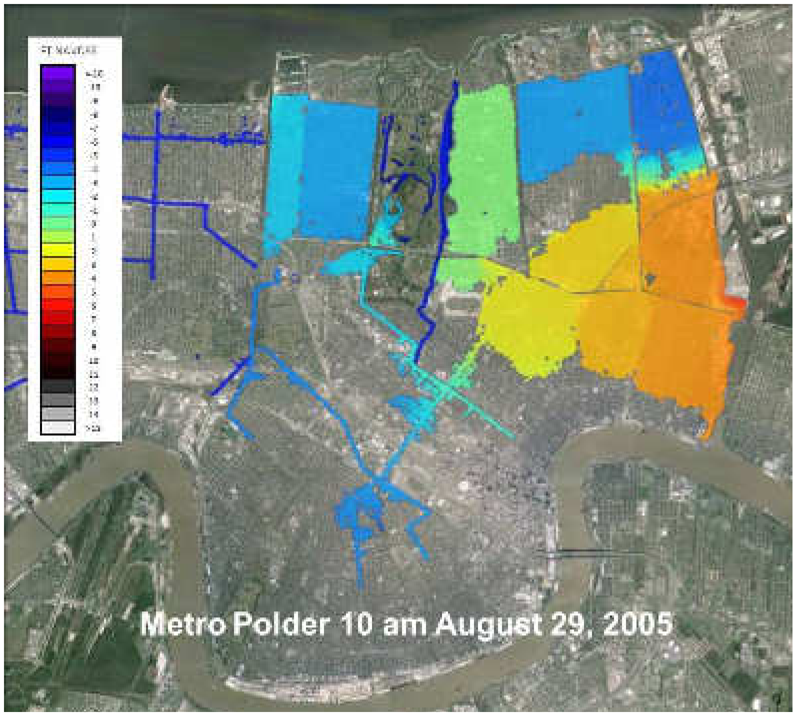
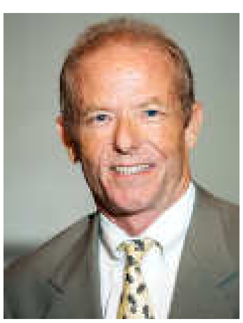
Managing Hurricane Surge Risks in the Supercomputing Era, Part II

Bob Jacobsen PE



Some of the information presented in this article resulted from recent work sponsored by the Southeast Louisiana Flood Protection Authority-East and the Louisiana Coastal Protection and Restoration Authority. However, this article does not represent the opinion of either agency, or of the Louisiana Section of the American Society of Civil Engineers.

This article is dedicated to the 1,400 Louisianans who lost their lives during Hurricane Katrina ten years ago.



Bob. Jacobsen grew up in Metairie and earned undergraduate and graduate degrees at LSU, including an MS in Civil (Environmental) Engineering. His 35-year career has focused on state-of-the-art environmental and water resource planning studies and conceptual designs for South Louisiana. Since 2001 he has been at the forefront of applying HPC/high-resolution hydrodynamic modeling for coastal restoration and hurricane storm surge protection. Bob served as the 2013-14 President of the American Society of Civil Engineers Louisiana Section.

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> Part I reviewed the pre-Katrina evolution, which is worth knowing in order to truly understand past mistakes which led to the City's devastation and issues which continue to threaten its future.

Part II: Post-Katrina Progress and Limitations in Surge Hazard Estimation and Implications for Surge Risk Management

A. Hurricane Katrina.

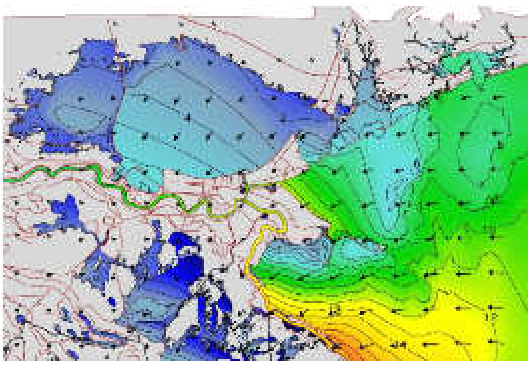
On August 29, 2005 Category 3 Hurricane Katrina passed just east of New Orleans. Figure 1 depicts the evolution of Katrina's surge and how Katrina's strong, broad core—with counterclockwise rotating eye-wall winds above 120 mph—created a massive westward-driven setup against major East-Bank topographic features, such as the Mississippi River and the metropolitan New Orleans SPH surge protection system.

The westward pile-up of water was critical at a large regional "Funnel" formed by levees along the Gulf Intracoastal Waterway (GIWW) and the Mississippi River Gulf Outlet (MRGO) east of where the channels converge. The merged interior GIWW channel (west of the junction)—flanked to the north and south by levees—conveyed surge to the Inner Harbor Navigation Canal (IHNC), into the heart of the City and its three polders (areas substantially below sea-level enclosed by levees): the Metro Polder west of the IHNC; the NO East Polder east of the IHNC and north of the GIWW; and the St. Bernard Polder east of the IHNC and south of the GIWW, (which also includes the New Orleans Lower 9th Ward on its western end). Katrina's surge could not exit the IHNC at the northern outlet to Lake Pontchartrain as quickly as it entered via the GIWW, (the Lock connecting to the Mississippi River at the southern end was closed) and levels in the IHNC rose rapidly.

Katrina's surge peak of 19.5 ft NAVD88 (19.2 ft above mean local level) along the MRGO (near Bayou Dupre) exceeded the Standard Project Hurricane (SPH) design surge of 12.1 ft above mean level by over 7 ft! Peak surge reached 18 ft NAVD88 further west in the Funnel (near Bayou Bienvenue), 15 ft NAVD88 in the GIWW (near the Paris Road Bridge just west of the junction), and 14 ft NAVD88 at the south end of the IHNC, all exceeding local protection system crowns. The surge peaks throughout the Funnel area would have been even higher had overtopping and breaches not occurred along the MRGO, GIWW, and IHNC.

Figure 1 also illustrates Katrina's "tilting" of Lake Pontchartrain—driving surge first to the southwest, then shifting to the south, and finally to the east. Southward-driven surge heights along the New Orleans Lakefront reached 11.8 ft NAVD88, raising levels in three outfall canals for the City's main interior drainage pump stations. The New Orleans Lakefront peak was 11.3 ft above Local Mean Level (LML), exceeding the SPH surge by nearly a foot. Later, eastward-driven surge—together with wave heights likely exceeding 10 ft—lifted decks on the Interstate "Twin Span" bridge from their piers.

Hurricane Katrina proved—as the previous decade of extreme surge scenarios had anticipated—that the 1960s-era SPH surge estimates and surge hazards were woefully outdated. Not only was the SPH itself obviously inadequate—dating to the late 1970s (see Sidebar on Hurricane Katrina)—but by 2005 surge scientists understood that additional hydrodynamic and landscape factors need to be incorporated in estimating surge hazards.



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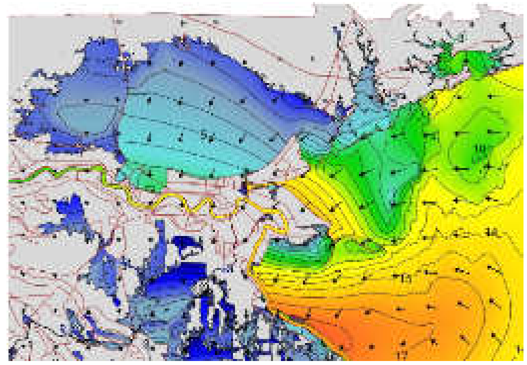

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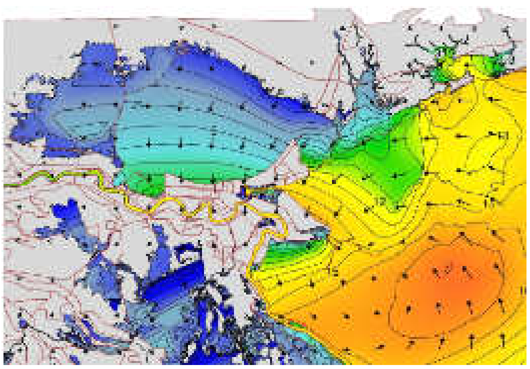

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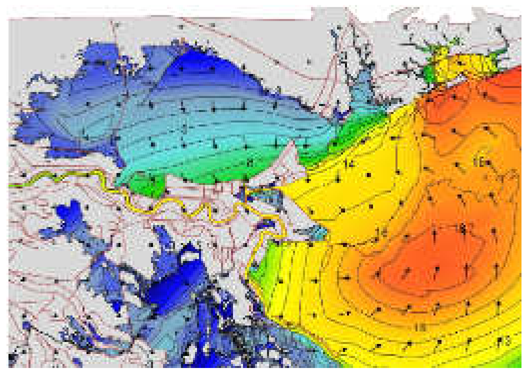

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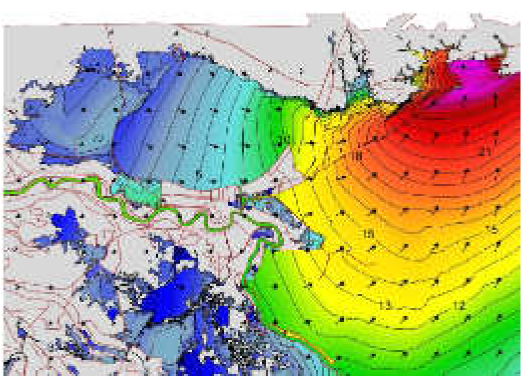

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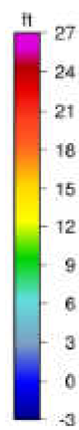


Surge Elevation (NAVD88)

Figure 1. Hurricane Katrina Surge
USACE 2008

Overtopping and breaching of the unfinished East-Bank SPH surge system caused catastrophic flooding in the three polders. Four major post-Katrina forensic investigations (ILIT 2006, Team Louisiana 2006, IPET 2006, and ASCE 2007) provided extensive documentation, including the role of engineering concessions on floodwall support conditions, levee materials, and elevation control. Altogether, the East-Bank polders experienced 16 major inflows, listed in Table 1 by polder.

Bob Jacobsen PE (2015) developed flow hydrographs and cumulative volume estimates for the 16 locations based on exterior surge, overtopping, and breach descriptions, together with detailed models of all three polders simulating the 16 inflows. (The simulated inflows and cumulative volumes were developed as part of a 2015 report for the Southeast Louisiana Flood Protection Authority-East, SLFPA-E, on interior topographic features and their effect on residual risk.) Table 1 includes the cumulative volume estimates and the percentage each location contributed to the total polder flooding. Figure 2 illustrates the peak inundation for the three polders. (Hourly snapshots from the simulations are presented in an appendix to the 2015 report.) The cumulative volume estimates and simulation results compare well with polder inundation information in the forensic reports.

Ten segments—all in the Funnel-IHNC area—experienced significant overtopping, causing major *erosion breaches* along six of the segments. Two major contributing factors to overtopping induced breaches were: a) actual crown elevations at all ten segments were below design elevations—due to a combination of outdated vertical control and post-construction settlement and subsidence—and; b) the use of hydraulic fill material along the MRGO. Overtopping along the MRGO began well before Katrina's peak surge. Overtopping and erosion breaches caused over 98 percent of the flooding in both the NO East and St. Bernard polders. (Some flood-side levee erosion from waves prior to overtopping may have also occurred along the MRGO levees.)

<u>Hurricane Katrina as a Meteorological Event</u>

On Sunday August 28, 2005 Hurricane Katrina intensified in the Gulf of Mexico to a Category 5 storm as it passed over the Loop Current, becoming the seventh strongest Atlantic hurricane on record—with a central pressure (C_P) of 902 millibars (mb) and maximum sustained wind (V_{MAX}) of175 mph. The radii of maximum winds, hurricane force winds, and tropical storm force winds (R_{MAX}, R_H, and R_{TS}) were large—at 21, 105, and 227 miles, respectively (compared to 12, 52, and 202 miles for Category 5 Hurricane Rita later that same year).

At its peak Katrina's intensity was extreme but not unprecedented, given that ten hurricanes have reached Category 5 in the Gulf of Mexico since 1851 (or an average return period of less than 20 years). Hurricane Katrina's large size at Category 5 intensity made it rarer, but its peak integrated kinetic energy (IKE) at over 120 terajoules was only the second highest of storms analyzed since 1989.

During landfall Katrina's core decayed to top winds of 126 mph (a strong Category 3), while C_P remained very low, at 920 mb. The wind-field spread out, with R_{MAX}, R_H, and R_{TS} growing to 40, 135, and 282 miles. The storm's forward speed (V_F) was a rapid 15 mph.

A landfalling Category 3 or higher hurricane is **<u>not</u>** a rare event for Southeast Louisiana, with a recently suggested return period of less than 20 years (Bob Jacobsen 2012). A *strong* Category 3 landfall has a much longer return period, on the order of 50 years. Major hurricanes with larger cores are rarer, so the Southeast Louisiana landfall return period for a "Katrina near-eye wind-field" is longer, but less than 100 years. As a comparison, devastating Category 4 hurricanes made landfall in Southeast Louisiana in 1893, 1915, and 1965; the latter, Betsy, with peak winds approaching 150 mph and a R_{MAX} of about 80 miles. *Thus, as a <u>local</u> wind-field event for Southeast Louisiana—dominated by the storm's near-eye wind-field—Hurricane Katrina does not appear to be that unusual.*

A much more extreme landfall return period of nearly 400 years has been suggested by Resio et al (2007), but is based on the return frequency for the landfall C_P of 920 mb, indicative of a borderline Category 4/5 storm, instead of the V_{MAX}, together with the 40-mile R_{MAX}. Katrina's full landfall wind-field—with extended R_H and R_{TS} causing significant surge impacts as far away as northwest Florida—does justify a longer return period estimate for a Central-Northern Gulf event. However, Southeast Louisiana surge conditions were a result of Katrina's near-eye wind-field. Interestingly, Hurricane Rita produced a greater volume of surge in Lake Pontchartrain than Katrina.

Portions of I-wall structures in five segments suffered major *collapse breaches*—failures which occurred prior to surge levels reaching wall crowns. In one I-wall failure—IHNC East, South of Florida Ave—the collapse occurred hours before, and several feet below, the peak surge, evidencing a serious geotechnical design flaw. The other four I-wall collapses occurred later, with water levels approaching but generally below the SPH surge. Three collapse breaches were in the Metro Polder Lakefront outfall canals, producing nearly two-thirds of the polder's flood water.

The forensic investigations determined that faulty assumptions and under-design contributed to all five collapse breaches. Technical "know how" was ample at the time of floodwall design and collapses with water levels below SPH surge were clearly preventable. (Three senior geotechnical engineers from Louisiana made significant contributions to the forensic investigations: Gordon P. Boutwell PhD, PE; Louis J. Capozzoli PhD, PE; and Billy R. Prochaska PE.)

In addition to under-design, the breaches can be attributed to the absence of a Factors of Safety (FOS) to address SPH surge uncertainty. The US Army Corps of Engineers (USACE) had authorization to determine design FOSs. The USACE likely lacked authorization to provide resiliency—i.e., strengthening measures enabling resistance to breaching during overtopping.

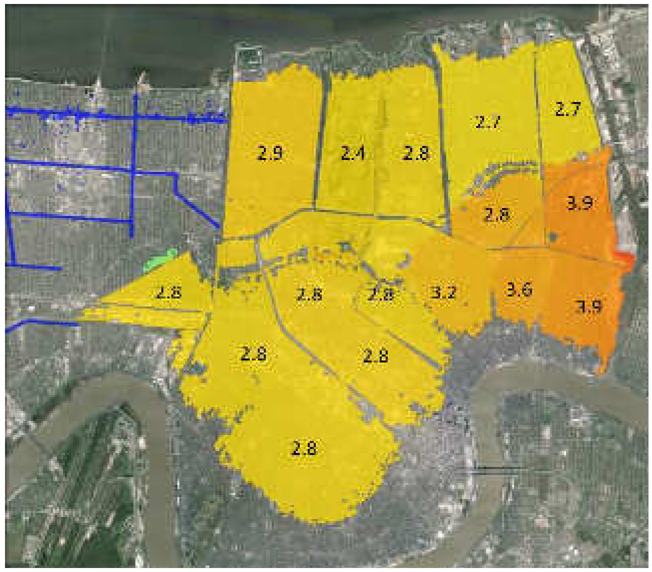
For the second time in 40 years New Orleans surge risk management proved to be painfully inadequate. Decades of compromise to the implementation and maintenance of the post-Betsy SPH-surge protection—driven in no small part by competing priorities—had aggravated polder vulnerability to a tragic extent that only a few appreciated. Disaster response and recovery agencies at all levels were ill prepared for the consequences of allowing for such residual risk; (see Sidebar on Katrina Consequences). Evacuation was credited with having reduced the loss of life—which would have likely been many times worse had officials not had the improved ContraFlow and other plans in place. However, the post-storm death toll and calamity of thousands stranded in the flooded City showed that evacuation plans were grossly inadequate (Wolshon 2006 and Campanella 2012).

City housing and associate economic recovery was hampered by the limited scope of the National Flood Insurance Program (NFIP, which ironically had stimulated higher project priorities under a separate USACE Southeast Louisiana, SELA, Drainage Program): 1) many owners of homes not under a mortgage—a large portion of the City's housing stock—had chosen not to purchase flood insurance, despite inexpensive NFIP premiums; 2) many home mortgagors not in polder 100-yr hazard zones (reduced by the SELA projects) had also chosen not to purchase flood insurance; and 3) home and commercial property owners who did have flood insurance were often under-insured.

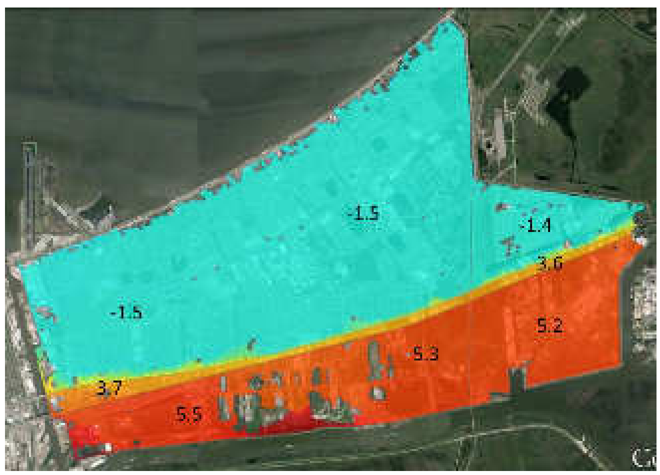
Hurricane Katrina Consequences

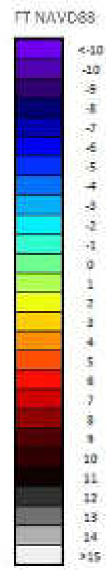
Hurricane Katrina flooding of the East-Bank constituted one of the worst natural catastrophes in the history of the United States. Over 1,400 Southeast Louisiana residents died directly or indirectly as a result of Hurricane Katrina; (see Boyd 2011 and Jonkman et al 2006.) 518 deaths occurred in residences, nursing homes, and other buildings directly as a result of exposure to flood waters or the collapse of the building they were in. As many as another 150 died in local facilities and shelters due to interference with critical healthcare (e.g., inability to obtain insulin, dialysis, etc.). Other impacts in the initial years following Hurricane Katrina (documented by The Greater New Orleans Community Data Center, Insurance Information Institute, U.S. Census Bureau, and FEMA) included:

- Orleans Parish population declined from about 455,000 to less than 200,000.
- St. Bernard Parish population declined from about 65,000 to 11,000.
- Severe declines in regional payrolls and consumer spending. Sales tax revenues fell by about 25 percent.
- Damage to over 70 percent of the metropolitan area's housing.
- $25 billion in Louisiana private insurance claims.
- $13 billion in Louisiana NFIP payments.
- Nearly $7 billion in FEMA assistance to agencies and institutions for clean-up, repair, and replacement of New Orleans infrastructure and public facilities, including roads, bridges, water systems, sewer systems, drainage systems, .
- Additional billions of dollars in federal aid to the State of Louisiana for recovery and repair projects, such as the replacement of the I-10 Twin Span Bridge.
- Tens of billions of dollars in self-insured losses by large corporations, including: electrical, gas, communication utility companies; private port facilities; railroads; petroleum and natural gas production and refining industry; and petrochemical industry.
- Total regional cumulative economic losses probably approaching $100 billion.



Metro Orleans and Jefferson Parishes





NO East

St. Bernard

Figure 2. Hurricane Katrina Peak Polder Inundation from Overtopping and Breach Simulations

Bob Jacobsen PE 2015

Table 1. 16 Major Polder Inflows During Hurricane Katrina

Polder/Location	Type	Cumulative Volume	
		Acre-Ft	Percent
Metro Polder (Orleans Parish and Old Metairie—27,268 acres)			
17th St Outfall Canal I-wall	Collapse Breach	32,399	34.1
Orleans Ave Outfall Canal I-wall	Opening	89	0.1
London Ave Outfall Canal I-wall, North	Collapse Breach	23,555	24.8
London Ave Outfall Canal I-wall, South	Collapse Breach	6,484	6.8
IHNC West, North of Florida Ave	Overtopping & Breaches	25,022	26.3
IHNC West, South of Florida Ave	Overtopping	7,524	7.9
		95,072	***100***
NO East Polder (Inside Maxent Levee—14,792 acres)			
IHNC East I-wall	Collapse Breach	757	1.4
IHNC East	Overtopping	12,494	23.3
Citrus Back Levee (IHNC to Paris Rd)	Overtopping	33,289	62.1
Citrus Back Levee (East of Paris Rd)	Overtopping & Breaches	7,037	13.1
		53,578	***100***
St. Bernard Polder (Inside 40 Arpent Levee—20,015 acres)			
IHNC East I-wall, South of Florida Ave	Collapse Breach	2,166	1.4
IHNC East I-wall, North of Claiborne Ave	Overtopping & Breach	13,107	8.5
IHNC East Floodwall	Overtopping	3,400	2.2
MRGO and 40 Arpent Levees (IHNC to Paris Rd)	Overtopping & MRGO Levee Breaches	32,260	20.8
MRGO and 40 Arpent Levees (Paris Rd to Violet Canal)		43,276	27.9
MRGO and 40 Arpent Levees (Violet Canal to Reggio)		60,677	39.2
		154,885	**100**

B. Twenty-Five Advances in Hurricane Surge Science

Demands for better estimates of surge hazard followed in the wake of Hurricane Katrina (and Hurricane Rita later that same year). Over the next several years concern for extreme surge hazard expanded throughout the Gulf and Atlantic Coasts—spurred on by subsequent storms (e.g., Gustav and Ike in 2008 and Sandy in 2012) and warnings about accelerating climate change, rising ocean temperatures, sea-level rise, and coastal erosion. In addition, coastal residents and their leaders sought better surge forecasts to improve evacuation and other emergency preparations and responses. (The scientists at the LSU Hurricane Center had actually provided remarkable experimental supercomputer-based surge forecasts for Katrina using the Advanced Circulation Model, ADCIRC.) As a result, in the decade since Hurricane Katrina the federal government has invested hundreds of millions of dollars in better spatially and temporally resolved data and depictions of hurricane winds and coastal surge. These depictions rely heavily on High Performance Computing (HPC) processing. The investment has substantially advanced hurricane climatology and surge physics, together with the State of the Practice (SOP) for two-dimensional (2D) surge modeling, surge joint probability analysis (JPA), and “what-if” scenarios.

i. Hurricane Climatology

Since 2005 meteorologists and climatologists have painted an increasingly more detailed picture of hurricane attributes, atmospheric physics, and trends (Bob Jacobsen PE 2012, 2013). Six key advances have included the following:

1. Improved wind data collection and analysis, and understanding of extended wind-field characteristics. Investigators have examined wind-field energy indicators (such as storm IKE), asymmetries in Holland B, and structures such as secondary eyewalls and banding. Researchers have made closer studies of the effects of the extended wind-field characteristics on surge (e.g., 2008’s massive surge that resulted from very large, Category 2 Hurricane Ike). A critical finding—reinforced by 2012 Hurricane Isaac in Southeast Louisiana—is that large, slow-moving, low intensity hurricanes can create extreme surges along very shallow coastal regions.
2. Further knowledge of hurricane genesis, intensification, and decay. Meteorologists better understand the role of deep ocean heat energy associated with the Gulf of Mexico’s Loop Current and regional atmospheric conditions.
3. Global climate cycles and trends. Climatologists have shed more light on several cycles (such as the 30-90 day Madden-Julian Oscillation, the inter-annual El Niño-Southern Oscillation, and the Atlantic Multi-decadal Oscillation) affecting hurricane frequency over various time scales and continued their research on potential long-term trends associated with global warming.
4. Historical record refinement. Researchers have continued to upgrade hurricane information dating to the mid-1800s by combing through various sources of pressure, wind, surge, and other data.
5. Paleo-climatology. Geologists have studied indications of very extreme surge return frequency in the coastal Holocene stratigraphy (Wallace et al 2010).
6. Enhancements in quantifying regional probabilities for storm central pressure, maximum wind speed, radius of maximum winds, P_C/V_{MAX}, R_{MAX}, V_F, track (θ), and Holland B.

These advances have supported development of better:

- Empirical storm sets for wind hazard analysis; (see Vickery et al 2009 and Emanuel et al 2010).
- Hurricane joint probability method (JPM) approaches employed in more than a dozen post-Katrina Flood Insurance Study (FIS) surge hazard analyses extending from Texas to New York.

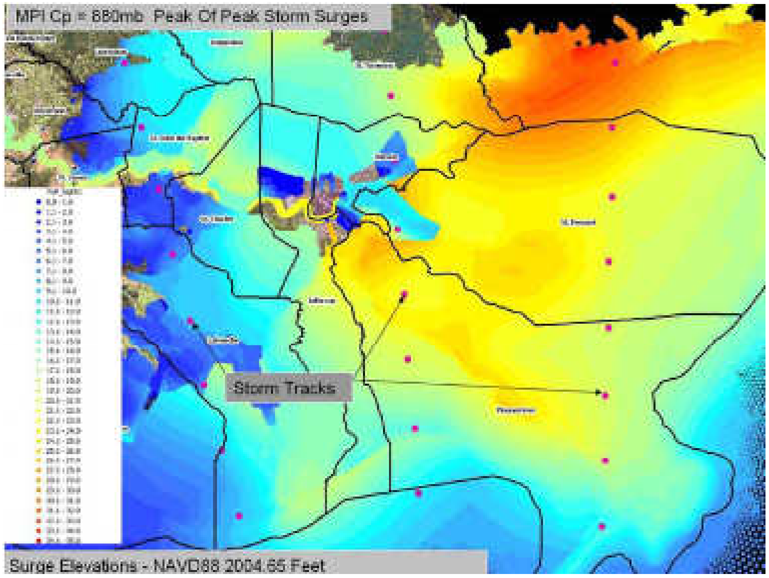


Figure 3. Maximum Probable Intensity MOM for Southeast Louisiana
USACE 2009

- Surge maximum-of-maximums (MOMs) for Category 1 through 5 hurricanes (National Oceanic and Atmospheric Administration, NOAA).
- Maximum Probable/Possible Hurricanes. The physical extreme of a North-Central Gulf of Mexico hurricane heading for Southeast Louisiana was revised to include a P_C of 880 mb (a ΔP of over 130 mb) and an R_{MAX} of 25 nautical miles. Figure 3 depicts a surge MOM for this hurricane.

Future work in these topics should improve estimates of extreme hurricane characteristics and return frequency. However, these estimates will retain considerable uncertainty for many decades to come.

ii. Surge Physics

Since Katrina, surge investigators have improved understanding and representation of surge physics. Fundamental 2D (and even 3D) hydrodynamic equations (referred to as the Shallow Water Equations)—encompassing the full range of physical actions have long been well established (gravity, tides, Coriolis, atmospheric pressure, wind-water drag, canopy and wind sheltering effects, hydrodynamic frictional drag, wave radiation stress, baroclinic stress, and turbulence). Three major advances in surge physics have been:

1. Greater spatial and temporal refinements of the physics. HPC has enabled studying surge physical interaction at more detailed local scales.
2. High resolution nodal attribute data. Topography/bathymetry (topo/bathy), land-cover data, and spatially variable empirical coefficients have allowed evaluation and improvement of formulations for wind-water and hydrodynamic drag, and approaches to canopy and wind-sheltering effects.
3. Nos. 1 and 2 in turn, have enabled scientists to study the details of surge hindcasts, and to develop a quantitative understanding of ***Surge Response***—what happens to surge, where, when, why, and how landscapes (Resio et al 2009 and Irish et al 2009). Location-specific explicit surge-response functions (Figure 4) are similar in concept to a stage-discharge function for a river. They provide peak surge as a function of hurricane attributes (P_C/V_{MAX}, R_{MAX}, V_F, track/θ, and Holland B) and local coastal features—facilitating a significant improvement over old "rules of thumb"—such as 2.75 miles of coastal wetland reduces surge by 1 ft. (See the Side-Bar, Ten Surge-Response Points.)

Ten Surge-Response Points

1. Extreme surge is foremost a product of wind-water drag—with wind setup proportional to fetch and wind speed squared, and inversely proportional to depth. Researchers have shown that surge is much higher for open coasts facing extended shallow continental shelves (unlike tsunamis).
2. Complex hurricane forerunners can also contribute to surge—such as those driven by long-shore currents along regional shelves which can create a significant perpendicular setup associated with Coriolis force (Kennedy et al 2011).
3. The passage of the hurricane wind-field over large, shallow interior bays and lakes can produce drastic localized "tilting," regardless of the "filling" from the prior forerunner or main surge. Slow moving weaker hurricanes are capable of producing extreme tilting of large, shallow, interior water bodies—as the wind set-up has time to "fully develop." (This occurred in 2012 at Braithwaite Louisiana on the East-Bank just south of St. Bernard Parish during Category 1 Hurricane Isaac, which experienced a worse surge than during Hurricane Katrina.)
4. Setup increases with the presence of topographic blocking features—without which surge will spread out.
5. Counteractions to inland surge created by the landscape—such as from topographic "speed bumps" (e.g., cheniers and road embankments) and hydrodynamic friction (e.g., vegetation) decline dramatically with drowning of features. Features that significantly reduce inundation from small-to-moderate surge can have much less effect on extreme surges.
6. The counteraction of hydrodynamic friction also depends on surge velocity. Thus, setup from slow moving storms may be relatively unaffected by coastal vegetation.
7. Similarly, while coastal (exterior) channels contribute significantly to the conveyance of tides and small-to-moderate surges, their relative impact also declines with regional landscape drowning during extreme surges. The exterior channels do increase interior salinity, causing serious degradation to the wetlands. Wetlands loss results in greater inundation for more frequent small-to-moderate surges, which, in turn further exacerbates wetlands loss.
8. The impact of coastal features during surge events is both storm- and time-specific—resulting in complex impacts on surge hazard. A coastal feature can reduce surge in one area while exacerbating it in another. Closing a coastal channel may aggravate surge for some locations under certain scenarios.
9. Additional setup is contributed by gradients in wave radiation stress associated with wave-breaking in high wave fields. While particularly important along open coasts, the additional wave contribution to set up also needs to be factored in for large interior water bodies such as Lakes Pontchartrain and Borgne.
10. For smooth, uniform open coasts Surge-Response can be a very smooth (almost linear) function of hurricane attributes (see Figure 12). However for complex coasts, with large shallow water bodies and range of topographic features, local response can be highly sensitive to slight changes in the storm's local winds, track, and forward speed—making for a more non-linear Surge-Response function.

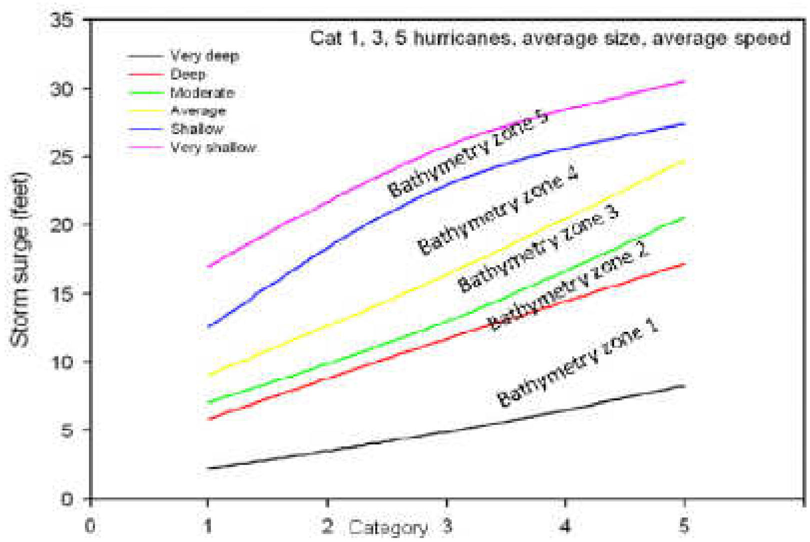


Figure 4. Example of a Surge-Response Function and Idealized Shelf Type

Fitzpatrick et al 2010

In the coming years scientists will continuing to investigate Surge-Response topics, especially the quantification of localized "tilting" during complex wind-wave conditions and hydrodynamic drag during overland inundation at even more refined scales. Teasing out the nuanced influences of terrain, channels, and various forms of vegetation during changing surge depth and velocity are also central to coastal protection and restoration interests.

iii. HPC/High-Resolution Modeling of Surge-Response

In the years before and after Katrina, continuing rapid microprocessor improvements allowed surge modelers to organize numerical methods (see Sidebar on Numerical Methods) to take advantage of increasingly available and affordable HPC clusters. Ongoing HPC gains have facilitated eight notable advances in surge modeling (Bob Jacobsen PE 2013).

1. Tighter spatial discretization. HPC now easily supports models with ***millions*** of spatial computation locations—represented as nodes in a 2D grid or mesh. Regional surge models can resolve critical features to scales of less than 100 ft, (with local models refining features to less than 30 ft).
2. Nodal attributes. With more highly resolved landscapes, model developers (e.g., ADCIRC, an open source code) can provide detailed spatial specification for topo/bathy, wind sheltering, canopy-induced wind reduction, and land-cover effects on hydrodynamic friction.
3. Boundary and initial conditions. Models can address seasonal variations in regional mean water levels, time varying river inflows, and levee overtopping.
4. Coupling with wave models. The importance of wave radiation stress gradients on surge heights and currents (and of surge depths and currents on wave heights and periods) led model developers to incorporate wave models (e.g., STWAVE and SWAN) directly into the surge hydrodynamic model code for seamless computation of both surge and wave conditions.
5. Wetting and drying. Algorithms to start and stop flow computations at an advancing or retreating inundation front have been improved, along with approaches to issues associated with wetting and drying accuracy and efficiency.
6. Longer pre-storm simulations. Surge investigators can "spin-up" their models with weeks of tide and local wind simulations.
7. Integration with better wind modeling. High-resolution surge modeling is able to employ a variety of hurricane wind-field inputs, both for historic and synthetic storms, which take into account recent advances in hurricane wind-field science.
8. Code developments. In addition to ADCIRC—which has been widely applied for over 10 years—in recent years additional parallelized 2/3D hydrodynamic codes have become available (FVCOM, ADH, MIKE21, and DELFT3D). Researchers have advanced the accuracy and efficiency of numerical methods, and the specific application of various HPC architectures. In turn, researchers have also learned how to better optimize spatial resolution in conjunction with these methods to achieve better accuracy and efficiency.

Numerical Methods

A set of algebraic equations is employed to approximate the complex, partial differential Shallow Water Equations. Computer codes are used to solve this set of algebraic equations, which are written separately for each node in the domain. Subdomains are created and then assigned, one each, to the hundreds of micro-processors in an HPC cluster. Over a simulated time-step—e.g., one second—the equations are solved in parallel for nodes within each subdomain by the HPC processors. Between time-steps output and inputs from each subdomain are transferred and incorporated as needed across subdomain boundaries. This process is then repeated until the entire simulation is completed.

Progress in HPC/High-Resolution surge modeling has led to improved accuracy (bias) and precision—as indicated by average errors and the standard deviation of errors in observed versus predicted high water marks in hindcasts. (See Dietrich et al 2011 which discusses modeling of Hurricanes Katrina, Rita, Gustav, and Ike with an ADCIRC+SWAN model having more than five million nodes). Currently, overall regional accuracy can be less than 15 percent. Discounting issues with wind and surge data, regional HPC/High-Resolution surge hindcast precision is also probably better than 15 percent. (Dietrich et al 2011 and found precisions better than 25 percent including these other sources of local error.) Worse local errors are present in places with complex wind and wave setup, and at lower surges due to greater influence of local topo/bathy and friction issues. ***Importantly, because understanding of Surge-Response is still developing, the HPC/High-Resolution surge modeling SOP currently does <u>not</u> provide for calibration of models for NFIP FISs.***

Supercomputing is now part of the SOP for surge hazard analysis, with the HPC version of ADCIRC being applied in all Gulf and Atlantic coastal FISs—as well as in the preparation of the maximum intensity MOM shown in Figure 3. The accuracy, precision, and increasing economy of HPC/High-Resolution surge modeling has also precipitated its use in surge forecasting. The ADCIRC Development Group is currently teaming with several partners to provide the Coastal Emergency Risk Assessment (http://coastalemergency.org/) surge forecasts for use by emergency response agencies.

In the coming decades, further improvements in empirical representations of key surge physics, HPC, and understanding of Surge-Response will support more refined models—ultra-High Resolution regional meshes capturing key features to scales of tens of feet. These should lead to further modest gains in hindcast and forecast accuracy and precision. In addition, future better understanding of Surge-Response will lead to acceptable methods of calibrating HPC/High-Resolution surge models.

iv. Joint Probability Analysis

The demand for better quality surge hazard analysis across the Gulf and Atlantic Coasts has led to the use of HPC/High-Resolution modeling in all surge FISs. Analysts, in turn, have furthered six enhancements of surge JPM (see Part I):

1. Wider use of tide-gauge analysis using Extreme Value Functions (EVFs, see Part 1). Lengthening tide records and improvements in vertical referencing have allowed better "data-driven" evaluations of surge return period, as shown in Figure 5. These tide-gauge analyses are proving useful to assess JPM results. Researchers are also examining EVF types with broader empirical basis.
2. More sophisticated empirical techniques and climate models, which can improve the representation of track and wind-field variability.
3. JPM-OS (Toro 2008). To keep the number of storms manageable, post-Katrina analysts developed two sophisticated approaches to determining an optimized sample (OS) of storms for the JPM sets. One approach, conducts a preliminary surge hazard analysis with a much coarser (and faster running) surge model using a very large number of synthetic storms. The results of the preliminary surge hazard analysis are evaluated at locations of interest, and a smaller group of storms is then selected to effectively represent surge hazard curves at the various locations. Mathematical techniques are used to optimize storm selection. The smaller, JPM-OS set of storms is then simulated with the HPC/High-Resolution model.
4. Surge-Response OS (Resio et al 2009). A second approach takes advantage of the Surge-Response concept. The OS is used to construct explicit Surge-Response functions for locations throughout the region. Location-specific peak surge are provided for any combination of hurricane attributes (e.g., C_P, R_{MAX}, V_F, θ, and landfall location, X). A separate hurricane joint-probability equation gives the frequency for any combination. Using these two functions, peak surge and joint probability are generated for thousands of synthetic hurricane combinations, and these are then used to compute

each location’s surge hazard curve. In the JPM-OS approach there is no focus on explicitly representing Surge-Response. However, both approaches need to ensure that the OS is adequate to capture complex, non-linear Surge-Responses—such as for large sheltered coastal bays and lakes.

5. Epsilon Term (Resio et al 2012). . Additional factors affecting surge hazard which are treated for convenience as normally distributed random variables can be lumped into a single variable—termed epsilon—by adding their individual standard deviations (σ) in quadrature (taking the square root of the sum of their squares). Example factors can include tide timing, surge model hindcast residual error, Holland B, and wind-field variability. Post-Katrina JPM approaches have incorporated epsilon into the surge hazard curve. Prior to the numerical integration of the surge hazard curve (see Part I), each surge mass probability point is expanded using a range of normally distributed points reflecting the epsilon σ. The numerical integration of this expanded set of points adjusts the surge hazard curve to account for the variables. Including an epsilon term for tide timing, surge model hindcast residual error, Holland B, and wind-field variability, adds one to two feet to the estimated 100-yr surge for some Southeast Louisiana locations.
6. Hurricane Sampling Uncertainty. Besides those random variables addressed with the epsilon term, post-Katrina JPM approaches have recognized the importance of other residual uncertainties, such as hurricane sampling uncertainty. This particular uncertainty refers to the limited length of the hurricane record on which the joint probabilities (and thus the hazard curve and individual hazard levels) are based. If an EVF is fitted to the surge hazard curve the residual error in the fit is inversely proportional to the square root of the record length and EVF residual error can be used as a proxy for hurricane sampling uncertainty. The σ and Confidence Interval (CI) associated with the residual error then provide estimates of the σ and CI for surge sampling uncertainty. As with any EVF fit, the estimate of hurricane sampling uncertainty for surge hazard is sensitive to the choice of EVF.

In the coming years JPA will continue to evolve with further improvements in hurricane climatology expanding the array of hurricane attributes and refining estimates of their probabilities, and with more advances in Surge-Response and HPC/High-Resolution modeling. JPA will be enhanced by the ability to expand OSs to hundreds, if not thousands, of storms. There will likely be an increased blending of empirical and JPM approaches to JPA.

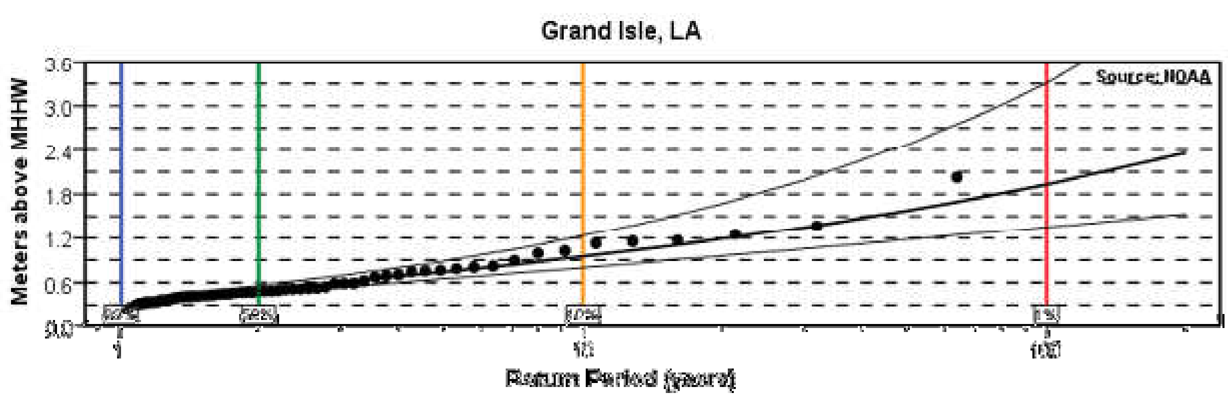


Figure 5. Fit of the EVF to Grand Isle Tide Gauge with 95%CI
http://tidesandcurrents.noaa.gov/est/curves.shtml?stnid=8761724

iv. What-If Scenarios

HPC/High-Resolution surge modeling has also led to two advances in modeling “what if” surge scenarios.

1. The use of modified High Resolution models—topo/bathy, land-cover, coefficients, etc.—to simulate a future condition—relative sea level rise (RSLR), coastal erosion, restoration—or surge protection project. The models can then be used in conjunction with JPM s (JPM-OS or Surge-Response OS) to evaluate changes in surge hazards. To date most efforts have used limited, smaller OSs than for current conditions, but the approaches allow some indication of impacts on key hazard levels, e.g., 100-yr, 500-yr, and 1,000-yr.
2. Use of codes with constituent transport physics—such as FVCOM, ADH, MIKE21, and DELFT3D—to study surge-related geomorphological and water quality impacts. These models are most useful in evaluating local impacts, such as sediment erosion and deposition around barrier islands and coastal passes and saltwater intrusion—and proposed mitigation measures. They can employ regional High Resolution models for surge event boundary conditions. Depending on the application, some simulations can run with modest parallelization available in the workstation.

In the future, continued HPC improvements will allow for more detailed spatial refinement of scenario conditions, simulation of complete JPM storm sets, and evaluation of greater ranges of scenarios.

C. The Post-Katrina FIS Surge Hazard Estimate

In 2008 the USACE completed new surge hazard estimates for Southeast Louisiana, documented in a NFIP FIS, as part of a multi-action response to Katrina; (see Sidebar). Table 2 presents 100- and 500- post-Katrina surge hazard estimates at two locations—the New Orleans Lakefront and along the MRGO south of Lake Borgne—along with the pre-Katrina SPH, 100- and 500-yr surge estimates discussed in Part I. The Table 2 post-Katrina surge estimates reflect correction of errors in a FORTRAN code used to compute FIS surge hazards; (see Bob Jacobsen PE 2015; Woods Hole Group 2015 discusses the FORTRAN errors). The corrected estimates are less than one foot higher than the published FIS estimates. The corrected estimates are referred to in this article as FIS estimates since they were derived with the general FIS SOP.

On the basis of surge depth, the New Orleans Lakefront post-Katrina corrected 100-yr estimate is 0.2 *lower* than the pre-Katrina (1966) estimate. (The uncorrected estimate is 1.1 ft less.) The corrected 500-yr estimate is only 0.8 ft higher. Interestingly, without the additional wave setup contribution to the post-Katrina estimates, the new corrected 100-yr surge would be closer to a foot lower, and the 500-yr estimates would be almost identical.

USACE Post-Katrina Surge Related Actions

Since 2005 the USACE has undertaken six parallel efforts:

1. Revised surge hazard analysis for NFIP FIS; (USACE 2008).
2. Support for Katrina forensic investigations by the Interagency Performance Evaluation Task Force, (IPET 2006-09).
3. Design and construction of a protection system for the 100-yr surge—known as the Hurricane and Storm Damage Risk Reduction System (HSDRRS)—for NFIP accreditation (USACE 2011).
4. Design of HSDRRS resiliency measures to address 500-yr surge (USACE 2013).
5. Polder inundation residual risk evaluation; (IPET Volume VIII, 2009).
6. Comprehensive *Louisiana Coastal Protection and Restoration (LaCPR)* Study of other regional surge risk reduction projects for up to 1,000-yr surge; (USACE 2009).

In the course of these activities the USACE led and/or funded many surge science advances discussed in Section B, which it then integrated into the FIS surge hazard analysis. The FIS surge hazard analysis—which employed a Katrina validated HPC/High-Resolution ADCIRC model, the Resio Surge-Response JPM approach, and an OS of 152 storms—provides the basis for most of the surge evaluations in all six USACE efforts. The USACE's approach to the Southeast Louisiana FIS contributed greatly to practices followed and refined in ensuing FISs across the Gulf and Atlantic Coasts. This FIS surge hazard analysis SOP also reflects important methodology limitations (see Sidebar on FNIP programmatic constraints). For a comprehensive discussion of the SOP in surge hazard analysis see Bob Jacobsen PE 2013.

On the other hand, the post-Katrina analysis increases 100- and 500-yr hazard estimates at the MRGO location substantially—almost 5 and 7 ft, respectively, (without an IHNC Barrier; addition of the IHNC Surge Barrier raises these estimates by another 1 and 2 ft). Table 2 shows a much larger spread between the 100- and Nominal 500-yr hazards in the post-Katrina versus the pre-Katrina (1966) estimates at both locations: 2.6 versus 1.6 ft at the New Orleans Lakefront and 3.2 ft versus 1.2 ft at the MRGO (without the IHNC Barrier).

According to this FIS analysis, Hurricane Katrina's surge at the New Orleans Lakefront and MRGO was 2.2 and 2.8 ft above the new 100-yr level, respectively, and 0.4 ft below a Nominal 500-yr level, at both locations. This corresponds to roughly a 400-yr event for both locations (using a log-linear interpolation). The FIS analysis thus suggests that Katrina's surge should be regarded as an extremely unlikely event.

Given the disastrous history of surge hazard underestimation for New Orleans—and associated inadequate risk management—the FIS analysis warrants a closer look.

Table 2. Comparison of Pre- and Post-Katrina Surge Hazards

	NO Lakefront		**MRGO (Bayou Dupre)**			
			Without IHNC Barrier		*With IHNC Barrier*	
Pre-Katrina	**ft MSL (NGVD)**	**Above LML**	**ft MSL (NGVD)**	**Above LML**		
Local Mean Level	1.0		0.9			
SPH	11.5	10.5	13	12.1		
100-yr	10.3	9.3	12.5	11.6		
500-yr	11.9	10.9	13.7	12.8		
Post-Katrina	**ft NAVD88**	**Above LML**	**ft NAVD88**	**Above LML**	**ft NAVD88**	**Above LML**
Local Mean Level	0.5		0.3			
Katrina Actual	11.8	11.3	19.5	19.2		
Uncorrected 100-yr	8.7	8.2	16.4	16.1		
Uncorrected 500-yr			20.2	19.9		
Corrected 100-yr	9.6	9.1	16.7	16.4	17.6	17.3
Corrected 500-yr	12.2	11.7	19.9	19.6	21.7	21.4

D. Limitations of the FIS Surge Hazard Estimate

The constraints imposed by the NFIP on surge hazard analysis (see Sidebar)—together with further improvements in hurricane climatology, surge physics, surge modeling, and JPMs—have clarified many significant issues in the post-Katrina FIS surge hazard analyses.

Table 3 lists ten issues, along with the potential magnitude of surge uncertainty associated with each issue. For convenience each uncertainty is treated as normally distributed and Table 3 gives the current approach to evaluating each σ. The combined σ for all ten can easily exceed 25 percent at sensitive locations (σ values are added in quadrature). Importantly, these issues are treated differently under SOPs for NFIP FISs versus local residual risk management—given different priorities.

The first four issues, 1 through 4, are addressed in the JPM epsilon term discussed in Section B.iv. Two of the four—surge model hindcast and tides—are prone to local variations, which are typically ignored in a regional FIS but would be important for local residual risk reduction. Interestingly, the FIS for Southeast Louisiana actually documented a notable hindcast under-prediction error along the New Orleans Lakefront.

Issues 5 through 8 tend to be highly localized, with local values of σ for Nos. 5, 6, and 7 currently requiring professional judgment. The σ values for these issues have not been a subject of the FIS SOP but would be important to local residual risk reduction. Issues 5, 6 and 7 could be important sources of underestimation of Surge-Response for large, shallow, inland lakes and bays.

Uncertainty associated with Issue 9—hurricane sampling—is employed in FIS formal evaluation of surge hazard uncertainty and CI. For the Southeast Louisiana FIS, the hurricane sampling σ was estimated using an EVF fit to JPM surge hazard curves, (see Section B.iv)—yielding a value of about 10 percent (8 percent for the East-Bank). However, a reasonably conservative estimate for local residual risk management would be twice that value based on: a) the hurricane sampling uncertainty associated with the Grand Isle tide gauge record (Figure 5); and b) reconsidering the record length represented by the storms employed in estimating the joint probabilities. (The FIS considered the 65-yr storm record to be equivalent to a nearly 400-yr record since storms defining joint probabilities were drawn from a coastal region 6.1 times bigger than Southeast Louisiana.)

<u>NFIP Constraints on Surge Hazard Estimates</u>

FIS surge hazard estimates should be carefully reviewed prior to use for other than NFIP purposes. Important programmatic constraints on these estimates include:

- The emphasis on the 100-yr hazard, which means the other hazard level estimates have a much lower priority. Estimates of more extreme local surge hazard developed in the course of an FIS—such as the 500-yr surge—should be regarded as "Nominal."
- Tolerance for modest regional error. As noted in Section B.iii HPC/High-Resolution surge models are not currently calibrated. Interestingly, a margin for uncertainty is not used in the delineation of 100-yr flood hazards zones. The NFIP multi-billion dollar national fund has always been heavily subsidized.
- Tolerance for larger localized errors. The FIS SOP focus on regional error, as well as budget and schedule constraints, mean that localized error reduction is often sacrificed. (A common localized source of error is characterization of topo/bathy/drag for key features.) Budget constraints also mean that local surge hazard estimates can become significantly outdated between re-studies.

Local leaders are highly sensitive to the impact of flood zones on community economic stability and growth, and thus monitor FISs closely for overestimation errors. On the other hand, local officials are typically less concerned with underestimation errors. Underestimation tends to be a concern only if there is a focus on local residual risk.

Local surge risk managers planning for potential catastrophic surge impacts—concerns well beyond those of the NFIP—must address extreme risks to a specific community, population, and critical economic and cultural resources. Such objectives demand higher quality estimates of 100-yr, 500-yr, and greater hazards. These objectives also demand a higher quality assessment of uncertainties. Moreover to ensure an adequate FOS in design, local projects for reducing risk beyond the NFIP require *reasonably conservative* estimates of the uncertainties.

Table 3. Ten Issues Affecting Current Southeast Louisiana Surge Hazard Analysis

Factor	Potential Surge σ	Evaluation of σ	FIS SOPs	Localized Variation?	Local Residual Risk Reduction SOP
1. General accuracy and precision of HPC/High-Resolution surge model	>15%	Residual error from hindcast validation.	Region-wide uniform σ included in epsilon.	Yes	Evaluate hindcast bias and precision at a sub-regional scale and adjust epsilon or include in CI
2. Timing of tides	<0.3 ft	Tidal analysis.		Yes	Adjust for local tide range.
3. Wind-field shape (Holland B)	>10%	Holland B surge-response analysis indicates direct effect on surge		No	Same as NFIP.
4. Additional wind-field characteristics (e.g., banding)	>5%	Residual error between surge modeling with high resolution wind fields versus the simpler wind-fields.		No	
5. Pre-storm setup and rainfall accumulations in interior lakes and bays	>10%	Requires professional judgment.	Not currently addressed.	Yes	Include a reasonably conservative factor in CI
6. Empirical representations of hydrodynamic and wind-water drags at sensitive locations	>10%	Requires professional judgment.		Yes	
7. OS representativeness of Surge-Response at sensitive locations	>10%	Requires professional judgment.		Yes	
8. Surge-Response function—depends on interpolation method	>5%	Residual error between function and actual OS results.		Yes	
9. Hurricane sampling	>8%	Use regional hurricane history to develop joint probabilities. Fit EVF to the surge hazard curve.	Region-wide uniform σ included in surge CI	No	Depending on exposure, include slow-moving low intensity storms in the joint probabilities. Use a reasonably conservative approach to the selection of EVF type and assigned sample length; adjust using analysis of local tide gauge record.
10. Representativeness of historical hurricane record	>10%	Requires professional judgment.	Not currently addressed.	No	Adjust future surge hazard for trends; include a reasonably conservative factor in CI for climate cycle and trend uncertainty.

The pre-Isaac Southeast Louisiana FIS hurricane sampling also underplays the contribution of slow-moving less powerful storms to the overall frequency of hurricanes capable of producing a 100-yr surge. This is a potential source of underestimation bias in the FIS analysis.

Finally, Issue 10 considers whether the period of observed hurricanes is representative of the current hurricane climate. The Southeast Louisiana FIS incorporated an adjustment to hurricane joint probabilities based on an initial effort to account for cycles of Gulf of Mexico hurricane activity in the observed 65-yr record. Uncertainties associated with this adjustment are not addressed in FIS surge hazards but would be appropriate for local projects.

Besides these ten issues for the current surge hazard estimate, there are potential long-term trends—e.g., increasing hurricane frequency and/or intensity, RSLR, coastal land loss, etc.—which could cause future surge hazards to be underestimated. These non-stationary issues are not included in FIS estimates of current surge hazard.

Based on the FIS overall uncertainty σ of 8 percent—which only addresses Issue 9 (and not conservatively)—the corrected FIS 100-yr surge estimate of 9.6 ft NAVD88 for the New Orleans Lakefront has a 90% upper confidence limit (UCL) at 10.9 ft, or 1.3 ft higher. (The 90%UCL for the uncorrected 100-yr surge is 9.9 ft.) However, a more reasonably conservative σ for residual risk management purposes addressing all ten issues would be at least three times that, giving a 90%UCL at 13.5 ft, or 3.9 ft higher—see Figure 6. As noted previously, the post-Katrina spread between FIS 100- and 500-yr surge estimates for the New Orleans Lakefront was 2.6 ft. ***Thus, a reasonably conservative 90%UCL for the 100-yr surge is actually much higher than the base estimate for the 500-yr surge—an essential point for local surge residual risk management!***

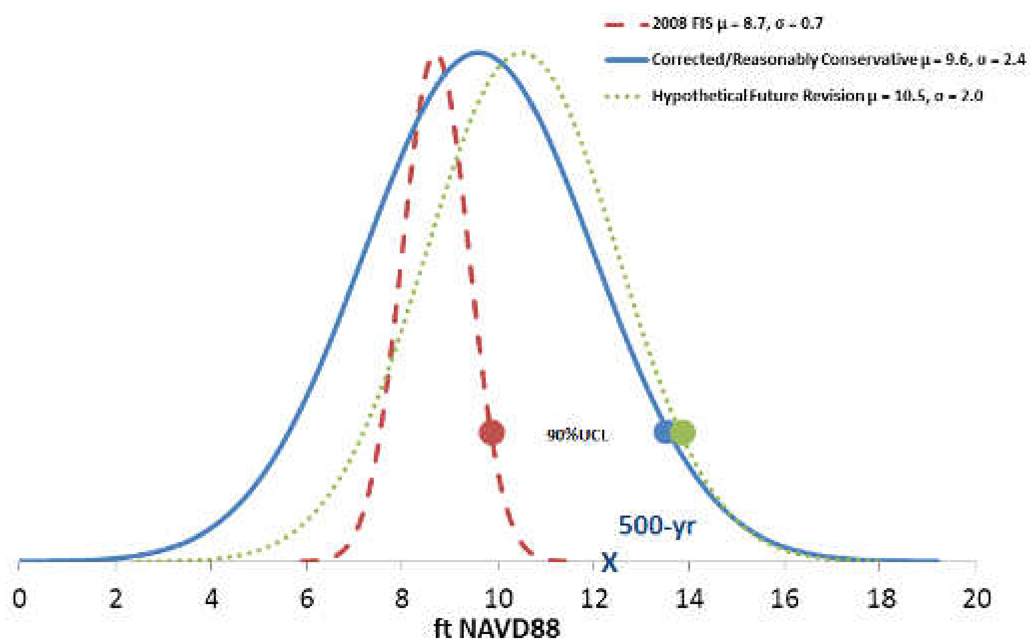


Figure 6.
New Orleans Lakefront 100-yr Surge Uncertainty Distribution

A reasonably conservative consideration of all uncertainties indicates that FIS surge hazard values could really be regarded as "Scientific Guesstimates." The FIS could easily overestimate true return periods by a factor of two. Nominal 500-yr surge estimates are subject to even greater uncertainty than the 100-yr estimates. Thus, Hurricane Katrina's surge along the MRGO could be regarded as closer to a 200-yr event than the 400-yr event indicated by the FIS analysis.

In addition to uncertainties about local surge magnitude, there is an important issue regarding *independent* exposures to extreme surges at the polder and regional scale. Locations with independent exposures have separate hazard events. A polder or region with multiple independent surge hazard exposures is subject to a multiple of the surge hazard. Table 4 presents the equivalent polder and regional return periods for a range of local surge hazards—for the case of two and five independent exposures, respectively. Note that in this case the average return period for a 100-yr surge becomes 50 years for a polder and 20 years for a region. In this case, over a longer timeframe of 10 years, a 100-yr event has a 40 percent regional probability of occurrence. Table 4 also includes the equivalent regional return periods if the local surge hazard is increased by a factor of two. Thus, in this case what might be considered to be a local Nominal 500-yr surge event could have a regional return period of 50-yrs, which over a 10-yr timeframe has an 18 percent regional probability of occurrence. To date, the actual multiples for polder and regional 100- and 500-yr events in the New Orleans area have not been defined.

All of the above limitations point toward a crucial and ironic fact: after three centuries and the loss of thousands of lives and multiple devastations, the New Orleans surge hazard is still subject to being significantly underappreciated!

Those with the responsibility for managing local surge risks beyond the NFIP increasingly recognize that surge hazards must be regularly reanalyzed with appropriate rigor. However, improvement of surge hazard estimates requires major investments in scientific research, data collection, HPC, and administrative functions. In the meantime, for residual risk management purposes, FIS estimates of 100- and 500-yr surge can be corrected for FORTRAN errors and likely local bias issues (see Bob Jacobsen PE 2015). Importantly, as depicted in Figure 6, in the near future revising surge hazard estimates will not appreciably reduce reasonably conservative uncertainty, and may have little effect on the 100-yr 90%UCL; (see Sidebar).

<u>Future Reduction of Surge Hazard Uncertainties</u>

Uncertainties can be considered "aleatory" (reflecting inherent and irreducible randomness in the natural phenomena) or "epistemic" (depending on the state of our knowledge and potentially reducible in the future with further improvements to observations, analysis, and modeling). Aleatory uncertainties—such as Issues 2, 3, and 5—are appropriate for inclusion in the epsilon term and incorporation into the base hazard estimate (again No. 5 is currently ignored in the FIS). Uncertainties with the other seven issues (Nos. 1, 4, 6, 7, 8, 9 and 10) are largely epistemic and can be either included in the epsilon term or used to construct CIs (again Nos. 6, 7, and 8 are currently ignored in the FIS). Importantly, upper limits of CIs (UCL) are lower if σs are included in epsilon. Issues 5, 6, 7, and 10 are currently subject to professional judgment. Research over the next ten years and continued improvements in HPC/High-Resolution and JPMs may be able to reduce Nos. 1, 4, 5, 6, 7 and 8. However, many more decades of hurricane observations will be necessary to reduce uncertainties in Issues 9 and 10.

Table 4. Equivalent Return Periods (years)

Local Hazard	Polder Hazard (Example of Two Independent Exposures)	Regional Hazard (Example of Five Independent Exposures)	Future Regional Hazard (Local Hazard *X* 2)
100	50	20	10
500	250	100	50
1,000	500	200	100

E. Post-Katrina Surge Risk Management

Following the extensive damage caused by Hurricane Katrina, Congress provided 70 percent funding for an accelerated repair and completion of the New Orleans regional surge system. This new authorization directed the USACE to address the NFIP 100-yr hazard—as re-establishing protection to NFIP-level requirements was immediately needed to revitalize City property values and the economy. Furthermore, the NFIP objective would be quicker, easier, and cheaper to finish than protection to a more extreme level. The USACE emphasized this pivot with an explicit re-designation of the project as a "Hurricane and Storm Damage Risk Reduction System" (HSDRRS), eliminating reference to a "Protection System." ***Importantly, the HSDRRS authorization—for the first time ever—provided that surge levees for New Orleans would be designed for a level below the Record Surge!*** The post-Katrina design along the New Orleans Lakefront for a 100-yr surge (uncorrected) is for a surge elevation 2.3 ft less than the previous SPH-surge protection objective, and 3.1 ft below Katrina's surge.

The NFIP requires that levee elevations be at least 2 ft higher than the 100-yr surge, and higher if necessary to prevent wave overtopping and erosion. The NFIP elevation for wave overtopping can be set straightforwardly (above the 0.1 percent wave run-up). The USACE used an alternative approach, setting elevation based on a statistical treatment of 100-yr overtopping uncertainty (see Sidebar). The USACE adopted the latter ***Elevation FOS*** approach and set HSDRRS crown elevations so that the estimate of 100-yr overtopping at a 90 percent non-exceedance level (q90, equivalent to an 80%UCL) would not exceed a limit of 0.1 cfs/ft (USACE 2011). (They also set a q50 limit of 0.01 cfs/ft.)

Table 5 includes the previous SPH High-Level and 100-yr HSDRRS hydraulic design elevations for the two locations. The HSDRRS design elevation increased by 0.5 ft for the NO Lakefront and by 9.6 ft for along the MRGO location (with the IHNC Barrier). (Final crown elevation may be slightly higher than hydraulic design depending on geometry, overbuild, and other construction considerations.)

In the engineering and construction of the HSDRRS the USACE implemented several major geotechnical improvements over the previous SPH project, including use of the batter pile-supported "T-" and "L-" designs for floodwalls; more rigorous levee material and construction requirements; and the adoption of more accurate GPS-based vertical control methods. In the East-Bank post-Katrina rebuild, batter-pile supported walls were employed along more than 20 percent of the 111 mile system, including a new 1.8-mile barrier across the Funnel (Silbert 2010). The basic HSDRRS construction was essentially completed in 2013—at a cost approaching $14 billion—and received NFIP accreditation in February 2014.

Monte Carlo Analysis of HSDRRS Overtopping Uncertainty

HSDRRS overtopping was evaluated with empirical equations---such as the standard weir equation for free overflow and the Van der Meer equation for levee wave overtopping. These equations give overtopping rates (q, cubic feet per second per linear foot, cfs/ft) as a function of freeboard (crown minus the 100-yr surge), wave height and period, embankment geometry, and an empirical loss coefficient. To assess uncertainty in q, a standard Monte Carlo technique was employed. The equation is solved tens of thousands of times, with each solution using randomly drawn values for key inputs reflecting their own uncertainties. The set of results thus provides an uncertainty distribution for q. The variation for the 100-yr surge, wave height and period, and the loss coefficient were determined by respective uncertainty distributions. For surge uncertainty, the USACE used the sampling uncertainty discussed above.

To address surge risks beyond the NFIP 100-yr level, the USACE (working for IPET, see earlier Sidebar) undertook an initial attempt at quantifying the residual polder inundation hazard. The work employed HPC modeling of an FIS storm subset in an innovative JPM-OS. The polder inundation hazard addressed additional probabilities related to interior flood levels, such as overtopping, breaching, rainfall, interior routing, and drainage pumping. Figure 7 shows the Nominal 500-yr surge inundation hazard.

Table 5. Comparison of Pre- and Post-Katrina Levee Design

	NO Lakefront		MRGO (Bayou Dupre)			
			Without IHNC Barrier		*With IHNC Barrier*	
Pre-Katrina						
SPH High-Level Design	16.0 ft MSL	4.5 ft above SPH; 15.0 ft Above LML	17.5 ft MSL	4.5 ft above SPH; 16.6 ft Above LML		
Post-Katrina						
HSDRRS Design (w/o RSLR)	16.0 ft NAVD88	6.4 ft above 100-yr; 15.5 ft Above LML			26.5 ft NAVD88	8.9 ft above 100-yr; 26.2 ft Above LML
Corrected 100-yr q90	0.66 cfs/ft				1.05 cfs/ft	
Corrected 500-yr q90	10.69 cfs/ft				31.41 cfs/ft	

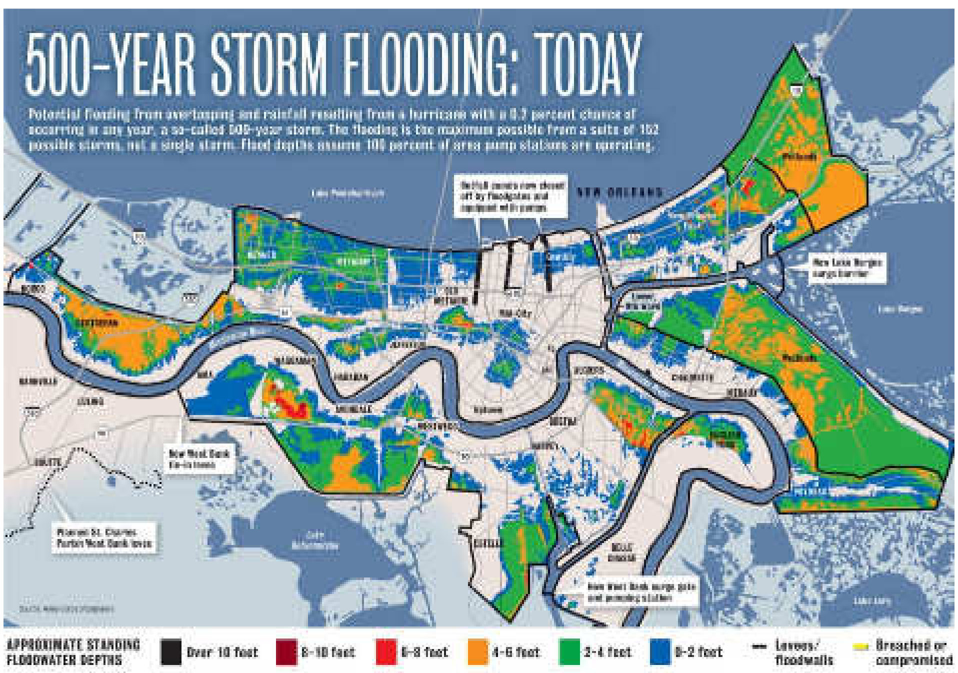


Figure 7. ***Nominal*** *** 500-yr Surge Inundation**
Times-Picayune 2012 (from IPET 2009)

In the same year, 2009, the USACE completed the LaCPR Report (see earlier Sidebar) authorized by Congress to evaluate options for further federal action in reducing residual risks beyond the NFIP HSDRRS, including but not limited to higher levees. The LaCPR study employed the results of the FIS hazard analysis, as well as additional HPC/High-Resolution surge modeling for various alternatives. As a result of the LaCPR Study—together with other state and local efforts (including their own HPC/High-Resolution surge modeling)—ten residual risk reduction components have seen post-Katrina developments:

1. Evacuation. Given the clearly acknowledged surge hazard limits for the HSDRRS, federal, state, and local hurricane response agencies have continued to refine plans for mandatory evacuation—adjusting the ContraFlow Plan, modifying evacuee sheltering arrangements, and addressing individuals with health, financial, and logistical hardships. Advances in hurricane forecasting—including surge—have improved confidence in mandatory evacuation notices. An August 2008 mandatory evacuation of the City during Hurricane Gustav highlighted ongoing progress in the City's evacuation, as well as the need for more; (see Wolshon 2006 and Campanella et al 2012).
2. Flood insurance. Given the limited pre-Katrina participation in the NFIP and coverages, local Congressional representatives have worked to a) expand the USACE SELA program to further reduce interior 100-yr flood hazard zones, thereby reducing premiums for more polder properties; and b) ensure the NFIP premiums for 100-yr hazard zones remain affordable.
3. HSDRRS floodwall and levee resiliency. In response to the Katrina failures, Congress authorized and funded the USACE to provide HSDRRS resiliency against catastrophic breaching during greater than 100-yr surge events. Overtopping during a 500-yr storm is likely to produce thousands of acre-ft of interior flooding—a significant but not catastrophic volume (less than a 100-yr/24-hr rainfall). On the other hand, breaching can produce many times the volume of overtopping, and over a shorter time (see Bob Jacobsen PE 2015). To provide resiliency against collapse breaching the USACE design called for all features to withstand the Nominal 500-yr surge. For floodwalls, resiliency against overtopping induced erosion breaching is provided by concrete splash pads, as well as overbuilt height for RSLR through 2057. Levee overtopping resiliency is being addressed through armoring protective against 500-yr overflow (USACE 2011). The USACE evaluated 500-yr overtopping uncertainty and employed the 500-yr q90 as an ***Armoring FOS***. In addition the USACE has conducted large-scale physical experiments on wave-induced turf erosion and pilot projects to evaluate the installation and maintenance of high performance turf reinforcement mat (HPTRM).
4. HSDRRS upgrade. The USACE's 2009 LaCPR Report investigated options for HSDRRS upgrade to more extreme hazard levels—including a 1,000-yr level. The LaCPR Study suggested that even upgrading the HSDRRS to meet Katrina's record surge was not cost-effective given other options. However, the Louisiana Coastal Protection and Restoration Authority's (CPRA) 2013 Master Plan and the Louisiana Section of the American Society of Civil Engineers (in their 2012 Report Card) have recommended a higher levee system for New Orleans. As of today, no detailed investigation of HSDRRS upgrade has been initiated.
5. The Lake Pontchartrain Barrier Plan. The USACE LaCPR Study and the SLFPA-E (see Ben C. Gerwick 2012) revisited the original Barrier Plan (see Part I). Both investigations showed that a low barrier can reduce Lake "filling" from surge forerunners associated with some storms. However, such a barrier only modestly reduces overall hazard, due to the fact that it does not prevent Lake "tilting." Any Barrier Plan would also have some impact on surrounding surge hazard outside the Lake. The CPRA has initiated further investigation of potential ways to optimize a low barrier.
6. Removal of Mississippi River levees. The LaCPR Study investigated the effect of taking down some levees in Plaquemines Parish. This investigation showed some reduction of East-Bank surge hazard,

in addition to potentially facilitating restoration of wetlands in the lower delta. At this time no further investigation of removing downriver levees has been initiated.

7. Coastal protection and restoration projects. The USACE LaCPR Study, the Louisiana CPRA Master Plan, as well as local agencies, have identified numerous basin and sub-basin scale projects to refurbish and enhance barrier islands, ridges and cheniers, and wetlands, as well as close additional man-made canals. Many of these projects have been promoted as a means to reduce surge; (see Smith et al 2010). One cost-effective measure to complement the HSDRRS would likely be the restoration and maintenance of a band of resilient coastal forests fronting the system to reduce wave heights (see Bob Jacobsen PE 2015). However, this measure would require modifying HSDRRS design criteria to allow consideration of vegetation impacts on waves.
8. Polder interior compartmentalization. The Bob Jacobsen PE 2015 report examined numerous options and recommended three for further engineering evaluation: i) improvements to the East Jefferson/St. Charles parish line barrier, ii) upgrade of remaining IHNC Basin I-walls; and iii) use of the Central Wetlands to reduce surge levels in the IHNC Basin. Further engineering evaluation of these projects is required to confirm feasibility, followed by securing funding for final design and construction.
9. Interior drainage. Interior drainage reduces risks associated with overtopping volumes; (see Bob Jacobsen PE 2015). 10,000 cfs of pumping capacity is equivalent to removing 20,000 acre-ft/day of inundation. Following Katrina, the USACE continued to implement drainage improvements under SELA. However, no improvements addressing surge risk reduction have been studied.
10. Flood-proofing. The various post-Katrina studies and plans have recommended further development of "Non-Structural Alternatives" for surge risk reduction. These include more stringent ordinances; building codes; and public investment to implement greater a) elevation of residential, commercial, and public buildings (i.e., even more than required by the NFIP); b) flood-proofing of critical electric, gas, communication, water, and sewage utilities and transportation components; and c) flood-proofing of key community, historic, and cultural assets. (Recall from Part I that flood-proofing is one of the earliest and most basic ways to manage flood risk.)

F. Limitations of Post-Katrina Surge Risk Management

Post-Katrina surge risk management for New Orleans has many serious limitations. Foremost, as over its entire history, surge risk management is subject to the potential errors and uncertainties of the surge hazard estimate. *Thus, the issues with the FIS surge hazard estimates discussed in Section D mean that surge risks to life and property are likely to be underestimated.*

Ten additional technical issues for the HSDRRS are:

1. Elevation FOS. The USACE developed the 100-yr q90 estimates to support NFIP accreditation and therefore used an NFIP approach to overtopping uncertainty. A reasonably conservative approach to overtopping uncertainty—with reasonably conservative treatment of surge, wave, and other conditions—would substantially increase estimates of 100-yr q90. Recomputed 100-yr q90s for the New Orleans Lakefront and MRGO levees are 7 and 11 times specified erosion limit of 0.1 cfs/ft. Thus, when considered from a local residual risk management and not simply an NFIP perspective, the HSDRRS 100-yr design has a minimal Elevation FOS. Recomputed q50 and q90 significantly affect levee reaches inland from open lakefronts—such as along the East-Bank levees in St. Charles Parish with 100-yr q90s re-estimated above 5 cfs/ft. Correction of surge hazard uncertainty reveals that these reaches have negative freeboard at the q90. (Recomputed q90s use the levee hydraulic design elevation. They reflect correction of FORTRAN errors noted earlier; modification of inland wave heights; and changes to the Monte Carlo overtopping analysis. These changes also affect

computation of the median overtopping, q50, which has a limit of 0.01 cfs/ft; see Bob Jacobsen PE 2015.)

2. Armoring FOS. The 500-yr q90s (and q50s) are affected by the same issues as the 100-yr overtopping estimates. Recomputed 500-yr q90s at New Orleans Lakefront and MRGO are 10.7 and 31.4 cfs (and over 60 cfs in St. Charles Parish). These revised estimates mean that the degree of risk reduction provided by selected armoring measures is likely to be significantly less than anticipated. More rigorous armoring—i.e., stone or paving instead of HPTRM—could be appropriate to provide a greater 500-yr resiliency.
3. Supplemental levee lifts. Supplemental levee lifts will be required along most HSDRRS levee segments over the upcoming years to a) continue meeting the 2007 design elevation, given post-construction consolidation and settlement—especially high for inland levee reaches built across former swamps; and b) compensate for RSLR in accordance with the USACE's 2057 design elevation. These levee lifts are not currently federally funded. Thus, vulnerable reaches could be exposed to even greater 100- and 500-yr overtopping if levee crowns fall below their design elevation.
4. Armoring implementation. Installing armoring soon will result in future expensive removal during future lifting and reinstallation. Deferring armoring exposes the system to breach risks but might be practical if the deferral is only for a short time. The issue becomes more complex as the time horizon is extended to account for more consolidation, settlement, RSLR, and even revised 100-yr surge estimates.
5. Impact of coastal erosion and vegetation changes on future surge. The USACE assessment of RSLR on 2057 design elevations did not include further increases in surge height due to coastal erosion and vegetation change.
6. Vertical control methodologies. Remaining issues with the GEOID model and ellipsoid height measurements can still introduce errors on the order of several tenths of a foot.
7. Subsurface weaknesses. Legacy pipelines, localized voids, transmissive soils, and slip planes could still present opportunities for collapse breaching—especially for a few remaining I-wall segments. More research is needed on techniques for investigation of these geotechnical weaknesses, as well as how to characterize collapse breach probabilities.
8. Structural design weaknesses. There are concerns for future T-Wall pile corrosion and batter pile down-dragging (due to subsurface settlement/subsidence) which could affect long-term performance, as well as for system flood-side armoring (see Turner 2011).
9. Operation of 11 major channel gates and 4 additional perimeter pump stations entail significant complexities and long-term costs.
10. Maintenance. Similarly, there are large long-term challenges and costs associated with maintaining extensive reaches of levees, floodwalls, armoring, breakwaters, gates, pump stations, etc.

Beyond technical issues with the HSDRRS, as well as other risk reduction measures such as coastal projects (see Sidebar), effectively meeting future surge risk management challenges—as over the City's entire history—continues to involve a competition over limited resources and political will. For example:

Technical Challenges for Coastal Projects to Reduce Surge Risk

Surge-Response physics indicate that coastal landscape features have a smaller impact on extreme surge hazards. However, the evaluation of coastal protection and restoration with HPC/High-Resolution modeling to gauge the degree of inland surge reduction (and with JPMs for extreme hazards) is still in its infancy and needs further scientific research. For example, the evaluation of the wave-reduction effects of coastal forests has yet to be fully assessed. Proposals for large-scale refurbishment of wetland platforms and ridges using the transfer of sediment from the Mississippi River to regional sub-basins will require a skillful combination of diversions, dredging, and sediment pipelines to maximize benefits and minimize costs and adverse water quality impacts. It is unlikely these projects can be optimized for both ecosystem productivity and extreme surge reduction.

- Evacuation contingencies for those with health, logistical, or financial problems remain underfunded.
- The voters of St. Bernard Parish have twice declined to pass a tax to increase funding for operations and maintenance (O&M) of their respective portion of the HSDRRS.
- Coastal restoration plans must consider those whose ways of life are tied to the existing coastal landscape and ensure that short- and long-term impacts are reasonable and justifiable given uncertainties about the long-term success of restoration projects.
- Staunch private property interests oppose the establishment of incentives (much less mandates) to expand flood insurance participation and private coverage, as well as the imposition of greater flood-proofing requirements.

Challenges over how to best coordinate surge risk management components have been just as daunting, given continuing fragmentation of responsibilities among a plethora of federal, state, and local entities. Fragmentation of responsibility and the absence of “system accountability” were repeatedly acknowledged as major contributors to the Katrina disaster (ILIT 2006, Team Louisiana 2006, IPET 2006, ASCE 2007, Boyd et al 2014). Ironically, the current situation is in some ways worse than before Katrina. Four examples include:

1. Design decisions involving the tradeoff of construction costs/schedule versus long-term O&M costs/headaches. The USACE is responsible for design/construction with a 70 percent cost share; the state CPRA is responsible for a 30 percent match and review; while the local levee authorities (SLFPA-E, as well as the West authority, SLFPA-W, and the Pontchartrain Levee District, PLD) are responsible for 100 percent of O&M. Eliminating this division could have changed key design decisions related to subsurface and structural weaknesses, as well as “right-sizing” of the system (rebuilding instead on 40 Arpent and Maxent Levees, and upgrading IHNC and outfall canal floodwalls instead of installing barriers and perimeter pump stations).
2. Rational risk reduction. The USACE has been reluctant to raise HSDRRS elevation, resiliency, and Elevation and Armoring FOSs beyond narrowly construed Congressional authorizations (as with the SPH design before that). These interpretations do not allow for cost-effective management of residual risk, which is largely the responsibility of the CPRA and local authorities.
3. Formal NFIP HSDRRS re-evaluation and re-accreditation (for 2023). The CPRA and local levee authorities—together with FEMA and the USACE—will have to determine if a re-analysis of the surge hazard is required, as well as if treatment of surge uncertainty needs to be revisited. Some local authorities concerned with residual risk have shown understandable interest in a more rigorous restudy. Complicating a restudy is the fact that the CPRA and the local HSDRRS managers are not the local NFIP agencies, some of which may be opposed to initiating a revision of NFIP FIS.
4. Coastal protection and restoration priorities. In 2013 SLFPA-E sued oil and gas operators responsible for decades-old dredging of coastal canals to obtain compensation and restitution for impacts on East-Bank HSDRRS surge levels. (The impact of these canals on the East-Bank HSDRRS will require a sophisticated analysis of local surge-response.) Opponents of the lawsuit argue (in part) that a) a local authority should not undertake such litigation unilaterally, given the authority/responsibility of CPRA; b) litigation as it is being pursued is not the proper way to facilitate an optimal coastal result; and c) the litigation is discouraging the defendants from engaging in cooperative solutions to coastal restoration and protection.

G. Implications for Sustainable Surge Risk Management

The Simple Lesson is that all flood tragedies—and Katrina was not an exception—are due to a) the underestimation of the hazard and b) the failure to prioritize appropriate risk management measures, with the former heavily influencing the latter. The Supercomputing Era has produced—and will continue to produce—remarkable high-resolution surge forecasts, hindcasts, and hazard analysis. However, dramatic risk reductions—for loss of life and economic devastation—are only attainable if we pay very close attention to a) and b)!

NFIP levees are to surge what fire departments are to fires—they are complements to effective evacuation preparedness and property insurance.

<u>**Six Lessons for Surge Hazard Analysis**</u>

1. Be familiar with the nature of surge probabilistic estimates. Demand the highest quality estimates of surge hazards when addressing catastrophic risks—i.e., beyond the NFIP. Advances in hurricane climatology, HPC/High-Resolution surge modeling, and JPA are continuing to improve the quantification of the surge hazard curve, including for polder interiors.
2. But appreciate the limitations of surge hazard estimates, especially those developed for NFIP purposes. A new analysis—aimed at being more rigorous than required for the NFIP and taking into account recent advances in surge science—could reduce this return period significantly.
3. Understand how uncertainty is treated for the NFIP versus for local residual risk reduction, as well as reasonably conservative treatment of uncertainties. Surge hazards should really be regarded as "Scientific Guesstimates." In particular, regard 500-yr surge estimates as NOMINAL. A reasonably conservative 90%UCL for the 100-yr surge can exceed the Nominal 500-yr surge and provide a better basis for an Elevation FOS.
4. Furthermore, understand the nature of multiple independent polder and regional exposures.
5. Institutionalize periodic updating of the surge hazard analysis—including for the polder interiors. Moreover, support critical research to improve hurricane climatology, HPC/High-Resolution modeling, JPA, overtopping analysis, breach probability estimation, etc. However, recognize the large uncertainties that are likely to remain for decades to come. Also appreciate different needs within a region: residual risk management should sponsor frequent, high quality re-analyses that closely re-examine extreme hazards, while the NFIP may accept a long lapse before revising the FIS.
6. Study additional extreme hurricane surge scenarios—such as MOMs for maximum probable storms—to fully appreciate the "worst case" hazard.

<u>**Ten Lessons for Surge Risk Management**</u>

1. Demand the highest quality quantitative risk assessments to estimate consequences at each hazard level. Educate the whole community on the nature of risk.
2. Understand all flood risks and examine surge risk reduction measures in context with other rainfall and river flood hazards.
3. Set the highest consensus surge risk management priorities in stone. Make them a permanent, marquee community commitment that all future leaders must uphold. Don't consider a risk management component a consensus priority if there are significant opposing interests that will work to undermine continuing political and financial support.
4. <u>***Eliminating loss of life is the top priority***</u>. Ensure readiness of evacuation plans to address the limits of NFIP surge protection systems and their FOSs (see below). Treat uncertainties in protection

system performance reasonably conservatively for loss of life risks (unlike in the NFIP). Ensure evacuation plans address those with health, logistical, or financial problems in self-evacuating.

5. ***Expanding flood insurance participation and coverage is the second priority***. Consider incentives and even mandates. For a community as a whole, flood recovery will be quicker, broader, and more effective if more property damage is covered by insurance.
6. Evaluate additional residual risk reduction measures as a "system;" the various components need to function synergistically (see Boyd et al 2013). Beyond evacuation and flood insurance, there are eight potential measures:
   i. Minimal NFIP surge protection system (e.g., 100-yr with minimal FOSs);
   ii. Greater system FOSs to address overtopping and other uncertainties; more reasonably conservative treatment of uncertainties;
   iii. System breaching resiliency, per specification for more extreme surge (e.g., 500-yr);
   iv. Higher system, per specification for more extreme surge (e.g., 500-yr with appropriate FOSs);
   v. Restoration and protection of large-scale coastal features;
   vi. Interior compartmentalization (for polders);
   vii. Enhanced interior drainage and pumping capacity (for polders); and
   viii. Flood-proofing.

   Select measures on the basis of cost-effectively reducing residual risks. Don't oversell the benefits of a surge risk reduction option, especially to the detriment of Priorities 1 and 2.
7. Be mindful of apparent complementary interests, as they can become competing interests—as evidenced in the past by the SELA drainage program and Lakefront revenue generation. Recognize the need for coastal restoration but understand the limited role of coastal features in mitigating extreme surge. Coastal restoration projects are usually optimized for long-term coastal habitat and ecosystem productivity, not for surge reduction. While not mutually exclusive, these objectives are likely to involve major tradeoffs. Use of limited surge risk reduction funds on coastal restoration may not be prudent, and vice versa.
8. Ensure that professionals are allowed independence to choose their methodologies, provide authoritative findings and recommendations, and discuss limitations and uncertainties. Ensure that all professional determinations are well-documented and provide clear authorship by name—for example, on surge protection system FOSs. Let the range of technical differences be defined by recognized experts within the respective professional field.
9. Ensure transparency in surge risk reduction planning and implementation. Monitor progress in new projects and maintenance of existing projects; routinely publish clear, complete, and concise status reports. Surge risk reduction projects have a history of gradually succumbing to competing interests despite the obvious public good and potential high benefit-to-cost ratio. The media and public watch dogs must stay vigilant to ensure that surge risk management priorities are effectively sustained.
10. Recognize that surge risk management is never finished. Leaders must invest in continuous improvement in all areas. They must be prepared to address increases in hazard estimates, to periodically re-evaluate risk reduction measures for gaps and weaknesses, and to fix them.

Ten Lessons for Hurricane Surge Protection Systems

1. When surge protection systems are built to complement implementation of the NFIP, understand the programmatic goals and limitations of the NFIP, NFIP hazard analysis, NFIP surge uncertainty treatment, NFIP overtopping analysis and *limited* FOS, and NFIP accreditation. (See Lessons 8 and 9

above.) Ensure that the public understands that NFIP surge protection systems leave considerable residual risk to life and property.

2. Surge protection systems can have significant adverse impacts on areas outside the system—both communities and coastal landscapes.
3. Additional life-saving and economic drivers for urban centers can warrant systems that exceed NFIP requirements: higher hazard level design, higher FOSs to address uncertainties in the 100-yr condition, and/or resiliency against greater storms. Understand what this entails and determine who will pay for and maintain system enhancements. Resiliency can be a better investment than more height—but there are many factors to consider: residual overtopping and breaching risks, authorizations, costs, long-term performance of resiliency measures, O&M, etc.
4. Some communities with excellent evacuation programs and modest uninsured exposure may be satisfied with a minimal NFIP levee system (e.g., minimal FOS). If NFIP credit becomes available for levees below 100-yr hazard, these may be optimal for some communities.
5. Don't allow federal support for design/construction to excuse local buy-in. **Local communities must regard themselves as the ultimate owner of the system and its limitations!** Remember the adage that "no one washes a rental car."
6. Understand the responsibilities as well as the limits of the federal agent—particularly if it is the USACE. Understand the special USACE culture of narrowly construing Congressional authorizations and the impact this will have on any need for flexibility in the face of new information. Also understand the typical timetable and budgeting approaches of the USACE.
7. Establish one local agent to represent the community as the co-sponsor for all NFIP surge protection system design, construction, and O&M decisions. This entity should also be the local NFIP coordinator and in charge of residual property risk reduction measures. This will facilitate clear lines of authority, responsibility, and ultimate accountability.
8. Monitor for inevitable design issues which pit cheaper/faster construction alternatives versus those with lower long-term O&M costs and headaches.
9. Ensure appropriate local funding commitment. Don't pursue alternatives with O&M budgets that the local community cannot afford. Provide perimeter systems that are "right sized" and carefully weigh decisions to encompass low density areas (especially wetlands). Leveeing canals may be preferable to enclosing them behind massive gated structures and pump stations that impose complex and expensive O&M requirements.
10. Make sure that the local community understands all long-term needs and costs associated with keeping NFIP accreditation, such as for levee lifts.

A Final Lesson: The Lake Okeechobee Herbert Hoover Dike

Lake Okeechobee in south Florida, shown in Figure 8—at over 700 square miles in area—is the second largest freshwater lake lying entirely within the lower 48 states. Lake Okeechobee is extremely shallow, averaging about 9 ft in depth. In 1928 a strong Category 4 hurricane made landfall near West Palm Beach Florida with winds of 145 mph. Residents along the shores of Lake Okeechobee—40 miles plus inland—thought themselves safe from surge.

However, a combination of long fetch, strong winds, and very shallow depth caused a severe "tilting" of the water surface, without any "filling" 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 Lake Okeechobee surge caused 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. The Herbert Hoover Dike has been raised several times and is currently about 30 ft above the surrounding ground.

Figure 8 compares the size and depth of Lake Okeechobee in Florida with Lake Pontchartrain. The NFIP 100-yr surge depth (above mean level) for the south shore of Lake Okeechobee is about 1 ft greater than for the south shore of Lake Pontchartrain. However, the crest freeboard for the Herbert Hoover Dike above the 100-yr surge is much greater than for the HSDRRS—by almost 10 ft. The catastrophic 1928 Lake Okeechobee Hurricane produced a surge reportedly 10 ft greater than the current NFIP 100-yr surge. On the other hand, Hurricane Katrina produced a surge about 3 ft above the 100-yr surge (uncorrected) at the New Orleans Lakefront. It is apparent that the Herbert Hoover Dike was not designed simply for NFIP accreditation.

Figure 8. Comparison of Lakes Pontchartrain and Okeechobee (Florida)
Google Earth Imagery (same scale)

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