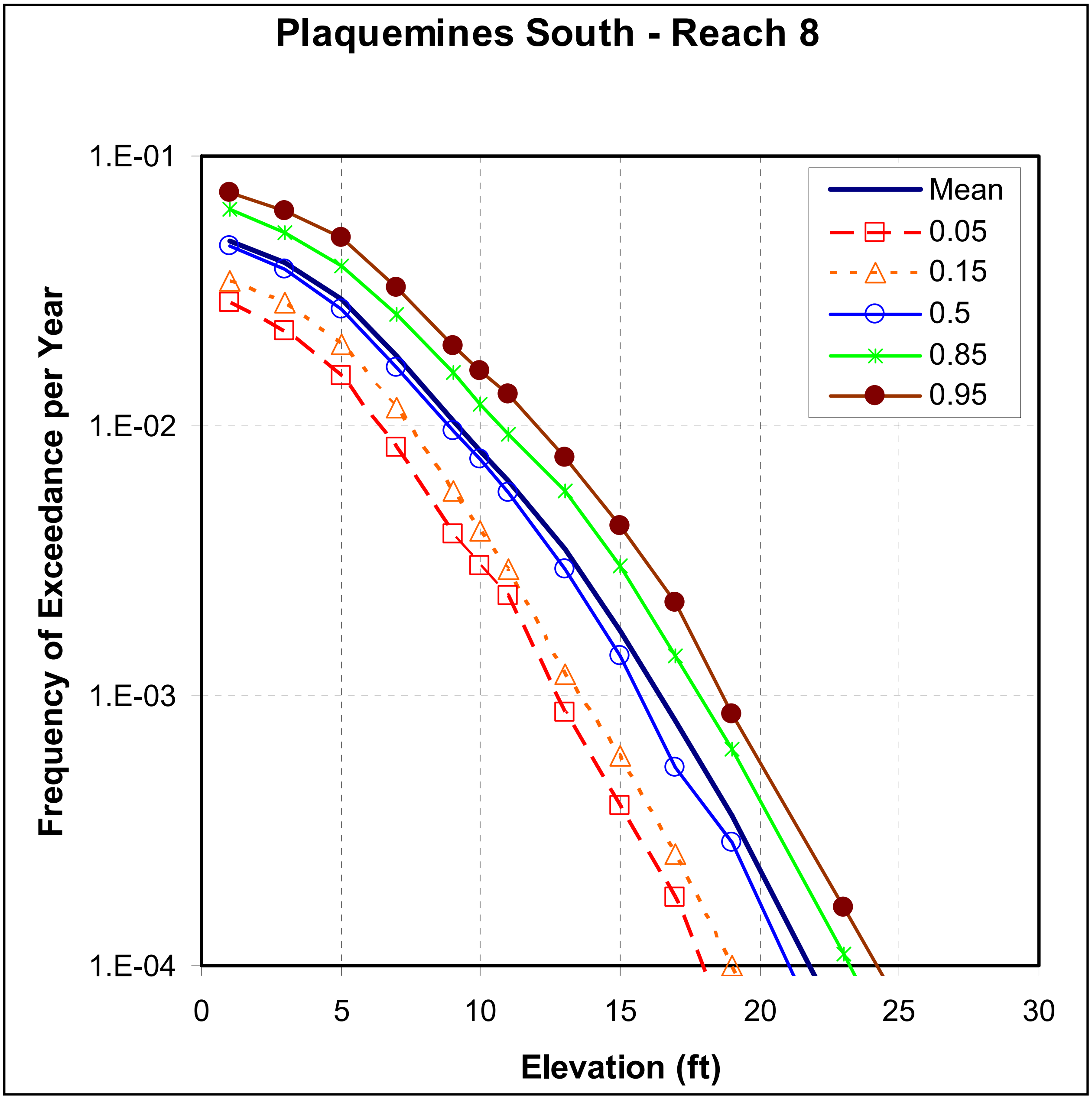

Figure A-34. Hurricane hazard curves for Plaquemines reach 8.

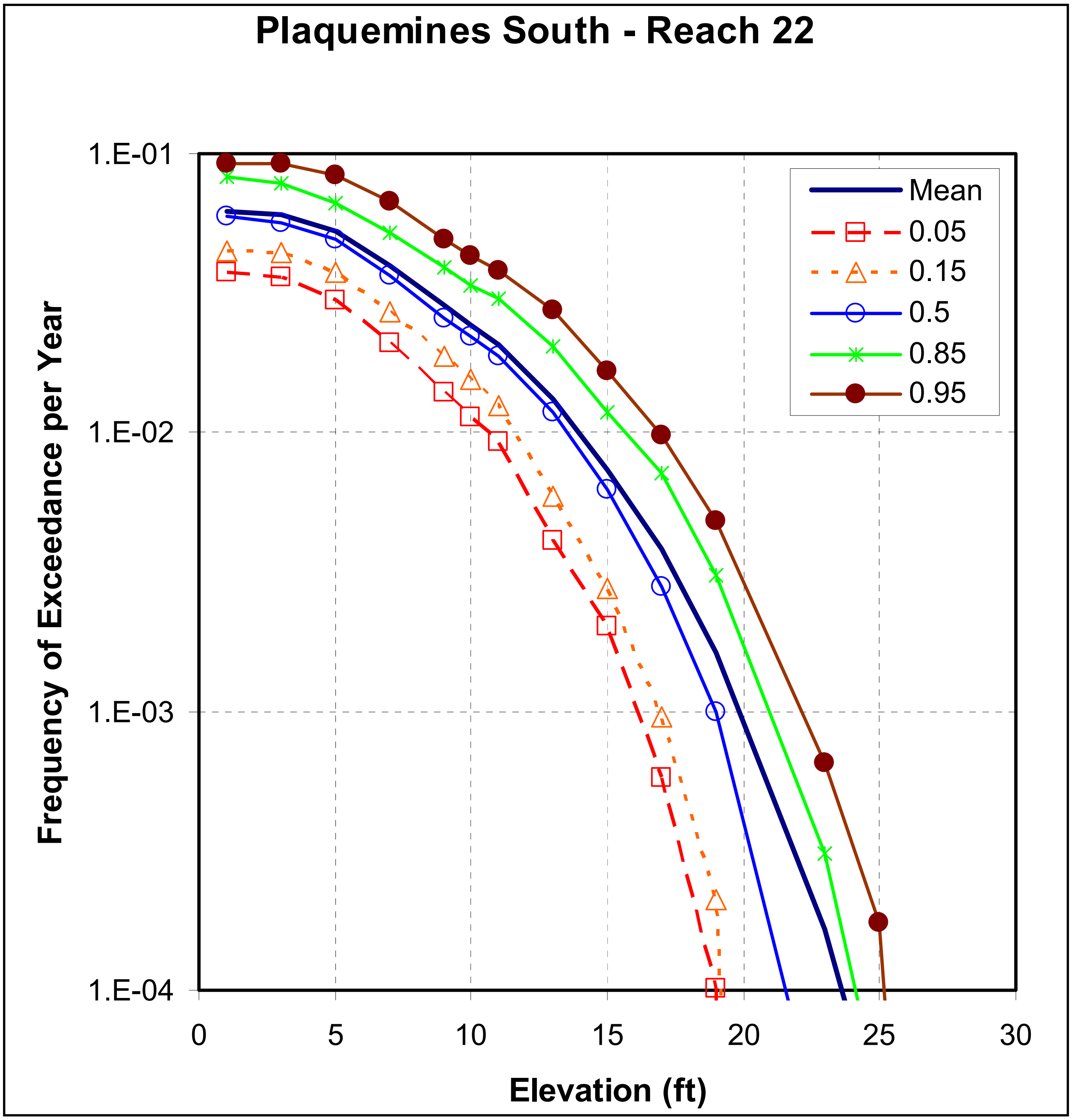

Figure A-35. Hurricane hazard curves for Plaquemines reach 22.

Appendix B
Levee and Floodwall Fragility-Uncertainty Results

Table B-1. Pre-Katrina Levee Fragility Uncertainty Results

<table>
<tr><th rowspan="3">Reach</th><th colspan="6">Median Curve P(x)=0.63</th><th colspan="6">0.95 Curve P(x)=0.185</th><th colspan="6">0.05 Curve P(x)=0.185</th></tr>
<tr><th colspan="2">Pf (Breach|No Overtopping)</th><th colspan="4">Pf(Breach|Overtopping)</th><th colspan="2">Pf (Breach|No Overtopping)</th><th colspan="4">Pf(Breach|Overtopping)</th><th colspan="2">Pf (Breach|No Overtopping)</th><th colspan="4">Pf(Breach|Overtopping)</th></tr>
<tr><th>Design Elev. (L) 6ft from TOW (W)</th><th>Top of Levee/Top of Wall</th><th>1/2 ft</th><th>1 ft</th><th>2 ft</th><th>3 ft</th><th>Design Elev. (L) 6ft from TOW (W)</th><th>Top of Levee/Top of Wall</th><th>1/2 ft</th><th>1 ft</th><th>2 ft</th><th>3 ft</th><th>Design Elev. (L) 6ft from TOW (W)</th><th>Top of Levee/Top of Wall</th><th>1/2 ft</th><th>1 ft</th><th>2 ft</th><th>3 ft</th></tr>
<tr><td>1</td><td>0.012</td><td>0.019</td><td>0.019</td><td>0.019</td><td>0.500</td><td>1.000</td><td>0.053</td><td>0.085</td><td>0.085</td><td>0.085</td><td>1.000</td><td>1.000</td><td>0.002</td><td>0.003</td><td>0.003</td><td>0.003</td><td>0.081</td><td>1.000</td></tr>
<tr><td>2</td><td>0.023</td><td>0.040</td><td>0.040</td><td>0.040</td><td>1.000</td><td>1.000</td><td>0.020</td><td>0.035</td><td>0.035</td><td>0.035</td><td>0.874</td><td>1.000</td><td>0.001</td><td>0.002</td><td>0.002</td><td>0.002</td><td>0.055</td><td>1.000</td></tr>
<tr><td>3</td><td>0.011</td><td>0.018</td><td>0.018</td><td>0.018</td><td>0.500</td><td>1.000</td><td>0.051</td><td>0.083</td><td>0.083</td><td>0.083</td><td>1.000</td><td>1.000</td><td>0.002</td><td>0.003</td><td>0.003</td><td>0.003</td><td>0.081</td><td>1.000</td></tr>
<tr><td>4</td><td>0.052</td><td>0.090</td><td>0.090</td><td>0.090</td><td>1.000</td><td>1.000</td><td>0.169</td><td>0.294</td><td>0.294</td><td>0.294</td><td>1.000</td><td>1.000</td><td>0.011</td><td>0.020</td><td>0.020</td><td>0.020</td><td>0.222</td><td>1.000</td></tr>
<tr><td>5</td><td>0.011</td><td>0.018</td><td>0.018</td><td>0.018</td><td>0.500</td><td>1.000</td><td>0.050</td><td>0.081</td><td>0.081</td><td>0.081</td><td>1.000</td><td>1.000</td><td>0.002</td><td>0.003</td><td>0.003</td><td>0.003</td><td>0.081</td><td>1.000</td></tr>
<tr><td>6</td><td>0.353</td><td>0.538</td><td>0.538</td><td>0.538</td><td>1.000</td><td>1.000</td><td>0.781</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>0.090</td><td>0.138</td><td>0.138</td><td>0.138</td><td>0.256</td><td>1.000</td></tr>
<tr><td>7</td><td>0.007</td><td>0.012</td><td>0.012</td><td>0.012</td><td>0.500</td><td>1.000</td><td>0.033</td><td>0.053</td><td>0.053</td><td>0.053</td><td>1.000</td><td>1.000</td><td>0.001</td><td>0.002</td><td>0.002</td><td>0.002</td><td>0.081</td><td>1.000</td></tr>
<tr><td>8</td><td>0.060</td><td>0.104</td><td>0.104</td><td>0.104</td><td>1.000</td><td>1.000</td><td>0.195</td><td>0.338</td><td>0.338</td><td>0.338</td><td>1.000</td><td>1.000</td><td>0.013</td><td>0.023</td><td>0.023</td><td>0.023</td><td>0.223</td><td>1.000</td></tr>
<tr><td>9</td><td>0.527</td><td>0.736</td><td>0.736</td><td>0.736</td><td>1.000</td><td>1.000</td><td>0.927</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>0.151</td><td>0.210</td><td>0.210</td><td>0.210</td><td>0.286</td><td>1.000</td></tr>
<tr><td>10</td><td>0.124</td><td>0.210</td><td>0.210</td><td>0.210</td><td>1.000</td><td>1.000</td><td>0.371</td><td>0.627</td><td>0.627</td><td>0.627</td><td>1.000</td><td>1.000</td><td>0.028</td><td>0.048</td><td>0.048</td><td>0.048</td><td>0.229</td><td>1.000</td></tr>
<tr><td>11</td><td>0.262</td><td>0.417</td><td>0.417</td><td>0.417</td><td>1.000</td><td>1.000</td><td>0.653</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>0.064</td><td>0.102</td><td>0.102</td><td>0.102</td><td>0.244</td><td>1.000</td></tr>
<tr><td>12</td><td>0.184</td><td>0.303</td><td>0.303</td><td>0.303</td><td>1.000</td><td>1.000</td><td>0.508</td><td>0.837</td><td>0.837</td><td>0.837</td><td>1.000</td><td>1.000</td><td>0.043</td><td>0.071</td><td>0.071</td><td>0.071</td><td>0.235</td><td>1.000</td></tr>
<tr><td>13</td><td>0.189</td><td>0.310</td><td>0.310</td><td>0.310</td><td>1.000</td><td>1.000</td><td>0.518</td><td>0.852</td><td>0.852</td><td>0.852</td><td>1.000</td><td>1.000</td><td>0.045</td><td>0.073</td><td>0.073</td><td>0.073</td><td>0.236</td><td>1.000</td></tr>
<tr><td>14</td><td>0.058</td><td>0.100</td><td>0.100</td><td>0.100</td><td>1.000</td><td>1.000</td><td>0.188</td><td>0.326</td><td>0.326</td><td>0.326</td><td>1.000</td><td>1.000</td><td>0.013</td><td>0.022</td><td>0.022</td><td>0.022</td><td>0.223</td><td>1.000</td></tr>
<tr><td>15</td><td>0.097</td><td>0.165</td><td>0.165</td><td>0.165</td><td>1.000</td><td>1.000</td><td>0.299</td><td>0.511</td><td>0.511</td><td>0.511</td><td>1.000</td><td>1.000</td><td>0.022</td><td>0.037</td><td>0.037</td><td>0.037</td><td>0.227</td><td>1.000</td></tr>
<tr><td>16</td><td>0.257</td><td>0.410</td><td>0.410</td><td>0.410</td><td>1.000</td><td>1.000</td><td>0.646</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>0.063</td><td>0.100</td><td>0.100</td><td>0.100</td><td>0.244</td><td>1.000</td></tr>
<tr><td>17</td><td>0.214</td><td>0.348</td><td>0.348</td><td>0.348</td><td>1.000</td><td>1.000</td><td>0.568</td><td>0.925</td><td>0.925</td><td>0.925</td><td>1.000</td><td>1.000</td><td>0.051</td><td>0.083</td><td>0.083</td><td>0.083</td><td>0.239</td><td>1.000</td></tr>
<tr><td>18</td><td>0.051</td><td>0.082</td><td>0.082</td><td>0.082</td><td>0.775</td><td>1.000</td><td>0.215</td><td>0.345</td><td>0.345</td><td>0.345</td><td>1.000</td><td>1.000</td><td>0.008</td><td>0.014</td><td>0.014</td><td>0.014</td><td>0.128</td><td>1.000</td></tr>
<tr><td>19</td><td>0.045</td><td>0.072</td><td>0.072</td><td>0.072</td><td>0.725</td><td>1.000</td><td>0.189</td><td>0.304</td><td>0.304</td><td>0.304</td><td>1.000</td><td>1.000</td><td>0.007</td><td>0.012</td><td>0.012</td><td>0.012</td><td>0.120</td><td>1.000</td></tr>
<tr><td>20</td><td>0.165</td><td>0.274</td><td>0.274</td><td>0.274</td><td>1.000</td><td>1.000</td><td>0.467</td><td>0.775</td><td>0.775</td><td>0.775</td><td>1.000</td><td>1.000</td><td>0.038</td><td>0.064</td><td>0.064</td><td>0.064</td><td>0.233</td><td>1.000</td></tr>
<tr><td>21</td><td>0.027</td><td>0.043</td><td>0.043</td><td>0.043</td><td>0.535</td><td>1.000</td><td>0.117</td><td>0.189</td><td>0.189</td><td>0.189</td><td>1.000</td><td>1.000</td><td>0.004</td><td>0.007</td><td>0.007</td><td>0.007</td><td>0.087</td><td>1.000</td></tr>
<tr><td>22</td><td>0.023</td><td>0.040</td><td>0.040</td><td>0.040</td><td>1.000</td><td>1.000</td><td>0.030</td><td>0.053</td><td>0.053</td><td>0.053</td><td>1.000</td><td>1.000</td><td>0.002</td><td>0.003</td><td>0.003</td><td>0.003</td><td>0.085</td><td>1.000</td></tr>
<tr><td>23</td><td>0.294</td><td>0.462</td><td>0.462</td><td>0.462</td><td>1.000</td><td>1.000</td><td>0.704</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>1.000</td><td>0.073</td><td>0.115</td><td>0.115</td><td>0.115</td><td>0.248</td><td>1.000</td></tr>
<tr><td>24</td><td>0.014</td><td>0.023</td><td>0.023</td><td>0.023</td><td>0.500</td><td>1.000</td><td>0.063</td><td>0.103</td><td>0.103</td><td>0.103</td><td>1.000</td><td>1.000</td><td>0.002</td><td>0.004</td><td>0.004</td><td>0.004</td><td>0.081</td><td>1.000</td></tr>
<tr><td>25</td><td>0.071</td><td>0.122</td><td>0.122</td><td>0.122</td><td>1.000</td><td>1.000</td><td>0.226</td><td>0.391</td><td>0.391</td><td>0.391</td><td>1.000</td><td>1.000</td><td>0.016</td><td>0.027</td><td>0.027</td><td>0.027</td><td>0.224</td><td>1.000</td></tr>
<tr><td>26</td><td>0.008</td><td>0.013</td><td>0.013</td><td>0.013</td><td>0.500</td><td>1.000</td><td>0.036</td><td>0.059</td><td>0.059</td><td>0.059</td><td>1.000</td><td>1.000</td><td>0.001</td><td>0.002</td><td>0.002</td><td>0.002</td><td>0.081</td><td>1.000</td></tr>
<tr><td>27</td><td>0.061</td><td>0.105</td><td>0.105</td><td>0.105</td><td>1.000</td><td>1.000</td><td>0.196</td><td>0.341</td><td>0.341</td><td>0.341</td><td>1.000</td><td>1.000</td><td>0.014</td><td>0.023</td><td>0.023</td><td>0.023</td><td>0.223</td><td>1.000</td></tr>
<tr><td>28</td><td>0.089</td><td>0.153</td><td>0.153</td><td>0.153</td><td>1.000</td><td>1.000</td><td>0.278</td><td>0.477</td><td>0.477</td><td>0.477</td><td>1.000</td><td>1.000</td><td>0.020</td><td>0.035</td><td>0.035</td><td>0.035</td><td>0.226</td><td>1.000</td></tr>
</table>

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
29	0.867	0.986	0.986	0.986	0.986	1.000	0.991	1.000	1.000	1.000	1.000	1.000	0.503	0.573	0.573	0.573	0.573	1.000
30	0.062	0.092	0.092	0.092	0.322	0.607	0.207	0.308	0.308	0.308	1.000	0.607	0.014	0.020	0.020	0.020	0.071	0.607
31	0.054	0.081	0.081	0.081	0.288	0.560	0.184	0.275	0.275	0.275	0.979	0.560	0.012	0.018	0.018	0.018	0.064	0.560
32	0.046	0.068	0.068	0.068	0.250	0.500	0.157	0.234	0.234	0.234	0.858	0.500	0.010	0.015	0.015	0.015	0.055	0.500
33	0.719	0.874	0.874	0.874	0.877	0.994	0.976	1.000	1.000	1.000	1.000	0.994	0.294	0.358	0.358	0.358	0.359	0.994
34	0.500	0.678	0.678	0.678	0.682	0.937	0.869	1.000	1.000	1.000	1.000	0.937	0.173	0.235	0.235	0.235	0.237	0.937
35	0.923	0.993	0.993	0.993	0.993	1.000	0.996	1.000	1.000	1.000	1.000	1.000	0.639	0.688	0.688	0.688	0.688	1.000
36	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.011	0.011	0.011	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000	0.000	0.000	0.133	0.133	0.133	0.133	0.133	0.000	0.003	0.003	0.003	0.003	0.003	0.000
38	0.000	0.000	0.000	0.000	0.000	0.000	0.232	0.232	0.232	0.232	0.232	0.000	0.024	0.024	0.024	0.024	0.024	0.000
39	0.036	0.101	0.101	0.101	0.635	0.912	0.305	0.858	0.858	0.858	1.000	1.000	0.002	0.006	0.006	0.006	0.035	0.912
40	0.024	0.069	0.069	0.069	0.490	0.803	0.216	0.615	0.615	0.615	1.000	1.000	0.001	0.004	0.004	0.004	0.027	0.803
41	0.047	0.132	0.132	0.132	0.737	0.960	0.382	1.000	1.000	1.000	1.000	0.960	0.003	0.007	0.007	0.007	0.041	0.960
42	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
43	0.019	0.055	0.055	0.055	0.414	0.724	0.175	0.501	0.501	0.501	1.000	0.724	0.001	0.003	0.003	0.003	0.023	0.724
44	0.008	0.023	0.023	0.023	0.250	0.500	0.076	0.219	0.219	0.219	1.000	0.500	0.000	0.001	0.001	0.001	0.014	0.500
45	0.929	0.994	0.994	0.994	0.994	1.000	0.996	1.000	1.000	1.000	1.000	1.000	0.652	0.698	0.698	0.698	0.698	1.000
46	0.612	0.943	0.943	0.943	0.943	1.000	0.962	1.000	1.000	1.000	1.000	1.000	0.166	0.256	0.256	0.256	0.256	1.000
47	0.079	0.205	0.205	0.205	1.000	1.000	0.330	0.854	0.854	0.854	1.000	1.000	0.010	0.027	0.027	0.027	0.132	1.000
48	0.605	0.939	0.939	0.939	0.939	1.000	0.960	1.000	1.000	1.000	1.000	1.000	0.164	0.254	0.254	0.254	0.254	1.000
49	0.090	0.231	0.231	0.231	1.000	1.000	0.367	0.942	0.942	0.942	1.000	1.000	0.012	0.031	0.031	0.031	0.133	1.000
50	0.888	0.991	0.991	0.991	0.991	1.000	0.994	1.000	1.000	1.000	1.000	1.000	0.532	0.593	0.593	0.593	0.593	1.000
51	0.096	0.246	0.246	0.246	1.000	1.000	0.388	0.991	0.991	0.991	1.000	1.000	0.013	0.033	0.033	0.033	0.133	1.000
52	0.900	0.993	0.993	0.993	0.993	1.000	0.995	1.000	1.000	1.000	1.000	1.000	0.550	0.607	0.607	0.607	0.607	1.000
53	0.076	0.198	0.198	0.198	1.000	1.000	0.319	0.829	0.829	0.829	1.000	1.000	0.010	0.026	0.026	0.026	0.132	1.000
54	0.001	0.002	0.002	0.002	0.250	0.500	0.011	0.025	0.025	0.025	1.000	0.500	0.000	0.000	0.000	0.000	0.011	0.500
55	0.024	0.059	0.059	0.059	0.304	0.583	0.166	0.418	0.418	0.418	1.000	0.583	0.002	0.005	0.005	0.005	0.024	0.583
56	0.037	0.092	0.092	0.092	0.436	0.748	0.248	0.620	0.620	0.620	1.000	0.748	0.003	0.007	0.007	0.007	0.034	0.748
57	0.009	0.023	0.023	0.023	0.250	0.500	0.066	0.169	0.169	0.169	1.000	0.500	0.001	0.002	0.002	0.002	0.019	0.500

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
58	0.001	0.002	0.002	0.002	0.250	0.500	0.012	0.027	0.027	0.027	1.000	0.500	0.000	0.000	0.000	0.000	0.011	0.500
59	0.028	0.071	0.071	0.071	0.354	0.652	0.196	0.494	0.494	0.494	1.000	0.652	0.002	0.006	0.006	0.006	0.028	0.652
60	0.000	0.001	0.001	0.001	0.500	1.000	0.004	0.010	0.010	0.010	1.000	1.000	0.000	0.000	0.000	0.000	0.022	1.000
61	0.605	0.939	0.939	0.939	0.939	1.000	0.960	1.000	1.000	1.000	1.000	1.000	0.163	0.254	0.254	0.254	0.254	1.000
62	0.608	0.941	0.941	0.941	0.941	1.000	0.961	1.000	1.000	1.000	1.000	1.000	0.165	0.255	0.255	0.255	0.255	1.000
63	0.038	0.103	0.103	0.103	1.000	1.000	0.172	0.463	0.463	0.463	1.000	1.000	0.005	0.013	0.013	0.013	0.130	1.000
64	0.002	0.005	0.005	0.005	0.687	1.000	0.031	0.070	0.070	0.070	1.000	1.000	0.000	0.000	0.000	0.000	0.031	1.000
65	0.000	0.001	0.001	0.001	0.500	1.000	0.003	0.007	0.007	0.007	1.000	1.000	0.000	0.000	0.000	0.000	0.019	1.000
66	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.032	0.032	0.032	0.032	0.000	0.000	0.000	0.000	0.000	0.000	0.000
68	0.000	0.000	0.000	0.000	0.000	0.000	0.090	0.090	0.090	0.090	0.090	0.000	0.000	0.000	0.000	0.000	0.000	0.000
69	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
71	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
72	0.395	0.663	0.663	0.663	0.663	1.000	0.768	1.000	1.000	1.000	1.000	1.000	0.124	0.208	0.208	0.208	0.208	1.000
73	0.082	0.169	0.169	0.169	0.500	1.000	0.220	0.453	0.453	0.453	1.000	1.000	0.022	0.046	0.046	0.046	0.136	1.000
74	0.378	0.588	0.588	0.588	1.000	1.000	0.843	1.000	1.000	1.000	1.000	1.000	0.086	0.133	0.133	0.133	0.227	1.000
75	0.772	0.937	0.937	0.937	1.000	1.000	0.997	1.000	1.000	1.000	1.000	1.000	0.244	0.296	0.296	0.296	0.315	1.000
76	0.544	0.770	0.770	0.770	1.000	1.000	0.953	1.000	1.000	1.000	1.000	1.000	0.138	0.195	0.195	0.195	0.253	1.000
77	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000
78	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.017	0.017	0.017	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000
79	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80	0.003	0.006	0.006	0.006	0.500	1.000	0.015	0.026	0.026	0.026	1.000	1.000	0.000	0.001	0.001	0.001	0.059	1.000
81	0.394	0.589	0.589	0.589	1.000	1.000	0.826	1.000	1.000	1.000	1.000	1.000	0.103	0.155	0.155	0.155	0.262	1.000
82	0.611	0.814	0.814	0.814	1.000	1.000	0.963	1.000	1.000	1.000	1.000	1.000	0.186	0.248	0.248	0.248	0.304	1.000
83	0.008	0.010	0.010	0.010	0.963	1.000	0.061	0.074	0.074	0.074	1.000	1.000	0.001	0.001	0.001	0.001	0.089	1.000
84	0.684	0.871	0.871	0.871	1.000	1.000	0.982	1.000	1.000	1.000	1.000	1.000	0.222	0.283	0.283	0.283	0.324	1.000
85	0.005	0.006	0.006	0.006	0.878	0.994	0.039	0.048	0.048	0.048	1.000	1.000	0.000	0.001	0.001	0.001	0.081	0.994
86	0.748	0.914	0.914	0.914	1.000	1.000	0.992	1.000	1.000	1.000	1.000	1.000	0.260	0.317	0.317	0.317	0.347	1.000

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
87	0.004	0.004	0.004	0.004	0.774	0.972	0.028	0.034	0.034	0.034	1.000	1.000	0.000	0.000	0.000	0.000	0.071	0.972
88	0.324	0.501	0.501	0.501	1.000	1.000	0.745	1.000	1.000	1.000	1.000	1.000	0.082	0.126	0.126	0.126	0.252	1.000
89	0.005	0.007	0.007	0.007	0.895	0.996	0.042	0.051	0.051	0.051	1.000	1.000	0.000	0.001	0.001	0.001	0.082	0.996
90	0.460	0.666	0.666	0.666	1.000	1.000	0.884	1.000	1.000	1.000	1.000	1.000	0.126	0.182	0.182	0.182	0.273	1.000
91	0.353	0.538	0.538	0.538	1.000	1.000	0.781	1.000	1.000	1.000	1.000	1.000	0.090	0.138	0.138	0.138	0.256	1.000
92	0.002	0.002	0.002	0.002	1.000	1.000	0.015	0.018	0.018	0.018	1.000	1.000	0.000	0.000	0.000	0.000	0.092	1.000
93	0.140	0.235	0.235	0.235	1.000	1.000	0.410	0.688	0.688	0.688	1.000	1.000	0.032	0.054	0.054	0.054	0.231	1.000
94	0.007	0.008	0.008	0.008	0.942	0.999	0.053	0.064	0.064	0.064	1.000	1.000	0.001	0.001	0.001	0.001	0.087	0.999
95	0.131	0.221	0.221	0.221	1.000	1.000	0.387	0.653	0.653	0.653	1.000	1.000	0.030	0.051	0.051	0.051	0.230	1.000
96	0.456	0.660	0.660	0.660	1.000	1.000	0.880	1.000	1.000	1.000	1.000	1.000	0.124	0.180	0.180	0.180	0.272	1.000
97	0.833	0.958	0.958	0.958	1.000	1.000	0.998	1.000	1.000	1.000	1.000	1.000	0.322	0.371	0.371	0.371	0.387	1.000
98	0.011	0.013	0.013	0.013	0.989	1.000	0.083	0.101	0.101	0.101	1.000	1.000	0.001	0.001	0.001	0.001	0.091	1.000
99	0.003	0.004	0.004	0.004	0.730	0.957	0.025	0.030	0.030	0.030	1.000	1.000	0.000	0.000	0.000	0.000	0.067	0.957
100	0.007	0.008	0.008	0.008	0.947	0.999	0.055	0.066	0.066	0.066	1.000	1.000	0.001	0.001	0.001	0.001	0.087	0.999
101	0.004	0.005	0.005	0.005	0.843	0.989	0.035	0.042	0.042	0.042	1.000	1.000	0.000	0.000	0.000	0.000	0.078	0.989
102	0.683	0.870	0.870	0.870	1.000	1.000	0.982	1.000	1.000	1.000	1.000	1.000	0.221	0.282	0.282	0.282	0.324	1.000
103	0.484	0.691	0.691	0.691	1.000	1.000	0.901	1.000	1.000	1.000	1.000	1.000	0.134	0.192	0.192	0.192	0.277	1.000
104	0.009	0.010	0.010	0.010	1.000	1.000	0.067	0.081	0.081	0.081	1.000	1.000	0.001	0.001	0.001	0.001	0.092	1.000
105	0.506	0.714	0.714	0.714	1.000	1.000	0.915	1.000	1.000	1.000	1.000	1.000	0.142	0.201	0.201	0.201	0.281	1.000
106	0.008	0.010	0.010	0.010	0.971	1.000	0.066	0.079	0.079	0.079	1.000	1.000	0.001	0.001	0.001	0.001	0.090	1.000
107	0.003	0.004	0.004	0.004	0.766	0.970	0.027	0.033	0.033	0.033	1.000	1.000	0.000	0.000	0.000	0.000	0.070	0.970
108	0.387	0.581	0.581	0.581	1.000	1.000	0.819	1.000	1.000	1.000	1.000	1.000	0.101	0.152	0.152	0.152	0.261	0.000
109	0.272	0.431	0.431	0.431	1.000	1.000	0.670	1.000	1.000	1.000	1.000	1.000	0.067	0.106	0.106	0.106	0.246	1.000
110	0.422	0.622	0.622	0.622	1.000	1.000	0.852	1.000	1.000	1.000	1.000	1.000	0.112	0.166	0.166	0.166	0.267	1.000
111	0.039	0.063	0.063	0.063	0.375	0.678	0.168	0.270	0.270	0.270	1.000	1.000	0.006	0.010	0.010	0.010	0.062	0.678
112	0.039	0.068	0.068	0.068	0.250	0.500	0.128	0.225	0.225	0.225	0.832	1.000	0.009	0.015	0.015	0.015	0.055	0.500
113	0.005	0.008	0.008	0.008	0.250	0.500	0.007	0.012	0.012	0.012	0.368	0.500	0.000	0.000	0.000	0.000	0.013	0.500
114	0.007	0.012	0.012	0.012	0.250	0.500	0.033	0.054	0.054	0.054	1.000	1.000	0.001	0.002	0.002	0.002	0.041	0.500
115	0.000	0.000	0.000	0.000	0.000	0.000	0.090	0.090	0.090	0.090	0.090	0.042	0.001	0.001	0.001	0.001	0.001	0.000

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)				Pf (Breach|No Overtopping)		Pf(Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
116	0.015	0.024	0.024	0.024	0.250	0.500	0.067	0.108	0.108	0.108	1.000	1.000	0.002	0.004	0.004	0.004	0.041	0.500
117	0.226	0.365	0.365	0.365	0.476	0.789	0.591	0.956	0.956	0.956	1.000	1.000	0.054	0.088	0.088	0.088	0.114	0.789
118	0.311	0.484	0.484	0.484	0.610	0.897	0.728	1.000	1.000	1.000	1.000	1.000	0.078	0.121	0.121	0.121	0.153	0.897
119	0.396	0.591	0.591	0.591	0.720	0.954	0.828	1.000	1.000	1.000	1.000	1.000	0.104	0.155	0.155	0.155	0.189	0.954
120	0.032	0.052	0.052	0.052	0.319	0.604	0.140	0.225	0.225	0.225	1.000	1.000	0.005	0.009	0.009	0.009	0.052	0.604
121	0.307	0.479	0.479	0.479	0.604	0.893	0.722	1.000	1.000	1.000	1.000	1.000	0.077	0.120	0.120	0.120	0.151	0.893
122	0.455	0.660	0.660	0.660	0.785	0.975	0.880	1.000	1.000	1.000	1.000	1.000	0.124	0.180	0.180	0.180	0.214	0.975
123	0.195	0.319	0.319	0.319	0.421	0.732	0.530	0.870	0.870	0.870	1.000	1.000	0.046	0.076	0.076	0.076	0.100	0.732
124	0.006	0.009	0.009	0.009	0.250	0.500	0.026	0.042	0.042	0.042	1.000	1.000	0.001	0.001	0.001	0.001	0.041	0.500
125	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.023	0.023	0.023	0.023	0.023	0.000	0.000	0.000	0.000	0.000	0.000
126	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.043	0.043	0.043	0.043	0.043	0.001	0.001	0.001	0.001	0.001	0.000
127	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016	0.016	0.016	0.000	0.000	0.000	0.000	0.000	0.000
128	0.475	0.682	0.682	0.682	1.000	1.000	0.895	1.000	1.000	1.000	1.000	1.000	0.131	0.188	0.188	0.188	0.276	0.980
129	0.633	0.831	0.831	0.831	1.000	1.000	0.970	1.000	1.000	1.000	1.000	1.000	0.196	0.258	0.258	0.258	0.310	1.000
130	0.000	0.000	0.000	0.000	1.000	1.000	0.001	0.001	0.001	0.001	1.000	1.000	0.000	0.000	0.000	0.000	0.084	1.000
131	0.000	0.000	0.000	0.000	0.000	0.000	0.028	0.028	0.028	0.028	0.028	0.000	0.000	0.000	0.000	0.000	0.000	0.000
132	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.001	0.001	0.001	0.001	1.000	0.000	0.000	0.000	0.000	0.000	0.500
133	0.109	0.185	0.185	0.185	1.000	1.000	0.331	0.563	0.563	0.563	1.000	0.503	0.025	0.042	0.042	0.042	0.228	0.503
134	0.217	0.352	0.352	0.352	1.000	1.000	0.574	0.933	0.933	0.933	1.000	1.000	0.052	0.084	0.084	0.084	0.239	1.000
135	0.000	0.000	0.000	0.000	1.000	1.000	0.001	0.001	0.001	0.001	1.000	1.000	0.000	0.000	0.000	0.000	0.091	1.000

Table B-2. 2007 Levee Fragility Uncertainty Results

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
1	0.012	0.019	0.019	0.019	0.019	1.000	0.053	0.085	0.085	0.085	0.085	1.000	0.002	0.003	0.003	0.003	0.003	1.000
2	0.001	0.001	0.001	0.001	1.000	1.000	0.001	0.002	0.002	0.002	1.000	1.000	0.000	0.000	0.000	0.000	0.029	1.000
3	0.003	0.018	0.018	0.018	0.018	1.000	0.018	0.104	0.104	0.104	0.104	1.000	0.000	0.002	0.002	0.002	0.002	1.000
4	0.052	0.090	0.090	0.090	1.000	1.000	0.169	0.294	0.294	0.294	1.000	1.000	0.011	0.020	0.020	0.020	0.222	1.000
5	0.011	0.018	0.018	0.018	0.018	1.000	0.050	0.081	0.081	0.081	0.081	1.000	0.002	0.003	0.003	0.003	0.003	1.000
6	0.353	0.538	0.538	0.538	1.000	1.000	0.781	1.000	1.000	1.000	1.000	1.000	0.090	0.138	0.138	0.138	0.256	1.000
7	0.007	0.012	0.012	0.012	0.012	1.000	0.033	0.053	0.053	0.053	0.053	1.000	0.001	0.002	0.002	0.002	0.002	1.000
8	0.060	0.104	0.104	0.104	1.000	1.000	0.195	0.338	0.338	0.338	1.000	1.000	0.013	0.023	0.023	0.023	0.223	1.000
9	0.527	0.736	0.736	0.736	1.000	1.000	0.927	1.000	1.000	1.000	1.000	1.000	0.151	0.210	0.210	0.210	0.286	1.000
10	0.124	0.210	0.210	0.210	1.000	1.000	0.371	0.627	0.627	0.627	1.000	1.000	0.028	0.048	0.048	0.048	0.229	1.000
11	0.262	0.417	0.417	0.417	1.000	1.000	0.653	1.000	1.000	1.000	1.000	1.000	0.064	0.102	0.102	0.102	0.244	1.000
12	0.184	0.303	0.303	0.303	1.000	1.000	0.508	0.837	0.837	0.837	1.000	1.000	0.043	0.071	0.071	0.071	0.235	1.000
13	0.189	0.310	0.310	0.310	1.000	1.000	0.518	0.852	0.852	0.852	1.000	1.000	0.045	0.073	0.073	0.073	0.236	1.000
14	0.058	0.100	0.100	0.100	1.000	1.000	0.188	0.326	0.326	0.326	1.000	1.000	0.013	0.022	0.022	0.022	0.223	1.000
15	0.097	0.165	0.165	0.165	1.000	1.000	0.299	0.511	0.511	0.511	1.000	1.000	0.022	0.037	0.037	0.037	0.227	1.000
16	0.257	0.410	0.410	0.410	1.000	1.000	0.646	1.000	1.000	1.000	1.000	1.000	0.063	0.100	0.100	0.100	0.244	1.000
17	0.214	0.348	0.348	0.348	1.000	1.000	0.568	0.925	0.925	0.925	1.000	1.000	0.051	0.083	0.083	0.083	0.239	1.000
18	0.051	0.082	0.082	0.082	0.082	1.000	0.215	0.345	0.345	0.345	0.345	1.000	0.008	0.014	0.014	0.014	0.014	1.000
19	0.045	0.072	0.072	0.072	0.072	1.000	0.189	0.304	0.304	0.304	0.304	1.000	0.007	0.012	0.012	0.012	0.012	1.000
20	0.165	0.274	0.274	0.274	1.000	1.000	0.467	0.775	0.775	0.775	1.000	1.000	0.038	0.064	0.064	0.064	0.233	1.000
21	0.027	0.043	0.043	0.043	0.043	1.000	0.117	0.189	0.189	0.189	0.189	1.000	0.004	0.007	0.007	0.007	0.007	1.000
22	0.023	0.040	0.040	0.040	1.000	1.000	0.030	0.053	0.053	0.053	1.000	1.000	0.002	0.003	0.003	0.003	0.085	1.000
23	0.294	0.462	0.462	0.462	1.000	1.000	0.704	1.000	1.000	1.000	1.000	1.000	0.073	0.115	0.115	0.115	0.248	1.000
24	0.014	0.023	0.023	0.023	0.023	1.000	0.063	0.103	0.103	0.103	0.103	1.000	0.002	0.004	0.004	0.004	0.004	1.000
25	0.071	0.122	0.122	0.122	1.000	1.000	0.226	0.391	0.391	0.391	1.000	1.000	0.016	0.027	0.027	0.027	0.224	1.000
26	0.008	0.013	0.013	0.013	0.013	1.000	0.036	0.059	0.059	0.059	0.059	1.000	0.001	0.002	0.002	0.002	0.002	1.000
27	0.061	0.105	0.105	0.105	1.000	1.000	0.196	0.341	0.341	0.341	1.000	1.000	0.014	0.023	0.023	0.023	0.223	1.000

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
28	0.089	0.153	0.153	0.153	1.000	1.000	0.278	0.477	0.477	0.477	1.000	1.000	0.020	0.035	0.035	0.035	0.226	1.000
29	0.867	0.986	0.986	0.986	0.986	1.000	0.991	1.000	1.000	1.000	1.000	1.000	0.503	0.573	0.573	0.573	0.573	1.000
30	0.062	0.092	0.092	0.092	0.322	0.607	0.207	0.308	0.308	0.308	1.000	0.607	0.014	0.020	0.020	0.020	0.071	0.607
31	0.054	0.081	0.081	0.081	0.288	0.560	0.184	0.275	0.275	0.275	0.979	0.560	0.012	0.018	0.018	0.018	0.064	0.560
32	0.046	0.068	0.068	0.068	0.250	0.500	0.157	0.234	0.234	0.234	0.858	0.500	0.010	0.015	0.015	0.015	0.055	0.500
33	0.719	0.874	0.874	0.874	0.877	0.994	0.976	1.000	1.000	1.000	1.000	0.994	0.294	0.358	0.358	0.358	0.359	0.994
34	0.500	0.678	0.678	0.678	0.682	0.937	0.869	1.000	1.000	1.000	1.000	0.937	0.173	0.235	0.235	0.235	0.237	0.937
35	0.923	0.993	0.993	0.993	0.993	1.000	0.996	1.000	1.000	1.000	1.000	1.000	0.639	0.688	0.688	0.688	0.688	1.000
36	0.000	0.000	0.000	0.000	0.000	0.000	0.011	0.011	0.011	0.011	0.011	0.000	0.000	0.000	0.000	0.000	0.000	0.000
37	0.000	0.000	0.000	0.000	0.000	0.000	0.133	0.133	0.133	0.133	0.133	0.000	0.003	0.003	0.003	0.003	0.003	0.000
38	0.000	0.000	0.000	0.000	0.000	0.000	0.232	0.232	0.232	0.232	0.232	0.000	0.024	0.024	0.024	0.024	0.024	0.000
39	0.036	0.101	0.101	0.101	0.635	0.912	0.305	0.858	0.858	0.858	1.000	0.912	0.002	0.006	0.006	0.006	0.035	0.912
40	0.024	0.069	0.069	0.069	0.490	0.803	0.216	0.615	0.615	0.615	1.000	0.803	0.001	0.004	0.004	0.004	0.027	0.803
41	0.047	0.132	0.132	0.132	0.737	0.960	0.382	1.000	1.000	1.000	1.000	0.960	0.003	0.007	0.007	0.007	0.041	0.960
42	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
43	0.019	0.055	0.055	0.055	0.414	0.724	0.175	0.501	0.501	0.501	1.000	0.724	0.001	0.003	0.003	0.003	0.023	0.724
44	0.008	0.023	0.023	0.023	0.250	0.500	0.076	0.219	0.219	0.219	1.000	0.500	0.000	0.001	0.001	0.001	0.014	0.500
45	0.727	0.980	0.980	0.980	0.980	1.000	0.989	1.000	1.000	1.000	1.000	1.000	0.221	0.298	0.298	0.298	0.298	1.000
46	0.612	0.943	0.943	0.943	0.943	1.000	0.962	1.000	1.000	1.000	1.000	1.000	0.166	0.256	0.256	0.256	0.256	1.000
47	0.079	0.205	0.205	0.205	1.000	1.000	0.330	0.854	0.854	0.854	1.000	1.000	0.010	0.027	0.027	0.027	0.132	1.000
48	0.605	0.939	0.939	0.939	0.939	1.000	0.960	1.000	1.000	1.000	1.000	1.000	0.164	0.254	0.254	0.254	0.254	1.000
49	0.090	0.231	0.231	0.231	1.000	1.000	0.367	0.942	0.942	0.942	1.000	1.000	0.012	0.031	0.031	0.031	0.133	1.000
50	0.710	0.976	0.976	0.976	0.976	1.000	0.986	1.000	1.000	1.000	1.000	1.000	0.212	0.291	0.291	0.291	0.291	1.000
51	0.096	0.246	0.246	0.246	1.000	1.000	0.388	0.991	0.991	0.991	1.000	1.000	0.013	0.033	0.033	0.033	0.133	1.000
52	0.728	0.980	0.980	0.980	0.980	1.000	0.989	1.000	1.000	1.000	1.000	1.000	0.222	0.298	0.298	0.298	0.298	1.000
53	0.076	0.198	0.198	0.198	1.000	1.000	0.319	0.829	0.829	0.829	1.000	1.000	0.010	0.026	0.026	0.026	0.132	1.000
54	0.001	0.002	0.002	0.002	0.002	0.500	0.011	0.025	0.025	0.025	0.025	0.500	0.000	0.000	0.000	0.000	0.000	0.500
55	0.024	0.059	0.059	0.059	0.304	0.583	0.166	0.418	0.418	0.418	1.000	0.583	0.002	0.005	0.005	0.005	0.024	0.583
56	0.037	0.092	0.092	0.092	0.436	0.748	0.248	0.620	0.620	0.620	1.000	0.748	0.003	0.007	0.007	0.007	0.034	0.748

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
57	0.009	0.023	0.023	0.023	0.250	0.500	0.066	0.169	0.169	0.169	1.000	0.500	0.001	0.002	0.002	0.002	0.019	0.500
58	0.001	0.002	0.002	0.002	0.002	0.500	0.012	0.027	0.027	0.027	0.027	0.500	0.000	0.000	0.000	0.000	0.000	0.500
59	0.028	0.071	0.071	0.071	0.354	0.652	0.196	0.494	0.494	0.494	1.000	0.652	0.002	0.006	0.006	0.006	0.028	0.652
60	0.000	0.001	0.001	0.001	0.001	1.000	0.004	0.010	0.010	0.010	0.010	1.000	0.000	0.000	0.000	0.000	0.000	1.000
61	0.605	0.939	0.939	0.939	0.939	1.000	0.960	1.000	1.000	1.000	1.000	1.000	0.163	0.254	0.254	0.254	0.254	1.000
62	0.608	0.941	0.941	0.941	0.941	1.000	0.961	1.000	1.000	1.000	1.000	1.000	0.165	0.255	0.255	0.255	0.255	1.000
63	0.017	0.049	0.049	0.049	0.049	1.000	0.096	0.278	0.278	0.278	0.278	1.000	0.002	0.005	0.005	0.005	0.005	1.000
64	0.002	0.005	0.005	0.005	0.005	1.000	0.031	0.070	0.070	0.070	0.070	1.000	0.000	0.000	0.000	0.000	0.000	1.000
65	0.000	0.001	0.001	0.001	0.001	1.000	0.003	0.007	0.007	0.007	0.007	1.000	0.000	0.000	0.000	0.000	0.000	1.000
66	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
67	0.000	0.000	0.000	0.000	0.000	0.000	0.032	0.032	0.032	0.032	0.032	0.000	0.000	0.000	0.000	0.000	0.000	0.000
68	0.000	0.000	0.000	0.000	0.000	0.000	0.090	0.090	0.090	0.090	0.090	0.000	0.000	0.000	0.000	0.000	0.000	0.000
69	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
70	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
71	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
72	0.395	0.663	0.663	0.663	0.663	1.000	0.768	1.000	1.000	1.000	1.000	1.000	0.124	0.208	0.208	0.208	0.208	1.000
73	0.082	0.169	0.169	0.169	0.169	1.000	0.220	0.453	0.453	0.453	0.453	1.000	0.022	0.046	0.046	0.046	0.046	1.000
74	0.378	0.588	0.588	0.588	1.000	1.000	0.843	1.000	1.000	1.000	1.000	1.000	0.086	0.133	0.133	0.133	0.227	1.000
75	0.772	0.937	0.937	0.937	1.000	1.000	0.997	1.000	1.000	1.000	1.000	1.000	0.244	0.296	0.296	0.296	0.315	1.000
76	0.544	0.770	0.770	0.770	1.000	1.000	0.953	1.000	1.000	1.000	1.000	1.000	0.138	0.195	0.195	0.195	0.253	1.000
77	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000
78	0.000	0.000	0.000	0.000	0.000	0.000	0.017	0.017	0.017	0.017	0.017	0.000	0.000	0.000	0.000	0.000	0.000	0.000
79	0.000	0.000	0.000	0.000	0.000	0.000	0.010	0.010	0.010	0.010	0.010	0.000	0.000	0.000	0.000	0.000	0.000	0.000
80	0.003	0.006	0.006	0.006	0.500	1.000	0.015	0.026	0.026	0.026	1.000	1.000	0.000	0.001	0.001	0.001	0.059	1.000
81	0.394	0.589	0.589	0.589	1.000	1.000	0.826	1.000	1.000	1.000	1.000	1.000	0.103	0.155	0.155	0.155	0.262	1.000
82	0.611	0.814	0.814	0.814	1.000	1.000	0.963	1.000	1.000	1.000	1.000	1.000	0.186	0.248	0.248	0.248	0.304	1.000
83	0.008	0.010	0.010	0.010	0.963	1.000	0.061	0.074	0.074	0.074	1.000	1.000	0.001	0.001	0.001	0.001	0.089	1.000
84	0.684	0.871	0.871	0.871	1.000	1.000	0.982	1.000	1.000	1.000	1.000	1.000	0.222	0.283	0.283	0.283	0.324	1.000
85	0.005	0.006	0.006	0.006	0.878	0.994	0.039	0.048	0.048	0.048	1.000	0.994	0.000	0.001	0.001	0.001	0.081	0.994

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
86	0.748	0.914	0.914	0.914	1.000	1.000	0.992	1.000	1.000	1.000	1.000	1.000	0.260	0.317	0.317	0.317	0.347	1.000
87	0.004	0.004	0.004	0.004	0.774	0.972	0.028	0.034	0.034	0.034	1.000	0.972	0.000	0.000	0.000	0.000	0.071	0.972
88	0.324	0.501	0.501	0.501	1.000	1.000	0.745	1.000	1.000	1.000	1.000	1.000	0.082	0.126	0.126	0.126	0.252	1.000
89	0.005	0.007	0.007	0.007	0.895	0.996	0.042	0.051	0.051	0.051	1.000	0.996	0.000	0.001	0.001	0.001	0.082	0.996
90	0.460	0.666	0.666	0.666	1.000	1.000	0.884	1.000	1.000	1.000	1.000	1.000	0.126	0.182	0.182	0.182	0.273	1.000
91	0.353	0.538	0.538	0.538	1.000	1.000	0.781	1.000	1.000	1.000	1.000	1.000	0.090	0.138	0.138	0.138	0.256	1.000
92	0.002	0.002	0.002	0.002	1.000	1.000	0.015	0.018	0.018	0.018	1.000	1.000	0.000	0.000	0.000	0.000	0.092	1.000
93	0.140	0.235	0.235	0.235	1.000	1.000	0.410	0.688	0.688	0.688	1.000	1.000	0.032	0.054	0.054	0.054	0.231	1.000
94	0.007	0.008	0.008	0.008	0.942	0.999	0.053	0.064	0.064	0.064	1.000	0.999	0.001	0.001	0.001	0.001	0.087	0.999
95	0.131	0.221	0.221	0.221	1.000	1.000	0.387	0.653	0.653	0.653	1.000	1.000	0.030	0.051	0.051	0.051	0.230	1.000
96	0.456	0.660	0.660	0.660	1.000	1.000	0.880	1.000	1.000	1.000	1.000	1.000	0.124	0.180	0.180	0.180	0.272	1.000
97	0.833	0.958	0.958	0.958	1.000	1.000	0.998	1.000	1.000	1.000	1.000	1.000	0.322	0.371	0.371	0.371	0.387	1.000
98	0.011	0.013	0.013	0.013	0.989	1.000	0.083	0.101	0.101	0.101	1.000	1.000	0.001	0.001	0.001	0.001	0.091	1.000
99	0.003	0.004	0.004	0.004	0.730	0.957	0.025	0.030	0.030	0.030	1.000	0.957	0.000	0.000	0.000	0.000	0.067	0.957
100	0.007	0.008	0.008	0.008	0.947	0.999	0.055	0.066	0.066	0.066	1.000	0.999	0.001	0.001	0.001	0.001	0.087	0.999
101	0.004	0.005	0.005	0.005	0.843	0.989	0.035	0.042	0.042	0.042	1.000	0.989	0.000	0.000	0.000	0.000	0.078	0.989
102	0.683	0.870	0.870	0.870	1.000	1.000	0.982	1.000	1.000	1.000	1.000	1.000	0.221	0.282	0.282	0.282	0.324	1.000
103	0.484	0.691	0.691	0.691	1.000	1.000	0.901	1.000	1.000	1.000	1.000	1.000	0.134	0.192	0.192	0.192	0.277	1.000
104	0.009	0.010	0.010	0.010	1.000	1.000	0.067	0.081	0.081	0.081	1.000	1.000	0.001	0.001	0.001	0.001	0.092	1.000
105	0.506	0.714	0.714	0.714	1.000	1.000	0.915	1.000	1.000	1.000	1.000	1.000	0.142	0.201	0.201	0.201	0.281	1.000
106	0.008	0.010	0.010	0.010	0.971	1.000	0.066	0.079	0.079	0.079	1.000	1.000	0.001	0.001	0.001	0.001	0.090	1.000
107	0.003	0.004	0.004	0.004	0.766	0.970	0.027	0.033	0.033	0.033	1.000	0.970	0.000	0.000	0.000	0.000	0.070	0.970
108	0.387	0.581	0.581	0.581	1.000	1.000	0.819	0.819	0.819	0.819	0.819	1.000	0.101	0.101	0.101	0.101	0.101	1.000
109	0.272	0.431	0.431	0.431	1.000	1.000	0.670	1.000	1.000	1.000	1.000	1.000	0.067	0.106	0.106	0.106	0.246	1.000
110	0.422	0.622	0.622	0.622	1.000	1.000	0.852	1.000	1.000	1.000	1.000	1.000	0.112	0.166	0.166	0.166	0.267	1.000
111	0.039	0.063	0.063	0.063	0.375	0.678	0.168	0.270	0.270	0.270	1.000	0.678	0.006	0.010	0.010	0.010	0.062	0.678
112	0.039	0.068	0.068	0.068	0.250	0.500	0.128	0.225	0.225	0.225	0.832	0.500	0.009	0.015	0.015	0.015	0.055	0.500
113	0.005	0.008	0.008	0.008	0.250	0.500	0.007	0.012	0.012	0.012	0.368	0.500	0.000	0.000	0.000	0.000	0.013	0.500
114	0.007	0.012	0.012	0.012	0.250	0.500	0.033	0.054	0.054	0.054	1.000	0.500	0.001	0.002	0.002	0.002	0.041	0.500

Reach	Median Curve P(x)=0.63						0.95 Curve P(x)=0.185						0.05 Curve P(x)=0.185					
	Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)				Pf Fragility Curve (Breach|No Overtopping)		Pf Fragility Curve (Breach|Overtopping)			
	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft	Design Elev. (L) 6ft from TOW (W)	Top of Levee/Top of Wall	1/2 ft	1 ft	2 ft	3 ft
115	0.000	0.000	0.000	0.000	0.000	0.000	0.090	0.090	0.090	0.090	0.090	0.000	0.001	0.001	0.001	0.001	0.001	0.000
116	0.015	0.024	0.024	0.024	0.250	0.500	0.067	0.108	0.108	0.108	1.000	0.500	0.002	0.004	0.004	0.004	0.041	0.500
117	0.226	0.365	0.365	0.365	0.476	0.789	0.591	0.956	0.956	0.956	1.000	0.789	0.054	0.088	0.088	0.088	0.114	0.789
118	0.311	0.484	0.484	0.484	0.610	0.897	0.728	1.000	1.000	1.000	1.000	0.897	0.078	0.121	0.121	0.121	0.153	0.897
119	0.396	0.591	0.591	0.591	0.720	0.954	0.828	1.000	1.000	1.000	1.000	0.954	0.104	0.155	0.155	0.155	0.189	0.954
120	0.032	0.052	0.052	0.052	0.319	0.604	0.140	0.225	0.225	0.225	1.000	0.604	0.005	0.009	0.009	0.009	0.052	0.604
121	0.307	0.479	0.479	0.479	0.604	0.893	0.722	1.000	1.000	1.000	1.000	0.893	0.077	0.120	0.120	0.120	0.151	0.893
122	0.455	0.660	0.660	0.660	0.785	0.975	0.880	1.000	1.000	1.000	1.000	0.975	0.124	0.180	0.180	0.180	0.214	0.975
123	0.195	0.319	0.319	0.319	0.421	0.732	0.530	0.870	0.870	0.870	1.000	0.732	0.046	0.076	0.076	0.076	0.100	0.732
124	0.006	0.009	0.009	0.009	0.250	0.500	0.026	0.042	0.042	0.042	1.000	0.500	0.001	0.001	0.001	0.001	0.041	0.500
125	0.000	0.000	0.000	0.000	0.000	0.000	0.023	0.023	0.023	0.023	0.023	0.000	0.000	0.000	0.000	0.000	0.000	0.000
126	0.000	0.000	0.000	0.000	0.000	0.000	0.043	0.043	0.043	0.043	0.043	0.000	0.001	0.001	0.001	0.001	0.001	0.000
127	0.000	0.000	0.000	0.000	0.000	0.000	0.016	0.016	0.016	0.016	0.016	0.000	0.000	0.000	0.000	0.000	0.000	0.000
128	0.475	0.682	0.682	0.682	0.804	0.980	0.895	1.000	1.000	1.000	1.000	0.980	0.131	0.188	0.188	0.188	0.222	0.980
129	0.633	0.831	0.831	0.831	1.000	1.000	0.970	1.000	1.000	1.000	1.000	1.000	0.196	0.258	0.258	0.258	0.310	1.000
130	0.000	0.000	0.000	0.000	1.000	1.000	0.001	0.001	0.001	0.001	1.000	1.000	0.000	0.000	0.000	0.000	0.084	1.000
131	0.000	0.000	0.000	0.000	0.000	0.000	0.028	0.028	0.028	0.028	0.028	0.000	0.000	0.000	0.000	0.000	0.000	0.000
132	0.000	0.000	0.000	0.000	0.250	0.500	0.001	0.001	0.001	0.001	1.000	0.500	0.000	0.000	0.000	0.000	0.021	0.500
133	0.109	0.185	0.185	0.185	0.252	0.503	0.331	0.563	0.563	0.563	0.768	0.503	0.025	0.042	0.042	0.042	0.057	0.503
134	0.217	0.352	0.352	0.352	1.000	1.000	0.574	0.933	0.933	0.933	1.000	1.000	0.052	0.084	0.084	0.084	0.239	1.000
135	0.000	0.000	0.000	0.000	1.000	1.000	0.001	0.001	0.001	0.001	1.000	1.000	0.000	0.000	0.000	0.000	0.091	1.000