ASSOCIATION OF STATE
DAM SAFETY OFFICIALS

THE JOURNAL OF Dam Safety

VOLUME 13 | ISSUE 3 | 2015

ISSN 1944-9836

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Hurricane Surge Hazard Uncertainty in Coastal Flood Protection Design

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BACKGROUND

In 1928—almost eighty years prior to Hurricane Katrina—a strong Category 4 hurricane made landfall near West Palm Beach, Florida with maximum winds of 145 miles per hour. Residents living some 40 miles or more inland from the Atlantic coast along the shores of interior Lake Okeechobee thought themselves safe from coastal surge. However, they experienced one of the most devastating surge events in U.S. history.

Lake Okeechobee (Figure 1) is the second largest freshwater lake in the lower 48 states with over 700 square miles of surface area. The lake is also very shallow with an average depth of only 9 feet. As wind setup is proportional to fetch and wind speed squared, and inversely to depth, the combination of long fetch, strong winds, and very shallow depth all contributed to a severe "tilting" of the water surface, without any "filling" of the lake from the ocean. Southward winds across Lake Okeechobee created a surge depth reportedly reaching 20 ft, overwhelming an existing dike on the south shore. After the eye passed and winds reversed direction, northward winds caused a surge on the north shore.

The surge overtopping the Lake Okeechobee dike was estimated to have resulted in over 2,500 deaths, making it the second deadliest hurricane in U.S. history. The dike was subsequently reconstructed to provide greater protection from future wind-driven tilting of Lake Okeechobee, and has been raised several times. The Herbert Hoover Dike is currently about 30 ft above the surrounding ground.

The Lake Okeechobee Hurricane of 1928 is unfortunately one of many "perfect storms" illustrating critical factors in surge physics, the occurrence of extreme events, and the cruel consequences of not fully appreciating the physics and risks. A "short list" of such hurricanes would also include Last Island (1856), Cheniere Caminada (1893), Galveston (1900), Chesapeake–Potomac (1933), Labor Day (1935), New England (1938), Hazel (1954), Carla (1961), Betsy (1965), Camille (1969), Frederic (1979), Hugo (1989), Opal (1995), Ivan (2004), Katrina (2005), Rita (2005), Ike (2008), and Sandy (2012).

INTRODUCTION

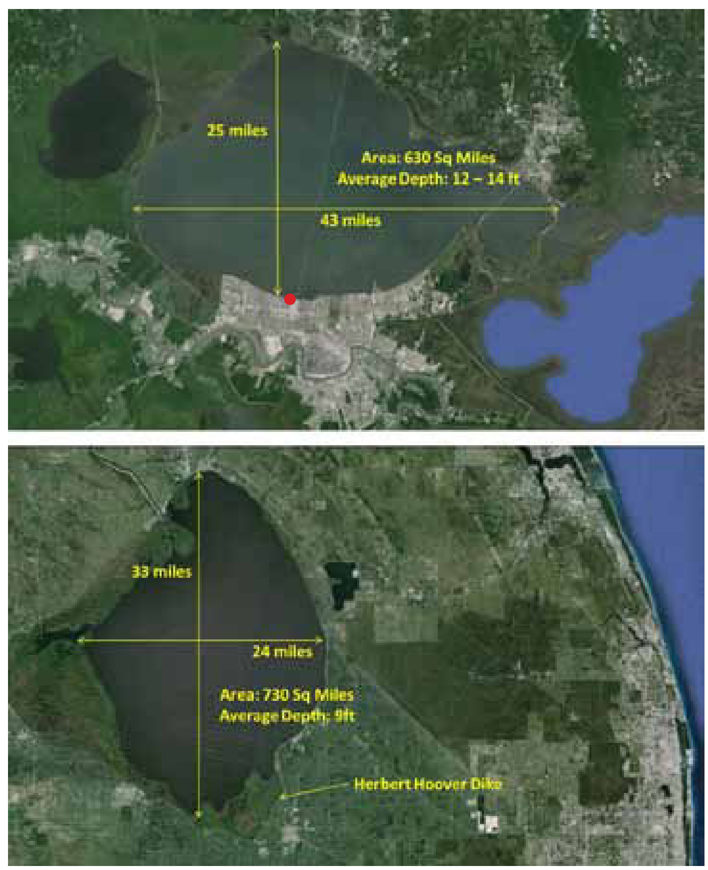

Figure 1. Lakes Okeechobee (Florida) and Pontchartrain (Louisiana)

Google Earth Imagery (same scale)

Since the founding of the earliest permanent settlements, community leaders have relied on estimates of flood likelihood to protect lives, property, and common resources. Today's hurricane surge risk managers require sound mathematical treatments of surge probabilities—the frequency of occurrence of any given *still water level* (SWL, in elevation, e.g., feet, with respect to some vertical datum, ignoring waves). Surge risk managers are less concerned with the *discrete* probability of a given SWL than the *cumulative* probability—the frequency that the given SWL is expected to occur or be exceeded. This cumulative (or return) frequency is commonly expressed using its inverse, return period, and is referred to as the surge SWL *hazard*.

The 100-year surge hazard is a fundamental benchmark for coastal property flood damage insurance under the National Flood Insurance Program (NFIP), and is the subject of extensive NFIP-sponsored investigations. For this reason, local surge risk managers often use the NFIP 100-yr SWL for a variety of other planning purposes—including a range of local structural and non-structural flood damage mitigation projects, as well as evacuation and emergency response plans to reduce loss of life.

Local surge risk managers increasingly recognize that the 100-yr hazard does not represent a particularly extreme probability when viewed over a long planning time scale: over a 30-yr period there is a 26 percent chance of such an event occurring. In addition, risk managers with broad geographic responsibilities must recognize the potential for independent surge exposures. A regional return frequency of a 100-yr event may be many multiples of one percent. Over a 30-yr period, the probability of a 100-yr surge event with four independent exposures exceeds 70 percent.

In response to a deepening appreciation for surge event probabilities, local surge risk managers are seeking estimates for more extreme events—such as for 500-yr, 1,000-yr, or even greater return periods. However, surge risk managers must also appreciate the magnitude of uncertainties in surge hazard estimates. Evaluation of overtopping uncertainty is required for NFIP accreditation of 100-yr levee systems as well as for recognition of some flood reduction for lower embankments. Moreover, it is crucial for proper consideration of residual risks, and risk reduction measures beyond the NFIP, intended to protect lives and critical community resources.

To further an understanding of surge hazard uncertainty, this paper:

- Reviews how the surge hazard curve—the SWL *cumulative distribution function* (CDF)—is constructed and discusses the evaluation of ten uncertainty factors in the SWL CDF which stem from three sources: 1) the hurricane joint probability equation; 2) the surge model; and 3) the optimized sample of synthetic storms.
- Investigates the choice of assigning uncertainty factors for incorporation into the CDF itself versus for development of CDF confidence limits, and the associated nonlinear effects on the expected 100-yr SWL and the corresponding upper limit of the 90 percent confidence interval (90% UCL).
- Examines differing practices for the treatment of surge hazard uncertainty and their implications for surge risk management and presents the example of the post-Katrina NFIP analysis and surge levee design for Southeast Louisiana.

A list of acronyms used in this paper is provided on p. 37.

SURGE SWL CDF

A range of surge hazards—e.g., from 10- to 10,000-yr return—for a specific location of interest is mathematically depicted using a CDF curve. To construct a surge CDF, a set of local, individual SWL events—each with its own discrete frequency (mass probability) is first developed. Today, this is done either from a record of SWL observations (e.g., a tide gauge), or a synthetic set of surge events developed in a *joint probability analysis* (JPA) of surge SWL. The synthetic set is designed to properly represent the range of key hurricane attributes, such as central pressure, radius of maximum winds, forward velocity, track angle, and landfall distance to the location of interest (C_p, R_{max}, V_f, Θ, and X).

There are two basic approaches to developing the synthetic set of SWL-frequency points. Empirical methods emphasize expanding on historical observations to create an artificial record much longer (e.g., an order of magnitude) than the longest return period of interest. The empirical approach produces an artificial record with variability in the combination of hurricane attributes that is consistent with the generally observed joint probabilities in the regional climatology. Vickery et al (2009) developed an artificial 100,000-yr record for a coastal wind hazard analysis.

For surge hazard analysis, SWLs for each storm in the set are simulated using a sophisticated computer model which mimics the physical interaction of wind, surge, and waves with the coastal landscape. In the past, surge simulation of an entire empirically-derived artificial record has not been practical. An alternative approach to the storm set, termed the *joint probability method* (JPM), instead employs a sample of hurricanes with various joint-probabilities. Early efforts (with relatively coarse, fast-running models) simply used a few equally incremented values for each characteristic. Thus, for one location of interest three values for five characteristics yields a set of 243 storms. Expanded regional studies and more complex surge models have required smaller, better representative JPM sets, and techniques have been developed to provide an *optimized sample* (OS). In one approach, a JPM-OS is derived by first constructing CDFs with thousands of storms simulated with a coarse model, and then selecting a much smaller set mathematically optimized (e.g., with variable weighting of storms) to replicate the preliminary CDFs. The OS is then simulated with the more complex model (Toro 2008).

Figure 2a illustrates an OS of 76 SWL-frequency points. In this OS several hypothetical storms share the same general frequency (they have common attributes, but different landfall locations). Figure 2b shows a histogram of the combined frequency by 1-ft SWL Bins. The CDF is developed by numerically integrating the frequencies through

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each SWL Bin. Figure 2c zooms in on the storms for SWL less than 4.0 ft. Examples of the numerical integration are shown in Table 1. Figure 2d presents the CDF. Particular SWL hazards—such as the 100-yr SWL—are the *expected* values with respect to the integrated variables and are simply taken from the curve. In the case of Figure 2d the expected 100-yr SWL is 8.4 ft.

An innovative JPM approach uses an intermediate step of developing location-specific Surge-Response functions (Resio et al 2009). Similar in concept to a stage-discharge function for a river, the Surge-Response function defines SWL in terms of the hurricane attributes. In this JPM approach, the OS is used to construct the local Surge-Response function. Thus, the Surge-Response-OS has a different purpose than the JPM-OS. Once constructed, a Surge-Response function can be used to provide an estimated local SWL for thousands of different combinations of C_p, R_{max}, V_f, Θ, and X.

A separate hurricane joint-probability equation gives the frequency for any combination of C_p, R_{max}, V_f, Θ, and X. Using this approach, thousands of synthetic surge events—SWL-frequency points—are generated and used to compute each SWL Bin-frequency.

The surge CDF curve as constructed with either JPM approach is non-parametric—i.e., it is not defined by a single equation. For some surge risk management efforts it is useful to apply an *extreme value function* (EVF) as a proxy for the non-parametric CDF. Various probability distribution equations, which exhibit suitable asymmetry (skewness) and tailing properties, can be fitted to the CDF and compared for their ability to approximate the non-parametric CDF curve. Some EVFs which are commonly used include the Log-Normal, Log-Pearson, Gumbel, Weibull, and Frechet equations—the last three being variants of the Generalized Extreme Value (GEV) equation. The Log-Pearson equation is well established for use in riverine flood hazard analysis.

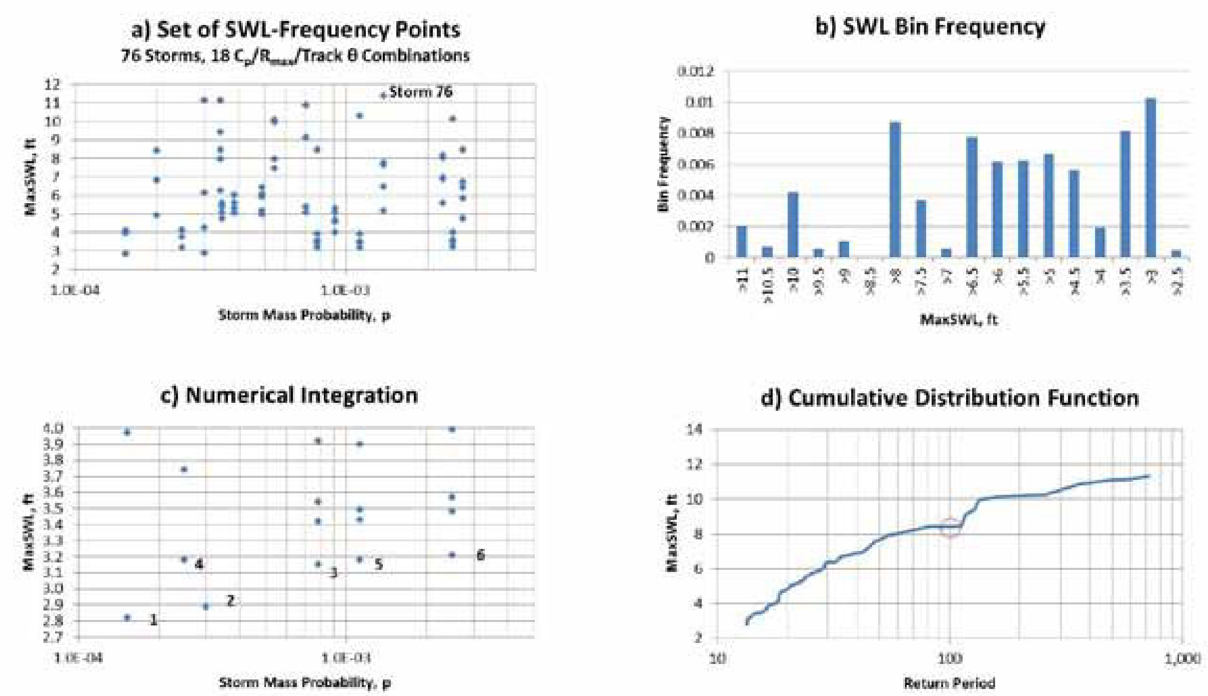

Figure 2. Example of SWL Probabilities and the SWL CDF

Table 1. Example Numerical Integration of CDF

Storm	SWL(ft)	Frequency	Numerical Integration	Cumulative Frequency	Return Period (years)
76	11.34	0.00139	76	0.00139	719.42
75	11.13	0.000346	76 and 75	0.00174	576.04
…					
6	3.21	0.0025	76 thru 6	0.071849	13.92
5	3.18	0.00113	76 thru 5	0.072979	13.70
4	3.18	0.00025	76 thru 4	0.073229	13.66
3	3.15	0.00079	76 thru 3	0.074019	13.51
2	2.89	0.000302	76 thru 2	0.074321	13.46
1	2.82	0.000154	76 thru 1	0.074475	13.43

When an EVF is fitted to the non-parametric CDF, estimates of uncertainty in the equation's approximation of the CDF are also usually shown—in the form of a confidence interval. Importantly, this particular confidence interval only takes into account the uncertainty in the curve fitting step and does not reflect uncertainties associated with the surge-frequency points themselves. Figure 3 illustrates a GEV equation fitted to a set of cumulative distribution points—in this case developed from a tide gauge record for Grand Isle, Louisiana. The figure also illustrates the uncertainty with the fit in the form of upper and lower limits of a 95 percent confidence interval. The tide-record CDF points in Figure 3 could have additional uncertainties—such as in the gauge performance.

Any surge CDF and 100-yr SWL estimate derived with a JPM, such as those shown in Figure 2d, have uncertainties attributable to issues with the hurricane joint probability equation, the surge model, and the storm OS (Resio Surge-Response OS or Toro JPM-OS) used to construct it. It is often convenient to evaluate uncertainty factors as normally distributed in terms of SWL—as either fixed values or linearly dependent on the SWL. In this case the standard deviation

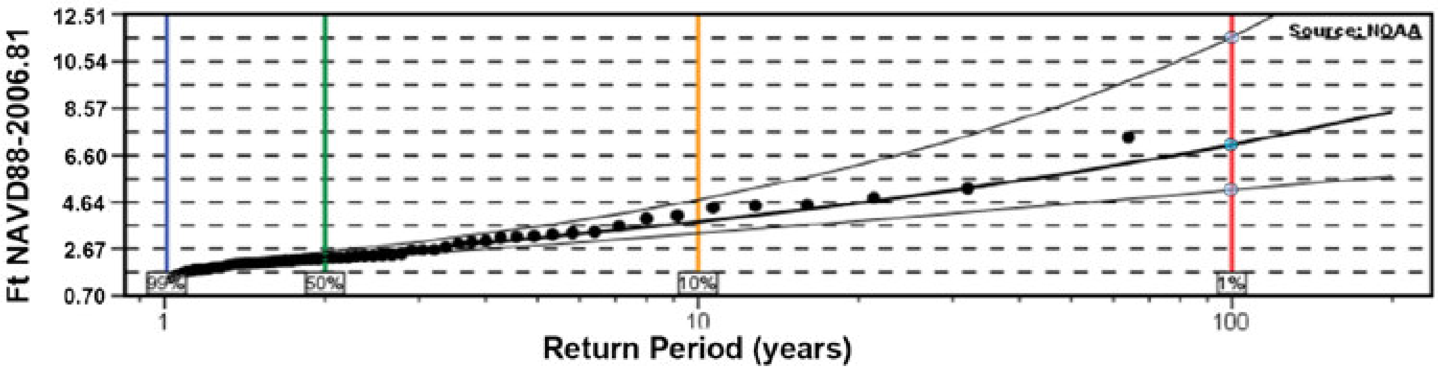

Figure 3. Grand Isle LA Tide Station Return Frequency with 95 Percent Confidence Interval

NOAA (http://tidesandcurrents.noaa.gov/est/est_station.shtml?stnid=8761724)

(σ) for factors can be combined together by adding in quadrature. However the use of normal distributions should be considered carefully to avoid over- or under-estimating distribution tails.

Table 2 summarizes ten stationary uncertainty factors that fall within the three components of the Surge-Response JPM, together with evaluation methods. Four factors lack well-established methods of evaluation and require professional judgment. Six factors can have significant localized variability within a general region. All have σ magnitudes capable of exceeding 10 percent. (Ten factors with σ values of 10 percent have a combined σ, in quadrature, of 32 percent). The following three sections examine these stationary uncertainty factors.

Table 2. Summary of Ten Stationary SWL Uncertainty Factors For Surge-Response JPM

FACTOR	EVALUATION METHOD	MAGNITUDE OF 100-YR σ %SWL OR FT	SIGNIFICANT LOCALIZED VARIATION?
HURRICANE JOINT PROBABILITY UNCERTAINTIES			
1. Hurricane sampling	Fitting extreme value function to the JPA CDF, incorporating all hurricane joint probability uncertainties; sensitive to the assigned sample length.	>10%	No
2. Historical record representativeness of climate cycles	No well-established method; requires professional judgment.	Difficult to define, likely >10%	No
MODEL UNCERTAINTIES			
3. Surge model	Residual error from hindcast validation.	>10%	Yes
4. Timing of tides	Tidal analysis.	0.1 to > 5ft	Yes
5. Wind-field shape (Holland B)	As percent of SWL; using Holland B Surge-Response analysis.	>10%	No
6. Additional wind-field characteristics (e.g., banding)	Residual error between surge modeling with high resolution wind fields versus the OS wind-fields.	>5%	No
7. Other meteorological conditions	No well-established method; requires professional judgment.	Difficult to define; >10% at sensitive locations	Yes
8. Empirical representations of hydrodynamic and air-sea drags	No well-established method; requires professional judgment.	Difficult to define; >10% at extreme winds and sensitive locations	Yes
SURGE-RESPONSE OS UNCERTAINTIES			
9. OS representativeness	No well-established method; requires professional judgment.	Difficult to define, likely >10% at sensitive locations	Yes
10. Surge-Response function	Residual error between predicted SWL from function to OS results.	Depends on interpolation >5%	Yes

HURRICANE JOINT PROBABILITY EQUATION UNCERTAINTY

In order to describe the hurricane climatology pertinent to the local surge hazard, a hurricane joint probability equation is constructed using probabilistic equations for each hurricane attribute—for example $p(C_p, R_{max}, V_f, \Theta, X)$. Recent joint probability equations have been developed in three steps:

- An EVF is constructed to describe the frequency of hurricane C_p within the region around the location of interest by fitting to the observed record. The EVF selection involves professional judgment, particularly the characteristic slope at high return periods. The equation can be for either landfall or offshore peak intensity. For surge modeling a trend in C_p versus distance before and after landfall—reflecting typical hurricane decay dynamics—is also applied to describe changing intensity over the course of the track.
- Empirical equations are constructed to represent the probability of R_{max}, V_f, and Θ for each C_p and are then combined with the C_p-frequency equation.
- The regional landfall is subdivided according to a spacing deemed sufficient to provide a suitable range of distances, X, to the location of interest. If the region is divided into five landfall locations, the joint probability for each landfall location is modified to be $0.2p(C_p, R_{max}, V_f, \Theta)$.

The three steps entail two uncertainties related to the hurricane joint-probability equations:

- Residual errors associated with fitting the various probability equations for C_p, R_{max}, Vf, Θ, and decay to the current available sample of hurricanes (*hurricane sampling errors*). These residual errors are readily quantifiable. Importantly, the magnitude of the error depends on the record length/sample size. Each residual error can be expressed as a single Θ value. (Note: Inspection of the residual errors could indicate that non-normal distributions may be appropriate.) The residual error in C_p-frequency can be considered as a function of the frequency. In addition, hurricane sampling error may need to account for the quality of hurricane observations in the record as many data are actually estimates.
- Uncertainties associated with the representativeness of the historical record of C_p, R_{max}, Vf, Θ, and decay observations, in terms of long-term stationary conditions (*hurricane record representativeness*). An observed hurricane C_p record, say 75 years, may not be representative of an "average 75-yr period" due to various climate cycles affecting hurricane frequency and intensity. Similarly, the record may not be representative for R_{max}, V_f, Θ, and decay correlations and probabilities. While careful examination of the record may allow for some reasonable adjustments to the historical data set, this uncertainty is difficult to quantify.

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Hurricane sampling errors can be translated into SWL uncertainties and combined into a single SWL *hurricane sampling error*. For convenience, the combined SWL *hurricane sampling error* can be treated as normally distributed (i.e., ignoring skew in C_p-frequency residual error), with the standard deviation noted as σ_S. The location-specific value for σ_S can be given as a function of SWL (or return period). The value of σ_S can be evaluated in two ways: with a Monte Carlo approach or with the residual error for a SWL EVF.

Monte Carlo Approach to Evaluating σ_S

The Monte Carlo approach can be used to evaluate an overall SWL hurricane sampling error when an empirically-based JPA is employed to simulate an artificial record. The approach involves re-developing the artificial record many times. Each storm in each iteration has randomized values for the hurricane attributes. CDFs are then computed for each iteration. These CDFs are then used to define a median CDF (with a median 100-yr SWL) and σ_S at each return period, including a 100-yr σ_S. The estimates of σ_S at each return period are a function of the length of the artificial record, with more iterations allowing this function to be better defined.

Vickery et al 2009 used the Monte Carlo approach in evaluating hurricane sampling error for wind hazard, replicating their artificial 100,000-yr record hundreds of times. However, to date, using the Monte Carlo approach for analyzing a surge hazard σ_S has not been practical due to the time and expense of re-modeling the entire artificial hurricane record—even with a JPM-OS to reduce the number of storms in the record.

A Monte Carlo approach is practical for the Surge-Response OS approach as re-modeling of the OS is not required. Instead the frequencies for SWL-frequency points would simply be randomized by using the combined residual error in the joint probability equation. In this approach the CDF can be recomputed numerous times, using more iterations to allow the estimate of σ_S to converge.

SWL EVF Approach to Evaluating σ_S

The SWL hurricane sampling error can also be evaluated by fitting an EVF to the results of the JPM—i.e., to the SWL CDF—and determining the residual error. This approach is limited if a) the SWL EVF is the same type as that used for the CP-frequency, as this influences the fit; and b) the JPM does not apply randomized values for all the hurricane attributes based on joint probability uncertainties.

The estimation of σ_S by fitting an EVF to the JPM results is affected by hurricane record length. For a hurricane record length (L):

$$\frac{\sigma_{S1}}{\sigma_{S2}} = \sqrt{\frac{L_2}{L_1}}$$

L would typically be the length of the historical record used to develop the hurricane joint probability equation, but may be increased according to professional judgment when the geographical extent of the historical record is larger than the region under study. Notably, if L is overestimated then σ_S is underestimated.

As an alternative to the JPM SWL CDF, an EVF can be applied to a local tide gauge record (where available). The residual error from this fit can then be used to estimate σ_S. This avoids the intermediate hurricane joint probability expression and provides a very simple, direct approach to estimating σ_S. Figure 3 illustrates the fitting of the GEV curve to the tide record CDF for Grand Isle, Louisiana and associated confidence limits. (Note, however, that in Figure 3 the confidence limits have been developed without the assumption of a normal distribution.) The large confidence limits in Figure 3 reflect the actual tide gauge record length.

SURGE MODEL UNCERTAINTY

The estimated peak surge SWL for any hypothetical combination of C_p, R_{max}, V_f, Θ, and X depends on many factors not practical or within the professional capability to simulate with a wind/surge/wave model. These factors introduce random variability to SWL estimates and are collectively referred to as *model uncertainty*. When treated as normally distributed, individual σ values can be combined together in quadrature to provide an overall, domain-wide, σ_M. Model uncertainty may have asymmetry due to potential over-or under-prediction bias. Importantly, model uncertainty differs markedly at a regional versus a local scale. Six key factors include:

- Lumped uncertainties in modeling wind/surge/wave physics, hurricane conditions, and landscape conditions (topography, bathymetry, wind/surge/wave frictional effects, etc.) that are reflected in the overall modeling residual error in hindcasting one or more specific surge events. Dietrich et al (2011) evaluated four surge hindcasts prepared with a state-of-the-art ADCIRC-SWAN model and found regional (domain-wide) scatter index (root mean square error, RMSE divided by mean surge) ranging from 16 to 28 percent. Localized values were not documented but can easily be twice as high. Furthermore, normalized regional model bias for the four hindcasts was found to range from -7 to 15 percent. Notably, the current practice is not to calibrate models for use in simulating a synthetic storm set, as improving Surge-Response representation across a full range of storms and locations is not yet fully understood.
- The timing of the local tide for a hypothetical surge event. The magnitude of tides can also vary significantly within a study region.
- The extent and distribution of the full wind-field, e.g., as described by the Holland B parameter. Holland B has been considered as varying with SWL (Resio et al 2007).
- Additional wind-field conditions, e.g., banding.
- Other meteorological conditions, such as pre-storm (pre-forerunner) water level and storm rainfall. The latter may correlate inversely with both C_p and V_f but with considerable random scatter.
- Empirical drag representations that differ from hindcast conditions. For example, the hydrodynamic drag coefficient for

many storm scenarios can vary widely from the values assigned according to a particular hindcast. And, the air-sea drag hindcast may not capture conditions in very shallow water bodies during extreme storms—such as the Lake Okeechobee Hurricane of 1928.

STORM OS UNCERTAINTY

For the Toro JPM there are uncertainties with respect to the optimization of the JPM-OS. These can be estimated by evaluating the residual error in the OS representation of a) the hurricane joint probability equation, and/or b) the surge hazard. In the second case the residual error is determined by comparing the local CDFs developed with the OS and complex model versus those derived from the much larger storm set and simplified model. The JPM-OS uncertainty can vary between local CDFs.

For the Surge-Response approach to JPM, there are two locally varying uncertainties:

- The OS adequacy for representing Surge-Response. If the surge response is assumed to be overly smooth, then the number of storms may not be sufficient to capture non-linear effects. Capturing the Surge-Response for large, shallow, sheltered water bodies and coastal regionals with extensive natural topographic and conveyance features requires more storms at very low and very high C_P, greater variation in V_F and Θ, and tighter landfall spacing (see Irish et al 2009).
- Interpolation of the non-parametric tabulated Surge-Response function.

Both Surge-Response-OS uncertainties can be treated as normally distributed. If there is a location with a reasonable number of historical surge SWL records—and the specific storm and landscape conditions for each historical storm can be simulated—the combined σ for the model, the Surge-Response-OS, and Surge-Response equation, could be assessed. Otherwise, evaluating OS uncertainties requires considerable professional judgment.

INCORPORATING UNCERTAINTIES INTO THE CDF

Uncertainties about the CDF arising from the above ten sources can remain outside of the CDF—in which case they can be used to construct confidence limits above and below the curve. Alternatively, because the CDF is itself a probabilistic function, uncertainties can be added to the set of explicit joint-probability variables. When an uncertainty factor is incorporated among the CDF integration variables it is reflected in changes to the CDF. (By definition, the CDF is determined with respect to the explicit variables.) Incorporation of a normally distributed uncertainty factor into the CDF will therefore increase the expected 100-yr SWL and reduce the confidence interval around the 100-yr SWL.

Consider the contribution of tide to surge SWL in Southeast Louisiana. The domain-wide tide has a median value of 0 ft relative to local mean sea level and σ of 0.66 ft. The tide σ could be used to

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provide confidence limits in a 100-yr SWL. For a location with a 100-yr SWL of 13 ft, the 95%UCL is 14.3 ft, 1.3 ft (1.96σ), or 10 percent above the expected value.

As an alternative to confidence limits, the tide could be included as an explicit variable for the CDF. When the tide is incorporated into the integral, tidal variability is addressed in the hazard. In the new *with-tide* CDF, the 100-yr SWL will increase slightly (on the order of 0.2 ft) and a SWL of 14.3 ft will have a slightly lower return period than in the *without-tide* CDF. When more uncertainty variables are incorporated into the integral, the 100-yr SWL could be expected to rise more. This removes these uncertainties too from outside the integral and spreads them across the return periods.

Empirical JPA approaches attempt to incorporate many uncertainty factors explicitly by making the lengthy artificial record address more conditions (e.g., Holland B) and a CDF for the entire record integrates for the empirical distributions of these conditions. In surge JPM approaches, the OS could be expanded to cover one or two additional explicit variables with large impact (e.g., Holland B and tides, especially on the Atlantic Coast). But the time and expense of running wind/surge/wave models prohibit adding many explicit variables: the OS size increases drastically with added variables.

As an alternative, SWL uncertainty factors that have a linear influence on the CDF can simply be addressed by modifying the SWL-frequency points—and the SWL Bin-frequency values—prior to numerical integration. A normally distributed SWL uncertainty (or combination of factors) incorporated in this way has been referred to as a SWL *epsilon* term (Resio et al 2012). Each single SWL-frequency point can be replaced with numerous SWL values reflecting the epsilon (ε) standard deviation (σ_ε). Figure 4a through 4c illustrate the expansion of the SWL-frequency points from Figure 2 using a σ_ε of 0.2*SWL and the resulting CDF. Figure 4d shows the CDF for a range of σ_ε.

A normally distributed SWL epsilon has the added benefit of smoothing the numerical integration—as shown in Figure 4c. However, SWL epsilon is not included for the main purpose of smoothing. Variables are included in SWL epsilon to define how they modify the SWL hazard and, mathematically, are no different than explicit variables. Importantly, incorporating variables via SWL epsilon has the same effect on shifting the CDF and reducing confidence intervals as including them explicitly.

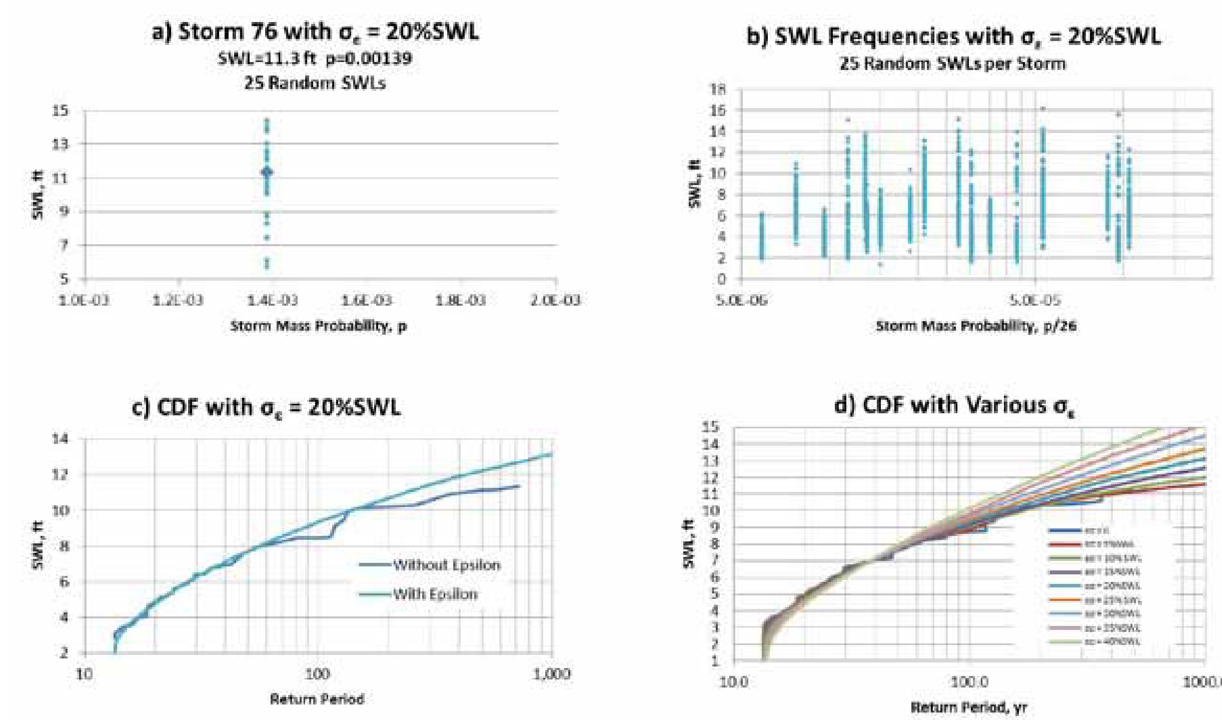

Figure 4. SWL CDF With Epsilon

RELATIONSHIP BETWEEN EPSILON, THE CDF, AND CDF CONFIDENCE LIMITS

As previously noted, for convenience all ten SWL uncertainties can be treated as normally distributed. Combining the ten σ values together in quadrature, the overall uncertainty can be represented by σ_{Total}. The σ_{Total} can be considered as having two components: those factors incorporated into the SWL CDF—represented by σ_ε (assuming as an epsilon term)—and the remaining uncertainty used to establish confidence limits—represented by σ_{CL}.

The σ_{Total} equals $\sqrt{\sigma_\varepsilon^{\,2} + \sigma_{CL}^{\,2}}$ and, thus, the relationship between σ_ε and σ_{CL} for any given σ_{Total} is nonlinear. The apportionment of uncertainties between σ_ε and σ_{CL} has a complex impact on both the CDF itself and the confidence intervals. Table 3 illustrates the nonlinear variation in σ_{CL} with σ_ε at three σ_{Total} values. Using the CDFs in Figure 4d, Columns A and B present the change in expected 100-yr SWL for σ_ε between 0.1 and 40 percent. For σ_{Total} of 20, 30, and 40 percent, Columns C-D, E-F, and G-H then show the resulting σ_{CL}-90%UCL for each combination of σ_{Total} and σ_ε. Table 3 shows that when higher portions of uncertainty are included as σ_ε versus σ_{CL}, the expected 100-yr SWL increases and the 90%UCL decreases. For example, at σ_{Total} equal to 30 percent, as σ_ε increases from 5 to 25 percent the expected 100-yr SWL increases by 0.6 ft and the 90%UCL falls by 1.2 ft.

PROFESSIONAL PRACTICES FOR THE TREATMENT OF SWL UNCERTAINTIES

There is no "rule" regarding the assignment of uncertainties to σ_ε or σ_{CL}. Natural, irreducible sources of variability (also termed aleatory variability)—such as tides, wind-field Holland B and banding, meteorological conditions, vegetation conditions, etc.—may be reasonable to incorporate into the integral because they are seen as intrinsic to what is meant by an "expected 100-yr surge event." On the other hand, those that reflect the current limitations of information or models (epistemic uncertainty) might be considered appropriate for leaving outside the integral. However, complicating this division is the fact that some estimated uncertainties—e.g., the residual errors for the surge model and the Surge-Response function—encompass both aleatory and epistemic uncertainties.

The choice of assigning uncertainties to the CDF versus confidence limits—as well as the evaluation of the ten uncertainty factors themselves—can be influenced by the risk management purposes for the estimates of expected surge hazard and confidence limits. For example, uncertainties can be treated one way for the NFIP—where the risks are basically regarded as actuarial/financial and local/regional risks are diluted by aggregation at a national scale—and another way for the planning and design of community flood defense systems addressing catastrophic risks to actual local populations and critical resources. Table 4 highlights differences in the State of the Practice (SOP) in evaluating the ten uncertainty factors for the NFIP versus local risk reduction projects.

Table 3. Example Effect of Increasing σ_ε on 90%UCL

A	B	C	D	E	F	G	H
		σ_{TOTAL} = 20%SWL		σ_{TOTAL} = 30%SWL		σ_{TOTAL} = 40%SWL	
σ_ε %SWL	Expected 100-yr SWL ft	σ_{CL} %SWL	90%UCL ft	σ_{CL} %SWL	90%UCL ft	σ_{CL} %SWL	90%UCL ft
0.1	8.7	20.0	11.6	30.0	13.1	40.0	14.6
5	8.9	19.4	11.7	29.6	13.3	39.7	14.8
10	9.1	17.3	11.7	28.3	13.4	38.7	15.0
15	9.2	13.2	11.2	26.0	13.2	37.1	14.9
20	9.3	0.0	9.3	22.4	12.8	34.6	14.7
25	9.5			16.6	12.1	31.2	14.4
30	9.7			0.0	9.7	26.5	14.0
35	9.8					19.4	13.0
40	10.1					0.0	10.1

$\sigma_{TOTAL} = \sqrt{\sigma_\varepsilon^2 + \sigma_{CL}^2}$

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NFIP FIS SOP

The NFIP manages a very large, national fund to cover flood damage claims for residential and small business property. The fund is supported partially by premiums assessed on property owners in flood risk zones and partially by federal subsidies. The NFIP actuarial risk management relies on the expected 100-yr SWL to delineate special flood hazard areas, define individual insurance policies, and assess premiums. Confidence limits have generally not been used in the delineation of flood hazard zones. Political and institutional factors can favor under-estimating expected 100-yr SWLs. NFIP Flood Insurance Studies (FISs) for surge hazard are typically regional in nature—covering multiple coastal counties.

Thus, in recent FISs the interests of the NFIP have been satisfied with focusing on the CDF (ignoring confidence intervals) and incorporating into the CDF only those uncertainties that are well-defined and *region-wide*. As noted in Table 4, the FIS SOP incorporates the first four model uncertainties into the CDF—either explicitly or with the aid of a SWL epsilon term. The FIS SOP then equates σ_{CL} with σ_S and ignores localized uncertainties and uncertainties related to the historic representativeness of hurricane data and storm OS. In the future, the FIS SOP could be revised if institutional drivers change, studies become more geographically narrow, and/or with future methodology improvements such as those listed in Table 4.

Table 4. State of the Practice for Addressing Ten Stationary SWL Uncertainty Factors

FACTOR	NFIP FISs	LOCAL PROJECTS TO REDUCE SURGE RISK	FUTURE IMPROVEMENTS
HURRICANE JOINT PROBABILITY UNCERTAINTIES			
1. Hurricane sampling (σ_S)	Included in σ_{CL}.	Use a reasonably conservative approach.	More comparison with tide gauge analysis.
2. Historical record representativeness of climate cycles	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Perhaps some insights from studies of paleo-climatology.
MODEL UNCERTAINTIES			
3. Surge model	Region-wide uniform error; included in CDF via σ_ε; sub-regional variations not evaluated for FIS.	Include local error either by adjusting σ_ε or σ_{CL}.	Improved model representation of local topography, bathymetry, and landscape conditions.
4. Timing of tides	Included in CDF as explicit variable or via σ_ε using a region-wide uniform factor.	Use local tides by adjusting σ_ε or σ_{CL}.	
5. Wind-field shape (Holland B)	Region-wide uniform factor; included in CDF as explicit variable or via σ_ε.	Same as NFIP.	Use of higher resolution wind-fields with OS.
6. Additional wind-field characteristics (e.g., banding)	A region-wide uniform factor is assessed and included in epsilon.	Same as NFIP.	Use of higher resolution wind-fields with OS.
7. Other meteorological conditions	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Improved modeling of physical processes, pre-storm, and storm conditions.
8. Empirical representations of hydrodynamic and air-sea drags	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Improved modeling of physical processes and storm conditions.
SURGE-RESPONSE OS UNCERTAINTIES			
9. OS representativeness	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Larger and better optimized OSs.
10. Surge-Response function	Not currently included.	Include local error in either σ_{CL}.	Better interpolation schemes to reduce residual error.

SOP for Local Projects to Reduce Residual Surge Risks

The SOP for planning and design of local projects for reducing catastrophic surge risks—the probability of fatalities, damage to crucial commercial/industrial activities, cultural/social costs, regional economic impairment, etc.—emphasizes the use of robust confidence limits. Engineers of flood risk reduction measures have legal and ethical obligations to carefully assess the impact of *all* uncertainties in order to provide a reasonable *Factor of Safety (FOS)*. For these purposes, it may be important to avoid reducing the UCL due to over-inclusion of factors in σ_ε as opposed to σ_{CL}—e.g., epistemic uncertainties. Furthermore, as shown in Table 4, these projects require that estimates for local uncertainties and for difficult-to-define uncertainties be included in σ_{CL}.

In addition to addressing all sources of uncertainty and being careful regarding which ones to assign to σ_ε versus σ_{CL}, local residual surge risk reduction projects may find it appropriate to use *reasonably conservative* approaches to estimate difficult-to-define uncertainties.

Interestingly, Vickery et al (2009) illustrate a conservative approach in defining wind hazard uncertainties. The uncertainties are considered twice: in the median CDF—which integrates for the uncertainties included in the Monte Carlo analysis—and again in defining the confidence interval with the same uncertainties. For some purposes (e.g., actuarial) this approach may constitute an unnecessary "double counting" of these uncertainties, while for others (e.g., engineering design) this approach provides a desired FOS.

SOP for Evaluating Overtopping Uncertainty for Coastal Flood Protection

In the design of coastal levees and floodwalls engineers must evaluate overtopping uncertainty—not only to assess potential interior inundation from overtopping, but more importantly to assess the potential for catastrophic breaching caused by erosion during overflow. σ_{CI} is a key contributor to overtopping uncertainty.

Where 100-yr overtopping (including wave overtopping) is not totally prevented, the NFIP accreditation of 100-yr coastal barriers requires that an engineer "*must evaluate the uncertainty in the estimated base flood loading conditions. Particular emphasis must be placed on the effects of wave attack and overtopping on the stability of the levee" (44CFR65.10)*. Evaluation of overtopping uncertainty is also required to credit some flood reduction associated with the presence of lower (less than 100-yr) barriers. Importantly, the NFIP overtopping analysis provides that σ_{CL} may simply be equated with σ_S. However, design of local coastal flood protection with greater elevation and resiliency FOSs to protect lives and critical community resources requires a complete, as well as a reasonably conservative, estimate of σ_{CI}.

NON-STATIONARY SURGE SWL ISSUES

In addition to the ten stationary uncertainty factors, there are non-stationary concerns with surge hazard CDFs. Non-stationary issues are defined by observed or hypothesized trends—e.g., sea level rise, regional subsidence, coastal erosion, long-term changes in the frequency or intensity of hurricanes, changes to the built landscape—and imply that the future SWL CDF and its confidence limits will differ from today. Estimates of these trends can also include their own confidence limits. The impact of trends on expected surge hazards and confidence limits is assessed with a *what-if* JPM that reflects conditions at some future time. The joint-probability equation and/or surge model are modified in accordance with the forecasted trend and the OS is re-simulated, providing a new set of SWL-frequency points. Integration then provides a CDF representative of the future state. Modifications to the ten stationary uncertainty factors can also be considered and employed in the development of the *what-if* CDF and confidence limits.

Re-simulating the entire OS may not be practical for investigating multiple *what-if* scenarios and/or several future time periods. To evaluate a range of future conditions, sensitivity tests using a few selected storms are usually performed. These can provide an indication of the potential impact of the trend but are not sufficiently rigorous to modify the expected surge hazard value and its confidence limits.

The SOP for NFIP FISs does not include evaluating non-stationary SWL issues. The NFIP does not provide for the regular revision of FISs and some areas have gone decades between FISs. Furthermore, updated FISs do not always include a complete reanalysis of surge hazards.

Non-stationary issues are crucial for local surge risk managers, and for the design of local projects to reduce residual surge risk, especially for a long project design life. As with stationary uncertainties, the risk management purposes of the local project influence the range and details in the treatment of non-stationary issues.

EXAMPLE: SOUTHEAST LOUISIANA

Following Hurricane Katrina in 2005 the U.S. Army Corps of Engineers (USACE) performed a regional surge hazard analysis to address NFIP FIS requirements for Southeast Louisiana and utilized the Surge-Response JPM approach. The analysis relied on the assumption that Southeast Louisiana surge response is very smooth, using an OS comprised of 3 C_p values, 15 C_p/R_{max} combinations, and 30 $C_p/R_{max}/V_f/\Theta$ combinations. A 152-storm OS was generated, with most of these 30 combinations being applied at 9 landfall locations (5 primary and 4 secondary).

The NFIP analysis developed a joint probability equation for hurricane attributes by employing a Gumbel type curve, which has two coefficients, to represent C_p-frequency for Southeast Louisiana. R_{max} was defined as a linear function of C_p, with normally distributed

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variation, while V_f and Θ were defined as non-parametric functions of Θ and X, respectively, with normally distributed variation. A linear C_P decay function was also employed. The determination of these relationships employed a 65-yr record, modified to address some apparent cycles in storm frequency. These estimates drew on a wider geographic sample of storms than just those making landfall in Southeast Louisiana, wider by a factor of 6.1. The NFIP analysis employed this factor to adjust the "effective" hurricane sample length to 396 years.

The 152-storm Surge-Response OS results and joint-probability equation were used to estimate 68,040 SWL-frequency points at each location of interest in the region. The 68,040 points reflected 21 Gulf of Mexico Cp (900 - 960 in 3 millibar increments); 40 Rmax (1-40 in single nautical mile increments); 3 Vf (6, 11, 17 knots); 3 Θ (-45 , 0 , and 45); and 9 landfalls for each Θ (5 main tracks plus 4 intermediate tracks).

Local estimates for σ_S were developed using residual error in the fit of a Gumbel curve to the SWL CDF. This approach has three key limitations:

- The approach employed the same curve type, Gumbel, that was used to generate CP-frequency. Thus, the fit of SWL return frequency to a Gumbel curve has been somewhat predetermined.
- The frequency values for the 68,040 points used to create the CDF do not reflect uncertainties in the joint probability equation.
- The residual error estimate was based on the 396-yr characterization of the record length.

The values of σ_S for the 100-yr SWL determined from the Gumbel fit were generally less than 10 and 12.5 percent for the East– and West-Bank regions, respectively.

The NFIP analysis defined regional σ values for four of the six model uncertainties:

- For tides: 0.66 ft.
- For Holland B: 0.15*SWL ft.
- For region-wide model hindcast residual error and additional wind-field variations (plus some additional OS variations of Θ): about 1.9 ft.

The overall uncertainty for these factors only, σ_M*, was given by Resio et al 2012 as $\sqrt{2^2 + (0.15*SWL)^2}$.

The NFIP analysis applied this σ_M* as σ_ε to randomize the SWL value for each SWL-frequency point, expanding each point by a factor of 21. This yielded a total expanded set of 1,428,840 points. These points were evaluated in SWL Bins with 1 ft increments, which were then numerically integrated to produce the location-specific CDFs. The epsilon term increased the expected 100-yr SWL—by generally about 1 ft—and these four factors were removed as uncertainties for the CDF confidence limits.

The NFIP analysis as noted above equates σ_{CL} to σ_S. Consistent with NFIP SOP, the Southeast Louisiana FIS did not incorporate values for the other five factors listed in Table 2, and did not address local variation in hindcast error. While the FIS did discuss the general suitability of C_P, R_{max}, V_f, and Θ variations, as well as track spacing, it did not provide uncertainty value for the OS adequacy. The FIS did not discuss residual error in the Surge-Response function fit to OS results.

In contrast to the NFIP σ_{CL}, for local surge residual risk management purposes, a reasonably conservative 100-yr σ_{CL} could address the following:

- An alternative σ_S using an actual record length of 65 years, instead of the synthetic 396 years, in the Gumbel fit to the CDF. An alternative estimate for 100-yr SWL σ_S may be warranted, as indicated by the value of σ_S derived from the observed Grand Isle SWL-frequency record. The Figure 2 SWL-frequency curve for the Grand Isle tide gauge data—using the GEV curve—shows median and upper confidence limits (for the 95 percent confidence interval) for the 100-yr SWL at 7.1 and 11.5 ft. The tide-gauge based upper band of 62 percent at the 100-yr SWL is much larger than that associated with the NFIP analysis—for which the typical upper band for a 95 percent confidence interval (at $1.96\sigma_S$) is less than 20 percent of the expected 100-yr SWL. Using the actual record length of 65 years produces σ_S values more consistent with the Grand Isle record. These alternative σ_S values are 15 to 20 percent of SWL for the East-Bank.
- The residual error in the fit of Surge-Response functions to OS. Using information from the NFIP FIS, the authors have compared the 152 OS peak SWL results to the predicted SWLs from the Surge-Response function at 274 locations. This comparison reveals an average RMSE of 2.3 ft, in addition to slight under- and over-prediction biases for the New Orleans regional East- and West-Banks, respectively. The residual error in the fit of Surge-Response functions to OS indicates an additional σ value on the order of 15 to 20 percent of SWL.
- The combined σ for the other five uncertainties (hurricane record representativeness, local variations in the wind/surge/wave hindcast error, other meteorological conditions, drag representations, and OS representativeness) could very reasonably be assigned a value of 10 to 15 percent of SWL, especially for many locations exposed to large interior water bodies.

The combination of all three indicates that a reasonably conservative value for the 100-yr σ_{CL} is on the order of 23.5 to 32 percent.

It is important to acknowledge that this magnitude for a σ_{CL} implies upper and lower limits of confidence intervals that may become

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unrealistic. A 90%UCL (SWL + 1.645*σ_{CL}*SWL) equates to 1.39 to 1.53*SWL, which appears to be reasonably conservative compared to an NFIP value as low as 1.1*SWL. However, a 98%UCL (SWL + 2.33*σ_{CL}*SWL) equates to 1.55 to 1.75*SWL. Further research is needed to determine if using a slightly truncated normal distribution, or other distribution, could be appropriate.

Interestingly, the expected value of the 500-yr SWL is less than the 90%UCL for the 100-yr SWL using the reasonably conservative σ_{CL}, indicating the latter provide a greater FOS. Overall uncertainty increases with higher SWLs, (though timing of tide is a constant and the model hindcast error generally declines with increasing SWL), and the 500-yr σ_{CL} is higher than the 100-yr σ_{CL}.

The USACE designed the post-Katrina New Orleans regional surge levee—known as the Hurricane and Storm Damage Risk Reduction System (HSDRRS)—with the primary objective of accreditation under the NFIP. The HSDRRS design therefore employed the NFIP analysis of the 100-yr SWL and associated σ_{CL} in the design and the evaluation of overtopping uncertainty.

To evaluate 100-yr wave overtopping the design (USACE 2011) employed empirical overtopping equations which use inputs for the 100-yr SWL and associated significant wave height and wave period. To address 44CFR65.10.b.iv, a Monte Carlo technique was then used—employing the NFIP estimates of 100-yr SWL σ_{CL}, (together with σ values for significant wave height and period, and the empirical coefficient). The design established limits (based on erosion protection) for both median and 90 percent non-exceedance 100-yr overtopping rates (100-yr q50 and q90; the q90 is the upper limit of an 80%UCL).

However, consideration of overtopping uncertainty from the viewpoint of local residual risk management, and the application of a suitable FOS, warrant using a reasonably conservative σ_{CL} estimate, such as defined above. A reasonably conservative 100-yr σ_{CL} is about three times greater than the NFIP 100-yr σ_{CL}. Analysis of overtopping uncertainty using the empirical overtopping equation and the Monte Carlo technique shows that the q90 is highly sensitive to the value of σ_{CL}. Figure 5 illustrates that tripling σ_{CL} can increase q90 by a factor of ten and raise the levee elevation required to meet the q90 limit by two-feet. Applying a reasonably conservative treatment of uncertainty to evaluating the 500-yr SWL shows a similar increase in the 500-yr q90.

Local surge risk managers should employ these reasonably conservative treatments of 100- and 500-yr SWL uncertainty—and 100- and 500-yr q90—to mitigate surge risks beyond the purpose of the NFIP accredited levee system. *Foremost in addressing residual risk is evacuation preparedness*. Other measures can include raising the design FOS for barrier elevation; upgrading the design FOS for resiliency armoring to prevent breaching during overtopping; adding interior compartmentalization features; expanding flood proofing requirements; and broadening flood insurance participation.

Hurricane surge hazard for Southeast Louisiana is likely to worsen in the future due to non-stationary issues (see Smith et al 2010). The region experiences substantial rates of regional coastal land subsidence—which when combined with sea level rise defines regional relative sea level rise (RSLR). In addition, Southeast Louisiana surge hazard is increasing due to significant coastal erosion and vegetation loss. Researchers have investigated these non-stationary issues, and developed useful estimates of trends and associated uncertainties (see Reed et al 2009, Louisiana CPRA 2012, Visser et al 2012). Current RLSR is as high as 0.03 ft/yr, three

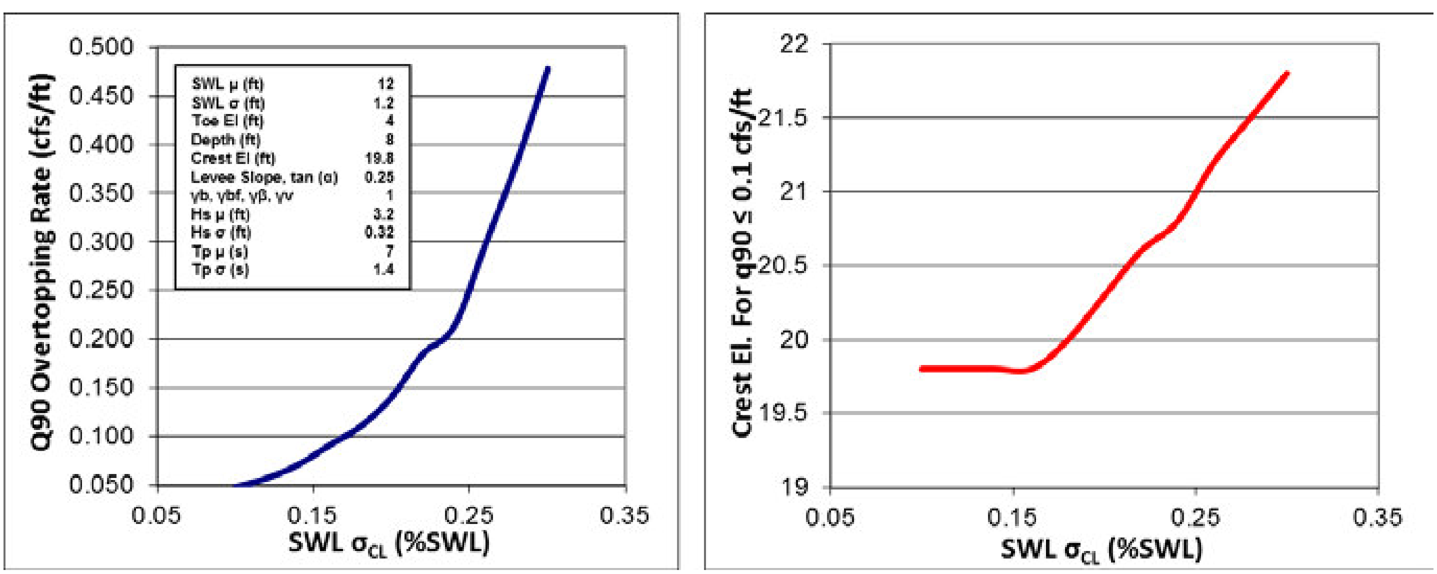

Figure 5. Overtopping q90 and Levee Elevation as a Function of SWL σ_{CL}

times higher than the current average global sea level rise alone. The potential for increasing hurricane frequency and intensity in the Gulf of Mexico due to global climate changes is a subject of ongoing research (e.g., Biasutti et al 2012).

The HSDRRS design provided a limited evaluation of one non-stationary issue—RSLR—for a 50-yr period. The evaluation was based on a sensitivity test of the SWL response at eleven locations to re-simulating nine storms with three higher assumed relative sea level rises. RLSR was simulated with a simple adjustment to surge model mean water level. The sensitivity test results were used to provide generalized estimates of 50-yr increase in 100- and 500-yr SWLs. For residual risk management purposes, a more thorough investigation of non-stationary issues should be considered. Such an investigation should encompass greater regional detail in subsidence, the additional consideration of coastal erosion and vegetation loss, refining the localized Surge-Response, and updating the JPM.

SUMMARY AND CONCLUSIONS

Surge hazard estimates such as the expected 100-yr SWL have ten important stationary uncertainty factors, each capable of exceeding 10 percent. Evaluating uncertainty factors—as well as assigning them either for incorporation into the CDF itself or for use in confidence limits—requires professional judgment. Estimates of the expected 100-yr SWL and 90%UCL can legitimately differ for different purposes. For the purposes of the NFIP, several stationary uncertainty factors are currently ignored. The NFIP surge hazard analysis can also ignore important non-stationary factors. However, in the design of local projects for managing catastrophic residual risks, reasonably conservative approaches are needed to evaluate all uncertainties. In the case of Southeast Louisiana, the NFIP value of σ_{CL} for 100-yr SWL confidence limits is one-third of the σ_{CL} determined using a reasonably conservative approach. A levee 100-yr overtopping q90 based on the reasonably conservative σ_{CL} can be ten times the q90 based on the NFIP σ_{CL}.

The purposes for, and methods of, evaluating surge SWL and the associated uncertainty should be carefully considered in the management of hurricane surge risks. NFIP estimates for 100-yr SWL and associated uncertainty are not appropriate for all coastal flood protection projects.

Figure 1 compares the size and depth of Lake Okeechobee in Florida with Lake Pontchartrain in Southeast Louisiana. The NFIP expected 100-yr SWL at the point shown on the south shore of Lake Pontchartrain is 9 ft NAVD88, or about 8.5 ft above the average SWL. The NFIP expected 100-yr SWL along the southern shore of Lake Okeechobee is about 23 ft NAVD88, about 10 ft above the normal pool. Thus, the NFIP expected 100-yr SWL surge depth for the south shore of Lake Okeechobee is slightly greater than for the south shore of Lake Pontchartrain—by 1.5 ft.

The design crest for the HSDDRS along the south shore of Lake Pontchartrain is 7.5 ft above the expected 100-yr SWL (at 16.5 ft NAVD88), while the crest of the Herbert Hoover Dike is about 17 ft above the expected 100-yr SWL (about 40 ft NAVD88 or 30 ft above the surrounding land surface). Thus, the 100-yr freeboard (the crest height above the 100-yr SWL) is much greater for the Herbert Hoover Dike than for the HSDRRS—by almost 10 ft.

Recall that the catastrophic 1928 Hurricane produced a surge depth reportedly approaching 20 ft along the shores of Lake Okeechobee—10 ft greater than the 100-yr SWL. On the other hand, Hurricane Katrina produced a surge below the 100-yr SWL at the location on Lake Pontchartrain. It is apparent that the Herbert Hoover Dike was not designed simply for NFIP accreditation and provides an elevation FOS addressing additional risks.

A separate surge hazard analysis for the New Orleans area was provided in 2009 by the Interagency Performance Evaluation Taskforce (IPET) in their Volume VIII Report. IPET used a traditional rather than a Surge-Response JPM approach, and employed a subset of the 152-storms for their 76-storm OS. IPET incorporated several aleatory uncertainties in an epsilon term as part of their CDF integration and addressed several epistemic uncertainties to develop confidence intervals. The IPET analysis entailed a different set of OS surge-frequencies, and allocated different uncertainties to epsilon and confidence intervals than the USACE NFIP analysis. As with the USACE NFIP analysis, the IPET uncertainty analysis did not address local variation in model residual error, effects of rainfall and wind drag, and the representativeness of the historical record. Uncertainty related to the optimization of the 76-storm OS was also not addressed. And, as with the USACE NFIP study, IPET did not examine the Grand Isle tide gauge frequency analysis to improve the estimate of sampling uncertainty. IPET 100-yr SWLs were generally lower than those of the USACE NFIP (by about 1 ft) but included larger confidence intervals. The IPET analysis was separate from the USACE NFIP analysis and was not used in the HSDRRS design.

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List of Acronyms

Central Pressure	C_p
Cumulative Distribution Function	CDF
Epsilon Term	ε
Extreme Value Function	EVF
Factor of Safety	FOS
Federal Emergency Management Agency	FEMA
Feet	ft
Flood Insurance Study	FIS
Forward Velocity	V_f
Generalized Extreme Value Equation	GEV Equation
Hurricane Record Length	L
Landfall Distance to the Location of Interest	X
Joint Probability Analysis	JPA
Joint Probability Method	JPM
National Flood Insurance Program	NFIP
National Oceanic and Atmospheric Administration	NOAA
Optimized Sample	OS
Overtopping Rate, Median	q50
Overtopping Rate, 90% Non-Exceedance	q90 (equal to the 80%UCL)
Radius of Maximum Winds	R_{max}
Root Mean Square Error	RMSE
Standard Deviation for Expected SWL Hazard	σ (expressed as ft of SWL)
Standard Deviation for Expected SWL Hazard, Total Uncertainty	σ_{TOTAL}
Standard Deviation for Expected SWL Hazard, Confidence Limits	σ_{CL}
Standard Deviation for Expected SWL Hazard, Epsilon	σ_{ε}
Standard Deviation for Expected SWL Hazard, Hurricane Sampling Error	σ_S
Standard Deviation for Expected SWL Hazard, Model Uncertainty	σ_M
Still Water Level	SWL
Track Angle	Θ
Upper Limit of 90 Percent Confidence Interval	90%UCL
U.S. Army Corps of Engineers	USACE
Year	yr

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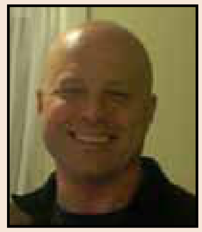

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The ASDSO Journal Editorial Committee would like to thank Daniel Heilman, HDR for providing technical expertise in reviewing this paper.