Appendix C

Four Priority Issues with the USACE Surge Hazard and HSDRRS Overtopping Analysis

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AP Photo Gerald Herbert, 2012

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Under Task Order From

Louisiana Coastal Protection and Restoration Authority

Baton Rouge, Louisiana

And For

Southeast Louisiana Flood Protection Authority—East

Prepared By

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The opinions expressed in this Report are those of Bob Jacobsen PE, LLC and do not represent the opinions of the Louisiana Coastal Protection and Restoration Authority, the Southeast Louisiana Flood Protection Authority—East, Lonnie G. Harper & Associates, Woods Hole Group, Michael Beck, Nathan Dill (formerly with Woods Hole Group), or any other party.

Executive Summary

1. The May 2013 Report *Hurricane Surge Hazard Analysis: The State of the Practice and Recent Applications for Southeast Louisiana* by Bob Jacobsen PE, LLC identified important limitations with the US Army Corps of Engineers (USACE) 2005-09 Southeast Louisiana surge hazard analysis and the Hurricane and Storm Damage Risk Reduction System (HSDRRS) design. Limitations encompassed various practices used in developing estimates of the 100- and 500-year (yr) surge still water levels (SWLs) and associated significant wave height (H_S), and the uncertainties in these estimates. In turn, these limitations led to concerns with estimates of the HSDRRS wave overtopping rates—both median and 90% non-exceedance level (q50 and q90)—used in elevation (100-yr) and resiliency (500-yr) design. (The HSDRRS design allows for some wave overtopping.)
2. The May 2013 Report was prepared from a broad flood risk management perspective and not limited to practices acceptable under the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP). The NFIP needs for determining the 100-yr surge hazard were the basis for the USACE 2005-09 analysis and HSDRRS design.
3. The May 2013 Report concluded that many outdated practices likely mean that estimates of the 100-yr SWLs, H_S, q50, and q90 are too low. However, the NFIP may not require revision of the analysis any time soon, or revision of the HSDRRS elevation design. A future revised analysis is even more likely to substantially increase estimates of 500-yr surge conditions, such that current estimates should only be regarded as "Nominal." Future changes to 500-yr estimates may lead to significant increases in resiliency requirements for some HSDRRS reaches. Ensuring adequate 500-yr resiliency is critical for comprehensive surge risk management.
4. As a result of the May 2013 Report and reviewing parallel investigations by others (see Sections 1.4 and 2.0), Bob Jacobsen PE has identified ***Four Priority Issues***—again from the perspective of comprehensive surge risk management—which i) appear to have a significant, wide-spread effect on SWL, H_S, and/or overtopping estimates, and ii) are amenable to expedited investigation and straightforward responses and revision of estimates. This Report provides a summary of these four priority issues together with proposed responses. Addressing these Four Priority Issues does not obviate the need to update the remaining outdated practices.
5. The four priority issues and proposed responses are:

   Priority Issue 1: The USACE FORTRAN code for estimating the 100- and 500-yr SWL applies only half the value of the epsilon term; (see Attachment A for more information on the epsilon term).

   Proposed Response: Correct the FORTRAN code to apply the full value of the epsilon term to the computation of the surge hazard CDFs, together with the typographical errors. This increases 100-yr SWL expected values generally by 0.5 to 1.2ft.

   Priority Issue 2: The H_S estimates for inland reaches—which assumes no vegetation effects on waves—are low. Many are below 20 percent of depth, reducing both q50 and q90 estimates.

   Proposed Response: For an assumption of open water fronting all reaches, apply the H_S-Depth index value of 0.4 at all reaches (as recommended by the USACE Engineers Research and Development Center), absent the presence of a reliable breakwater structure.

   Alternative: Reconsider a higher H_S-Depth index value (0.6) for actual open water reaches in accordance with general coastal engineering guidelines. For interior reaches consider potential wind speed and reach-specific fetch limitations associated with 100- and 500-yr SWL conditions using accepted methods. Also modify the design approach to allow consideration of resilient incidental breakwater features and foreshore vegetation (e.g., swamp forest) on the estimate of H_S.

   Priority Issue 3: The SWL standard deviation values (SWLσ) employed in the HSDRRS design for confidence intervals do not provide a reasonably conservative Factor of Safety; (see Attachment A for more information on SWLσ, noted there as σ_{CL}).

Proposed Response: Use reasonably conservative values for 100- and 500-yr SWLσ of 25 and 30 percent, respectively (for the East-Bank). Use the modified SWLσ in the analyses of overtopping uncertainty (q90). The nature and distribution of SWLσ uncertainty should be further investigated to support future updates to freeboard and overtopping uncertainty analysis.

Priority Issue 4: The Monte Carlo MatLab code for quantifying HSDRRS overtopping uncertainty contains an H_S "hard cap." This cap produces non-normal distributions for H_S and distorts estimates of both q50 and q90.

Proposed Response: Remove the hard cap and allow the overtopping uncertainty analysis to use a normal distribution of H_S and the recommended value for $H_S\sigma$. The nature and distribution of H_S uncertainty should be further investigated to support future updates to the overtopping uncertainty analysis. Estimates of q90 will increase due to responses to Priority Issues 1, 2, 3, and 4 combined; for a residual risk consideration, by more than a factor of 100 at some reaches.

Option: If H_S distribution tail values are physically unrealistic then it may be appropriate to modify the design assumption of a normal distribution.

6. The combined responses to the four issues indicate a need for higher elevations in order to meet the current established overtopping limits for 100-yr q50 and q90. Elevation increases for some levee reaches could exceed 4 ft, but could be readily mitigated if: a) new research on grass and other in-place armoring shows the design limits for 100-yr q50 or q90 could be raised (from 0.01 and 0.1 cfs/ft, respectively); and/or b) reassessment of foreshore wave breaking and other conditions shows wave H_S and/or T_P associated with the 100-yr SWL are lower.
7. For NFIP purposes (e.g., accurate flood hazard mapping, HSDRRS re-accreditation) resolving the four issues may not become a priority for some time. This may be especially true if revised 100-yr overtopping volumes are shown to present a negligible interior flood hazard. FEMA is the ultimate arbiter of when a reanalysis is required for NFIP purposes.
8. More importantly, the four issues and proposed responses are a priority for comprehensive surge risk management. The issues significantly increase 500-yr q50 and q90 at current design elevations, indicating that greater armoring is needed in order to meet resiliency goals.
9. Based on these findings Bob Jacobsen PE, LLC makes the following three recommendations:
   a. SLFPA-E and CPRA should work with the USACE—in conjunction with FEMA and other regional levee and flood authorities—to establish a clear understanding of the four issues and agreement on the implications for NFIP (if any) and resiliency/armoring actions as soon as possible. ***It may be appropriate to address these issues and responses differently for NFIP versus resiliency/armoring and other residual risk management purposes***. These issues and responses may also affect other Louisiana surge hazard analyses and levee designs.
   b. To support comprehensive management of surge risks, SLFPA-E and CPRA—in conjunction with the USACE and other appropriate federal, state and local agencies—should plan for a timely revision of the regional surge hazard analysis in accordance with the SOP, as described in the May 2013 Report and this Report.
   c. SLFPA-E and CPRA should work with the USACE, FEMA, and all other relevant federal, state, and local parties to provide for cost-effective investments in flood risk reduction. The cost-effectiveness of further HSDRRS improvements should be carefully evaluated—particularly those that affect timely implementation of resiliency—as well as weighed versus other polder flood risk reduction investments. The latter potentially include additional interior drainage and pumping improvements, compartmentalization options, crucial coastal restoration projects, Mississippi River flood protection system improvements, and non-structural measures.
10. The USACE's July 2014 update of design information does not change the findings or recommendations of this Report.

Table of Contents

1.0 Background

1.1 Surge Hazard Analysis State-of-the-Practice Issues
1.2 HSDRRS Elevation Design Issues
1.3 HSDRRS Resiliency Design Issues
1.4 Additional Issues Raised by WHG and JNS
1.5 USACE Response to Surge Hazard Analysis and HSDRRS Design Issues

2.0 Scope of Follow-Up

3.0 Priority Issue 1: Reduced Epsilon Term in the FORTRAN Code for Estimating 100- and 500-yr SWL

4.0 Priority Issue 2: Low H_S Associated with the 100- and 500-yr SWL

5.0 Priority Issue 3: Low SWLσ Values

6.0 Priority Issue 4: H_S Hard Cap in the Monte Carlo MatLab Code

7.0 Conclusions and Recommendations

References

Attachment A: *Update on the State of the Practice for Addressing 100-yr Surge SWL Uncertainty*

Attachment B: *Lake Okeechobee Florida Hurricane Surge Hazard*

1.0 Background

1.1 Surge Hazard Analysis State-of-the-Practice Issues

In May 2013 Bob Jacobsen PE, LLC completed a five part Report: *Hurricane Surge Hazard Analysis: The State of the Practice and Recent Applications for Southeast Louisiana*. Bob Jacobsen PE, LLC initiated work on this Report in early 2011 for the Southeast Louisiana Flood Protection Authority—East (SLFPA-E). The May 2013 Report reviewed the then current surge hazard analysis state-of-the-practice (SOP) and associated methodologies in five parts:

I. Hurricane Climatology,
II. Modeling of Hurricane Surge Physics,
III. Hurricane Surge Return Frequency Analysis,
IV. Hurricane Surge Hazard Analysis for Polders (including overtopping and breaching), and
V. Hurricane Surge Hazard Analysis for Future Conditions.

The 2013 SOP encompasses many groundbreaking methodologies developed by the U.S. Army Corps of Engineers (USACE) in their 2005-09 analysis of Southeast Louisiana surge hazard. However, the USACE 2005-09 analysis was in many respects limited by its emphasis on examining 100-year (yr) hurricane surge sufficient for the purposes of the National Flood Insurance Program (NFIP). The USACE analysis was tailored to preparing NFIP flood maps and design of the HSDRRS to meet NFIP accreditation requirements. This limited analysis was also used to extrapolate an estimate of 500-yr surge for HSDRRS resiliency design and a preliminary residual risk assessment (IPET 2009), and 400- and 1000-yr estimates for a USACE Coastal Protection and Restoration Study (USACE 2009).

The 2013 SOP review goes beyond NFIP requirements to incorporate methodologies appropriate to the comprehensive management of extreme surge risks. In light of ongoing rapid advances in the SOP, the May 2013 Report raised numerous concerns with the 2005-09 analysis. The Report concluded that outdated/limited practices likely have a significant effect on the current surge hazard estimates. Three important issues were:

1. The hurricane joint probability expression—which was developed for Gulf of Mexico major hurricanes—needs to be expanded to account for large, very slow-moving storms that never attain Category 3 in the Gulf. Such storms are capable of producing significant surge—as evidenced by Hurricane Isaac (2012).
2. There have been many significant improvements to the Advanced Circulation (ADCIRC) and Steady Wave (STWAVE) models since the 2005-09 analysis (model mesh layout, topography and bathymetry, Manning's n, minimizing localized mass conservation errors, the physics of wind-surge-wave interactions, and others). A newer surge model, for example, may better address localized under-predication bias during extreme storms along the shores of large sheltered water bodies, such as Lake Pontchartrain.[1]

[1] Validation of hydrodynamic models almost always identifies some systemic and localized biases. Users of these models determine if these biases are significant enough to require adjustment of the results.

3. The analysis employed the assumption of a very smooth surge-response which allowed for limited combinations of hurricane conditions (central pressure, radius of maximum winds, forward velocity, track angle, landfall spacing) in the set of 152 hypothetical storms used to define local surge-response functions. This small number of storms (e.g., no stalled Category 1 storms and no landfalling Category 5 storms) may not be sufficient to capture more complex surge-response associated with sheltered water bodies which characterize the intricate Southeast Louisiana coast (see Attachment B). Computer technology now allows for modeling many more storm scenarios and the assumption is no longer needed.

The Report stated that the various concerns could affect estimates of the 100-yr surge still water level (SWL) by as much as two feet at some HSDRRS locations. The Report noted that the estimates of 500-yr surge are more problematic. (Bob Jacobsen PE, LLC has subsequently suggested that 500-yr surge estimates should be explicitly qualified as "Nominal" estimates.)

The Report also addressed the need to model many more storm and breach scenarios to properly assess residual risk for the polders inside the HSDRRS. Furthermore, the Report noted that assessment of future surge hazards required consideration of coastal erosion and vegetation changes—the 2005-09 analysis was limited to addressing relative sea level rise.

In addition to issues with the expected values of the 100- and 500-yr surge SWL—and wave conditions at these SWLs (such as significant wave height, H_S)—the May 2013 Report also discussed methodologies related to characterizing uncertainty about these estimates. Surge hazard estimates—like many natural hazard phenomena—have complex uncertainties but quantification of this uncertainty is crucial for planning and design efforts.

A normal distribution standard deviation (σ) provides a convenient method for describing SWL uncertainty for any return period. Attachment A presents an updated review of the procedures for estimating SWLσ and the USACE approach for Southeast Louisiana. (In Attachment A SWLσ is noted as σ_{CL}.) Reasonably conservative estimates of SWLσ for 100-yr SWL are on the order of 30 percent, equivalent to a 90% Confidence Interval of ±50 percent. The May 2013 Report raised concerns with the USACE estimates of 100-yr SWLσ listed in the HSDRRS design documentation, *HSDRRS Design Elevation Report,* (*DER)*, Draft Report, Version 4a, December 2011. Across the East-Bank HSDRRS, the 100-yr SWLσ values listed in the 2011 *DER* were less than 10 percent.

The findings from the May 2013 Report regarding the surge hazard analysis SOP were presented at SLFPA-E Coastal Committee meetings (open to the public), beginning in 2012 as the Report parts were developed. In early 2013 a meeting was held with the USACE to discuss the preliminary findings and solicit comments, clarifications, and additional input. Drafts of the five parts were shared with the USACE well in advance of the final release.

In the fall of 2012 Bob Jacobsen PE, LLC joined a Louisiana Coastal Protection and Restoration Authority (CPRA) team reviewing the USACE 2005-09 surge hazard analysis for purposes of state acceptance of the HSDDRS design. This team is led by Lonnie G. Harper & Associates (LGH), and includes Woods Hole Group (WHG) and Joseph N. Suhayda PhD (JNS) as sub-consultants. Bob Jacobsen PE, LLC is a sub-consultant to WHG on the CPRA team. LGH, WHG, and JNS all provided valuable peer review of the five parts.

Given concerns with outdated/limited methodologies in the USACE's 2005-09 analysis, and—moreover—the crucial surge residual risk management responsibilities of SLFPA-E and CPRA beyond NFIP related risks, the Bob Jacobsen May 2013 Report recommended that the Southeast Louisiana surge hazard analysis be completely redone. The Report provided a comprehensive list of technical recommendations for revising the analysis, as well as recommendations for key areas of research that could improve future re-analyses.

The final Report findings on the surge hazard analysis SOP, along with the recommendations, were presented to the full SLFPA-E Board in April 2013.

1.2 HSDRRS Elevation Design Issues

While the May 2013 Report was intended primarily to be a review of the 2013 SOP in surge hazard analysis, SLFPA-E commissioners requested a discussion of implications for the HSDRRS design. As permitted under the NFIP regulations for coastal levee system accreditation, the HSDRRS includes an allowance for minimal *wave* overtopping—localized, short duration, small in volume.[2] Importantly, per NFIP regulations (44CFR65.10.b.iv), when coastal levees and floodwalls are designed to allow minimal wave overtopping, the uncertainties in overtopping must be carefully considered. Large wave overtopping uncertainties can translate into large risks for levee erosion and catastrophic breaching. The USACE described the HSDRRS wave overtopping allowance and the methodology for computing overtopping and overtopping uncertainty in the 2011 *DER*.

The primary HSDRRS wave overtopping limit is specified in terms of the *median* estimated 100-year rate (100-year q50). To address overtopping uncertainty the USACE 2011 *DER* incorporated limits for the 90 percent non-exceedance 100-yr overtopping estimate (100-year q90). The 2011 *DER* specifies that uncertainty factors in overtopping are assumed to follow a normal distribution. The 100-yr q50 and q90 limits are 0.01 and 0.1 cfs/ft, respectively.[3]

The NFIP does not require an uncertainty factor for the 100-yr SWL freeboard—which for coastal levees is required to be at least two feet for the 100-yr SWL expected value. The USACE HSDRRS design does not include a 100-yr freeboard uncertainty factor, but does require HSDRRS elevations to exceed the "Nominal" 500-yr SWL. However, the 100-yr q90 design criteria typically affect the HSDRRS design elevation more than the "Nominal" 500-yr SWL.

Thus, the 100-yr q90 provides the primary means for addressing overtopping uncertainty per 44CFR65.10.b.iv, and could, depending on how it is evaluated, also provide an important design Factor of Safety.

The 2011 *DER* describes the empirical equations used by the USACE to compute HSDRRS wave overtopping. Wave overtopping equations (e.g., Van der Meer for levees) are a function of HSDRRS elevation and geometry; SWL, H_S at the HSDRRS toe, wave period (T_p), and several

[2] A minimal wave overtopping allowance can be a reasonable alternative to coastal levee designs which seek to eliminate all wave overtopping.

[3] These limits were based on preventing erosion of the protected-side embankment slope and breaching; Bob Jacobsen PE, LLC has not reviewed the overtopping limits.

coefficients. As discussed in Part IV of the May 2013 Report, these empirical equations themselves, while convenient, have large uncertainties. The 2011 *DER* also used an empirical breaker index equation to determine H_s at many HSDRRS reach toes as function of depth.

The May 2013 describes the Monte Carlo approach used in the 2011 *DER* to quantify overtopping q90. This Monte Carlo approach employed σ values for SWL, H_s, T_p, and the overtopping equation coefficient. As noted above, the 2011 *DER* listed values of SWLσ—at generally less than 10 and 12.5 percent of SWL on the East and West Banks, respectively—appear to be very low.

The May 2013 Report provided an analysis of the crucial sensitivities of the wave overtopping q50 to potential issues with estimates of SWL and H_s, and of q90 to estimates SWLσ and $H_s\sigma$. The q50 and q90 exhibit nonlinear responses to changes in input estimates. In one example:

- A 12.5 percent rise in SWL results in a three-fold increase in q50, and necessitates a 1.5 ft higher levee.
- Increasing SWLσ from 10 to 30% raises q90 by a factor of ten (see Figure 1), requiring a 2 ft higher levee.
- Underestimating H_s by 33% increases q50 by a factor of five, requiring a 2 ft higher levee.

The May 2013 Report noted many concerns with estimates of the H_S associated with 100-yr SWL and its contribution to overtopping. These included:

- The need for studies to validate wave breaker-depth index and overtopping empirical equations for large, shallow inland water bodies, such as Lakes Pontchartrain and Borgne.
- Applicable H_S values at inland (inundated) locations. For example, the 2011 *DER* provided an H_S of 1.6 ft at levee reach SC02-B-with a SWL of 10.6 ft (also equal to the depth), which is equivalent to a H_S-depth ratio of less than 0.15.
- The role of resilient wetland vegetation (e.g., swamp forests) on inland H_S. The 2011 *DER* appears to require that this role be ignored.

These preliminary findings—most notably the apparently very low values for 100-yr SWLσ and their potential effect on q90 and levee elevation—were relayed to the USACE in early 2013.

The final Report recommended that SLFPA-E and CPRA revise estimates of HSDRRS overtopping q50 and q90 in conjunction with redoing the entire surge hazard analysis (incorporating SOP treatments of uncertainty), as well as plan for future revisions. In addition, the Report recommended evaluating the addition of Factors of Safety criteria for the 100- and 500-yr freeboard, reviewing the overtopping limits, and re-examining the appropriateness of using the 90% Non-Exceedance Level as the Factor of Safety.

These findings and recommendations were included in the April 2013 presentation to the SLFPA-E Board.

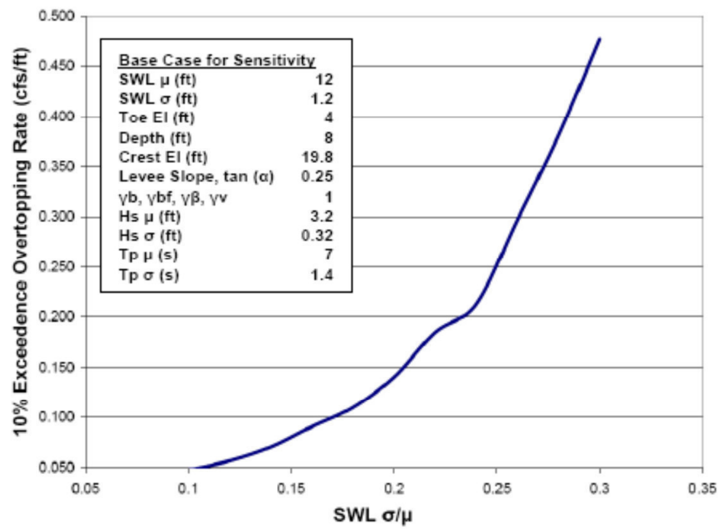

Figure 1 100-year q90 Sensitivity to Total SWL σ
Bob Jacobsen PE, LLC (May 2013)

1.3 HSDRRS Resiliency Design Issues

The May 2013 Report also reviewed the USACE's use of the "Nominal" 500-yr surge estimates in designing resiliency measures for HSDRRS levee reaches. The USACE employed estimates for the 500-yr q50 and q90 (the latter derived with the same Monte Carlo technique) to select levee armoring alternatives. The May 2013 Report noted that concerns with the 500-yr surge SWL estimates and with the USACE's SWLσ affect the 500-yr q50 and q90 estimates. The Report recommended revising the 500-yr q50 and q90 estimates to improve resiliency design decisions. These findings and recommendations were included in the April 2013 presentation to the SLFPA-E Board.

The same recommendations were reiterated by Bob Jacobsen PE, LLC in a June 2013 letter report to SLFPA-E reviewing the USACE *HSDRRS Levee Armoring Research and Recommendations Report*, (USACE 2013a).

1.4 Additional Issues Raised by WHG and JNS

In June 2013 parallel reviews of the USACE's 2005-09 surge hazard analysis were completed by WHG and JNS for the LGH-led CPRA team. These reviews are contained in the LGH report: *GNO Flood Protection System Notice of Construction Completion Design Assessment by Non-Federal Sponsor*. These reviews explored many of the above issues, and supported the need for a total revision of the Southeast Louisiana surge hazard analysis.

The WHG review included detailed inspections of computer codes used by the USACE, revealing two important code issues:

1. The FORTRAN code for estimating the 100- and 500-yr SWL expected values appeared to apply the *epsilon term* at half the true value. (See Attachment A for an explanation of the epsilon term.) The impact of this issue required more detailed investigations than undertaken at the time.

2. The MatLab code (developed by Royal Haskoning for the USACE) implementing the 2011 *DER* Monte Carlo analysis of overtopping uncertainty applied a *hard cap* to randomly selected H_s values. (See Section 6 below for more information on the hard cap issue.) The effect of the hard cap was to drastically reduce the resulting estimates of **both** the q50 and q90. Importantly, the q50 result from the Monte Carlo analysis should not differ too greatly from the overtopping estimate using the expected values for SWL, H_s and other inputs. The impact of this issue also required more detailed investigations than undertaken at the time.

The reviews by WHG and JNS also noted that the 0.4 breaker-depth index value applied by the USACE to determine H_S for 100- and 500-yr SWLs along open water reaches appeared to be lower than suggested in the technical literature (*Coastal Engineering Manual*, USACE 2003).

The June 2013 reports by WHG and JNS documenting their findings are part of the LGH-led CPRA team report.

1.5 USACE Response to Surge Hazard Analysis and HSDRRS Design Issues

Following sharing of the Bob Jacobsen PE, LLC May 2013 Report, as well as the LGH-led CPRA team June 2013 Report, the USACE and SLFPA-E organized a surge hazard analysis Workshop to examine and discuss issues with the 2005-09 analysis, as well as advances in the SOP. The Workshop was held on August 15-16, 2013 with technical and management representatives from the USACE, CPRA, and SLFPA-E.

Bob Jacobsen PE, LLC and WHG (Nathan Dill) made presentations on the issues described above in Sections 1.1 through 1.4. Representative from the USACE team (Agnew, Resio, Westerink, etc.) provided presentations on the USACE methodologies. A written response was prepared by the USACE in December 2013 and shared with SLFPA-E and CPRA. However, for most issues the USACE response did not alleviate the concerns expressed in the May and June 2013 Reports. For example, regarding the three major issues listed in Section 1.1:

1. The USACE asserted that the frequency of slow moving, large, low intensity hurricanes is accounted for in their analysis. However, the Gumbel equation used by the USACE to quantify the storm frequency was based on data for Category 3 or greater Gulf of Mexico hurricanes. *The joint probability expression for hurricane conditions should be updated to well represent all storms capable of producing 100-yr SWL.*
2. The USACE discussed advances in more recent surge models. In addition they discussed validation of these models with Hurricanes Gustav and Isaac, which apparently do not have local under-prediction bias along large sheltered water bodies. However this does not change the fact that the model employed in the 2005-09 analysis did contain local bias for the Hurricane Katrina validation. A possible explanation for the bias was offered

that indicated the bias could be storm-specific. There are physicals factors why the models may have these local biases for extreme surge, such as during Hurricane Katrina. These include higher pre-storm water levels in these sheltered water bodies than accounted for, rainfall, and complex wind-surge-wave interaction in these water bodies. *The analysis should be updated with newer models and a careful evaluation of these physical factors*.

3. The USACE maintained that the surge-response approach used in the 2005-09 analysis meets the needs of the analysis. The USACE did not discuss the problem of complex, highly nonlinear surge response for sheltered water bodies, although this is acknowledged in the technical literature explaining the surge-response approach. *The analysis should be redone with an expanded set of storms to describe the nonlinear surge response of water bodies such as Lakes Pontchartrain and Borgne (see the description of the 1928 Lake Okeechobee surge in Attachment B).*[4]

The December 2013 USACE response did not address:

- The reduced epsilon term in the FORTRAN code for estimating the 100- and 500-yr SWL.
- The low estimates of H_S associated with 100- and 500-yr SWLs, especially for HSDRRS inland reaches.
- The low SWLσ values in the 2011 *DER*.
- The H_s hard cap in the Monte Carlo MatLab code.

The Workshop participants generally agreed that future revision of the surge hazard analysis would be needed to stay abreast of the SOP, and that such revision would be of benefit in managing Southeast Louisiana surge risks. However, no strategies were explored for revising the analysis (including organization, resource requirements, methodologies, research needs, programmatic authorizations, funding, time table, etc.).

In December 2014 the USACE provided additional clarification—in response to an inquiry from the SLFPA-E—regarding the components of uncertainty addressed in SWLσ. This clarification was helpful in the preparation of the Attachment A update on the SOP for addressing SWLσ.

[4] Or other approaches could be employed and with more storms; e.g., the Toro JPM-OS approach—as used in other recent coastal surge hazard studies (see URS 2006); or Monte Carlo/Empirical Track approach—as used by Vickery in coastal wind hazard studies (see Vickery et al 2009).

2.0 Scope of Follow-Up

In the wake of the Workshop the LGH-led CPRA team discussed several options for further evaluating priority issues with the USACE 2005-09 surge and wave overtopping hazard analysis. Priority issues were considered to be those:

1. That could potentially result in significant, widespread increases in the USACE 100- and 500-yr SWL,H_S, and associated σ estimates, and/or the q50 and q90 estimates; and
2. That are amenable to expedited investigation, straightforward responses, and revision of estimates. Priority issues would not include revision/revalidation of the ADCIRC surge model, expansion of the surge-response OS, and re-simulation of the OS.

Substantial revision of the 100-yr SWL, H_S, and q50/ q90 estimates can potentially affect both NFIP and residual risk management actions. However, the following is recognized:

- Outdated/limited practices do not necessarily render surge hazard analyses unusable for NFIP actions—including accreditation of levees and preparation of flood maps. Due to schedules, resources, funding and other constraints—as well as its particular programmatic purposes—the NFIP can accept flood hazard analyses that may not be acceptable for other purposes.
- Furthermore, it is not unusual for the NFIP to continue to rely on analyses based on outdated/limited practices for many decades.
- However, CPRA, local communities, and the public cannot rely on the future, continued NFIP use of analyses based on outdated/limited practices, including for reaccreditation of the HSDRRS in 2023.
- State and local agencies that have concerns over flood hazard analyses (due to outdated/limited practices) are advised to present those concerns to FEMA for discussion of potential paths forward. In some instance they are actually required to do so under the terms of their participation in the NFIP.
- Moreover, as emphasized in the May 2013 Report, while analyses based on outdated/ limited practices may be used in the NFIP, they are not suitable for managing residual surge risks.

Following recommendations prepared by the LGH-led team, in October 2013 CPRA issued a task order authorizing the LGH-led team to conduct a further evaluation of priority issues. Under this task order Bob Jacobsen PE, LLC—in conjunction with WHG (with support from Nathan Dill of Ransom Consulting), JNS, and Michael Beck—has evaluated four priority issues:

1. The reduced epsilon term in the FORTRAN code for estimating the 100- and 500-yr SWL.
2. The low estimates of H_S associated with 100- and 500-yr SWLs, especially for HSDRRS inland reaches.
3. The low SWLσ values in the 2011 *DER*.
4. The H_S hard cap in the Monte Carlo MatLab code.

WHG has prepared a separate report documenting a) the full scope of USACE information obtained and reviewed—including databases associated with the 2011 *DER,* additional FORTRAN codes (including those employed to compute SWL sampling uncertainty), and the Monte Carlo MatLab code—and b) a series of sensitivity tests conducted with the Monte Carlo MatLab code assessing various treatments of the priority issues. The sensitivity tests included evaluating potential increases in HSDRRS elevation. Michael Beck has prepared reports documenting his assessment of surge hazard uncertainty. These WHG and Michael Beck reports are submitted to LGH separately from this Report by Bob Jacobsen PE, LLC.

This Report by Bob Jacobsen PE, LLC reviews the four priority issues and proposes responses to the surge hazard analysis appropriate to the comprehensive management of surge risks. Given a basic understanding of coastal engineering, the four issues are not difficult to comprehend. Sections 3, 4, 5, and 6 discuss each of the four issues and corresponding simple, straightforward proposed responses to resolve the issues. Section 7 then provides three basic recommendations by Bob Jacobsen PE, LLC based on the findings discussed in Sections 3 through 6.

An earlier version of this Report was prepared in April 2014 and submitted as part of a joint report with WHG by LGH to CPRA. Following the receipt of comments by CPRA in October 2014 Bob Jacobsen PE, LLC produced this Report as a separate, stand-alone report. This Report includes revisions to the earlier version as appropriate to address the CPRA comments.

In July 2014 the USACE released *Elevations for Design of Hurricane Protection Levees and Structures (EDHPLS)*, Version 2.0. The 2014 *EDHPLS* is an update, and retitling, of the 2011 *DER* and was obtained by CPRA and shared with the LGH-led team. The modifications in the 2014 *EDHPLS* did not change the four priority issues and therefore do not require any changes in the findings discussed in Sections 3 through 6 or in the recommendations discussed in Section 7.

3.0 Priority Issue 1: Reduced Epsilon Term in the FORTRAN Code for Estimating 100- and 500-yr SWL

Attachment A provides a technical review of the SWL cumulative distribution function (CDF) and the incorporation of the epsilon term into the CDF to address some modeling uncertainty variables. The latter produces improved expected values for 100- and 500-yr SWL. Importantly, including uncertainty variables in the epsilon term—and thereby incorporating these into the CDF—means they will not be included as part of determining 100- and 500-yr SWLσ.

The June 2013 LGH Report includes a WHG Task Two Completion Report (Appendix 1) that summarizes WHGs review of the USACE FORTRAN code for computing CDF curves. The WHG Report states the FORTRAN code contains an error with regard to the epsilon term. The error causes the code to apply only half the epsilon term value instead of the full value. Since the variables included in the epsilon term are not included in the SWLσ, the epsilon term should be applied at its full value. In addition, the WHG Task Two Completion Report identified several typographical errors with the FORTRAN code.

The Proposed Response addressing Priority Issue 1 is: Correct the FORTRAN code to apply the full value of the epsilon term to the computation of the surge hazard CDFs, together with the typographical errors. This corrects the 100- and 500-yr SWL expected values.

WHG in a separate report provides revised estimates for 100-yr SWL for selected HSDRRS reaches. 100-yr SWLs increased for 15 reaches by a range of 0.5 to 1.2 ft. As an example, for reach JL01 in Jefferson Parish the 100-yr SWL increased from 9.0 to 9.7 ft.

4.0 Priority Issue 2: Low H_S Associated with the 100- and 500-yr SWL

The 2011 *DER* outlines the USACE procedure for estimating H_S associated with the 100- and 500-yr SWL at the HSDRRS toe. This procedure was reviewed in detail by Bob Jacobsen PE, LLC and WHG to understand how low values for H_S were obtained for inland locations. WHG also reviewed the FORTRAN codes implementing this procedure. Based on this review, Bob Jacobsen PE, LLC believes that the low H_S values for inland locations were derived with a procedure that cannot be considered an acceptable practice.

To develop estimates of H_S associated with the 100- and 500-yr SWL the USACE took the unusual first step of estimating *depth-independent* 100- and 500-year H_s. Depth-independent 100- and 500-year H_S are by definition not the same as H_S associated with 100- and 500-year SWLs. Depth-independent 100- and 500-yr H_S values are commonly used in the design of open coast and offshore platforms and could be more extreme (conservative) when the return frequency analysis used to generate them is reasonable. However, the USACE procedure used the STWAVE maximum H_S values from the SWL Surge-Response OS storms (which were selected to optimize estimation of *surge*-response functions) and applied the same “response” approach used in developing SWL CDFs to develop H_S CDFs. For the H_s CDFs this procedure relied on developing a “wave-response function” correlating the STWAVE maximum H_S with hurricane characteristics. Importantly, inland locations are expected to have extremely nonlinear wave-response functions (more so than surge response functions) and the assumption of very smooth wave-response functions is not reasonable. Moreover, for inland locations the wave-response functions could only be developed with the subset storms that produced local inundation. The H_s CDF integration also employed a questionable epsilon term. Thus, the use of such 100- and 500-year H_s values is extremely problematic.

The USACE compared its 100- and 500-year H_s values with H_s values derived with a single, uniform “ceiling” H_s-Depth index parameter of 0.4, applied to the local depths at the 100- and 500-year SWL. The USACE cited literature and an opinion by the USACE Engineer Research and Development Center (ERDC) to justify use of this value. The effect of the 2011 *DER* approach was to reduce the H_s associated with the 100- and 500-year SWLs to 0.4 times the depth for HSDRRS reaches facing open water. For these locations this actually negated the need for even using the first step.[5]

However, for inland locations the first step typically produced 100- and 500-year H_s well below 0.4 times the depth (0.148 in the case of reach SC02-B in the East-Bank St. Charles Parish for the 100-year SWL). For these locations the USACE retained the result from the first step, i.e., employed the depth-independent 100- and 500-year H_S values.

The use of such 100- and 500-year H_S values for inland reaches appears to be inconsistent with other language in the 2011 *DER*. The 2011 *DER* discussed the need to regard inland reaches—which generally experience expansive inundated wetland foreshores, thus reducing fetch limitations—as essentially equivalent to reaches exposed to open water, particularly given the uncertain sustainability and resilience of wetland vegetation and incidental terrain features. The 2011 *DER* included the following statement recommending that a single H_s-Depth index value be used for the whole HSDRRS project:

[5] Lower H_S values were computed for reaches facing open water that have breakwater structures.

> *Because of the long shallow foreshores in front the levees and structures within the project area, ERDC recommends a value of 0.4 for the* *__entire__* *HSDRRS protection area* (emphasis added).

Following this reasoning requires the use of the uniform H_s-Depth index value of 0.4 at all reaches, not just those exposed to open water.

The Proposed Response addressing Priority Issue 2, Alternative 1, is: Apply the ERDC recommended breaker-depth index value of 0.4 ft at all reaches, absent the presence of a reliable breakwater structure. A uniform value of 10 percent as specified in the 2011 DER would continue to be used for $H_S\sigma$.[6]

WHG provides revised estimates for revised H_S at 100-yr SWL for selected inland HSDRRS reaches. The H_S at the 100-yr SWL increased by between 0.5 and 3 ft for 15 reaches under this proposed response.

WHG and JNS have further evaluated current engineering practices with respect to H_s-Depth index parameters for the HSDRRS. For reaches exposed to open, shallow water the *Coastal Engineering Manual* recommends a breaker-depth index value of 0.6 (see LGH Task Two Completion Report, Appendix 3 in LGH 2013 for additional discussion). Given the lack of studies for the particular characteristics of locally generated hurricane wind waves in Lakes Pontchartrain and Borgne the value of 0.6 may be more reasonable than 0.4 for estimating H_S associated with 100- and 500-year SWLs at reaches exposed to open water.[7]

For inland HSDRRS reaches Bob Jacobsen PE, LLC and WHG analyzed the ADCIRC/STWAVE peak SWL and H_S results provided by the USACE for 152 synthetic storm simulations at 15 inland locations. Figure 3 presents a scatter plot of 1486 H_S-Depth points, each representing the peak H_S and Depth that occurred for a given location and storm. (Peak H_S and Depth are assumed to have occurred simultaneously but time-series were not available to verify this assumption.) These results indicate a general H_S-Depth ratio for all inland areas of 0.27. This ratio—and the wide degree of scatter in the data—indicated that peak H_S may have been limited by a combination of storm-specific/location-specific inland wind speeds, ADCIRC's upwind and overlying canopy wind reduction factors, and wind fetch. There are readily accepted methods for applying likely fetch and wind-speed conditions associated with a 100-yr SWL event for individual HSDRRS reaches in order to estimate H_S.

An Alternative Proposed Response is: Reconsider applicable H_s-Depth index values for open water HSDRRS reaches in accordance with general coastal engineering guidelines. For interior reaches consider likely wind speed and fetch limitations associated with 100-yr SWL condition. Also modify the design approach to allow consideration of resilient incidental breakwater features and foreshore vegetation (e.g., swamp forest) on the estimate of H_S. This option would require development of acceptable methodologies for evaluating vegetation breakwaters.

[6] The value of 10 percent for $H_S\sigma$ also seems low but WHG and Bob Jacobsen PE, LLC did not evaluate $H_S\sigma$ for this proposed response.

[7] There may be some cases where even higher H_S values should be considered.

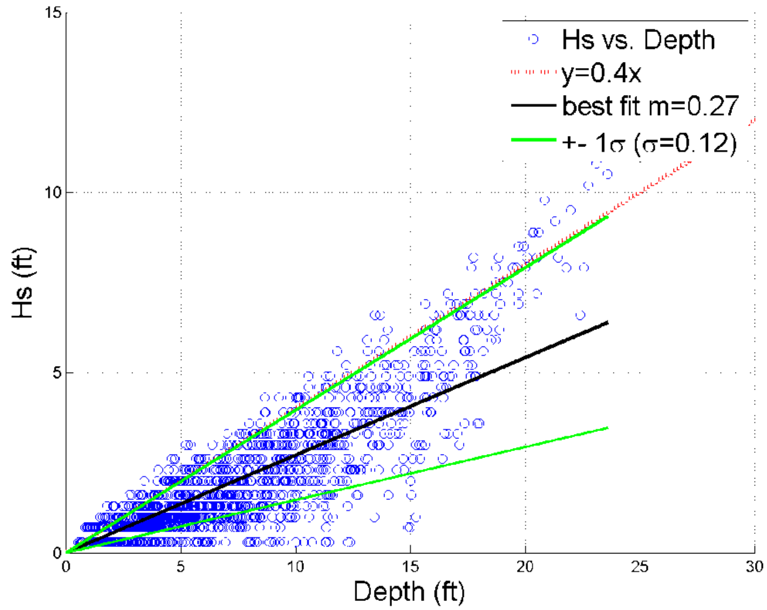

Figure 3. H_s-Depth Results from __ STWAVE Locations
Prepared by WHG

5.0 Priority Issue 3: Low SWLσ Values

As discussed in Section 1.2, the 2011 *DER* uses SWLσ (along with $H_S\sigma$ and $T_P\sigma$) in the Monte Carlo technique for assessing wave overtopping uncertainty and meeting the NFIP requirement 44CFR65.10.b.iv. Such Monte Carlo approaches are common in the engineering assessment of multiple uncertainties and their effect on the resulting uncertainty in a hydraulic design condition. These approaches require appropriate σ values.

Attachment A includes a detailed review of the State-of-the-Practice for estimating important components of 100-yr SWLσ (referred to as σ_{CL} in the attachment). This attachment reflects clarifications provided by a USACE December 1, 2014 letter on this subject.

Uncertainty components fall in three general categories depending on if they are related to the hurricane joint probability equation, the wind/surge/wave model, or the surge-response function. Four uncertainty components associated with the wind/surge/wave model and one associated with the surge-response function are addressed in the epsilon term and thus do not contribute to estimating SWLσ (see Section 4 and Attachment A). Seven uncertainty components remain to be addressed for estimating SWLσ (again, see Attachment A).

The USACE estimates of SWLσ as documented in the 2011 *DER* reflect two basic issues:

1. The USACE approach to one component, hurricane sampling uncertainty (σ_S),[8] produces estimates that are less than 10 percent of SWL for the East-Bank (12.5 percent for the West Banks). Attachment A reviews several limitations with the USACE's estimates of σ_S. Alternative estimates for σ_S in accordance with the observed SWL-frequency for Grand Isle tide gauge data (see Beck 2014) are on the order of 15 to 20 percent of SWL for the East-Bank. WHG provides estimates for the alternative σ_S for selected HSDRRS reaches. For the JL01 HSDRRS levee reach σ_S rose from 0.6 ft (for 100-yr SWL of 9.0), to 1.7 ft (for the revised 100-yr SWL of 9.7).
2. The 2011 *DER* provides only for the use of the USACE's σ_S in determining SWLσ and omits the remaining components. Attachment A reviews estimates of these remaining components, which depend to a great deal on professional judgment and the purposes for estimating SWLσ.

The USACE approach to σ_S and ignoring additional uncertainty components may be consistent with NFIP purposes. 44CFR65.10.b.iv is not clear what components should be used to evaluate SWLσ and how they should be estimated. An NFIP actuarial risk based approach may be sufficient for HSDRRS accreditation. However, assessing SWLσ as a part of design Factor of Safety, especially from a comprehensive risk management perspective, requires a reasonably conservative approach to estimating values for the seven uncertainty components.

Reasonably conservative values for the 100- and 500-yr SWLσ for use in comprehensive surge risk management are 25 and 30 percent of SWL, respectively.

[8] See . Resio et al 2007, Appendix G, *Estimation of Confidence Bands for Surge Estimates.*

The Proposed Response addressing Priority Issue 3 is: Use reasonably conservative values for 100- and 500-yr SWLσ of 25 and 30 percent (for the East-Bank). Use the modified SWLσ in the analyses of overtopping uncertainty (q90).

It is important to acknowledge that assuming a normal distribution of uncertainty with a SWLσ of this magnitude implies upper and lower confidence limits that become physically unrealistic at the far tail. The nature and distribution of SWLσ uncertainty should be further investigated to support future updates to freeboard and overtopping uncertainty analysis.

6.0 Priority Issue 4: H_S Hard Cap in the Monte Carlo MatLab Code

The USACE's overtopping uncertainty analysis—performed with a Monte Carlo approach—stipulates that input uncertainties follow a normal distribution—with σ values specified for SWL, H_s, T_p, and empirical coefficients. As previously noted in Section 1.4, during their inspection of the MatLab code implementing the Monte Carlo analysis WHG found an instruction to cap the values of H_s drawn from randomly sampling the H_s uncertainty distribution. The cap limits H_s to a maximum of 0.4 times the depth given by a simultaneous random sample of the SWL. Thus, the uncertainty for H_s applied in the Monte Carlo analysis is *not* normally distributed.

The use of this cap in the Monte Carlo analysis is not warranted. Reasonable $H_S\sigma$ values for the normal distribution of H_S uncertainty are provided for as discussed in Section 4 above and there is no reason for further modifying the H_S uncertainty distribution in the Monte Carlo analysis.

Of critical importance—as noted in WHG's separate report—is the skew in the overtopping uncertainty distribution produced by the cap. This skew causes significant underestimation of <u>both</u> the q50 and q90, with the q50 much less than the deterministic overtopping estimate using expected values for SWL, H_S, T_P , and the coefficients.

The Proposed Response addressing Priority Issue 4 is: Remove the hard cap and allow the overtopping uncertainty analysis to use a normal distribution of H_S and the recommended value for $H_S\sigma$. The nature and distribution of H_S uncertainty should be further investigated to support future updates to the overtopping uncertainty analysis.

Table 1 provides revised estimates of 100-yr q50 and q90 (along with the deterministic overtopping) associated with the recommended responses to Priority Issues 1, 2, 3, and 4 combined for 20 example East-Bank reaches. Table 2 provides the input used in the revised estimates. (The reach information is based on the 2011 *DER*.) The recalculated 100-yr deterministic wave overtopping and Q50 values are now very similar. Of the revised 100-yr Q50s and Q90s, 9 and 20, respectively, exceed the USACE specified limits (0.01 and 0.1 cfs/ft). Table 1 also provides the revised crown elevation (keeping the other reach inputs the same) required to meet both current specified limits. All 20 reaches would require increases, sixteen would require increases of 2 ft or greater, and six increases of 4 ft or greater.

Table 1. Revised Overtopping Rates at Twenty East-Bank HSDRRS Locations
Applying the Proposed Reponses to Four Priority Issues

Location	Design Elevation (ft NAVD88)	100-yr			*Nominal* 500-yr			Elevation Increase Required to Meet Overtopping Criteria*	
		Overtopping (cfs/ft)			Overtopping (cfs/ft)			Elevation	Increase
		Det	Q50	Q90	Det	Q50	Q90	(ft NAVD88)	(ft)
SC02-A	15.5	0.20	0.22	5.55	1.14	6.46	66.21	20.5	5.0
SC02-B	14.0	0.60	0.66	8.22	6.00	8.83	79.37	20.0	6.0
JL01	16.5	0.01	0.01	0.23	0.32	0.36	7.08	17.5	1.0
NO01	16.0	0.02	0.03	0.66	0.88	0.96	10.69	18.5	2.5
NO10	15.0	0.04	0.04	0.78	1.23	1.22	14.05	17.5	2.5
NE01	13.0	0.05	0.03	1.50	1.22	1.14	26.05	15.5	2.5
NE02	15.5	0.01	0.01	0.30	0.16	0.18	6.21	17.0	1.5
NE10	17.0	0.01	0.01	0.76	1.01	1.06	20.14	19.5	2.5
NE11A	22.0	0.04	0.05	1.82	1.90	1.76	26.27	26.5	4.5
NE11B	25.0	0.01	0.01	0.85	0.65	0.73	20.61	28.0	3.0
NE12A	28.0	0.01	0.01	0.58	0.43	0.48	14.83	31.0	3.0
NE12B	29.0	0.01	0.01	0.70	0.49	0.55	18.47	32.5	3.5
NE30	14.5	0.03	0.03	0.74	0.54	0.58	9.56	17.0	2.5
NE31	16.5	0.01	0.01	0.21	0.15	0.18	5.41	17.5	1.0
SB11	29.0	0.01	0.02	1.23	0.85	0.94	26.20	33.5	4.5
SB12	27.5	0.002	0.002	0.38	0.31	0.36	19.51	29.5	2.0
SB13	26.5	0.01	0.01	1.05	6.89	4.86	31.41	30.0	3.5
SB15	26.5	0.005	0.01	0.24	1.15	0.88	10.39	28.0	1.5
SB16	26.5	0.02	0.02	1.32	1.42	1.42	25.64	31.0	4.5
SB17	26.5	0.01	0.01	1.83	1.79	1.67	46.21	30.5	4.0

*To meet both the 100-yr q50 and q90 criteria (0.01 and 0.1 cfs/ft)

Table 2. Input for Revised Overtopping Rates at Twenty East-Bank HSDRRS Locations

Segment	Reach Information				100-yr							500-yr						
	Toe El	Design Crown El	Berm Factor	Slope	SWL 50	SWL σ	SWL 90	H_s	$H_S σ$	T_P	$T_P σ$	SWL 50	SWL σ	SWL 90	H_s	$H_S σ$	T_P	$T_P σ$
SC02-A	0	15.5	1.00	4.3	12.10	3.03	15.97	4.84	0.48	4.20	0.84	15.60	4.68	21.59	6.24	0.62	5.60	1.12
SC02-B	0	14.0	1.00	3	11.60	2.90	15.31	4.64	0.46	3.20	0.64	15.10	4.53	20.90	6.04	0.60	4.10	0.82
JL01	0	16.5	0.58	4	9.70	2.43	12.80	3.88	0.39	7.70	1.54	12.20	3.66	16.88	4.88	0.49	9.00	1.80
NO01	-4	16.0	0.73	5	9.60	2.40	12.67	5.44	0.54	7.20	1.44	12.20	3.66	16.88	6.48	0.65	8.50	1.70
NO10	3	15.0	1.00	3	9.80	2.45	12.94	2.72	0.27	7.20	1.44	12.30	3.69	17.02	3.72	0.37	8.50	1.70
NE01	0	13.0	0.74	4	9.40	2.35	12.41	2.19	0.22	6.70	1.34	11.70	3.51	16.19	2.73	0.27	6.70	1.34
NE02	-1	15.5	0.62	4	9.40	2.35	12.41	3.89	0.39	6.70	1.34	11.70	3.51	16.19	4.75	0.48	6.70	1.34
NE10	0	17.0	0.73	4	11.20	2.80	14.78	4.48	0.45	5.39	1.08	14.20	4.26	19.65	5.68	0.57	6.38	1.28
NE11A	0	22.0	0.60	4	14.70	3.68	19.40	5.88	0.59	8.25	1.65	18.20	5.46	25.19	7.28	0.73	9.90	1.98
NE11B	0	25.0	0.71	5	16.20	4.05	21.38	6.48	0.65	7.70	1.54	19.90	5.97	27.54	7.96	0.80	8.91	1.78
NE12A	0	28.0	0.64	4	17.20	4.30	22.70	6.88	0.69	8.03	1.61	21.10	6.33	29.20	8.44	0.84	9.02	1.80
NE12B	0	29.0	0.77	5	18.20	4.55	24.02	7.28	0.73	7.92	1.58	22.30	6.69	30.86	8.92	0.89	8.91	1.78
NE30	-1	14.5	0.77	4	9.30	2.33	12.28	3.11	0.31	6.70	1.34	11.60	3.48	16.05	3.81	0.38	6.70	1.34
NE31	0	16.5	0.70	4	9.50	2.38	12.54	3.80	0.38	6.70	1.34	12.00	3.60	16.61	4.80	0.48	6.70	1.34
SB11	0	29.0	0.77	5	18.80	4.70	24.82	7.52	0.75	7.92	1.58	23.10	6.93	31.97	9.24	0.92	8.91	1.78
SB12	0	27.5	0.67	4	17.60	4.40	23.23	7.04	0.70	5.94	1.19	21.70	6.51	30.03	8.68	0.87	6.93	1.39
SB13	0	26.5	0.68	4	17.60	4.40	23.23	7.04	0.70	6.27	1.25	21.70	6.51	30.03	8.68	0.87	14.30	2.86
SB15	0	26.5	0.77	5	14.90	3.73	19.67	5.96	0.60	8.91	1.78	18.20	5.46	25.19	7.28	0.73	14.41	2.88
SB16	0	26.5	0.72	5	17.30	4.33	22.84	6.92	0.69	8.36	1.67	21.20	6.36	29.34	8.48	0.85	10.56	2.11
SB17	0	26.5	0.63	5	18.20	4.55	24.02	7.28	0.73	8.14	1.63	22.60	6.78	31.28	9.04	0.90	9.90	1.98

7.0 Conclusions and Recommendations

The combined responses to the four issues indicate a need for higher elevations in order to meet the current established overtopping limits for 100-yr q50 and q90. Elevation increases for some levee reaches could exceed 4 ft, but could be readily mitigated if:

a. New research on grass and other in-place armoring shows the design limits for 100-yr q50 or q90 could be raised (from 0.01 and 0.1 cfs/ft, respectively) ; and/or
b. Reassessment of foreshore wave breaking and other conditions shows wave H_S and/or T_P associated with the 100-yr SWL are lower.

For NFIP purposes (e.g., accurate flood hazard mapping, HSDRRS re-accreditation) resolving the four issues may not become a priority for some time. This may be especially true if revised 100-yr overtopping volumes present a negligible interior flood hazard.

More importantly, the four issues and proposed responses are a priority for comprehensive surge risk management. The 500-yr q50 and q90 increases have significant implications for the selection of armoring alternatives—such as high performance turf reinforcement mat and slope paving—to meet resiliency goals.

Bob Jacobsen PE, LLC therefore makes the following three recommendations.

Recommendation 1: SLFPA-E and CPRA should work with the USACE—in conjunction with FEMA and other regional levee and flood authorities—to establish a clear understanding of the four issues and agreement on the implications for NFIP (if any) and resiliency/armoring actions as soon as possible. ***It may be appropriate to address these issues and responses differently for NFIP versus resiliency/armoring and other residual risk management purposes***.

SLFPA-E and CPRA should keep the Louisiana Department of Transportation and Water Resources Division (the State Coordinating Agency for the NFIP), and the parish governments (which have responsibility for administering the NFIP at the local level) apprised of the matter.

FEMA NFIP actions—such as preparation of flood maps and accreditation of flood reduction structures—can reflect practices that may not be suitable for more severe risk management. (Note that FEMA's acceptance of a practice for one action does not guarantee that the practice will continue to be accepted, particularly if it is found to be inconsistent with NFIP purposes.)

SLFPA-E and CPRA may wish to obtain additional opinions on these issues from recognized independent authorities, such as the National Academy of Engineering, the National Committee on Levee Safety, or the American Society of Civil Engineers.

Recommendation 2: To support comprehensive management of surge risks, SLFPA-E and CPRA—in conjunction with the USACE and other appropriate federal, state and local agencies—should plan for a timely revision of the regional surge hazard analysis in accordance with the SOP, as described in the May 2013 Report and this Report.

Recommendation 3: CPRA should work with the USACE, FEMA, and all other relevant federal, state, and local parties to provide for cost-effective investments in flood risk reduction. The cost-effectiveness of further HSDRRS improvements should be carefully evaluated—particularly those that affect timely implementation of resiliency—as well as weighed versus other polder flood risk reduction investments. The latter potentially include additional interior drainage and pumping improvements, compartmentalization options, crucial coastal restoration projects, Mississippi River flood protection system improvements, and non-structural measures.

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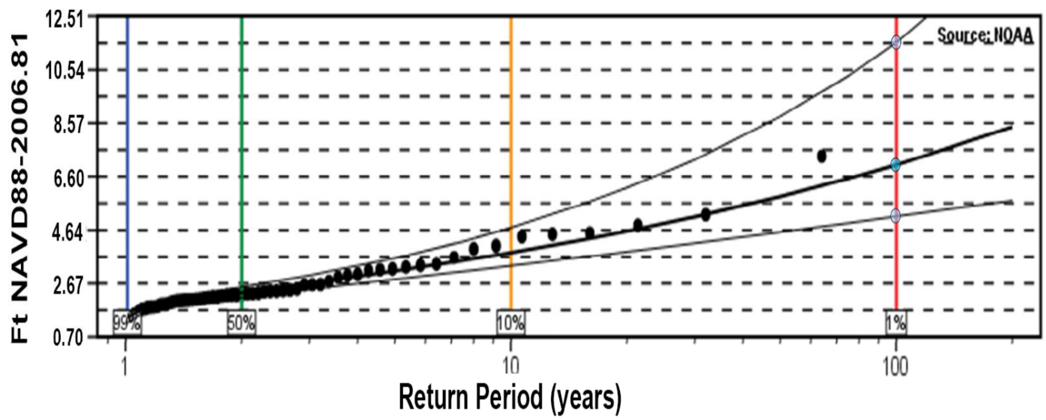
Attachment A

Update on the State of the Practice
for Addressing 100-yr Surge SWL Uncertainty

Including the USACE Approach to 2005-09 Surge Hazard Analysis and HSDRRS Design



NOAA

Bob Jacobsen PE, LLC

March 2015

This document discusses eight key concepts and associated technical approaches for addressing the hurricane surge 100-year (yr) still water level (SWL) uncertainty:

1. The surge SWL hazard cumulative distribution function (CDF);
2. Hurricane joint probability equation uncertainties;
3. Surge model uncertainties;
4. Storm sample uncertainties;
5. Incorporating uncertainties into the CDF;
6. Using an epsilon term to incorporate uncertainties into the CDF;
7. Relationship between epsilon, the CDF, and CDF confidence limits; and
8. Applying professional judgment to the treatment of SWL uncertainties

This document then reviews the US Army Corps of Engineers (USACE) approach to the 100-yr SWL uncertainty in their 2005-09 work for Southeast Louisiana and the design of the Hurricane and Storm Damage Risk Reduction System (HSDRRS).[1]

1. Surge SWL CDF

Surge hazard is depicted mathematically using a CDF curve which presents the surge SWL (elevation) that is expected to occur or be exceeded at various return frequencies (or at average return periods, the inverse of the return frequency). A SWL CDF is location-specific. To construct a CDF, a set of local, individual SWL events—each with its own discrete frequency (mass probability) is first developed. This is either done 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 as a function of key hurricane variables. Five key hurricane variables are 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). SWL-frequency points can be grouped by SWL increments (e.g., 0 - <0.5 ft, 0.5 - <1 ft, etc.) to create a histogram showing frequency by SWL *Bin*.

There are several methods that could be used for a JPA to create the set of SWL-frequency points. A widely-accepted joint probability method (JPM) is to develop a set of storms which expands on historical observations to create an artificial record much longer (e.g., an order of magnitude) than the longest return period of interest. The artificial record provides wide variability in the combination of hurricane attributes that is consistent with their generally observed joint probabilities. Vickery et al (2009) developed an artificial 100,000-yr record for a wind hazard analysis.

For surge hazard analysis, SWLs for each storm are simulated using a sophisticated computer model which mimics the physical interaction of wind, surge, and waves with the coastal landscape. The time and expense of surge simulations require that a much smaller set—an optimized sample (OS)—of storms is developed, in which the frequencies of selected storms are weighted (Toro 2008 and IPET 2009).

Figure 1a illustrates a set of 76 SWL-frequency points. In this set several hypothetical storms share the same general frequency (they have common attributes, but different landfall locations). Figure 1b shows a histogram of frequencies for SWL bins. The CDF is developed by numerical integrating the frequencies through each SWL Bin. Figure 1c zooms in on the storms for SWL less than 4.0 ft. Examples

[1] This document updates information presented in the May 2013 Report by Bob Jacobsen PE, LLC, *Hurricane Surge Hazard Analysis: The State of the Practice and Recent Applications for Southeast Louisiana*. In December 2014 the USACE provided additional clarification regarding their evaluation of surge SWL uncertainty. This document makes use of that clarification.

of the numerical integration are shown in Table 1. Figure 1d presents the CDF. Particular SWL hazards at a location—such as the expected 100-yr and 500-yr SWL—are simply taken from the curve. In the case of Figure 1d the expected 100-yr SWL is 8.4 ft.

Resio et al 2009 described an innovative JPM which uses an intermediate step of developing location-specific surge-response functions. Similar in concept to a stage-discharge function for a river, the surge-response function defines SWL in terms of the hurricane attributes. An OS of storms is then simulated to construct the local surge-response function. (Thus, the Surge-Response-OS has a different purpose than the Toro 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, hundreds of synthetic surge events—SWL-frequency points—are generated and used to compute each SWL Bin-frequency.

The surge CDF curve as constructed above 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.

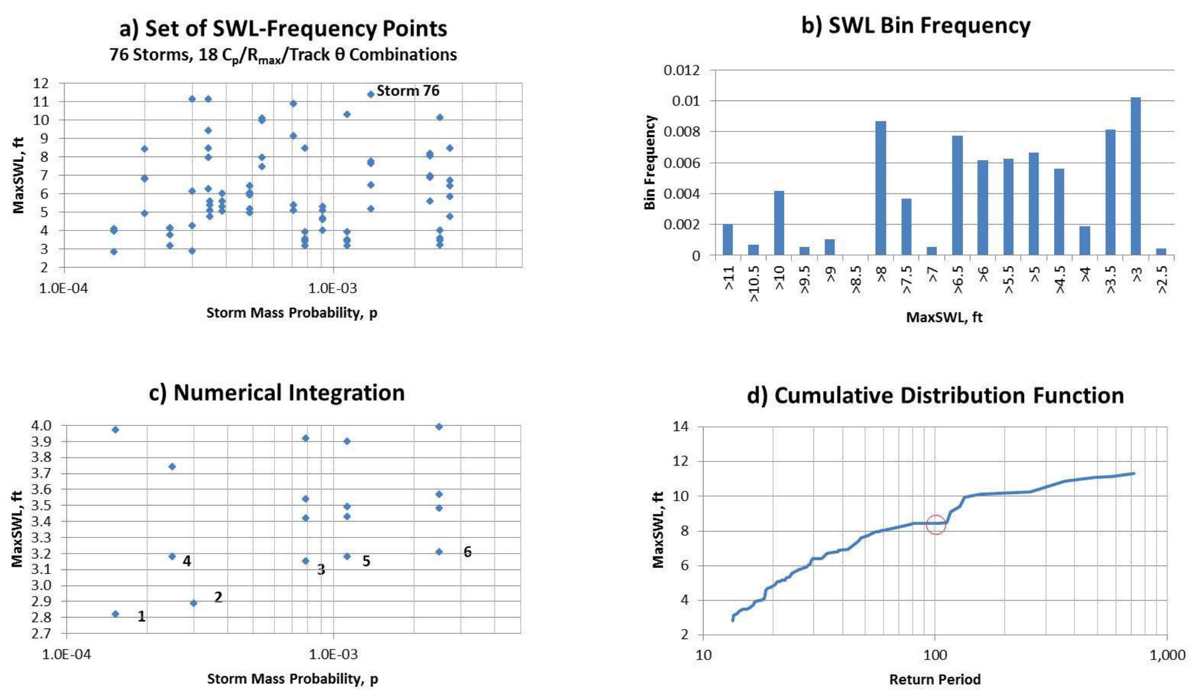


Figure 1 Example of SWL Probabilities and the SWL CDF

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 CDF points themselves. Figure 2 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 2 could have additional uncertainties—such as gauge performance and record gaps filled with estimated values.

Any surge CDF and 100-yr SWL estimate derived from a JPA, 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 (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.

The following three sections examine *stationary* uncertainty issues associated with the hurricane joint probability equation, the surge model, and the storm OS. There are additional non-stationary uncertainty factors—such as changes in hurricane climatology, sea level, and coastal landscape. Non-stationary uncertainties can be addressed by developing a separate *what-if* CDF, reflecting hypothesized changes to the joint-probability equation, surge model, an/or OS.[2]

[2] See Bob Jacobsen PE, LLC May 2013 Report, Part V.

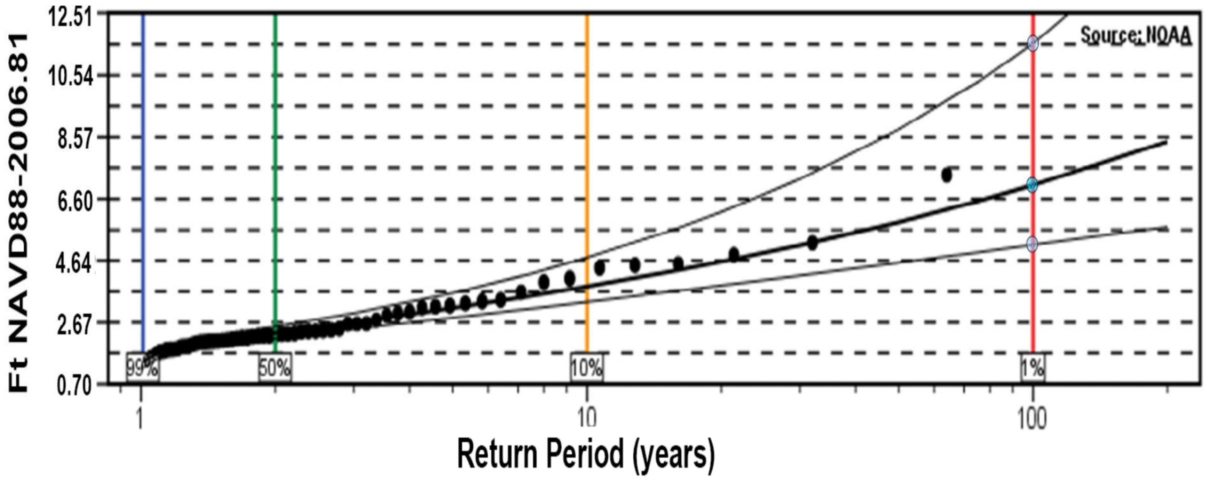


Figure 2. Grand Isle LA Tide Station Return Frequency with 95 Percent Confidence Interval
NOAA (http://tidesandcurrents.noaa.gov/est/est_station.shtml?stnid=8761724)

2. Hurricane Joint Probability Equation Uncertainty
To describe the hurricane climatology pertinent to the local surge hazard a hurricane joint probability equation—$p(C_p, R_{max}, V_f, \theta, X)$—is constructed using sub-equations for each of the five hurricane variables. The joint probability equation is developed in three steps:

1. An equation is constructed to describe the frequency of hurricanes of various intensity—central pressure (C_P)—making landfall within the region around the location of interest. A parametric C_P-frequency equation can be constructed by fitting an EVF to the observed record. The EVF selection involves professional judgment (e.g., the suitability of the curve slope at high return periods). The equation can be for either landfall or minimum Gulf of Mexico C_P (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.
2. 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.
3. 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:

1. Uncertainties associated with the representativeness of the historical record of C_p, R_{max}, V_f, θ, and decay observations *(hurricane sample representativeness*). This uncertainty associated with the representativeness of the record cannot be readily quantified. While careful examination of the record in the context of hurricane climatology may allow some improvements to the historical data set—for example to account for demonstrable climate cycles in hurricane activity—the observed hurricane record, say 75 years, may not be representative of an "average 75-yr period." Similarly, the equation types used to represent the observed C_p, R_{max}, V_f, and θ probabilities and decay may not prove optimal in the long run.

2. Residual errors associated with fitting the various probability equations for C_p, R_{max}, V_f, θ, and decay to the available sample of hurricanes (*hurricane sample uncertainty*). Importantly these residual errors depend greatly on the record length/sample size. The residual errors may not be uniform over the range of attributes—for example, the residual error in C_P-frequency may need to be expressed as a function of C_P. In addition, hurricane sampling uncertainty may need to account for the quality of hurricane observations in the record as many data are actually estimates.

   The uncertainties for each attribute probability can be combined into an overall residual error for the total joint-probability expression. The overall residual error for hurricane sampling can be translated into a SWL uncertainty, and, for convenience may be treated as normally distributed, with σ_S in ft. (σ_S could be analyzed as varying with SWL.) σ_S can be evaluated in two ways: with a Monte Carlo approach or with a SWL extreme value equation.

Monte Carlo Approach to Evaluating σ_S

In the first approach a Monte Carlo technique is used to evaluate the effect of the overall joint probability residual error. For the JPM which simulates an artificial record the technique involves re-developing the record many times (M). Each storm in each M iteration has randomized values for the hurricane attributes based on the sampling uncertainty. CDFs are then computed for each M iteration. These M 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.[3]

Vickery et al used this approach in evaluating hurricane sampling uncertainty for wind hazard, replicating their artificial 100,000-yr record M times and developing M wind hazard CDFs. However, using the Monte Carlo approach for this JPM is not actually practical for surge hazard analysis due to the time and expense of re-modeling the entire artificial 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 are simply randomized by using the combined residual error in the joint probability equation. In this approach the CDF can be recomputed numerous times, using a large M to allow the value of σ_S to converge.

The Monte Carlo approach to estimating the effect of hurricane sampling uncertainty is limited by the size of the historical record used to provide the hurricane attribute joint-probability equation.

SWL EVF Approach to Evaluating σ_S

The hurricane sampling uncertainty effect on SWL-frequency can also be evaluated by fitting a EVF to the SWL CDF. If a high quality tide gauge record is available near the location of interest, a very useful and straightforward method is to apply a suitable curve type to the record and then assess the residual error. This avoids the intermediate hurricane joint probability expression and provides a very simple and direct approach to estimating σ_S. Figure 2 illustrates the fitting of the GEV curve to the tide record CDF for Grand Isle Louisiana and associated confidence limits.

In the absence of an actual SWL record, a SWL EVF can be fitted to the results of the JPA—i.e., to the SWL CDF—and the residual error evaluated. In this case the evaluation will be limited if a) the SWL EVF

[3] Due to its magnitude the influence of modeling uncertainty must be removed to isolate the effect of hurricane sampling uncertainty.

is the same type as that used for the C_P-frequency, as this influences the fit evaluation; and/or b) the JPA does not apply randomized values for the hurricane attributes based on joint probability uncertainties.

The estimation of σ_S by fitting an extreme value equation to either tide gauge data or the JPA results is affected by hurricane record length (L): σ_{S2}/σ_{S1} for L_2/L_1 equals $\sqrt{L_2/L_1}$.

3. Surge Model Uncertainty

The peak surge SWL for any individual 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 the wind/surge/ wave model. These factors can collectively be referred to as *model uncertainty* and can be specific (e.g., particular physical processes) or non-specific. Model uncertainty introduces random variability to the expected SWL but it may also shift the expected SWL if factors entail over-or under-prediction bias. Model uncertainty factors can vary by location. Six key factors include:

1. Lumped uncertainties in modeling wind/surge/wave physics, hurricane conditions, and landscape interactions (topography, bathymetry, wind/surge/wave frictional effects, etc.) that could be considered applicable to all simulated storms and are appropriate for quantifying using the general model residual error in hindcasting, treated as a normal distribution. There are often major local variations in hindcast residual error.
2. Small amplitude tides.
3. Wind-field distribution as described by the Holland B parameter. Holland B has been considered as varying with SWL (Resio et al 2007).
4. Additional wind-field conditions, e.g., banding.
5. Other meteorological conditions, such as pre-storm (pre-forerunner) water level and rainfall. The latter may correlate inversely with both C_p and V_f but with considerable random scatter.
6. Wind-water drag during very extreme storms and the resulting setup.[4]

The individual σ can be combined together in quadrature to provide an overall σ_M. Factors 4, 5, and 6 are particularly important for interior, sheltered water bodies.

4. Storm OS Uncertainty

For the Toro JPM there are uncertainties with respect to the optimization of the JPM-OS. These can be quantified by evaluating the residual error in the OS representation of a) the hurricane joint probability equation, and/or b) the surge hazard—in this case by generating preliminary CDFs using the OS versus a larger storm set but with a much more simplified wind/surge/model.

For the surge-response approach to JPM, there are two locally varying uncertainties.

1. The OS adequacy for representing the true 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. Especially for large, shallow, sheltered water bodies the OS may need more storms at

[4] The particular mechanisms of extreme wind setup in very shallow water bodies may not be adequately captured by general air-sea drag approaches. The Lake Okeechobee Hurricane of 1928 created a 20 ft setup. There may be some correlation with wave conditions (heights and steepness) but there is likely to be considerable randomness.

very low and very high intensity, greater variation in V_f and θ, and tighter landfall spacing (see Irish et al 2009). This uncertainty factor is subject to also including significant local bias.

2. The Surge-Response function itself may be simplified (as a tabulated function, polynomial, or other equation) with a notable residual error compared to the OS.

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 the OS adequacy is likely to require considerable professional judgment.

5. Incorporating Uncertainties Into the CDF

Table 2 summarizes the ten uncertainty factors described above for the surge-response JPM. All have σ magnitudes capable of exceeding 10 percent. At 10 percent each these would combine (in quadrature) to equal 32 percent.

Uncertainty factors about the CDF 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 incorporated into the set of explicit joint-probability variables. This has the benefit of reducing uncertainty regarding the SWL CDF. SWL CDF points—such as the 100-yr SWL—are the *expected* values with respect to the integrated variables.

When an uncertainty factor is incorporated among the integration variables, i.e., inside the integral, it becomes reflected in the CDF. By definition, the CDF is then “determined” with respect to variables inside the integral—and, importantly, there is no further “uncertainty” with respect to these variables. When an uncertainty factor is incorporated into the CDF will be slight shifts in the CDF depending on the distribution for the factor. Incorporation of a normally distributed uncertainty can slightly increase 100-yr expected values.

Consider the example of small amplitude tides in Southeast Louisiana, which have a median value of 0 ft relative to LMSL and σ of 0.66 ft. The tide σ could be used to provide confidence limits in a 100-yr SWL. For example the upper limit of the 95% confidence interval is 1.3 ft, which would add 10 percent to a location with a 100-yr SWL of 13 ft.

As an alternative to confidence limits, tides could be included as an explicit variable for the CDF. When tides are incorporated into the integral, tidal variability gets converted to return period. In the new *with-tide* CDF, the 100-yr SWL will increase slightly (on the order of 0.2 ft) and the 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. But this removes these uncertainties too from outside the integral and spreads them across the return periods.

6. Using an Epsilon Term to Incorporate Uncertainties Into the CDF

Expanding the OS to cover one or two additional variables with large impact (e.g., tides and Holland B) may be practical. But the time and expense of running wind/surge/wave models prohibits including many more variables explicitly, as the OS increases exponentially with added variables.

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

Factor	Evaluation Method	Magnitude of σ % of SWL or ft	Local Variation Within Region
Hurricane Joint Probability Uncertainties			
Representativeness of historical record	Requires professional judgment.	Difficult to define, likely >10%	No
Hurricane sampling (σ_S)	Fitting extreme value function to tide-gauge record; or to the CDF from the JPA incorporating all hurricane joint probability uncertainties.	>10%	No
Model Uncertainties			
Surge model	Residual error from hindcast validation.	>10%	Yes
Tides	Tidal analysis.	0.1 to > 5ft	Yes
Wind-field shape (Holland B)	As percent of SWL; using Holland B surge-response analysis.	>10%	No
Additional wind-field characteristics (e.g., banding)	Residual error between surge modeling with high resolution wind fields versus the OS wind-fields.	<10%	No
Other meteorological conditions	Requires professional judgment.	Difficult to define; >10% at sensitive locations	Yes
Wind drag	Requires professional judgment.	Difficult to define; >10% at extreme winds and sensitive locations	Yes
Surge-Response OS Uncertainties			
OS adequacy to capture surge response	Requires professional judgment.	Difficult to define, likely >10% at sensitive locations	Yes
Surge-response function	Residual error between predicted SWL from function to OS results.	Depends on interpolation >5%	Yes

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 SWL-frequency point can be expanded with numerous SWL values reflecting the epsilon (ε) standard deviation (σ_ε). Figure 3a through 3c illustrate the expansion of the SWL-frequency points from Figure 1 using a σ_ε of 0.2*SWL and the resulting CDF. Figure 3d shows the CDF for a range of εσ.

A normally distributed SWL epsilon has the added benefit of smoothing the numerical integration—as shown in Figure 3c. The SWL-frequency values can be “jumpy,” and replacing each SWL value with a much large set of normally distributed values will smooth out the CDF. But 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.

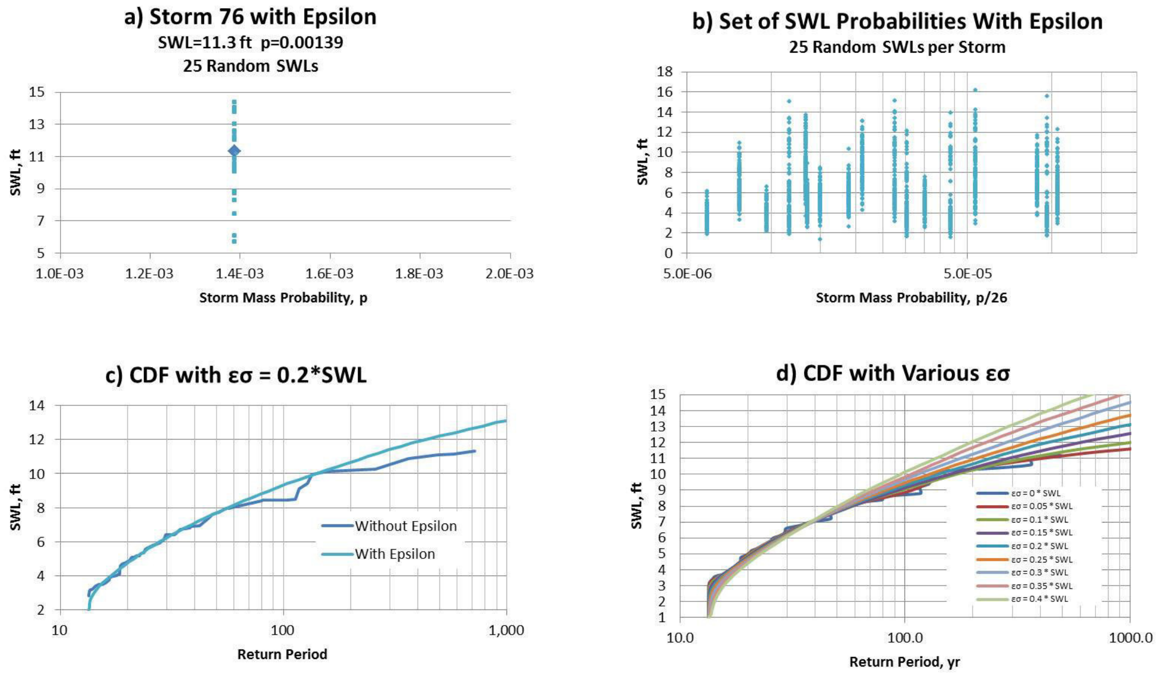


Figure 3. SWL CDF With Epsilon

The Monte Carlo evaluation of hurricane sampling uncertainty described above in Section 2 is essentially an application of a frequency epsilon. Importantly, the median CDF from this evaluation approaches the CDF for *the expanded integrand* with the entire M replications as a whole. Thus, the median CDF from this frequency epsilon can be regarded as integrating for the hurricane sampling uncertainty.

Epsilon has been applied in numerous NFIP Flood Insurance Studies (FISs), including for LA, MS, TX, SC, GA, and FL to cover some model uncertainty factors. However, the hurricane sampling uncertainty has not been included as part of epsilon in the NFIP studies—i.e., NFIP studies to date leave hurricane sampling uncertainties outside the integral.

7. Relationship Between Epsilon, the CDF, and CDF Confidence Limits

As previously noted, for convenience SWL uncertainties can be treated as normally distributed. Combining the individual σ together in quadrature, the overall uncertainty can be represented by a σ_{Total}. The σ_{Total} can be divided into those factors incorporated into the SWL CDF—represented by σ_{ε}, including either explicitly or with 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 (as noted above epsilon effects the CDF) and the confidence intervals. Using the CDF in Figure 1d, Table 3 presents the nonlinear variation in σ_{CL} with σ_{ε} at three σ_{Total} values together with the effect of σ_{ε} on the expected 100-yr SWL, and the upper limit of a 90 percent confidence interval (UCL90%) for each combination of σ_{Total} and σ_{ε}. Table 3 shows that when proportionally higher amounts of uncertainty are included as σ_{ε} versus σ_{CL}, the UCL90% are lower, despite the increase in the expected 100-yr SWL. For example, at σ_{Total} equal to 0.3*SWL, for a σ_{ε} increase from 0.5 to 0.25*SWL, the expected 100-yr SWL increases by 0.6 ft but the UCL90% falls by 1.2 ft.

Table 3. Example Effect of Incorporating Uncertainty into CDF on Confidence Limit

		σ_{Total} = 0.2*SWL		σ_{Total} = 0.3*SWL		σ_{Total} = 0.4*SWL	
σ_{ε} *SWL	Expected 100-yr SWL ft	σ_{CL} *SWL	UCL90% ft	σ_{CL} *SWL	UCL90% ft	σ_{CL} *SWL	UCL90% ft
0.001	8.7	0.200	11.6	0.300	13.1	0.400	14.6
0.05	8.9	0.194	11.7	0.296	13.3	0.397	14.8
0.10	9.1	0.173	11.7	0.283	13.4	0.387	15.0
0.15	9.2	0.132	11.2	0.260	13.2	0.371	14.9
0.20	9.3	0.000	9.3	0.224	12.8	0.346	14.7
0.25	9.5			0.166	12.1	0.312	14.4
0.30	9.7			0.000	9.7	0.265	14.0
0.35	9.8					0.194	13.0
0.40	10.1					0.000	10.1

8. Applying Professional Judgment to the Treatment of SWL Uncertainties

There is no "rule" regarding the assignment of uncertainties to σ_{ε} or σ_{CL}. Natural sources of variability (also termed aleatory variability)—such as tides, wind-field Holland B and banding, other meteorological conditions, wind drag—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 associated with the 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.

Other considerations requiring professional judgment can influence the assignment of uncertainties, especially the purposes for the estimates of expected surge hazard and confidence limits and the consequences of being wrong. In addition, four of the ten factors listed in Table 2 are difficult to define and evaluation of their magnitude also requires considerable professional judgment.

Given the role of professional judgment, estimates of the expected 100-yr SWL and corresponding UCL90% can legitimately differ for different purposes. For example, uncertainties can be treated one way for the NFIP—where the concern is for *national actuarial risk*—and another way for the planning and design of community flood defense systems addressing severe residual risks—where the concern is for *local actual catastrophic flood risk*. Table 4 highlights differences in the State of the Practice (SOP) in evaluating the ten uncertainty factors for the NFIP versus local residual risk reduction projects.

NFIP FISs

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, which is used to delineate special flood hazard areas, provide individual policies, and assess premiums. NFIP FISs for surge hazard are usually regional in nature—covering multiple coastal counties. Confidence limits are not used in the delineation of flood hazard zones, including the evaluation of 100-

yr flood protection levees (an exception being where there is a wave overtopping allowance). Political and institutional factors tend to favor under- versus over-estimating expected 100-yr SWLs.

Thus, in conducting a FIS, the interests of the NFIP can be satisfied with focusing on the CDF 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. FISs generally ignore the five localized uncertainties and uncertainties related to the historic representativeness of hurricane data and storm OS noted in Table 2. Thus, for NFIP purposes σ_{CL} ignores all but the hurricane sample uncertainty, and σ_{CL} is equated with only σ_S. With future methodology improvements, the FIS SOP could be revised.

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

Factor	NFIP FISs	Local Projects to Reduce Residual Surge Risk	Future Improvements
Hurricane Joint Probability Uncertainties			
Representativeness of historical record	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Perhaps some insights from studies of paleo-climatology.
Hurricane sampling (σ_S)	Included in σ_{CL}.	Use a reasonably conservative approach.	Use of Monte Carlo analysis to supplement tide gauge record analysis.
Model Uncertainties			
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 should reduce uncertainty.
Tides	Included in CDF as explicit variable or via σ_ε using a region-wide uniform factor.	Include local tides by adjusting σ_ε or σ_{CL}.	
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 should reduce uncertainty.
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 should reduce uncertainty.
Other meteorological conditions	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Improved modeling of physical processes, pre-storm, and storm conditions should reduce uncertainty.
Wind drag	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Improved modeling of physical processes and storm conditions should reduce uncertainty.
Surge-Response OS Uncertainties			
OS adequacy to capture surge response	Not currently included.	Include a reasonably conservative factor in σ_{CL}.	Improved understanding of surge-response should improve optimizing the OS.
Surge-response function	Not currently included.	Include local error in either σ_{CL}.	Better interpolation schemes should reduce residual error.

Local Projects to Reduce Residual Surge Risks

The SOP for planning and design of local projects for reducing residual surge risks—the probability of fatalities, damage to crucial commercial/industrial activities, cultural/social costs, regional economic impairment, etc.—emphasizes the use of confidence limits. Engineers of critical local flood protection systems carefully assess the impact of *all* uncertainties in order to provide a *Factor of Safety*. For these purposes, it is 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 include in 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.[5]

Vickery et al (2009) illustrate a conservative approach. In defining wind hazards and their uncertainties the uncertainties are purposefully considered twice: in the median CDF (which as previously noted 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 Factor of Safety.

9. The USACE 2005-09 Analysis of 100-yr SWL Uncertainty for Southeast Louisiana

The USACE's 2005-09 analysis was performed primarily to address NFIP requirements for Southeast Louisiana and utilized the surge-response JPM. The analysis relied on the assumption that Southeast Louisiana surge response is very smooth, using and OS comprise 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 for each location with some of these combinations being used among 9 landfall locations (5 primary and 4 secondary).

The 2005-09 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 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, by a factor of 6.1. The 2005-09 study employed this factor to adjust the "effective" hurricane sample length to 396 years.

The USACE surge-response OS results and joint-probability equation for each location were used to create 68,040 SWL-frequency points for each location.[6]

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[5] History shows that expected values provided in many professional fields are often wrong by large margins; see Nate Silver 2012. Managers of severe surge risks—like those responsible for dam safety—may want larger cushion. Importantly, regional surge risk managers can face long and geographically wide exposures. A regional levee manager responsible for five independent surge exposures faces a 63 percent chance of seeing a 100-yr event over a 20-yr period. Moreover, reasonably conservative approaches are also employed with regard to structural and geotechnical uncertainties in flood protection design. For example, a 50 percent Factor of Safety is not uncommon for slope stability (see USACE 2008).

[6] 21 Gulf of Mexico C_P (900 - 960 in 3 millibar increments); 40 R_{max} values (1-40 in single nautical mile increments);3 approach angles (-45 , 0 , and 45); 3 forward speeds (6, 11, 17 knots); and 9 tracks (5 main tracks + 4 intermediate tracks). Surge-response values were interpolated from the 152-storm OS results.

To assess hurricane sample uncertainty, the USACE did not use a Monte Carlo approach but evaluated the fit of a Gumbel curve to the SWL CDF.[7] The USACE's evaluation has three key limitations:

1. The approach employed the same curve type, Gumbel, that was used to generate C_P-frequency. Thus, the fit of SWL return frequency to a Gumbel curve has been somewhat predetermined.
2. The frequency values for the 68,040 SWL-frequency points used to create the CDF do not reflect uncertainties in the joint probability equation.
3. The Gumbel fit employed the synthetic record length of 396 years. This may be appropriate for some purposes but could overstate the independent information (i.e., sample size) for the regional hurricane climatology.

The value of the USACE σ_S for the 100-yr SWL was generally less than 10 and 12.5 percent for the East– and West-Bank regions, respectively.[8]

Alternative estimates for 100-yr SWL σ_S can be obtained by using 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 2005-09 analysis—for which the typical upper band for a 95 percent confidence intervals (at $1.96\sigma_S$) is less than 20 percent of the expected 100-yr SWL. Beck 2014 noted that using an actual record length of 65 years instead of the synthetic 396 years in the Gumbel fit to the CDF produced a value for σ_S more consistent with the Grand Isle record. These alternative σ_S are on the order of 15 to 20 percent of SWL for the East-Bank.

For modeling uncertainty, the analysis defined uniform σ values in terms of SWL to account 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 2005-09 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 CDF.[9] The epsilon term increases the expected 100-yr SWL—by generally about 1 ft—and removes these four factors as uncertainties for the CDF confidence limits.

[7] See *Estimation of Confidence Bands for Surge Estimates*, Appendix G in Resio et al 2007. Though the USACE wanted an estimate of σ_S for development of confidence limits, and opted not to incorporate hurricane sampling uncertainty into the CDF, they could still have used the Monte Carlo approach to evaluate σ_S, in which case they would not have used the median CDF from the Monte Carlo analysis.

[8] See USACE, *Hurricane and Storm Damage Risk Reduction System Design Elevation Report*, Draft, Version 4a, December 2011.

[9] A much smaller number of surge-response points than used in this case (68,040) might require greater randomized expansion (than a factor of 21) to ensure CDF-with-epsilon convergence.

The USACE set the σ_{CL} equivalent to their σ_S and did not incorporate any values for the other six factors listed in Table 2, consistent with NFIP SOP. The USACE provided the 2005-09 surge SWL hazard analysis to FEMA to support NFIP FISs for parishes throughout Southeast Louisiana.

(The USACE did discuss the general suitability of C_P ,R_{max}, V_f, and θ variations, as well as track spacing, but did not provide uncertainty value for the OS adequacy. While the USACE did not discuss residual error in the surge-response function fit to OS results, Woods Hole Group (2013) compared the 152 OS peak SWL results to predicted SWLs from the surge-response function at 274 locations and found that the locations had an average RMSE of 2.3 ft, in addition to slight under- and over-prediction biases for the East- and West-Banks, respectively.)

Regardless of NFIP purposes, a reasonably conservative 100-yr σ_{CL} can be developed for use in surge residual risk management and could include the following:

i. The alternative σ_S—15 to 20 percent of SWL;
ii. The combination of local variations in model residual error and the residual error in the fit of surge-response functions to OS—20 percent of SWL; and
iii. The combination of the other four model, surge-response function, and hurricane joint probability uncertainties—15 percent of SWL.

The second and third components together are 25 percent of SWL and the combination of all three provides a 100-yr σ_{CL} of about 30 percent. (The magnitude of σ_{Total} , combining σ_ε and σ_{CL} , using a reasonably conservative approach would be $\sqrt{2^2 + (0.33*SWL)^2}$.)

It is important to acknowledge that assuming a normal distribution for a σ_{CL} of 30 percent implies upper and lower limits of confidence intervals that may become unrealistic. A 90 percent non-exceedance limit equals 1.38*SWL but at 99 percent equals 1.7*SWL; (these correspond to the upper limits of 80 and 98 percent confidence intervals). Further research is needed to determine if using a slightly truncated normal distribution, or other distribution, could be appropriate.

10. The HSDRRS Design

The HSDRRS is designed to be NFIP accreditable in accordance with NFIP regulation 44CFR65.10. The HSDRRS elevation is based on allowing a minimal amount of wave overtopping at the 100-yr return. 44CFR65.10.b.iv states that such designs *"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."* The USACE HSDRRS design employed the 2005-09 NFIP analysis of the 100-yr SWL and associated σ_{CL} in this design and the evaluation of overtopping uncertainty.[10]

[10] 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.

To evaluate 100-yr wave overtopping the USACE design (USACE 2011) employed empirical overtopping equations which use inputs for the 100-yr SWL and associated significant wave height and wave period (H_S and T_P). To address 44CFR65.10.b.iv, a Monte Carlo technique was then used—employing the USACE estimates of 100-yr SWL σ_{CL}, (together with σ values for significant wave height and wave period).[11] The USACE 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% confidence interval). 44CFR65.10.b.iv does not define whether or how uncertainties may be included in the CDF integration and thus reflected in the expected 100-yr SWL. Nor does 44CFR65.10.b.iv indicate how σ_{CL} should be assessed.[12] For a design simply intended to meet NFIP purposes, the USACE's approach to determining the 100-yr SWL and σ_{CL} (described in Section 9) can be considered appropriate.[13]

However, considering overtopping uncertainty from the viewpoint of a Factor of Safety and local residual risk management warrants using a reasonably conservative σ_{CL} estimate, such as defined above. A reasonably conservative 100-yr σ_{CL} of 30 percent is about three times greater than the USACE's 100-yr σ_{CL}. The q90 is highly sensitive to the value of σ_{CL} and a three-fold increase in σ_{CL} can increase q90 by a factor of ten. Thus, from a residual risk management perspective higher levees and/or upgraded armoring could be considered to address 100-yr q90. In some areas this could imply two-foot levee increases (see Bob Jacobsen PE LLC May 2013).

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[11] See Bob Jacobsen PE, May 2013, Part IV, and Bob Jacobsen PE, *Evaluation of Five Priority Issues with the USACE Surge Hazard and HSDRRS Overtopping Analysis,* December 2014, for discussions of the USACE HSDRRS wave overtopping analysis. The USACE employed a similar analysis to evaluate 500-yr overtopping uncertainty.

[12] Those wanting further opinions on this issue could contact Federal Emergency Management Agency officials responsible for the NFIP, or organizations such as the National Academy of Engineering; the National Committee on Levee Safety; and The National Institute of Standards and Technology.

[13] This only addresses the technical approaches discussed in this document and Section 9 and does not address any other issues with the USACE analysis. Furthermore, as noted above NFIP SOPs are subject to revision in the future as methodologies improve or if risk management policies change.

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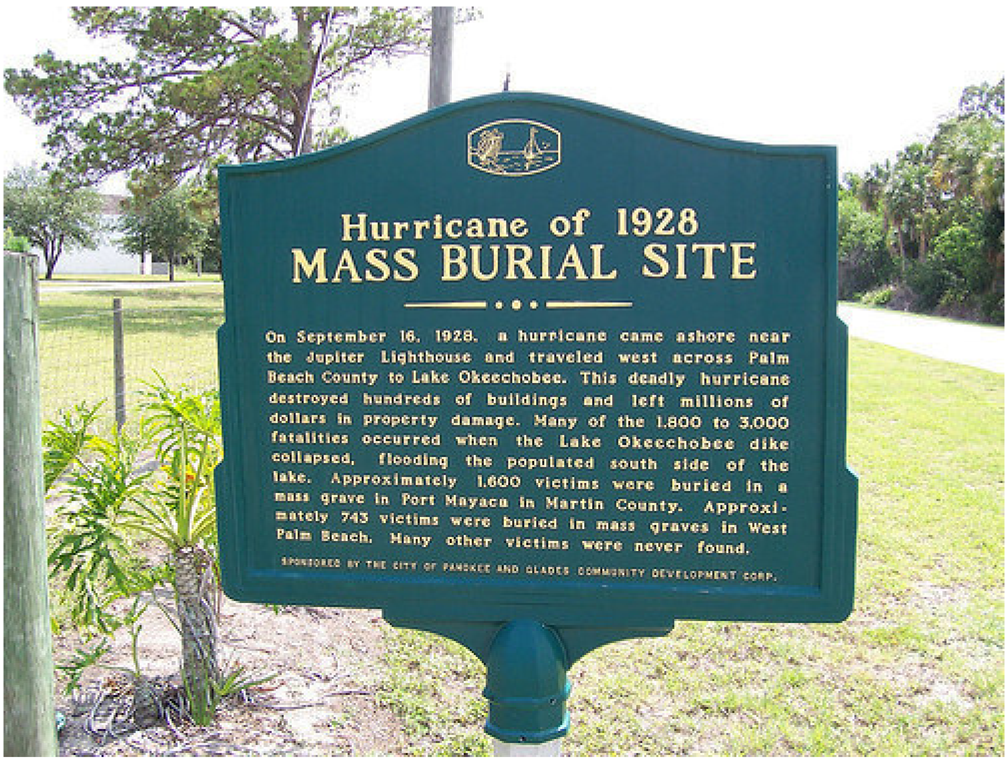
Attachment B

Lake Okeechobee Florida Hurricane Surge Hazard



https://c1.staticflickr.com/3/2071/2141942046_1a64dbe39e.jpg

Bob Jacobsen PE, LLC
March 2015

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 mph. Residents well inland from the Atlantic coast—some 40 miles or more—may have thought themselves safe from surge. However, those living along the shores of the interior Lake Okeechobee (Figure 1) experienced an extreme surge event. Lake Okeechobee—at over 700 square miles in area—is the second largest freshwater lake lying entirely within the lower 48 states. Moreover, Lake Okeechobee is extremely shallow, averaging only about 9 feet (ft) in depth.

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 US 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 these physics and probabilities. A "short list" would also include the Last Island Hurricane of 1856, the Cheniere Caminada Hurricane of 1893, the Galveston Hurricane of 1900, the Chesapeake–Potomac Hurricane of 1933, the Labor Day Hurricane of 1935, the New England Hurricane of 1938, Hurricane Hazel (1954), Hurricane Carla (1961), Hurricane Betsy (1965), Hurricane Camille (1969), Hurricane Frederic (1979), Hurricane Hugo (1989), Hurricane Opal (1995), Hurricane Ivan (2004), Hurricane Katrina (2005), Hurricane Rita (2005), Hurricane Ike (2008), and Hurricane Sandy (2011).

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 of depth 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 depth 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 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, for the Herbert Hoover Dike the barrier crest height above the 100-yr SWL is much greater than for the HSDRRS—by almost 10 ft.

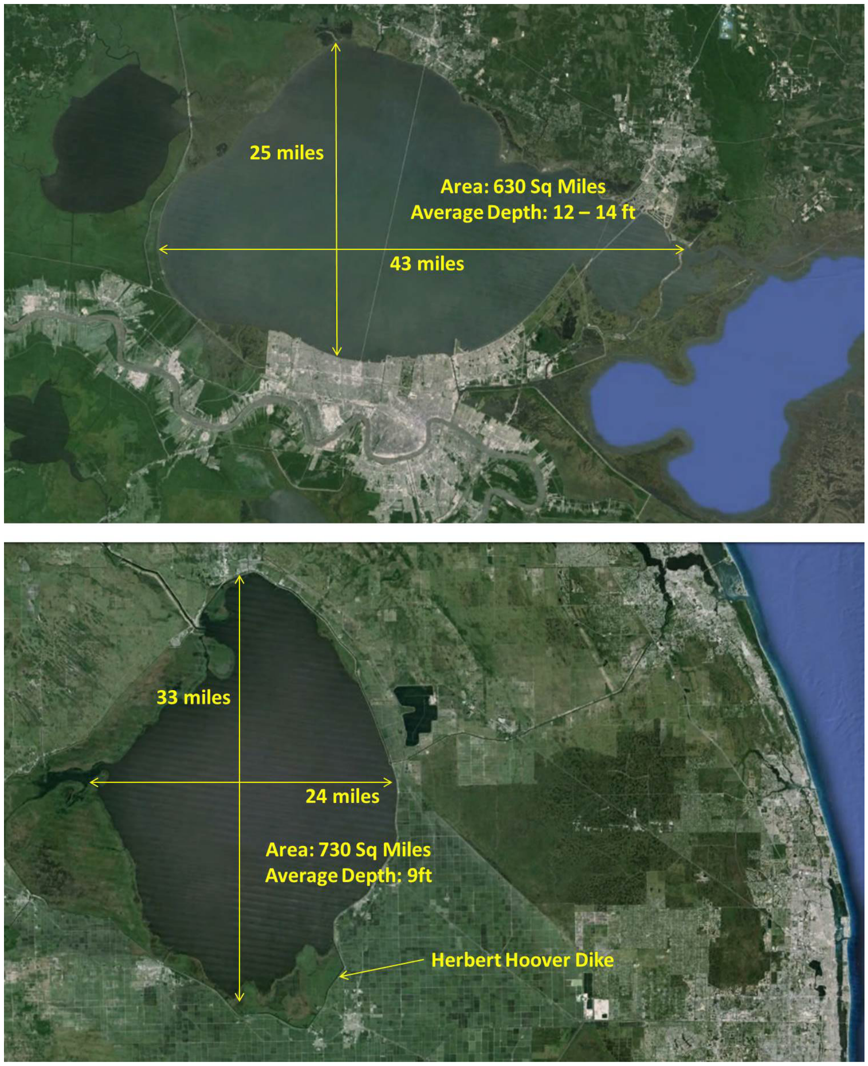


Figure 1. Comparison of Lakes Pontchartrain and Okeechobee (Florida)
Google Earth Imagery (same scale)