Hurricane Surge Hazard Analysis: The State of the Practice and Recent Applications for Southeast Louisiana

prepared for

The Southeast Louisiana Flood Protection Authority—East

Task Order 02-03-006

prepared by

Bob Jacobsen PE, LLC

Baton Rouge, Louisiana

May 2013

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Cover photographs taken from Figure 2, in *Hurricane Gustav (2008) Waves and Storm Surge: Hindcast, Synoptic Analysis, and Validation in Southern Louisiana* by J. C. Dietrich et al (Monthly Weather Review, Vol. 139, 2488 – 2522. See References for Part II)

Don't cross a river if it is four feet deep on average.

Nassim Nicholas Taleb
The Black Swan: The Impact of the Highly Improbable (2007)

…the amount of confidence someone expresses in a prediction is not a good indication of its accuracy—to the contrary, these qualities are often inversely correlated.

Nate Silver
The Signal and the Noise: Why So Many Predictions Fail, But Some Don't (2012)

Crying won't help you, praying won't do you no good.
Crying won't help you, praying won't do you no good.
When the levee breaks, mama, you got to move.

Kansas Joe McCoy and Memphis Minnie
When the Levee Breaks (1929)

This Report is dedicated to the families of New Orleans. Over the centuries we have reaped extensive benefits from hurricane surge risk management, but have endured tremendous suffering when this management has been inadequate. Today, thanks to federal investment, we enjoy greater hurricane surge risk reduction than millions of residents in other major port cities along the Gulf of Mexico and Atlantic coasts.

It is now increasingly up to us to maintain and improve surge risk management in the face of regional subsidence, coastal land loss, rising global temperatures and sea levels, changing and highly uncertain hurricane probabilities, levee settlement, and diminishing federal funding. Moreover, we must help confront severe surge risks to the residents of outlying communities and a fragile deltaic ecosystem. To meet these challenges, it is now up to us to ensure that we have the best surge hazard analysis and—just as importantly—that we understand and apply it.

About the Author

Bob Jacobsen is a 50-year resident of southeast Louisiana and his connection to the coast and New Orleans regional surge protection is both professional and personal.

Over the years Mr. Jacobsen has pursued education in both environmental policy and engineering, receiving Master's degrees from Louisiana State University in both Political Science and Civil Engineering. As time permits, he continues to work towards a PhD in Civil Engineering, with an emphasis on coastal hydrodynamics.

Mr. Jacobsen's 33-year career has focused on state-of-the-art planning studies and conceptual designs in environmental and water resource engineering and related program fields. During the first 20-years he worked on an array of major environmental contamination problems, including remediation of contaminated sediments for Superfund sites and scenic water bodies, removal of carcinogenic pollutants from important aquifers, and upgrading petrochemical wastewater treatment systems. Since 2001 he has specialized in hydrology/hydraulics issues in coastal Louisiana—encompassing both hurricane storm surge and coastal restoration. His wide ranging experience has allowed him to hone a blend of field, analytical, construction, and management skills, providing him with a unique perspective on south Louisiana environmental sustainability dynamics.

In the years following Hurricane Katrina Mr. Jacobsen worked on numerous coastal hydrodynamic projects for southeast Louisiana, including i) an hydraulic feasibility study for a proposed Mississippi River diversion near Garyville LA (lead author); ii) an analysis of the role played by the Mississippi River Gulf Outlet in conveying storm surge (lead author); iii) modeling of Lake Pontchartrain tidal exchange (lead author); iv) assessment of hurricane surge interactions with coastal landscape features (contributor); and v) an investigation of LIDAR topographic data accuracy and potential ADCIRC mesh improvements for the southeast Louisiana hurricane surge hazard analysis (contributor).[1] Between 2007 and 2011 he provided senior technical review on a surge hazard study for South Carolina and authored key reports for planning a surge hazard analysis for Georgia and Northeast Florida. In 2011 he started his own consulting practice in coastal hydrology and hydrodynamics.

Mr. Jacobsen has served on the local Baton Rouge Branch and Louisiana Section Boards for the American Society of Civil Engineers and is currently President-Elect for the Louisiana Section.[2]

His mother and sister still live in the Metairie house the family moved into in 1965, two weeks before Hurricane Betsy struck. He grew up wade fishing in Lake Pontchartrain and rekindles his love for Louisiana's unique coastal experiences with frequent summer forays to Grand Isle.

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[1] The first and second tasks were completed for the (now) Louisiana CPRA; the third, fourth, and fifth under contracts with the USACE. The fourth and fifth were tasks within projects directed by Joseph Suhayda, PhD, a co-worker at the time. The fifth effort was part of the senior technical review of the USACE's southeast Louisiana surge hazard analysis led by Dr. Suhayda and completed in late spring of 2007. Mr. Jacobsen and Dr. Suhayda were subsequently employed by Taylor Engineering (beginning in late summer 2007), which performed some STWAVE modeling as part of the USACE/FEMA southeast Louisiana surge hazard analysis. Mr. Jacobsen and Dr. Suhayda did not participate in the Taylor Engineering STWAVE work.

[2] During post-Katrina forensic studies several senior Branch members participated on investigation teams sponsored by the National Science Foundation, the State of Louisiana, and the Society, including Louis Capozzoli, PhD PE; Gordon Boutwell, PhD PE; and Billy Prokaska, PE. These members reached similar profound conclusions regarding the failure of the New Orleans surge protection system.

Acknowledgements

The Southeast Louisiana Flood Protection Authority-East (SLFPA-E) volunteer board commissioners, including several whose tenures have ended, deserve credit for the idea of this Report. Their earnest desire and firm commitment that the New Orleans perimeter surge protection system design, and all its underlying analyses, be made completely open, transparent, understandable, and subject to comprehensive professional scrutiny is the only reason this Report was undertaken. It has been a career highlight to assist them in serving the citizens of Orleans, Jefferson, and St. Bernard Parishes.

The person most responsible for carrying out the Board's vision is its indefatigable Regional Director, Robert Turner, PE. Bob has maintained an unflinching demand for a thorough and independent Report. As with every aspect of his leadership at SLFPA-E, he has constantly pushed to get the science and engineering right and to listen to everyone with something to say.

Thanks are owed to the SLFPA-E staff, including Chief Engineer Stevan Spencer, PE; Special Assistant Sheila Grissett; Assistant Betty Vignes; GIS Specialist Roger Colwell; Contract Engineer Bill Fogle; and the Parish Levee District Directors—Gerry Gillen, PE; Fran Campbell; and Nick Cali. They provided timely support on countless occasions.

During this effort the Louisiana Coastal Protection and Restoration Authority (CPRA) initiated a parallel evaluation of the U.S. Army Corps of Engineers 2005-2009 hurricane surge hazard analysis for southeast Louisiana. This separate project has been overseen by CPRA Engineer Manager Rickey Brouillette, PE and led by project manager David Minton, PE. Joseph Suhayda, PhD serves as the senior technical expert for the team and he is supported by Nathan Dill, Pat Fitzpatrick, PhD, and Peter Vickery, PhD. All have made important contributions to understanding and improving surge hazard analysis. The SLFPA-E agreed that drafts of this Report should be shared with CPRA, and in turn the CPRA team has provided a much needed review, together with additional insights. No doubt some minor errors and confusing sentences remain—but hopefully no major ones. The responsibility for these, however, rests entirely with the author of this Report.

Executive Summary

ES.1. Background

The region encompassing the Southeast Louisiana Flood Protection Authority—East (SLFPA-E) jurisdiction has a five-fold unique and unfortunate vulnerability to extreme hurricane surge:

1st. The region lies at the heart of the central-northern Gulf of Mexico, which is exposed to a high landfall frequency of powerful hurricanes due to the very warm waters of the Loop Current. The Loop Current not only fuels hurricane intensification but also the growth of wind fields; moreover, it sustains slow moving storms.

2nd. The protrusion of the Mississippi River delta into the central-northern Gulf of Mexico raises counterclockwise wind-driven surge on the eastern flank and creates critical exposures for the regional "corner" formed by the intersection with Mississippi coast, the "funnel" produced by the junction of the GIWW and MRGO levees, and Lake Pontchartrain "filling and tilting."

3rd. The vast low-lying delta platform on which the region rests is fragmenting and subsiding—with some of the world's highest relative sea level rise magnifying surge inundation.

4th. Expanding shallow coastal shelves, sounds, bays, and lakes enable hurricane winds to push surge inland with more momentum. And,

5th. Declining coastal vegetation reduces the landscape frictional drag on surge momentum.

These five factors have combined to create surge heights in excess of 20 ft twice in less than 40 years.

Two major institutional tools for managing hurricane surge risk are flood insurance—offered under the National Flood Insurance Program (NFIP), administered by the Federal Emergency Management Agency (FEMA)—and perimeter protection systems. In the wake of Hurricane Katrina, the U.S. Army Corps of Engineers (USACE) was directed both to a) revise the regional surge hazard analysis—as part of a NFIP update to the regional Flood Insurance Study (FIS)—and b) design and construct a NFIP accreditable levee system, known as the Hurricane and Storm Damage Risk Reduction System, (HSDRRS).

It is important to recognize that the NFIP and HSDRRS are directed primarily at managing property damage risks. In managing flood property losses the NFIP focuses on an analysis of the 100-year hurricane surge hazard (100-yr average recurrence, or 1% annual chance). Thus, the HSDRRS is designed to minimize 100-yr overtopping—consistent with a level which avoids erosion issues and which also does not aggravate the residual interior flood hazard associated with severe rainfall events. While the 100-yr hazard level may seem to many like a stringent criteria, it is widely recognized as inadequate for addressing critical residual risks to property, community infrastructure and cultural assets, regional and national economic interests, as well as human lives and livelihoods.

Between 2005-09[3] the USACE undertook a ground-breaking hurricane surge hazard analysis to estimate the 100-yr surge hazard for the regional FIS and accreditable HSDRRS design. The analysis employed considerable professional, academic, and other technical resources and greatly advanced the state of scientific knowledge and the engineering practice. The USACE also used the FIS analysis to estimate

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[3] The period from 2005-2009 represents the years in which the USACE made methodology decisions and performed the vast majority of the analysis. Many methodology choices are thus already over seven years old, and much of the analysis is over five years old. Documentation of the work is included in: IPET, *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Volumes I through VIII*, 2006-09; USACE, *Flood Insurance Study, Southeast Parishes of Louisiana, Intermediate Submission 2: Offshore Water Levels and Waves*, July 2008; USACE, *Elevations for Design of Hurricane Protection Levees and Structures*, Draft Report Version 4.0, August 18, 2010. USACE, *Louisiana Coastal Protection and Restoration, Final Technical Report*, June 2009.

500-yr surge for HSDRRS resiliency/armoring plans—to reduce breaching threats under more extreme events. In addition, the USACE and the Louisiana Coastal Protection and Restoration Authority (CPRA), have improvised on portions of the FIS analysis to assess residual 1,000-yr interior inundation hazards for HSDRRS polders and to study alternative future coastal protection and restoration scenarios.

Notably, the NFIP accepts programmatic, resource, cost, and schedule constraints on FIS surge hazard analysis consistent with its limited risk management goals. However, for regions with substantial surge risks, like SLFPA-E, it is appropriate for risk managers to employ more rigorous hazard analysis, updated more frequently to the most recent standards for accuracy and quantifying uncertainty.

ES.2. Objectives and Organization

This Report provides SLFPA-E with:

1. A comprehensive explanation of the evolving science and technical practice of hurricane surge hazard analysis. This review of surge hazard analysis and the encompassed methodologies is not restricted to the risk context of NFIP, but instead is undertaken from a broad risk perspective, congruent with the greater responsibilities of the SLFPA-E. To accomplish this objective this Report has been organized into five parts corresponding to the five major subjects (and tasks) in surge hazard analysis:

   Part I. Hurricane Climatology
   Part II. Modeling Hurricane Surge Physics
   Part III. Hurricane Surge Hazard Analysis
   Part IV. Hurricane Surge Hazard Analysis for Polders
   Part V. Hurricane Surge Hazard Analysis for Future Conditions

   Each part includes detailed technical information on the current approaches underlying each task, critical assumptions, and methodology limitations. Background information is taken not only from the USACE's southeast Louisiana study but from the scientific literature, other recent hazard studies, and several new analyses undertaken for this Report. For example, new information on Gulf of Mexico hurricane climatology is presented based on records through the 2011 season.

2. A review and evaluation of the USACE 2005-09 analysis within the context of the evolving state of the practice, in each part.

3. Recommendations for improving surge hazard analysis for southeast Louisiana.

In addition, this Executive Summary assesses implications of the above for the HSDRRS performance and provides recommendations for revising the HSDRRS design and improving surge risk management.

ES.3. Principal Findings on the State of the Practice for Surge Hazard Analysis

The state of the practice in hurricane surge analysis has rapidly evolved over the last five years in response to continued scientific and technical advances. These advances have largely been spurred on by a need for better surge forecasts, together with FISs for other locations along the Gulf of Mexico and Atlantic coasts. The USACE—both through New Orleans District and the Engineer Research and Development Center—has continued to play a crucial role in methodology improvements. **A major finding of this Report is that recent methodological advances provide for reduced systemic and local bias (error) in surge hazard analysis.** Five important advances include:

1. Understanding of the regional hurricane climatology has continued to progress since Hurricane Katrina (e.g., Hurricanes Gustav, Ike, and Isaac). Research on storm frequencies and characteristics is clarifying the importance of more factors to surge hazard, e.g., Holland B and Integrated Kinetic Energy. The particular role of the Loop Current and coastal water temperature in local hurricane return period, intensity, wind field extent, and dynamics is also becoming better understood, as is the surge threat of large, low intensity hurricanes.
2. Models have improved significantly regarding a) representation of physics in component wind, surge, and wave models; b) code developments (e.g., tight coupling with wave models); c) mesh resolution, quality, and node attributes (e.g., elevations and Manning's *n* values); and d) execution speed and the ability to complete extensive model performance tests (due to high performance parallel computing, HPPC, technology). Recent models are even more reliable, robust, and locally realistic than those developed five years ago.
3. HPPC speeds and capacity have multiplied many fold, which now allows the number of storms used in the joint probability analysis (JPA) to be greatly expanded and facilitates a Joint Probability Method with Optimal Sampling (JPM-OS) approach as opposed to a Surge Response-OS approach.[4]
4. Greater HPPC efficiency and improvements in JPM-OS further allow for a rigorous JPA of polder inundation hazards and residual risk management, moving beyond basic reach-by-reach overtopping hazard assessments.[5] This facilitates a full consideration of residual risk, uncertainties, and the "conservatism" of the design—i.e., a true "risk-based" design.
5. Greater HPPC efficiency also enable more sophisticated evaluations of future surge hazard scenarios, including such factors as varying regional response to relative sea level rise (RSLR), coastal land loss, and local settlement.

A second crucial finding is that despite advances in estimating surge hazards, uncertainties in surge hazard estimates remain very high, with the pace of future reduction likely to be very slow. Methods for quantifying uncertainties are well established and show that *overall surge hazard estimate uncertainty has a very large fractional magnitude, and non-normal distribution.* Applying a normal distribution to provide some indication of epistemic uncertainty magnitude, the 100-yr exterior surge

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[4] There are two different approaches to hurricane surge JPA. In the JPM-OS approach the storm set is selected to represent both a) the hurricane climatology (i.e., each storm represents a fraction of the overall frequency of storms) and b) the surge response of the region. In this case the number and characteristics of storms in the set are typically optimized through a comparison with a "surge hazard benchmark"—a less refined surge analysis of the region. A "wind hazard benchmark" can also be used to aid in selecting the set. In the Surge Response-OS approach, the storm set is selected only according to "b." If surge-response is considered smooth then the set can be substantially reduced, and surge response extensively interpolated and extrapolated. For complex coasts—such as those dominated by sheltered water bodies—a Surge Response-OS requires more storms, negating its main advantage. A major disadvantage of Surge Response-OS is that it does not support polder inundation hazard analysis. HPPC improvements now allow for both the use of large JPM-OS sets and elaborate benchmark testing.

[5] A polder inundation JPA is required to assess whole-polder inundation hazards (e.g., 100-yr)—incorporating reach exposure *independence* and varying reach seepage, overtopping, breaching, rainfall, pumping and internal routing. Reach exposure independence means that a 100-yr reach overtopping volume has a much shorter return period when regarded as polder surge inundation volume. For a hypothetical polder consisting of two reaches having with independent exposures, the 100-yr reach overtopping hazard constitutes a 50-yr polder hazard. The IPET Report (Volume VIII) provided a planning-level evaluation of polder inundation hazards with some basic features of expanded JPA. The IPET polder inundation JPA was undertaken prior to the USACE finalizing the HSDRRS design.

estimates for southeast Louisiana have a 90% confidence interval of *at least* ± 4.3, 5.1, and 6.1 ft (43, 34, and 30%) on surges of 10, 15, and 20 ft, respectively. Additional aleatory uncertainty can have a similar magnitude but is far from normally distributed.[6]

ES.4. Principal Findings on the 2005-09 Southeast Louisiana Surge Hazard Analysis

Review of the southeast Louisiana 2005-09 surge hazard analysis in light of recent methodology advances indicates that the analysis has seven important potential bias factors, including four sources of low—under-estimation—bias:

1. **The evaluation of hurricane climatology does not take into account the influence of large, slow-moving, low intensity hurricanes on the 100-yr surge**.
2. **The surge model contains several superseded approaches and the mesh contains outdated topographic, bathymetric, land cover, and HSDRRS data.** These limitations produce local bias in sensitive areas within the region. The model validation—which was done by comparing a Hurricane Katrina hindcast to surge observations—acknowledged one example of significant local bias: a consistent under-representation of surge height by more than 1.5 ft along the south shore of Lake Pontchartrain. The model likely has additional locations of under-estimation bias, as well as some locations with an over-estimation bias.
3. **The Surge Response-OS approach and small 152-storm set overly smooth the interpolation and extrapolation of regional surge response to variations in hurricane characteristics (see Footnote 2). The set does not include sufficient scenarios of extreme landfalling hurricanes for estimating the 500-yr hazard**—e.g., no landfalling Category 5 hurricanes.
4. **The 2057 analysis for the future 100-yr condition only uses a uniform 1.0 ft RSLR around the entire perimeter and applies a uniform increase to estimated surge still water and wave heights for most of the east-bank**.

One small upward bias factor:

5. The approach used to compute the cumulative distribution function (CDF) modestly increases the 100- and 500-yr exterior surge hazard estimates—at one location by 0.4 and 1.1 ft, respectively.

And two factors that could be significant but are difficult to gauge at this point:

6. The method used in characterizing foreshore wave heights associated with the 100- and 500-yr surge conservatively assumes Rayleigh distributed wave heights, but also a possibly low breaker index of 0.4.
7. The JPA for the 2011 conditions does not re-simulate all the storms in the set, but chose to adjust some storm results from the previous JPA for the 2007 conditions.

[6] Uncertainty due to measurement and model imprecision is termed epistemic, while that due to natural variability is termed aleatory. For surge still waters of 10, 15, and 20 ft the estimated standard deviation for total epistemic uncertainty are *at least* 2.6 (26%), 3.1 (21%), and 3.7 ft (19%), respectively. Standard deviations can be equated to 80%, 90%, or 95% confidence intervals by multiplying by 1.28, 1.65, or 1.98, respectively. Thus, the 90% confidence interval for a 100-yr 10 ft surge exceeds ±4.3 ft. There is additional, large, aleatory asymmetric uncertainty associated with the short length of hurricane climatological and surge records.

Review of the state of the practice also identifies five important limitations in the 2005-09 analysis regarding the quantification of uncertainty in surge hazard estimates:

1. **Uncertainties associated with hurricane dynamics**—e.g., intensification, growth, and decay.
2. **Uncertainty in the combined wind/surge/wave modeling** indicated by other recent studies.
3. **Uncertainties in the JPA method and CDF integration,** which have not been examined.
4. **Uncertainties for interior polder inundation hazard factors** such as seepage, overtopping, breaching, rainfall, pumping, and internal routing, which have not been quantified.
5. **Most importantly, the HSDRRS design allowance for uncertainty in the local wave overtopping rates**, which does not reflect the actual statistical uncertainties. The Monte Carlo analysis used to compute the allowance a) employed much lower standard deviations for exterior surge still water than those estimated, and b) did not vary the wave height with depth, as stipulated in the design analysis.

These bias factors and uncertainty issues indicate that the 2005-09 analysis is outdated for SLFPA-E surge risk management purposes beyond the 2013 NFIP FIS and HSDRRS accreditation.

ES.5. Recommendations for Improved Surge Hazard Analysis for Southeast Louisiana

Based on these findings and conclusions, the Report provides two major recommendations for revising the southeast Louisiana surge hazard analysis:

1. **The southeast Louisiana hurricane current and future surge hazard analyses should be updated as soon as possible to provide higher quality median and exceedance level estimates of exterior surge, waves, overtopping, and polder inundation over a full range of hazard levels.** Table ES.1 provides a list of specific recommendations, addressing each of the five tasks, to bring the regional surge hazard analysis up to the state of the practice.

   SLFPA-E should share this recommendation (and the findings supporting them) with the CPRA, USACE, and other federal, state, and local agencies with surge and polder flood risk management missions, including NFIP responsibilities.

   Given that SLFPA-E and CPRA are responsible for managing a full range of surge risks (see the *Louisiana's Comprehensive Master Plan for a Sustainable Coast*, 2012) it is appropriate for them to assert strong leadership in regional surge hazard analysis. SLFPA-E should work with CPRA to establish and fund a permanent program to regularly revise the southeast Louisiana surge hazard analysis—encompassing all five tasks—as part of the state's Master Plan process. The permanent program should be a cooperative partnership with FEMA, USACE, and NOAA (if mutually agreeable), the recently created Water Institute of the Gulf, and leading academic researchers on the various tasks. The revisions should incorporate updates to hurricane and regional data, statistical methods, and modeling approaches and codes in order to meet the needs of federal, state, and local community and ecosystem planners for high quality surge hazard estimates over a wide range (e.g., 10-yr to 10,000-yr)—addressing exterior, overtopping, and inundation hazards and their uncertainties.

2. **SLFPA-E should support a cooperative partnership with CPRA, FEMA, USACE, and NOAA to encourage and fund research for improving regional surge hazard analysis.** Table ES.2 presents a list of research topics—such as investigating potential climate change impacts on the way the Loop Current influences regional hurricane climatology.

This partnership should also develop "living" technical guidance to enhance the consistency and quality of methodologies. This guidance should include incorporating lessons learned from other regional surge studies and identifying best practices for various applications.

Given significant rainfall-only and Mississippi River flood vulnerability in southeast Louisiana, improved analysis of these hazards is also crucial to coordinated residual flood risk management by SLFPA-E, CPRA, and other federal, state, and local agencies.

ES.6. Implications for the HSDRRS Performance

The USACE used the 2005-09 analysis in the HSDRRS elevation design to minimize current 100-yr surge wave overtopping of levees. Floodwalls were designed higher, to future 2057 100-yr overtopping conditions (with RSLR), due to the excessive cost of subsequent crown increase. The outdated methodologies of the 2005-09 analysis--associated bias factors and uncertainty issues—imply the following six conclusions regarding levee performance *as designed* (excluding settlement overbuild):

1. **Revising the analysis for Bias Factors Nos. 1 and 2 above will likely raise median estimates of the exterior 100-yr surge (versus the current FIS estimates) at many HSDRRS reaches, perhaps by two feet at some locations. However, a complete re-analysis is updated is needed to determine the combined influence of all the bias factors on the exterior 100-yr surge estimate.** The 100-yr freeboard—height of the crown above the 100-yr surge still water—varies depending on reach estimated wave conditions. It ranges from 3.0 ft for a reach fronted by forests in St. Charles Parish north of Airline Highway, to over 10 ft for some reaches near the IHNC/GIWW Barrier. Increases to the 100-yr surge estimates are not likely to exceed HSDRRS crowns, but for certain low freeboard reaches could reduce freeboard below the two feet minimum required by FEMA. Higher 100-yr surge estimates could substantially increase estimates of wave overtopping—by factors of two or more. If a reassessment of foreshore wave characteristics substantially increases wave breaker index, the 100-yr wave overtopping estimates could increase by much higher multiples.
2. **Revising the analysis for Bias Factors Nos. 1, 2, and 3 are even more likely to raise median estimates for 500-yr surge and overtopping throughout the region.** The most significant impact is on reaches with low 500-yr freeboard, where there could be a significant threat of free flow overtopping and interior-side erosion and breaching. For example, a reach in St. Charles Parish north of Airline Highway with only 0.5 ft of 500-yr freeboard could show a negative freeboard under a revised analysis.
3. **Revised quantification of uncertainty addressing the above issues will notably increase statistical confidence intervals for 100- and 500-yr surge, waves, and overtopping.** Revisions for both bias and uncertainty together can increase the estimate of current overtopping hazards at exceedance levels by *an order of magnitude.*
4. **Revised median and 10% exceedance estimates of the 100-yr overtopping rate at many reaches will likely surpass the specified 100-yr criteria in the HSDRRS design for interior-side erosion protection** (0.1 and 0..01 cfs/ft)**.** Meeting current criteria will require raising the design elevation to reduce overtopping. Alternatively, overtopping criteria could be increased and the segment erosion protection modified (e.g., through armoring). However, increasing allowable overtopping rate must also ensure that the higher overtopping *volume* does not adversely affect the polder inundation hazard. Ongoing research on wave overtopping erosion of levees may also revise the erosion criteria, which could be increased or reduced depending on specific levee and wave characteristics.

5. **Revising the analysis for the bias factors and uncertainty issues is also likely to raise the polder inundation risk. However, an improved JPA based on the final HSDRRS design is needed to determine the magnitude of increase.** The IPET "planning level" estimates of the 100-yr surge inundation for the New Orleans metropolitan polders—based on a preliminary HSDRRS design without the IHNC/GIWW and Seabrook Barriers and other upgrades—indicated that *100-yr inundation volumes are far lower for surge than for a rainfall-only event*. An improved polder inundation hazard analysis—applied to the final HSDRRS design—is required to reassess this preliminary indication, as well as to evaluate the residual 500- and 1,000-yr polder inundation hazards and their uncertainties.
6. **An updated future analysis addressing Bias Factor No. 4—which takes into account varying regional impact of RSLR, erosion, and land cover change (e.g., New Orleans East Land Bridge)—is likely to show significant spatially-varying impacts to future 100-yr and 500-yr surges and HSDRRS reach overtopping.** The 2057 design elevations will need to be adjusted to take into account higher overtopping at some reaches.

These six performance concerns indicate that HSDRRS levees as designed have significant shortcomings for the SLFPA-E's management of surge risks.

ES.7. Additional Recommendations for the HSDRRS

The following four HSDRRS recommendations derive from the above findings and recommendations for improved surge hazard analysis, and the implications for the HSDRRS design:

1. **SLFPA-E should work with CPRA and USACE to revise surge (still water level), wave, and overtopping exceedance levels to reflect the total statistical (including non-normal) uncertainty. SLPFA-E should then work with the CPRA and USACE on determining if a 10% exceedance level is appropriate** (i.e., 80% confidence interval).[7]
2. **SLFPA-E should work with CPRA and USACE to add three exceedance level design criteria:**
   a. A minimum freeboard for the 100-yr/exceedance surge, in addition to the NFIP required 2 ft minimum 100-yr/median freeboard. SLFPA-E, CPRA, and USACE should define an appropriate 100-yr/exceedance freeboard. The requirement will necessitate raising some reaches, such as a levee in St. Charles Parish north of Airline Highway, which currently has a crown design of 14.0 ft for a 100-yr surge of 10.8 ft—a freeboard of 3.2 ft. A 100-yr surge estimate at the 10% exceedance level accounting for total uncertainty is likely to be above 15 ft.
   b. Reach-specific 100-yr/exceedance wave overtopping rates. This would replace the current uniform 0.1 cfs/ft criteria and could be higher or lower depending on reach erosion control. The allowable rate would be based on latest erosion research but would not exceed a limit required to minimize polder inundation impact. Revised estimates of local 100-yr/exceedance surge and waves will likely require upgrading wave breaking or crown elevation, and/or interior-side erosion control, for many reaches.

[7] The NFIP does not require allowances for uncertainty in the delineation of local flood hazards, largely because the uncertainty in annual claims can be managed actuarially across the nationwide program . However, locally borne risks associated with levee failure imply the need to account for uncertainty at an appropriate interval. The USACE levee certification guidance (*Process for the NFIP Levee System Evaluation*, August 2010, EC_1110-2-6067) suggests an exceedance level of *at most* 10% (equivalent to an 80% confidence interval).

The uniform design criterion for the median 100-yr overtopping (0.01 cfs/ft) could be eliminated if it provides no needed benefit.

c. Reach-specific 500-yr (resiliency) still water levels, waves, exterior scour velocities, overtopping rates, and seepage rates—at appropriate exceedance levels. These should be based on reach-specific conditions and the latest performance research and should consider the full range of failure mechanisms. SLFPA-E should work with the CPRA and USACE to clarify the HSDRRS authorization, and modify as needed, to allow selecting and prioritizing resiliency projects from among a full range of alternatives—with the objective of optimizing reduction in polder residual risk. Resiliency projects should include the option of further raising reach crowns.

SLFPA-E should work with the CPRA and USACE to upgrade structural designs as needed to be consistent with revised hydraulic design.

3. **SLFPA-E should work with the CPRA and USACE to accelerate installation of reasonable resiliency measure*s* which are not likely to be rendered obsolete in the near future** by revisions to surge hazard analysis, 100-yr and 500-yr exceedance level design criteria, and erosion research. If USACE construction funds are not available SLFPA-E should obtain state and/or local funding and expedite completion. Levee reaches with low freeboard (e.g., St. Charles Parish) should be prioritized for maintenance lifts.

4. **SLFPA-E should work with the CPRA and USACE to ensure a systematic approach to HSDRRS projects.** In general, the top priority should be minimizing 100-yr wave overtopping in accordance with design criteria at the specified exceedance level. The second priority should be 500-yr resiliency at an appropriate exceedance level. The third priority should be further upgrades to HSDRRS (e.g., the 2012 CPRA Master Plan “High Level” alternative). All polder HSDRRS components must be treated as equally important “links in a surge risk management chain.”

ES.8. Additional Recommendations for Surge Risk Management

Finally, the SLFPA-E should also work with the CPRA, regional parish governments, the USACE, and other appropriate agencies on seven further surge risk management actions:

1. **Complete studies to identify cost-effective internal compartmentalization projects** to reduce or control inundation in the event of an HSDRRS breach. Possible projects include diverting water from the IHNC/GIWW sub-basin to the Central Wetlands; reinforcing I-walls along the IHNC; and improving legacy barriers at parish boundaries.

2. **Maintain and improve critical coastal “lines of defense,”** per the CPRA 2012 Master Plan, such as the New Orleans East and Bayou LaLoutre Land Bridges and Biloxi Marsh.

3. **Examine regional surge hazard/risk impacts and issues associated with Mississippi River and other levees below the HSDRRS** as part of the Mississippi River Hydrodynamic and Delta Management Study.

4. **Continue to evaluate potential cost-effective Lake Pontchartrain Barrier alternatives that avoid adverse ecological and surge hazard impacts**.

5. **Conduct a state-of-the-practice "all flood" hazard analysis for the New Orleans region**. This analysis should be used to optimize surge risk management given other sources of flood hazard. In order to reduce polder 100-yr flood hazards, expanding interior drainage and pumping capacity and non-structural measures may take precedence over raising HSDRRS crowns. In order to reduce 1,000-yr flood hazards, attention may need to shift from HSDRRS improvements to Mississippi River levee upgrades.
6. **Upgrade polder infrastructure and revise building codes consistent with future polder "all flood" hazard analysis and sound risk management**.
7. **Implement reasonable policies to incentivize a broader segment of property owners to purchase flood insurance under the NFIP**.

Table ES.1. Recommendations for Updating the Southeast Louisiana Surge Hazard Analysis

Task	Recommendation
I. Hurricane Climatology	
1.	Revise the joint probability expression—and associated uncertainty—for southeast Louisiana regional hurricane landfall as a function of latest data on hurricane frequency, core intensity, core size, forward speed, and track, including hurricanes of any intensity.
2.	Use an appropriate data record; reassess evidence for a Gulf of Mexico climate cycle.
3.	Address scatter in relationship of central pressure deficit and maximum wind speed in joint probability expression.
4.	Address wind field distribution variability—e.g., Holland B, Integrated Kinetic Energy, etc.—for the full range of hurricane core intensities and sizes, in a revised joint probability expression.
5.	Address variability in intensification—associated with passage over the Loop Current/Eddies—and pre-landfall decay (infilling) for the full range of hurricane intensities, sizes, wind-field distributions, and forward speeds. in a revised joint probability expression.
6.	Re-evaluate the return period for regional landfall of a Hurricane Katrina and evaluate the return periods for Hurricanes Gustav and Isaac.
7.	Incorporate results of studies on future hurricane climatology as a function of climate change into estimates of uncertainty regarding future hurricane probabilities.
II. Modeling Hurricane Surge Physics	
1.	Revise the finite element mesh layout and resolution; refine fidelity of linear feature alignments (e.g., break lines); provide for reasonable consistency in resolution of similar landscapes and key landscape conveyance features.
2.	Revise mesh (node and interior weir boundary) elevations consistent with a current regional digital elevation model, including current applicable NAVD88 epoch.
3.	Revise other mesh attributes (e.g., Manning's *n*, surface canopy coefficient, surface directional roughness, eddy viscosity) consistent with current landscape information.
4.	Use a tightly coupled surge-wave code with full plane wave modeling and include all relevant physics terms. While SWAN-ADCIRC is the current state-of-the-practice HPPC surge code, alternatives should be evaluated as they become available.
5.	Evaluate choice of fully explicit versus implicit-explicit numerical scheme, wetting-drying approaches and parameters; and air-sea drag formulation.
6.	Support (e.g., sensitivity testing) decisions that vary from established guidance/state-of-the-practice.
7.	Provide model calibration/validation using Hurricanes Katrina, Gustav, and Isaac; explain choice of parameters that are/are not employed in calibration.
8.	Evaluate residual instabilities and local mass conservation errors in final calibration/validation.
9.	Evaluate potential local bias in final calibration/validation results and provide methods for correcting bias in the use of the model.
10.	Revise the estimate of uncertainty in regional surge modeling.

Table ES.1. Recommendations for Updating the Southeast Louisiana Surge Hazard Analysis (Continued)

Task	Recommendation
III. Hurricane Surge Hazard Analysis 1. Employ a true JPM-OS approach with a much expanded set size (e.g., hundreds of storms) in the surge JPA. The JPM-OS should be determined using appropriate regional wind and surge benchmarks. The surge benchmark should sufficiently capture critical nonlinear responses and surge hazard conditions—particularly around large sheltered water bodies. Sensitivity tests should be used to examine the scope of regional nonlinear surge response and surge hazard conditions.. Alternatively, the revised surge JPA can employ a Monte Carlo JPM. 2. Rigorously validate the surge JPA versus tide gauge-based return frequency analyses to evaluate potential bias in JPA results. 3. Employ an integration method which provides the median estimated CDF. Sensitivity tests should be conducted on possible variations to the integration method to identify the best approach. 4. Define and quantify all sources of normally and non-normally distributed uncertainty contributing to the overall uncertainty in the surge hazard analysis, including uncertainties in the hurricane climatology, wind/surge/wave model, the selected surge JPA method, and set size. Prepare uncertainty intervals for the estimated CDF based on all sources of uncertainty.	
IV. Hurricane Surge Hazard Analysis for Polders 1. Incorporate the improvements in the hurricane climatology, surge modeling, and exterior surge hazard analysis discussed in the Recommendations for Parts I, II, and III. 2. Provide a joint probability analysis (JPA) of polder inundation hazards, expanding on the IPET approach, and estimate the residual 100-, 500-, and 1,000-yr inundation hazards. 3. Base the polder inundation JPA on the larger JPM-OS set of storms as identified in the Part III recommendations. 4. Include a realistic quantification of the range of breach I-L cases and associated fragility conditions for each storm. 5. Estimate local wave conditions and HSDRRS wave overtopping with the state-of-the-practice methods that better account for local peak wave conditions during hurricane peak surge. 6. Further expand the inundation JPA to encompass the nonlinear influence of additional key probabilistics—such as exterior SWL and wave height—on inundation volume. 7. Examine the full influence of uncertainties—associated with the hurricane climatology, the exterior hurricane surge and local wave model, seepage, overtopping, breaching, rainfall, pumping, internal routing, and particular JPMs—on the inundation hazard estimate. Such treatment should be developed to allow estimating a range of confidence intervals—e.g., 80, 90, 95%. 8. Update estimates of the wave overtopping hazard for the HSDRRS design at each reach in accordance with No.5, and update confidence intervals using full uncertainties for surge and wave conditions.	
V. Hurricane Surge Hazard Analysis for Future Conditions 1. Follow the recommendations in Parts II, III, and IV for improved model development, exterior surge hazard analysis, and polder inundation hazard analysis. 2. Re-evaluate the future conditions hazards at appropriate intervals (e.g., Years 10, 25, 50, and 100) based on *all* recognized applicable coastal landscape trends—e.g., RSLR, coastal erosion, vegetation changes, perimeter system degradation, and polder subsidence—when the current exterior surge and interior polder inundation hazards analyses are revised. 3. Re-run all JPM-OS storms for the future conditions JPAs instead of using a small subset of storms to adjust the estimate of future hazard. 4. Use specific storm scenarios—e.g., a Katrina-like hurricane—to provide additional insight and aid public understanding of impacts to future surge hazard.	

Table ES.2. Research Topics for Improving Southeast Louisiana Surge Hazard Analysis

Task	Recommendation
I. Hurricane Climatology	
1.	Update information on various traditional and new characteristics for Gulf of Mexico and landfall hurricanes, as the historical record expands.
2.	Conduct more rigorous statistical analysis of data on these characteristics; particularly clarification of confidence intervals (i.e., uncertainty) in estimates of hurricane characteristics and correlations between characteristics, e.g., (CPD:Vmax2).
3.	Improve the joint probability expressions for Gulf of Mexico hurricanes, and landfalling regional hurricanes, including estimation of uncertainty.
4.	Revisit the selection of a representative GoM hurricane data record, taking into account quality of observations and accepted findings on GoM climate cycles.
5.	Investigate factors influencing the particular hurricane return frequencies for southeast Louisiana, especially the Loop Current and associated eddies.
6.	Further expand the joint probability expression to include additional important hurricane attributes contributing to surge, such as wind field asymmetry and banding.
7.	Assess the influence of secular climate trends on the Loop Current and other factors influencing GoM hurricanes.
II. Modeling Hurricane Surge Physics	
1.	Update Louisiana LIDAR DEMs, coastal water body bathymetry, raised feature topography, and land cover data sets.
2.	Acquire wind (at a range of averaging periods), SWL, current, and wave time-series data across a wide range of coastal landscape locations during hurricanes, as well as during normal tides and seasonal meteorological events.
3.	Improve and refine H*Wind files (10-min average) for surge calibration and validation.
4.	Improve treatment of surge physics, such as depth-variable hydrodynamic friction (e.g., Manning's n), the air-sea drag, wetting and drying, wave shoaling/breaking, and local time-varying rainfall.
5.	Further application of higher order steep-slope wave modeling, including capability of coupling with 2D SWL models.
6.	Advance numerical methods, codes (SWAN+ADCIRC and others), and HPPC techniques and systems.
7.	Incorporate 3D models for baroclinic analysis where needed to improve accuracy.
8.	Address significant raised feature erosion and other landscape dynamics during actual surge events where needed to accurately simulate surge and waves.
9.	Expand sensitivity analyses assessing the implications of model settings (e.g., numerical methods, modification of acceleration terms, time step, etc.), mesh resolution, node attributes, forcing data, coupled models, and other model aspects on runtime, stability, and performance.

Table ES.2. Research Topics for Improving Southeast Louisiana Surge Hazard Analysis (Continued)

Task	Recommendation
III. Hurricane Surge Hazard Analysis 1. Expand the number of high quality long-term regional gauge records. Long-term records for several regional USGS and USACE gauges can be enhanced by addressing datum and gap issues. 2. Further evaluate appropriate return frequency distribution equations for the analysis of tide gauge records. In particular, equations should provide reasonable treatment of extreme historical observations. 3. Examine nonlinear surge response and surge hazard conditions for complex coastlines, including sheltered water bodies, particularly for southeast Louisiana. 4. Assess JPM approaches and set size optimization, Cumulative Distribution Function integration techniques, and the estimation and treatment of hazard uncertainty. 5. Study JPM wind field (10-min average) representation of surge forcing conditions	
6. Investigate methods for wave hazard analysis; such as the appropriate application of 1D overland wave modeling (WHAFIS transect selection and attribution, local wind-wave boundary conditions, wave transformation parameters, etc.) and determining those locations and conditions where more advanced modeling (2D, Boussinesq, etc.) should be applied.	
IV. Hurricane Surge Hazard Analysis for Polders 1. Further research on local wave, seepage overtopping, breaching, rainfall, pumping, and interior routing processes, including laboratory and field studies to evaluate empirical formulations and coefficients. High priority issues include: • Appropriate wave height distributions for short duration surge peaks. • Appropriate breaker parameters or wave transformation models that can be applied to HSDRRS foreshore regions. • The role of preferential seepage pathways in initiating collapse breaching and field investigations to locate and characterize such pathways. • The wave and direct (weir) overflow expressions and coefficients for all phases of hurricane surge overtopping and breaching, for a variety of structures and conditions, including both average and instantaneous rates. • Exterior- and interior-side wave-induced, and free-flow induced, scour and breach initiation and development. • Wind setup and wave equations/models applicable to sheltered southeast Louisiana water bodies (e.g., Lake Borgne and Pontchartrain, Breton Sound, Barataria Bay, Mississippi River, etc.) and inundated polders and sub-basins (e.g., IHNC/GIWW and outfall canals). 2. Improve coupling of exterior surge, local wave, seepage, overtopping, breaching, rainfall, pumping, and internal routing models. 3. Further expand and enhance the inundation JPA to make it less speculative. 4. Better the analysis of non-surge polder flood hazards—such as rainfall-only events and overtopping/breaching during a Mississippi River flood—which are critical to evaluating the risk implications of surge inundation hazards	
V. Hurricane Surge Hazard Analysis for Future Conditions 1. Assess the influence of climate cycles and secular climate change on the CN-GoM hurricane climatology, SLR, and seasonal steric conditions, including influences mediated by the Loop Current. As part of assessing future hurricane climatology for the CN-GoM provide suitable JPM-OS sets for various future surge hazard evaluations. 2. Improve trend analyses for regional subsidence, coastal erosion, and vegetation conversion; elevation changes to perimeter systems and polder interiors; and HSDRRS fragility.	

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Part II. Modeling Hurricane Surge Physics

Part III. Hurricane Surge Hazard Analysis

List of Acronyms

AMO	Atlantic Multi-decadal Oscillation
CDF	Cumulative Distribution Function
CEM	Coastal Engineering Manual (USACE)
CLs	Confidence Limits (UCL/LCL—Upper/Lower Confidence Limits)
CN-GoM	Central-Northern Gulf of Mexico
CP	Central pressure
CPD or ΔP	Central pressure deficit
CPRA	Coastal Protection and Restoration Authority
CV and CV(RMSE)	Coefficient of variation and coefficient of variation for RMSE
ENSO	El Niño-Southern Oscillation
EST	Empirical Simulation Technique
FEMA	Federal Emergency Management Agency |
FIRM	Flood Insurance Rate Map
FIS	Flood Insurance Study
NFIP	National Flood Insurance Program
ft	Feet
GIS	Geographic Information System
GMH	GoM Major Hurricane
GMH/L	Which Makes Landfall at Any Category
GMH/LMH	Which Makes Landfall as a Major Hurricane
-500	Along 500-mi CN-GOM Coast
-151	Along 151-mi (2½° Latitude) Segment below New Orleans
-60	Along 60-mile (1° Latitude) Segment below New Orleans
GoM	Gulf of Mexico
GTN	General Technical Note (see Table of Contents)
H_s	Significant Wave Height
HHI	Hurricane Hazard Index
HII	Hurricane Intensity Index
HPPC	High Performance Parallel Computing
HSDRRS	Hurricane and Storm Damage Risk Reduction System
HSI	Hurricane Surge Index
IKE	Integrated kinetic energy
IKE_H and IKE_{TS}	IKE out to the extent of hurricane and tropical storm force winds
IPET	Interagency Performance Evaluation Task Force
JONSWAP	Joint North Sea Wave Project
JPA	Joint Probability Analysis
JPM and JPM-OS	Joint Probability Method and JPM with Optimal Sampling
km	Kilometer
LOI	Location of Interest
LaCPR Study	Louisiana Coastal Protection and Restoration Study (USACE)
MEOW	Maximum Envelop of Water
MJO	Madden–Julian Oscillation
MOM	Maximum of the Maximum
mph	Mile per hour
MPI	Maximum Probable (or Possible) Intensity
mb	Millibar

m	Meters
MsCIP	Mississippi Coastal Improvement Plan
NLCD	National Land Cover Database
NOAA	National Oceanic and Atmospheric Administration
CPC	Climate Prediction Center
CSC	Coastal Services Center
GFDL	Geophysical Fluid Dynamics Laboratory
HRD	Hurricane Research Division
NCDC	National Climate Data Center
NHC	National Hurricane Center
NRL	Naval Research Laboratory
NAO	North Atlantic Oscillation
PBL Model	Planetary Boundary Layer Model
PD	Pressure deficit
PDF	Probability Density Function
PJ	Petajoules
PMH	Probable Maximum Hurricane
r	Radial distance from the storm center
R^2	Coefficient of determination values
R_H and R_{TS}	Radius of hurricane and tropical storm force winds
R_{max}	Radius of maximum winds from the storm center
RFA	Return frequency analysis
RMSE	Root mean square error
RSLR	Relative sea level rise
s	Seconds
SDPI	Surge Damage Potential Index
SI	Scatter Index
SLFPA-E	Southeast Louisiana Flood Protection Authority—East
SLR	Sea level rise
SPH	Standard Project Hurricane
SSS	Saffir-Simpson Scale
SST	Sea surface temperatures
SWEs	Shallow Water Equations
SWL	Still water level
T_p	Peak wave period
TCHP	Tropical Cyclone Heat Potential
TJ	Terajoules
USACE	U.S. Army Corps of Engineers
V_f	Forward speed
V_{max}	Maximum sustained wind velocity
WDPI	Wind Damage Potential Index
yr	Year
θ	Heading angle
η	Difference between SWL and LMMSL; equal to the setup/setdown
μ and σ	Mean and Standard deviation

Introduction

This Introduction provides a background overview of six important topics in hurricane surge risk management for southeast Louisiana:

1. The concepts of hurricane surge hazard and risk;
2. Basic public and private tools for hurricane surge risk management;
3. The National Flood Insurance Program and perimeter surge protection;
4. The authorized New Orleans regional Hurricane and Storm Damage Risk Reduction System;
5. The 2005-2009 hurricane surge hazard analysis; and
6. Uncertainty in surge hazard estimates.

The purpose of this Report in supporting regional surge risk management is then described.

I.1 Hurricane Surge Hazard and Risk

Hurricane surge risk is the product of two components: the probability of given hurricane surge conditions at a location—i.e., the surge hazard—and the consequence of that surge.

For any particular surge still water and wave height (see Section 6 for definition of surge components) there is a quantifiable probability—given as a percent—that these can occur at a specific location in any year. For example, a surge of 15 feet or greater may have a two percent chance of occurring each year at a given location. This probability is also called a two percent *return frequency*, and is equivalent to the expectation that a surge of 15 ft or greater will occur at least one time out of every 50 years, *on average.* This 50-yr time frame is referred to as an *average* recurrence or return period. A one percent return frequency is equivalent to a 100-yr return period; a 0.2 percent chance to a 500-yr return period; and a 0.1 percent chance to 1,000-yr return period. The same still water level can have different return periods at different locations—e.g., at West End versus Little Woods along Lake Pontchartrain versus Shell Beach along Lake Borgne. A hurricane making landfall in southeast Louisiana will produce varying regional still water peaks, with varying return periods.

A local 100-yr surge hazard is not guaranteed to recur exactly on a 100-yr interval, but to recur on average once every 100 years over a very long time frame—e.g. about 10 times over 1,000 years. Probabilities can be computed for single occurrences over shorter (and longer) time frames than 100 years, as well as for multiple occurrences over various time frames. For example, a local surge at or above the 100-yr hazard has a 26% probability of occurring during the course of a 30-yr mortgage.

In any given year, a surge with a *local* 100-yr return period is twice as likely to occur as a *local* 200-yr surge, at any point. When considering surge hazard around the exterior of a polder (a Dutch work to describe the area within a continuous perimeter surge protection system) it is important to consider the *whole-perimeter* hazard. For polders, the relationship between local surge exposures is important to understanding *inundation hazard*. If the exposure at points all around a polder are highly dependent, a particular hazard level (e.g., 100-yr) at all locations is likely to be associated with the same storm. However, if the exposures are independent, the hazard at each location would be associated with separate storms. If a polder has two independent surge exposures, the combined probability of a 100-yr surge happening at one or the other location in a given year is close to 2%, or a 50-yr return period. (See General Technical Note 1 for a further discussion of return frequency concepts in hydrology.) Thus, a polder can be exposed to overtopping volumes much more frequently than the local hazard indicates.

A *surge hazard analysis* estimates the still water and wave heights associated with a full range of return periods at every location within a region. This analysis is typically presented in the form of a cumulative distribution function curve, as illustrated in Figure I.1. A surge hazard analysis also estimates the uncertainties associated with the proposed curve.

Estimates can also be developed for full range of consequences that can occur throughout a region with each local surge hazard level. These might include the number of people not evacuating who are likely to be killed; the number of residents suffering various physical and emotional illnesses; residential and commercial property damages; temporary and permanent business, employment, and personal income losses; impacts to historical and cultural assets and local ways of life; etc. A *surge risk analysis* presents the range of consequences as a function of return probability—e.g., graphs of cumulative distribution function curves for estimated deaths, housing units destroyed, insured property losses, uninsured property losses, decline in one year local gross domestic product, etc.

Assessing surge risk—hazard plus consequences—provides a rigorous way of describing the probability and magnitude of disasters for a given location, facilitating comparisons between types of disasters (e.g., a surge flood event versus a rainfall-only flood event) and locations, and supporting informed decisions about how to best manage risk.

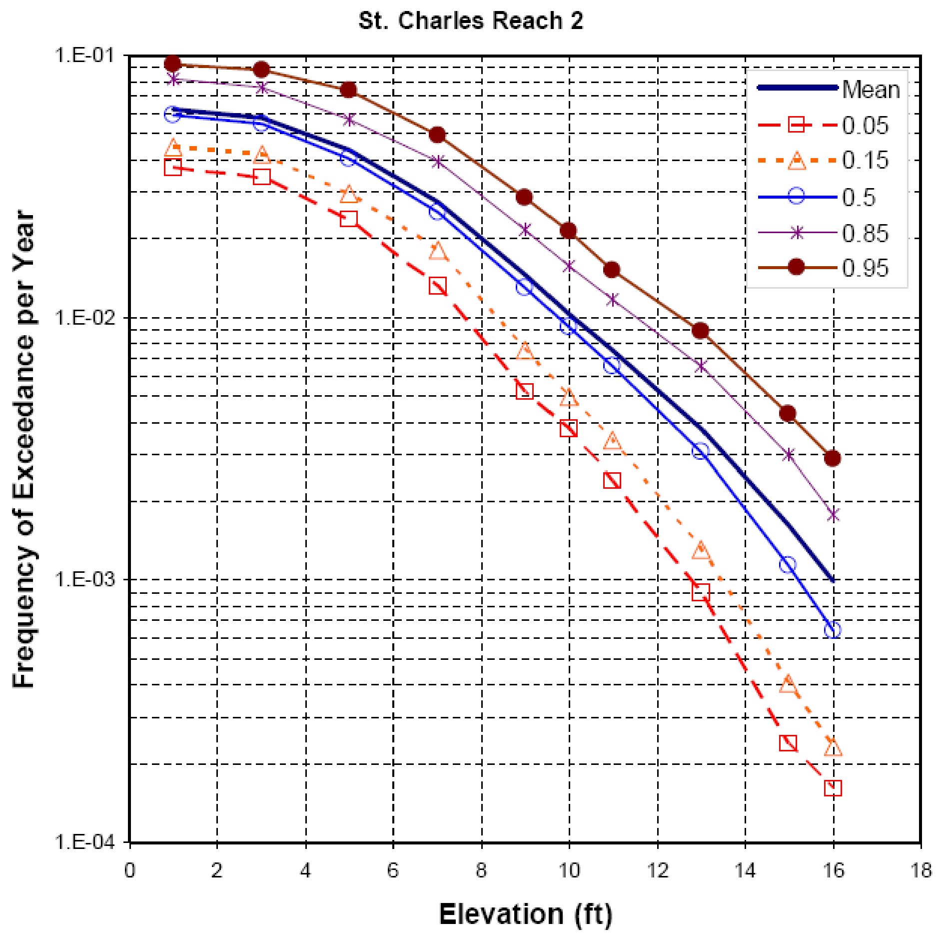

Figure I.1. Example of Surge Hazard Analysis with Confidence Limits

IPET 2009

I.2. Public and Private Hurricane Surge Risk Management

There are six principal governmental tools for surge risk management:

1. The Federal Emergency Management Agency (FEMA) sponsored National Flood Insurance Program (NFIP) covering both residential and commercial property damage. Other FEMA programs address local infrastructure losses.
2. Risk reduction by a perimeter levee/floodwall surge protection system. Perimeter systems may be sponsored by federal-local partnerships or they may be local-only projects. Those designed and constructed by the U.S. Army Corps of Engineers (USACE) in southeast Louisiana are done under a cost share partnership with the State of Louisiana Coastal Protection and Restoration Authority (CPRA), with long-term operations and maintenance provided by a local agency, such as the Southeast Louisiana Flood Protection Authority-East (SLFPA-E), with local funds.
3. Risk reduction through maintained and enhanced coastal "lines of defense"[8]—such as barrier islands, ridges, land bridges, and wetlands.
4. Risk reduction by maintained local infrastructure, such as internal drainage systems and compartmentalization structures within a polder;
5. Risk reduction through laws and regulations governing building standards, such as local zoning ordinances and building codes, buyouts, and subsidized elevation, some of which are required and some of which are voluntary under the NFIP.
6. Risk mitigation through emergency response and recovery programs, including, evacuation, flood fighting, flood recovery, rebuilding grants and loans, etc.

The residual risks—uninsured property damages; economic disruption; loss of life; health effects; loss of historic and cultural treasures; changes to a "way of life;" etc—are borne by individuals, volunteer organizations, businesses, and society at large.

Government sponsors must clearly define objectives and practical implications for the public tools. The public surge risk management must be understandable to the whole community—so that private residual risk management considerations can be properly weighed.

Proper application of public surge risk management tools by government agencies requires rational decision-making based on:

1. Scientifically Sound and Complete Information. For example, surge hydrologic boundaries must take precedence over political jurisdictions. Moreover, decision makers require good evaluations not just for surge hazards and consequences, but also for other related flood hazards—e.g., rainfall-only and Mississippi River. Agencies must also commit to re-analyzing hazards and risks to account for changing conditions, e.g., demographics, land use, climate, surge hazards, etc.
2. Rigorous Treatment of Uncertainties—in scientific information, hazard levels, consequences, and the performance of risk management tools. *The apparent precision of sophisticated analyses and plans can provide a false sense of security.* Agencies need to adopt straightforward ways of referencing and communicating fundamental surge risks and uncertainties.

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[8] See Lopez, J. A., *The Multiple Lines of Defense Strategy to Sustain Louisiana's Coast*, Lake Pontchartrain Basin Foundation December 12, 2005

3. Complete Life-Cycle Cost-Benefit Evaluation. The risk reduction and other benefits afforded by each tool must justify commitment of the sponsor resources necessary for the complete long-term development and sustainment of that tool. For example, a successful perimeter system requires the associated financial, human, political, and organizational resources not only for the initial construction phase, but also for anticipated additional construction phases, operations, and maintenance. Long-term opportunity and environmental costs must also be accurately identified and accounted for in the evaluation.
4. Consistency and Synergy. All the components must support the risk management objective, with no "weak or gold-plated links." For example, structures in a perimeter system should not be under-designed or excessively over-designed. Difficulties also arise when policies undermine risk management, such as providing local shelters when evacuation is mandated; encouraging "free riders;" and subsidizing a community's perimeter system.

The performance of the above tools is a third factor in the final calculation of surge risk. For the New Orleans area, in addition to organized evacuation, two important public institutional tools for surge risk management are the NFIP and the USACE designed perimeter surge protection system.

I.3. The NFIP and Perimeter Surge Protection

The federally administered NFIP provides property owners with an affordable way to manage threats of severe flood damage to their property, and communities with a way to reduce the risk that a critical mass of viable property owners can be wiped out. The NFIP requires that mortgages for homes subject to 100-yr flood (including surge) hazards be secured by flood insurance. Premiums for this insurance are generally below a fair market price, but nevertheless cost hundreds of dollars per month. Outside the 100-yr flood hazard the NFIP provides optional flood insurance to mortgagees and property owners, at premiums as much as 90 percent lower than for those exposed to the 100-yr hazard.[9] An artifact of the NFIP 100-yr threshold is a sharp transition in the value of homes located outside the 100-yr flood zone versus those in the 100-yr flood zone, with the latter often lowered by tens of thousands of dollars.

Risk management from the community perspective is greatly enhanced if most property owners not subject to the insurance mandate (either because the property is not under a commercial mortgage or the property is outside the 100-yr flood zone) nevertheless purchase optional flood insurance. NFIP flood insurance outside the 100-yr hazard offers an extremely good risk reduction value from a community perspective. However, individual owners are often not sufficiently motivated to take advantage of the value.

The NFIP currently has subsidized premium costs for flood insurance both inside and outside the 100-yr hazard, dramatically enhancing the attractiveness of flood insurance both to policy holders and for *local* risk management. However, under the recently passed Biggert-Waters Flood Insurance Reform and Modernization Act of 2012 subsidies are scheduled to decline significantly. Premiums for insuring a home inside the 100-yr hazard zone are expected to increase several fold, depending on the potential depth of a 100-yr flood. Despite the reduced subsidies, flood insurance remains the most important tool for managing flood damage risks to property.

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[9] It is important to note that the NFIP (which also includes a Community Rating System that adjusts local premiums based on community actions to reduce flood risks) strives to achieve many goals, some of which are not consistent—including conserving floodplains and minimizing development impacts; making flood insurance affordable; reducing flood claims; and maintaining a national actuarially sound insurance system.

To complement the NFIP, a reasonable surge risk management tool for a densely populated urban area is to construct a perimeter system that eliminates contribution of surge to the 100-yr flood hazard. An interior 100-yr flood hazard remains inside the polder for rainfall-only events. For southeast Louisiana, such systems can dramatically reduce the 100-yr (and 500-yr) flood zones with the polder. The *combination* of the NFIP together with a perimeter system can enhance property values, make housing more affordable, increase local discretionary spending, raise the attractiveness of the community to businesses, and support growth.[10]

For a critical urban region such as metropolitan New Orleans, coupling a 100-yr perimeter system with the NFIP is an especially effective tool in managing not only residential property damage risks, but important risks to the long-term viability of the community itself. *This is particularly true if property owners not subject to the NFIP mandate purchase flood insurance.* If the NFIP were eliminated, a higher perimeter protection system—likely at a much greater cost to the community—would be required to achieve the same level of risk management.

I.4. The New Orleans Hurricane and Storm Damage Risk Reduction System

In the wake of catastrophic loss of life and property from surge inundation during Hurricane Katrina in 2005, previous planning, design, and maintenance of New Orleans regional perimeter surge protection were severely criticized. The Interagency Performance Evaluation Task Force (IPET), the State of Louisiana, the Independent Levee Investigation Team, the American Society of Civil Engineers, and the National Academy of Engineers produced five major reports on the subject—the first three providing detailed forensic analyses, the last two primarily providing comments on the IPET report.[11] The foremost recommendation of these reports was for sound risk-based design and maintenance.

[10] These and other economic benefits are typically weighed against the total construction, maintenance, operation, opportunity, and environmental costs of the perimeter system, over a long term, as part of evaluating the feasibility of such systems. Interestingly, if the NFIP were based around a graduated flood hazard/risk analysis (i.e., not tied to the 100-yr threshold), the feasibility of perimeter systems could be reasonably evaluated for a range of surge risk management objectives. This might be very helpful to smaller communities.

[11] IPET, *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Volumes I through VIII*, 2006 - 2009.

Team Louisiana (van Heerden, I. L. et al), *The Failure of the New Orleans Levee System During Hurricane Katrina, A Report Prepared for Louisiana Department of Transportation and Development*, Baton Rouge, Louisiana, December 18, 2006.

Independent Investigation Levee Team (Seed, R. B. et al), *Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005, Final Report*, supported, in part, by the National Science Foundation, July 31, 2006.

American Society of Civil Engineers Hurricane Katrina External Review Panel (Andersen, C. F. et al), *The New Orleans Hurricane Protection System: What Went Wrong and Why*, 2007.

National Academy of Engineering and National Research Council of the National Academies, *The New Orleans Hurricane Protection System, Assessing Pre-Katrina Vulnerability and Improving Mitigation and Preparedness*, 2009.

The U. S. Congress authorized[12] the USACE to revise the southeast Louisiana FIS and rebuild the regional New Orleans hurricane surge perimeter protection system to a 100-yr level of hurricane surge protection, consistent with the NFIP. While this hazard objective affords some increased protection of lives over a lesser objective, federal, state, and local officials remain committed to comprehensive evacuation as the primary tool for saving lives. Given its objective primarily as a property damage risk management tool, the USACE renamed the New Orleans perimeter surge protection network as the Hurricane and Storm Damage Risk Reduction System (HSDRRS). The HSDRRS configuration and associated polders are shown in Figure I.2.

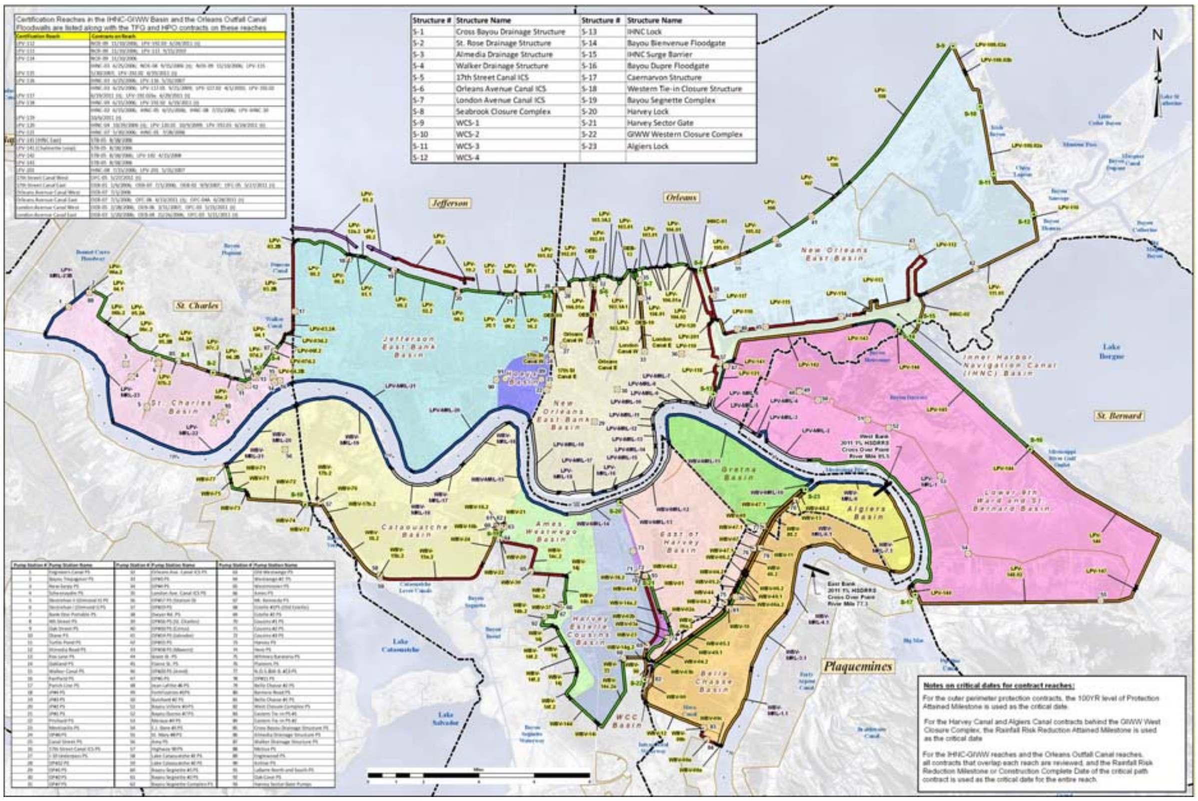

Figure I.2. The Hurricane and Storm Damage Risk Reduction System and Polders[13]

USACE

[12] See Construction headings of Chapter 3, Title II of the Emergency Supplemental Appropriations Act for Defense, the Global War on Terror, and Hurricane Recovery of 2006, and Chapter 3, Title III of the Supplemental Appropriations Act of 2008, (Public Laws 109-234 and 110-252, or the 4th and 6th Construction Supplementals); the Energy and Water Development Appropriation Act of 2006 and the Department of Defense Appropriations Act of 2006 (Public Laws 109-103 and 109-148).

[13] SLFPA-E encompasses three polders: New Orleans East, 9th Ward-St. Bernard, and East Jefferson-New Orleans Metro. Portions of St. Charles Parish between the Bonnet Carré Spillway and East Jefferson are currently part of the latter polder. With the addition of two closure structures—the Inner Harbor Navigation Canal (IHNC) structure east of Paris Road and the Seabrook structure at Lake Pontchartrain, the three polders are essentially subsumed within one large polder for primary surge protection purposes. The three polders continue to function somewhat independently for internal drainage and secondary surge protection purposes, although they all discharge to, and are exposed to, the IHNC/GIWW sub-basin. Additional drainage sub-basins exist within each polder.

To achieve the HSDRRS objective the USACE worked with FEMA to also revise the Southeast Louisiana Flood Insurance Study (FIS) which provides estimates of regional surge hazard for NFIP purposes.

Numerous federal, state, and local agencies, as well as community and business leaders (e.g., the Flood Protection Alliance), and professional organizations have urged that an HSDRRS based primarily on the NFIP and managing property damage risks is not sufficient. Problematic evacuation and loss of life; the critical regional/national role of the local port, oil and gas production, refining, chemical manufacturing, fisheries, tourism, and other infrastructure and economic activity; a large renter population; as well as the presence of unique historic/cultural assets are cited as good reasons for a 500- or 1,000-yr level of surge hazard protection. [14]

In addition to the 100-yr HSDRRS, Congress therefore authorized the USACE to undertake a comprehensive Louisiana Coastal Protection and Restoration Study (LaCPR Study) of HSDRRS enhancements and other long-term surge risk management measures. The LaCPR Study, completed in 2009, included three alternatives for improving the east-bank HSDRRS:

- Upgrade the HSDRRS to a 400-yr level, considered by the Study to be equivalent to a repeat of a Hurricane Katrina, with allowances for alternate tracks;
- Install barriers at the mouth of Lake Pontchartrain to achieve the 400-yr level; and
- Install barriers at the mouth of Lake Pontchartrain to achieve 1,000-yr level, considered equivalent to the surge risk for a strong Category 5[15] hurricane;

The LaCPR Study also included alternatives for building controls and coastal lines of defense. These alternatives were evaluated on the basis of number of residents affected (but without regard to an estimate of non-evacuees), mitigation of property and infrastructure damage, reduced economic impairment, and lessened impacts to historic/cultural assets. The alternatives were also assessed for cost, schedule, and environmental benefits (in the case of coastal restoration projects) and damages (in the case of new structures). The evaluation process eliminated an upgraded HSDRRS as cost inefficient.

The USACE produced a final array of five plans for the New Orleans area—plus one with a variation covering Plaquemines Parish. The five plans included one with coastal restoration measures only; three with coastal restoration and alternate polder building control plans (targeted at the 1, 0.25, and 0.1 percent risk levels); and one with coastal restoration and the Lake Pontchartrain barrier. Congress has not funded, and there is no current schedule, for further USACE investigation, evaluation, or detailed development of these five or other plans.

The CPRA, through development of *Louisiana's Comprehensive Master Plan for a Sustainable Coast, 2012*, has continued to evaluate HSDRRS enhancements—e.g., a "High Level" plan and possible Lake Pontchartrain Barrier Project—together with coastal "lines of defense," such as the New Orleans East Land Bridge, the Bayou LaLoutre Land Bridge, and the Biloxi Marsh. The 2012 Master Plan also calls for evaluating multiple Mississippi River diversion sites in Plaquemines Parish, which could also address. removal of long stretches of Mississippi River levees, potentially reducing surge hazards in the New Orleans area.

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[14] See the post-Katrina studies noted above; *Flood Protection and Coastal Restoration, Transition New Orleans Task Force*, Presented to Mayor-elect Mitch Landrieu, City of New Orleans, April 2010; the Louisiana Section of the American Society of Civil Engineers *2012 Report Card for Louisiana's Infrastructure*; and www.levees.org

[15] See Section 1 for a discussion of hurricane categories.

I.5. The 2005-2009 Hurricane Surge Hazard Analysis

Sophisticated hurricane surge hazard analyses have been undertaken as part of coastal FISs for several decades and consist of three tasks:

1. Characterizing regional hurricane climatology. A thorough scientific review of hurricanes approaching landfall in the region of interest is the basis for a probabilistic analysis of various characteristics influencing surge. In turn, these are used to examine the joint probability conditions of regional hurricanes and to produce a large representative set of synthetic hurricanes which can be used in the hazard analysis.
2. Developing hydrodynamic models. The modelers must capture the relevant scope and scale of hurricane surge still water and wave physics, including complex interactions with coastal features, as well as validate the models to demonstrate their capability to simulate the conditions produced by historic hurricanes and conditions of interest.
3. Analyzing hurricane surge hazard. The hurricane joint probability information is combined with the surge model to estimate the various return period exterior surge still water and waves (e.g., 50-, 100-, 500-, 1,000-yr, etc.) throughout the region.

Each task includes documentation of methodologies, presentation of results, and evaluation of results and uncertainties.

The NFIP FIS, IPET Study, HSDRRS design, and LaCPR Study all relied on a surge hazard analysis undertaken by the USACE between 2005 and 2009. Tasks 1, 2, and 3 were performed by a joint USACE-FEMA surge team.[16] The USACE performed a fourth task to provide input to the HSDRRS planning and design and IPET Risk and Reliability Report:

4. Evaluating the surge hazards for polders. The USACE analyzed 100-yr overtopping conditions at HSDRRS reaches to establish design requirements. The 100-yr design objective does not eliminate overtopping but requires that it be reduced to rates consistent with preventing erosion and impacting interior rainfall-only hazards. The HSDRRS design also has a resiliency requirement to provide for withstanding 500-yr overtopping. The USACE has also undertaken preliminary assessments of polder inundation hazards and risks as part of a 2009 IPET residual risk assessment and ongoing resiliency design.[17]

The USACE added a fifth task to support the LaCPR Study:

5. Assessing surge hazards for future conditions, including the influence of alternative future hurricane climatology, sea level rise, polder systems, regional subsidence, and coastal landscape scenarios on the 100-yr, 400-yr, and 1,000-yr surge hazards.[18]

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[16] Led by Donald T. Resio of the USACE Engineer Research and Development Center and Joannes J. Westerink of the University of Notre Dame; documented in the FEMA/USACE, *Flood Insurance Study, Southeast Parishes of Louisiana, Intermediate Submission 2: Offshore Water Levels and Waves*, July 2008.

[17] The design elevation effort led by Nancy Powell of the USACE New Orleans District with support from Royal Haskoning; documented in USACE New Orleans District, *Hurricane and Storm Damage Risk Reduction System, Design Elevation Report*, Draft Report Version 4.0, August 18, 2010. The evaluation of polder hazard led by Jerry Foster, USACE Headquarters; documented in IPET Volume VIII, 2009. Resiliency design is still in progress.

[18] Led by Donald T. Resio and Joannes J. Westerink. Task 5 is documented in USACE, *Louisiana Coastal Protection and Restoration, Final Technical Report*, June 2009.

In preparing the 2012 Master Plan, the Louisiana CPRA has also made extensive use of the 2005-09 surge hazard analysis.

It is important to note that the NFIP and its concentration on the 100-yr property risks can impose programmatic, resource, cost, and schedule constraints on flood hazard analysis. However, the multiple post-Katrina programs, spurred the USACE to employ considerable professional, academic, and other technical resources in conducting the 2005-09 effort. As a result, the USACE demonstrably enhanced the state of scientific knowledge and the state of practice for surge hazard analysis.

As part of this effort the USACE engaged a senior review team to suggest improvements.[19] The National Academy of Engineers' report also included comments on the USACE analysis. The USACE adopted suggestions of the peer review team which were deemed consistent with program requirements.

I.6. Uncertainty in Surge Hazard Estimates

As noted above, rational surge risk management must not only be mindful of the probability for surge events and consequences, but must also allow for uncertainty in estimating these probabilities and consequences. Compared to rainfall/riverine flood hazard estimates, surge hazard estimates are based on shorter historical records and generally involve more variables—with more complex interactions and subject to significant unknowns. Uncertainties can involve the precision of observations, measurements, and models (epistemic) and the sampling of natural variability (aleatory).

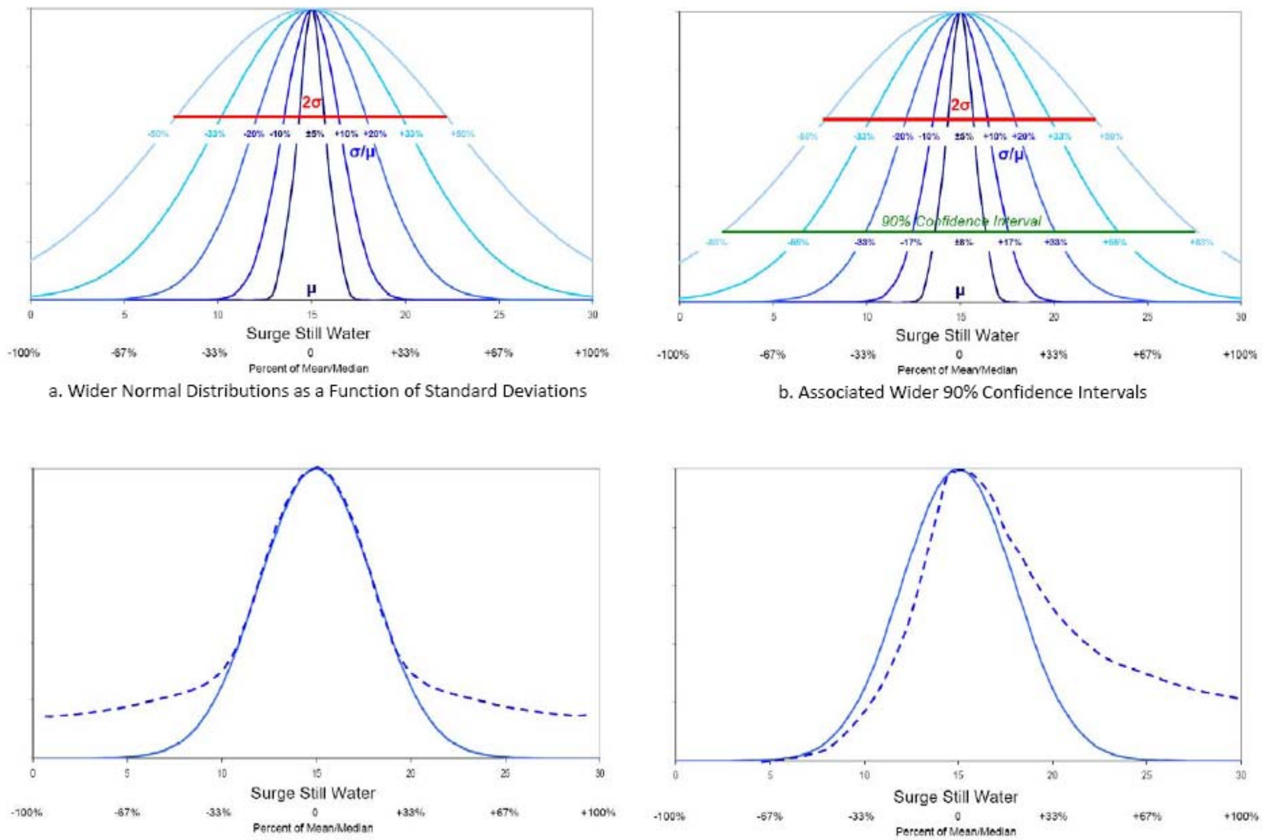
The NFIP does not require that local 100-yr flood hazards be defined with allowances for uncertainty. In part this is because risks associated with uncertainty to the NFIP can be managed actuarially across the entire national program. However, locally focused risk management does require accounting for the risk associated with uncertainty in hazard estimates. Given the multiple purposes of the 2005-09 surge hazard analysis, the USACE incorporated some analysis of uncertainty, including allowances for uncertainty in the HSDRRS design

For simplicity, epistemic uncertainty in a surge hazard estimate has been described with a normal distribution. Figure I.3.a presents a series of normal distribution curves around a median surge estimate of 15 ft. The series of curves illustrates that for higher relative standard deviations (i.e., the standard deviation as a percent of the median estimate) the distribution becomes wider. Figure 1.3.b. shows that for these curves, the 90% confidence interval also becomes much wider. The large uncertainty in surge hazard variables leads to wide uncertainty intervals in surge hazard estimates. The standard deviation for epistemic uncertainty alone for a 15 ft 100-yr surge estimate can be above 2.6 ft (21%), yielding a 90% confidence interval greater than 4.3 ft (34%).

Treating uncertainties as normally distributed may be supportable for certain purposes. However, over reliance on the assumption of a normal distribution can be misleading. Figure 1.3.c illustrates that a symmetrical distribution does not have to be normal, and can in fact have much "fatter tails," implying much higher probabilities for extreme events. Furthermore, critical uncertainties related to return frequency are not symmetrical. Figure 1.3.d compares a normal versus a skewed distribution. (See General Technical Note 1 for a further discussion of uncertainty.)

While there is extensive research on methods for quantifying uncertainties there have been no studies to guide the selection of appropriate confidence intervals for surge risk management.

[19] The review was led by led by Joseph N. Suhayda, Ph. D and is documented in USACE/FEMA, *Southeast Louisiana Joint Surge Study, Independent Technical Review, Final Report*, October 15, 2007.



a. Wider Normal Distributions as a Function of Standard Deviations

b. Associated Wider 90% Confidence Intervals

c. Symmetric Non-Normal Distribution with "Fat Tails"

d. Asymmetric Non-Normal Distribution

Figure I.3. Normal and Non-Normal Distributions

I.7. This Report

*The SLFPA-E has a broad hurricane surge risk management missio*n. Unlike the NFIP, the SLFPA-E surge risk management decisions are not limited to property protection and controlled by the 100-yr hazard, but encompass concern for the full range of surge consequences and probabilties.

SLFPA-E's primary focus is on perimeter protection, including working with CPRA and USACE to:

1. Ensure that the HSDRRS design is capable of meeting the 100-yr overtopping criteria through planning, design, and construction review, as well as maintaining and operating the HSDRRS.
2. Ensure that the HSDRRS design is capable of meeting 500-yr HSDRRS resiliency through planning, design, and construction review, as well as maintaining and operating the HSDRRS.
3. Identify projects to further enhance HSDRRS risk reduction performance.

However, the SLFPA-E's mission also encompasses working with an array of federal, state, and local agencies and partners to plan and implement key actions on the other five public surge risk management tools. *Given its broad mission, a state-of-the-practice analysis of surge hazards and uncertainties is critical to the mission of the SLFPA-E.*

Since the USACE 2005-09 effort, approaches to the various tasks in hurricane surge hazard analysis have continued to evolve rapidly. Advances have been especially spurred on by research for hurricane surge forecasting and by coastal FISs for Mississippi, Texas, North Carolina, South Carolina, Georgia/Northeast Florida, and Florida-Big Bend, West Coast Florida and Northwest Florida/Alabama. These advances have improved the estimation of surge hazards and the treatment of uncertainties, and have important ramifications for southeast Louisiana surge risk management.

Bob Jacobsen PE, LLC has prepared this Report, entitled *Hurricane Surge Hazard Analysis: the State of the Practice and Recent Applications for Southeast Louisiana*, in accordance with a Task Order from the SLFPA-E. The objective of this Report is to provide a comprehensive explanation of the evolving technical approach to hurricane surge hazard analysis and an evaluation of the USACE 2005-09 effort in the context of this evolution, including those steps critical to the USACE's HSDRRS design.

To accomplish this objective, this Report is organized into five parts, corresponding to the five surge hazard analysis tasks:

Part I. Hurricane Climatology
Part II. Modeling of Hurricane Surge Physics
Part III. Hurricane Surge Hazard Analysis
Part IV. Hurricane Surge Hazard Analysis for Polders
Part V. Hurricane Surge Hazard Analysis for Future Conditions

Each part provides a detailed discussion of the current state of the practice for the respective tasks—including the approaches, assumptions, and limitations. As Tasks 1 and 2 are the basis for the entire surge hazard analysis, Parts I and II include an extensive background for these subjects. Background information is taken not only from the USACE's southeast Louisiana hazard study but from other recent wind and surge hurricane hazard studies, the relevant scientific and technical literature, and several significant new analyses of these subjects conducted for this Report.

Each part examines the USACE's application of the respective task to southeast Louisiana, as well as other recent applications, including the State of Louisiana's 2012 Comprehensive Master Plan for a Sustainable Coast. Key comments from the USACE senior technical review are incorporated into the discussion. Each part is concluded with a list of essential findings and recommendations.

The recommendations include revising the 2005-09 surge hazard analysis to a) remedy significant biases resulting from outdated methods and b) better describe uncertainties. In addition, the recommendations note important research opportunities to significantly advance the current state of the practice. The final section of this Report's Executive Summary also addresses implications of these revisions for the HSDRRS design and other surge risk management actions.