Part I.
East-Bank Surge Inundation Hazard

Nola.com
http://photos.nola.com/tpphotos/2010/08/lakeview_in_the_katrina_flood.html

This Part summarizes the East-Bank 100- and 500-yr exterior surge hazard estimates; recent East-Bank hurricane surge events; the HSDRRS; and the surge inundation hazard for the three East-Bank polders. The exterior and overtopping hazard estimates have been partially revised in accordance with a comprehensive risk management perspective for 20 East-Bank HSDRRS locations, incorporating *reasonably conservative* treatments of uncertainty. This Part concludes with an overview of eight approaches to reducing East-Bank surge inundation hazard.

2. East-Bank Hurricane Surge Hazard

This Section presents information on the East-Bank hurricane surge hazard, including estimates of 100- and 500-yr surge hazard suited to comprehensive surge risk management purposes. The reader is strongly encouraged to review the *Supplement: **Hurricane Surge Hazard Primer***. This Primer summarizes important basic technical information (and terms) for surge phenomena, hazard, risk, uncertainty in surge hazard estimates, and the limitations of estimates under the NFIP. For a more detailed explanation of many key concepts, as well as references to important scientific literature, the reader should see the Bob Jacobsen PE May 2013 Report. The reader is cautioned that new information on regional surge hazard is constantly being developed by a number of sources, and some information can rapidly become dated.

2.1 Special Vulnerability of the East-Bank to Extreme Surges

The East-Bank has a unique vulnerability to extreme hurricane surge due to a combination of eight noteworthy factors:

1. The overall Southeast Louisiana region lies at the heart of the central-northern Gulf of Mexico, which is exposed to an exceptionally high landfall frequency of hurricanes due to the very warm waters of the Loop Current. The Loop Current fuels both hurricane intensification and the growth of wind fields. Figure 2.1 illustrates the relationship between the Loop Current and the 39 known hurricanes which reached Category 3 or higher in the Gulf of Mexico and subsequently made landfill along a 500-mile region centered on Southeast Louisiana—12 made landfall in Southeast Louisiana. Furthermore, and just as important for surge risks, the Loop Current sustains slow moving storms.
2. The protrusion of the Mississippi River delta into the central-northern Gulf of Mexico forms a natural “Wall” against which surge is driven by hurricane counterclockwise winds. This barrier contributes to a much greater surge hazard on the eastern versus western flank. Moreover, as illustrated in Figure 2.2, the intersection of the delta with the Mississippi coast creates a critical “Corner” in the northeast portion of the East-Bank. Surge heights exceeded 20 ft at the regional Corner twice in a 36-yr period (Camille 1969 and Katrina 2005).
3. Surge confinement in the East-Bank is exacerbated by river and hurricane protection levees. Two notable confinement features shown in Figure 2.3 are the “Funnel” produced by the junction of the Gulf Intracoastal Waterway (GIWW) and Mississippi River Gulf Outlet (MRGO) levees and the “Caernarvon Corner,” (east-bank of English Turn) which includes a combination of HSDRRS, Mississippi River, and local Plaquemines Parish levees.
4. The major East-Bank coastal sounds, bays, and lakes (e.g., Breton, Chandeleur, and Mississippi Sounds; Black and Eloi Bays, and Lakes Borne and Pontchartrain) are extremely shallow. These water bodies expand over surrounding marsh during a pre-landfall forerunner, are filled by the landfall main surge, and then become drastically tilted by strong, shifting winds as a hurricane passes overhead or nearby.

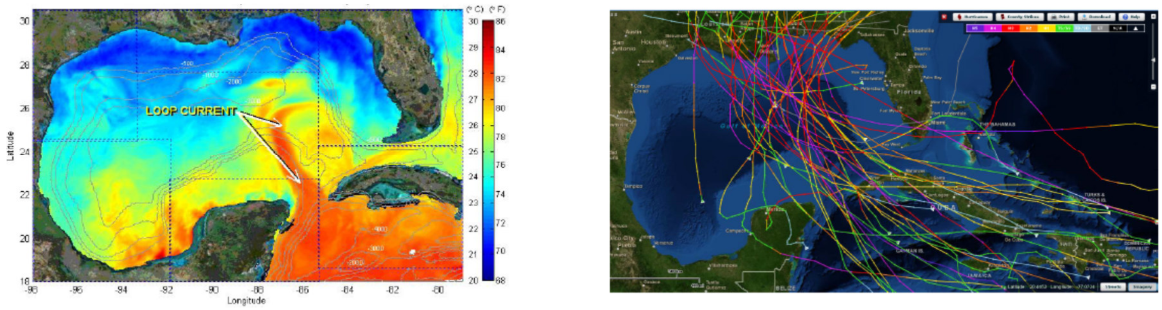

Figure 2.1. Relationship of Loop Current to Major Hurricanes in Central-Northern Gulf
WAVCIS, NOAA

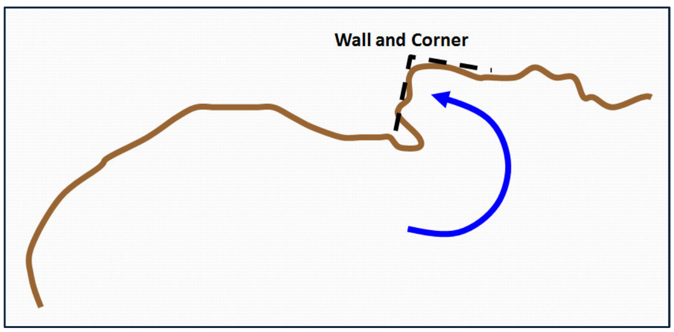

Figure 2.2. "Wall and Corner" Created by Protruding Mississippi River Delta

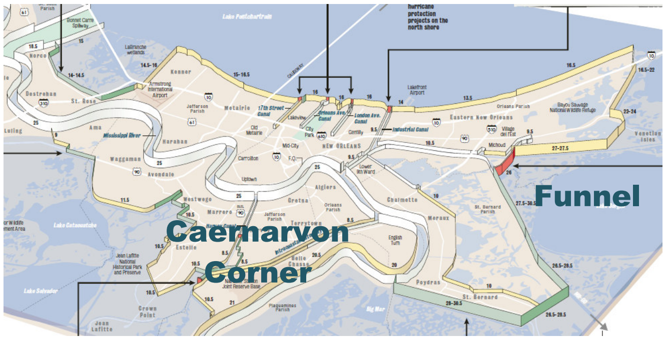

Figure 2.3. "Funnel" and "Caernarvon Corner"
Times-Picayune 2012

Figure 2.4. Mississippi River Levee Breach at ConocoPhillips Refinery

5. The vast low-lying delta platform on which the region rests is subsiding. The combination of subsidence and sea level rise results in one of the world's highest relative sea level rise (RSLR) rates—exceeding 1 cm/yr in parts of Plaquemines Parish (see Reed et al, 2009).
6. In addition to subsiding, abandoned delta lobes are rapidly fragmenting and eroding. Expanding shallow coastal sounds, bays, and lakes increase wind fetch and also surge conveyance.
7. Declining coastal forests reduce the landscape frictional drag on both extreme winds and surge.
8. Finally, if the Mississippi River is at moderate to high stage, inland propagation of surge, can threaten the integrity of the East-Bank River levee. Figure 2.4 shows one of two River levee breaches at the ConocoPhillips Refinery near Belle Chase from Hurricane Katrina surge. The two breaches were caused by levee overtopping, exacerbated by conditions at two adjacent loading docks, and resulted in extensive damage to the refinery.

2.2 The Current Hurricane Surge Hazard Estimate

In the wake of Hurricane Katrina, from 2005 to 2009 the USACE undertook a hurricane surge hazard analysis for Southeast Louisiana, including the East-Bank. In conducting the analysis the USACE employed considerable professional, academic, and other technical resources to greatly advance surge science and the practice of surge hazard analysis compared to what they were pre-Katrina. The surge hazard analysis supported four contemporaneous efforts by the USACE, the foremost being a regional NFIP Flood Insurance Study (FIS), sponsored by the Federal Emergency Management Agency (FEMA). The surge hazard analysis is documented in USACE, *Flood Insurance Study, Southeast Parishes of Louisiana, Intermediate Submission 2: Offshore Water Levels and Waves*, July 2008.[1] Three other purposes supported by the NFIP surge hazard analysis were:

- The design and construction of the NFIP HSDRRS (see Section 4 for a description of the HSDRRS). The development of 100-and Nominal 500-yr SWLs and associated H_s and T_p along the HSDRRS perimeter are documented in USACE, *HSDRRS Design Elevation Report (DER)*, Draft Report, Version 4a, December 2011.[2]
- An evaluation of post-Katrina polder surge inundation risks, led by the Interagency Performance Evaluation Task Force, (IPET), discussed further in Section 5. The entire IPET effort is documented in *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System*, Volumes I through VIII, 2006-09.
- Evaluation of 400- and 1,000-yr surge hazards and alternatives for additional coastal protection and restoration measures for reducing surge risks. The hazard analysis is documented in USACE, *Louisiana Coastal Protection and Restoration (LACPR)*, Final Technical Report, June 2009.

[1] The FIS surge hazard analysis is thus eight years old, with many methodology choices over a decade in age. Preliminary FIRMs are available online at:
www.lsuagcenter.com/en/family_home/home/design_construction/Laws+Licenses+Permits/Getting+a+Permit/Your+Flood+Zone/flood_maps/

[2] The USACE issued a new version retitled *Elevations for Design of Hurricane Protection Levees and Structures*, December 2014, which supersedes the HSDRRS *Design Elevation Report*, Version 4a, December 2011. This Setion was prepared in 2013 and does not include changes to 100- and 500-yr SWLs contained in the 2014 version.

Figure 2.5 shows twenty selected East-Bank HSDRRS locations.[3] Table 2.1 presents *partially revised* 100- and Nominal 500-yr estimates for the surge SWL, and wave H_s and T_p at these SWLs, for these locations. The following is a discussion of the accuracy of the USACE NFIP East-Bank surge hazard estimates, potential sources of bias, and the partial revision of the USACE estimates.

Note than in Southeast Louisiana Local Mean Sea Level (LMSL) along the open coast is about 0.2 NAVD88 (at Grand Isle) and is rises slightly progressively through the coastal sounds, bays, and lakes—to about 0.5 NAVD88 in Lake Pontchartrain. Due to steric and seasonal meteorological conditions, during late summer and early fall it is not unusual for Grand Isle and Lake Pontchartrain to have average SWLs remain at 0.5 and 1 ft above LMSL, with a high tide potentially adding 1 and 0.3 ft, for pre-surge peak SWLs of 1.7 and 1.8 ft NAVD88, respectively.

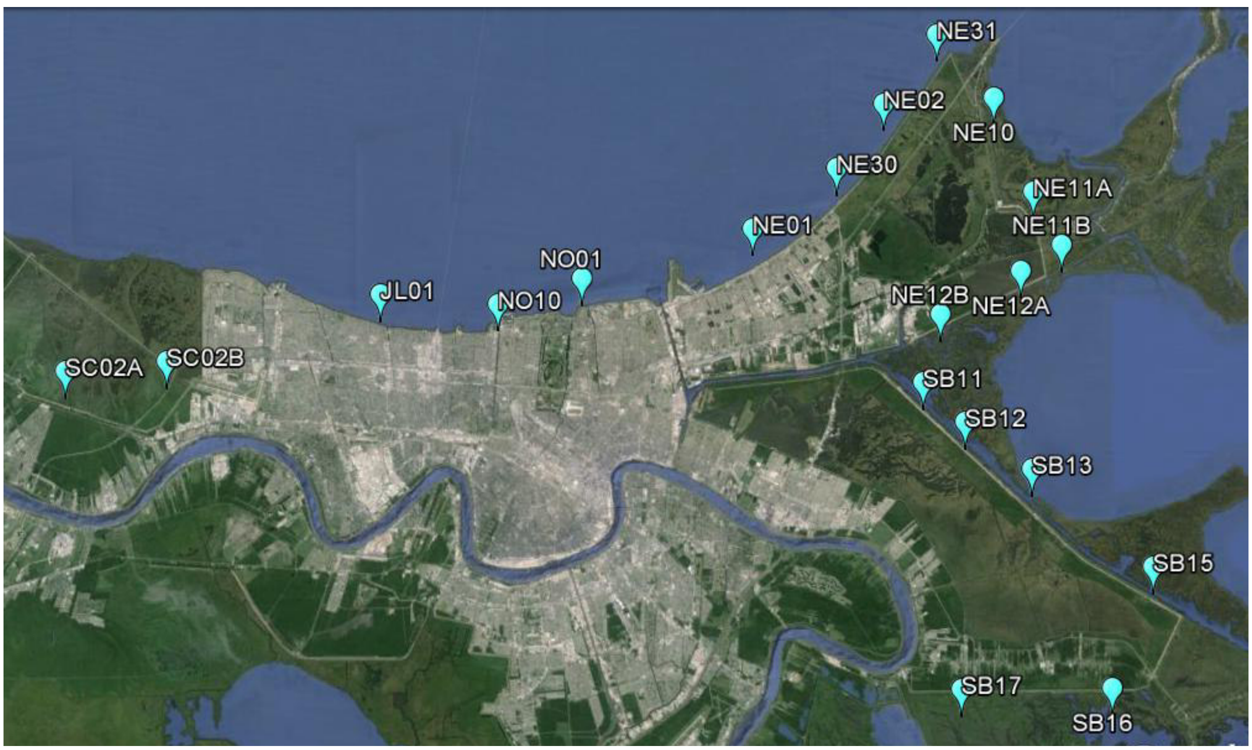

Figure 2.5. East-Bank Surge Hazard Locations

[3] The USACE has determined that river flood design elevations of the East-Bank Mississippi River levees exceed the 100-yr estimate for up-river surge, factoring in potential river flow variability. Therefore they did not designate any East-Bank portions as "co-located" with the HSDRRS. There are significant accuracy and uncertainty issues with the up-river surge estimate (see Bob Jacobsen PE April 2013) but this Report focuses on East-Bank surge hazards along designated HSDRRS.

Table 2.1. 100- and Nominal 500-yr Surge Hazards at Twenty East-Bank Locations (Partially Revised)*

Location	100-yr							Nominal 500-yr						
	SWL			Waves at SWL50				SWL			Waves at SWL50			
	SWL50	SWLσ	SWL90	H_s	$H_s σ$	T_P	$T_P σ$	SWL50	SWLσ	SWL90	H_s	$H_s σ$	T_P	$T_P σ$
	ft NAVD88	ft	ft NAVD88	ft	ft	s	s	ft NAVD88	ft	ft NAVD88	ft	ft	s	s
SC02-A	12.1	3.03	15.97	4.84	0.48	4.20	0.84	15.6	4.68	21.59	6.24	0.62	5.60	1.12
SC02-B	11.6	2.90	15.31	4.64	0.46	3.20	0.64	15.1	4.53	20.90	6.04	0.60	4.10	0.82
JL01	9.7	2.43	12.80	3.88	0.39	7.70	1.54	12.2	3.66	16.88	4.88	0.49	9.00	1.80
NO01	9.6	2.40	12.67	5.44	0.54	7.20	1.44	12.2	3.66	16.88	6.48	0.65	8.50	1.70
NO10	9.8	2.45	12.94	2.72	0.27	7.20	1.44	12.3	3.69	17.02	3.72	0.37	8.50	1.70
NE01	9.4	2.35	12.41	2.19	0.22	6.70	1.34	11.7	3.51	16.19	2.73	0.27	6.70	1.34
NE02	9.4	2.35	12.41	3.89	0.39	6.70	1.34	11.7	3.51	16.19	4.75	0.48	6.70	1.34
NE10	11.2	2.80	14.78	4.48	0.45	5.39	1.08	14.2	4.26	19.65	5.68	0.57	6.38	1.28
NE11A	14.7	3.68	19.40	5.88	0.59	8.25	1.65	18.2	5.46	25.19	7.28	0.73	9.90	1.98
NE11B	16.2	4.05	21.38	6.48	0.65	7.70	1.54	19.9	5.97	27.54	7.96	0.80	8.91	1.78
NE12A	17.2	4.30	22.70	6.88	0.69	8.03	1.61	21.1	6.33	29.20	8.44	0.84	9.02	1.80
NE12B	18.2	4.55	24.02	7.28	0.73	7.92	1.58	22.3	6.69	30.86	8.92	0.89	8.91	1.78
NE30	9.3	2.33	12.28	3.11	0.31	6.70	1.34	11.6	3.48	16.05	3.81	0.38	6.70	1.34
NE31	9.5	2.38	12.54	3.80	0.38	6.70	1.34	12.0	3.60	16.61	4.80	0.48	6.70	1.34
SB11	18.8	4.70	24.82	7.52	0.75	7.92	1.58	23.1	6.93	31.97	9.24	0.92	8.91	1.78
SB12	17.6	4.40	23.23	7.04	0.70	5.94	1.19	21.7	6.51	30.03	8.68	0.87	6.93	1.39
SB13	17.6	4.40	23.23	7.04	0.70	6.27	1.25	21.7	6.51	30.03	8.68	0.87	14.30	2.86
SB15	14.9	3.73	19.67	5.96	0.60	8.91	1.78	18.2	5.46	25.19	7.28	0.73	14.41	2.88
SB16	17.3	4.33	22.84	6.92	0.69	8.36	1.67	21.2	6.36	29.34	8.48	0.85	10.56	2.11
SB17	18.2	4.55	24.02	7.28	0.73	8.14	1.63	22.6	6.78	31.28	9.04	0.90	9.90	1.98

* Estimates have been revised from those reported in the USACE 2011 *DER* to better support ***local comprehensive surge risk management*** (see *Supplement* and Bob Jacobsen PE March 2015 Report, included as Appendix C). $H_s σ$ is 10 percent of H_s. T_P and $T_P σ$ are unchanged. SWL50 is the expected value. SWLσ is a reasonably conservative estimate of SWL uncertainty for development of confidence intervals. The 100- and 500-yr SWLσ are 25 and 30 percent of the respective SWL50. SWL90 is the 90 percent non-exceedance level, which is equivalent to the upper limit of the 80 percent confidence interval. The 100- and Nominal 500-yr H_s are 40 percent of the depth at the SWL50 (depends on toe elevation); NE01, NE02, and NE30 have lower H_S due to breakwaters.

Accuracy of the FIS Surge Hazard Estimate
The Bob Jacobsen PE May 2013 Report *Hurricane Surge Hazard Analysis: The State of the Practice and Recent Applications for Southeast Louisiana* identified three major aspects of the USACE FIS analysis that are not considered reasonable today for *comprehensive surge risk management purposes*—and that likely result in significant underestimation of 100- and 500-yr SWL at many locations:

1. The joint probability expression describing the hurricane climatology did not take into account the contribution of large, slow-moving, low intensity storms that never reach Category 3 in the Gulf of Mexico. For some locations this could understate the 100-yr SWL by more than 1 ft.
2. The FIS ADCIRC model mesh; topographic, bathymetric, and land cover data; physics representing wind-surge-wave interactions; and steps for ensuring local mass conservation are outdated. The FIS model produced local errors in sensitive areas within the East-Bank region.[4] The Hurricane Katrina validation described an under-estimation of more than 1.5 ft along the south shore of Lake Pontchartrain.[5]
3. The analysis relied on a smooth Surge-Response assumption, utilizing a small Surge-Response OS of 152 storms. Southeast Louisiana's complex, shallow coastline—with large interior sheltered water bodies—indicates that surge response is likely to be very nonlinear. In particular, an appropriate Surge-Response OS should include a larger range of tracks and forward speeds, in combination with varying intensity, size, wind-field shape, pre-storm meteorology, and rainfall. An adequate Surge-Response OS for sever risk management requires landfalling Category 5 hurricanes, which were not previously included. These limitations in the Surge-Response are likely to result in the under-prediction of surge hazards, particularly for extreme return periods.

The 100- and Nominal 500-yr SWL hazards given in Table 2.1 reflect (do not update for) these three outdated practices in the FIS analysis. These biases significantly affect the use of the 100-yr estimate—and especially the Nominal 500-yr estimate—for risk management purposes *beyond the NFIP*.[6] Thus, for purposes of comprehensive surge risk management, the Bob Jacobsen PE May 2013 report recommended that a revised surge hazard analysis be performed to correct these three biases and to update other outdated practices.

In a parallel 2013 review of the USACE FIS surge hazard analysis Woods Hole Group (WHG) identified a discrepancy in the USACE's FORTRAN code for computing the surge SWL hazard cumulative distribution function (CDF) curves. The March 2015 Bob Jacobsen PE Report (included as Appendix C) reviews this discrepancy.[7] The Table 2.1 median estimates of the 100- and Nominal 500-yr SWL (100- and 500-yr SWL50) for the 20 locations (provided by WHG) revise the USACE estimates to correct this discrepancy. The revised 100-yr SWL50 have an average increase of 0.4 ft, with higher increases along the western Lakefront. The Jefferson Parish Lakefront is listed as 9.7 ft in Table 2.1, compared to the USACE's value of 9.0 ft in the *DER*. The presentation of revised SWL50 values in Table 2.1 is consistent with comprehensive risk management objectives. (Revised values are not necessarily required for NFIP

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[4] Model bias is quantified by evaluating the correlation between predicted (hindcast) versus observed surge.

[5] As with riverine flood models, surge response models are not perfect and typically have some systemic and local bias. When a modeler identifies significant bias it is then up to those performing the surge hazard analysis to determine if it is appropriate to factor the bias into the estimate of surge hazard.

[6] The potential effect of these three biases on the FIS and HSDRRS accreditation requires a careful assessment of NFIP policies for bias tolerances, which is beyond the scope of this Report.

[7] The WHG review of the USACE FORTRAN code implementing the CDF numerical integration found that the epsilon term was applied at half its value, and in addition contained several typographical errors.

purposes.) Because they do not correct for other potential bias and outdating issues, the Table 2.1 values should only be regarded as *partial revisions*.

Interesting items regarding the Table 2.1 SWL hazard estimates include:

- The 100-yr SWLs range from 9.3 to 18.8 ft NAVD88.
- The Nominal 500-yr SWLs range from 11.6 to 23.1 ft NAVD88.
- The differences between the Nominal 500- and 100-yr SWLs range from 2.3 to 4.4 ft.
- Hazards along the south-central shore of Lake Pontchartrain are lower than along the south-west and south-east shores. This is due to higher cross-lake fetch length for south-west and south-east shore locations.
- The highest hazards are at the Funnel and Caernarvon Corner. The Funnel now includes the IHNC Surge Barrier (see Section 4). Prior to including the IHNC Surge Barrier, estimates of Funnel I00-yr surge SWL were about 1.5 to 2 ft lower.

The Bob Jacobsen PE May 2013 and March 2015 reports also discuss issues with USACE procedure for estimating inland 100- and Nominal 500-yr H_s.[8] To better support surge residual risk management, Table 2.1 values for 100-yr and Nominal 500-yr H_s apply a value of 0.4 for depth-based H_s for all locations, except those with fronting breakwaters. Because 100- and 500-yr SWL values have only been partially revised, the Table 2.1 values for H_s should also be regarded as partial revisions. The Table 2.1 values for T_p are those provided by the USACE.

Uncertainty of the East Bank Surge Hazard Estimate
The USACE's FIS analysis followed an NFIP approach to characterizing surge hazard uncertainty. The FIS analysis defined σ values for a few Surge-Response uncertainty factors (see Resio et al 2012) which it assigned to the epsilon σ:

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

A combined epsilon σ value is about $\sqrt{2^2 + (0.15*SWL)^2}$. The USACE analysis then incorporated this epsilon into the surge hazard CDF. As noted above, Table 2.1 reflects a revision of the USACE's SWL50 estimates to correct a discrepancy in their FORTRAN code implementing the numerical integration with epsilon.

The USACE analysis set the σ for confidence intervals using only an estimate of only hurricane sampling uncertainty. Other sources of uncertainties not used in epsilon, including important local uncertainties, were not used in developing the σ for surge hazard confidence intervals. The USACE estimates for hurricane sampling uncertainty were developed using the residual error in the fit of a Gumbel EVF curve to the SWL CDFs.[9] This hurricane sampling uncertainty estimate has three key limitations:

1. The Gumbel curve type is used as the basis for the hurricane intensity return frequency (and thus the Hurricane Joint Probability Function that is used to construct the CDF)—which influences the fit of a Gumbel curve to the CDF.

[8] Inland H_S values do not appear to properly reflect the design assumption that there will be no wave energy lost due to fronting vegetation.
[9] See *Estimation of Confidence Bands for Surge Estimates*, Appendix G in Resio et al 2007.

2. The frequency values for the points used to create the CDF do not reflect uncertainties in the joint probability equation; thus they reflect insufficient scatter.
3. The residual error estimate was based on characterizing the record length as 6.1 times longer than its actual length (396 versus 65 years), based on employing a hurricane record for a coastal region 6.1 times longer than the FIS region. Regarding the record length as this much larger allows the confidence interval to be reduced by a factor of 2.47, which would not be reasonably conservative for purposes beyond the NFIP.

The USACE values of the 100-yr hurricane sampling uncertainty σ were generally **less than 10 percent of SWL** for the East-Bank.[10]

The Bob Jacobsen March 2015 Report (see Appendix C, Attachment A) discusses an alternate, reasonably conservative σ for confidence intervals. For East-Bank comprehensive surge risk management three adjustments are made to the USACE σ:

i. Rather than using a 396-yr sample period, hurricane sampling uncertainty σ is developed using the actual record length of 65 years. The alternative value is consistent with the observed Grand Isle SWL-frequency record (see *Supplement*, Figure 4). The alternative hurricane sampling uncertainty σ values are 15 to 20 percent of SWL for the East-Bank.
ii. An estimate for the residual error in the fit of surge-response functions to OS is included, with an additional σ value of 15 to 20 percent of SWL.
iii. A combined σ value of 10 to 15 percent of SWL is included for the other five uncertainty factors (hurricane record representativeness, local variations in the wind/surge/wave hindcast error, other meteorological conditions, wind drag, and OS representativeness).

The combination of all three components indicates that a reasonably conservative value for the 100-yr σ-confidence limits is on the order of 23.5 to 32 percent—or about three times greater than used for the NFIP analysis. It is important to acknowledge that assuming a σ of this greater magnitude implies upper and lower confidence limits that may become unrealistic for intervals which are too extreme.[11]

Table 2.1 presents 100-yr and Nominal 500-yr SWLσ values for the twenty locations—based on using 25 and 30 percent, respectively—together with 100- and Nominal 500-yr SWL90 values. Again, while not required for NFIP purposes, the SWLσ values in Table 2.1 are appropriate for residual risk management. Because 100- and 500-yr SWL50 values have only been partially corrected, the Table 2.1 values for SWLσ and SWL90 should also be regarded as partial revisions. Table 2.1 applies the USACE suggested H_sσ and T_pσ of 10 and 20 percent respectively. The H_sσ is applied to the revised H_s values.

Importantly, the reasonably conservative 100-yr SWL90 values exceed the Nominal 500-yr SWL50 values at all twenty locations! The magnitude of uncertainty in the East-Bank SWL hazard is illustrated in Figure 2.6. The large uncertainty in just what is the SWL associated with the 100-yr return also implies great uncertainty for the return period associated with a particular SWL. Estimates of 100- and 500-yr return periods could easily be off by a factor of two: true return periods might be 50 and 250 years. ***Thus, surge hazard estimates should really be regarded as Scientific Guesstimates!***

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

[11] For a σ of 30 percent, the SWL01 and SWL99 (the lower and upper limit of a 98 percent confidence interval) equal 0.3*SWL and 1.7*SWL—or 3 and 17 ft for a 100-yr SWL of 10 ft. Further research is needed to determine if using a slightly truncated normal distribution, or other distribution, could be appropriate.

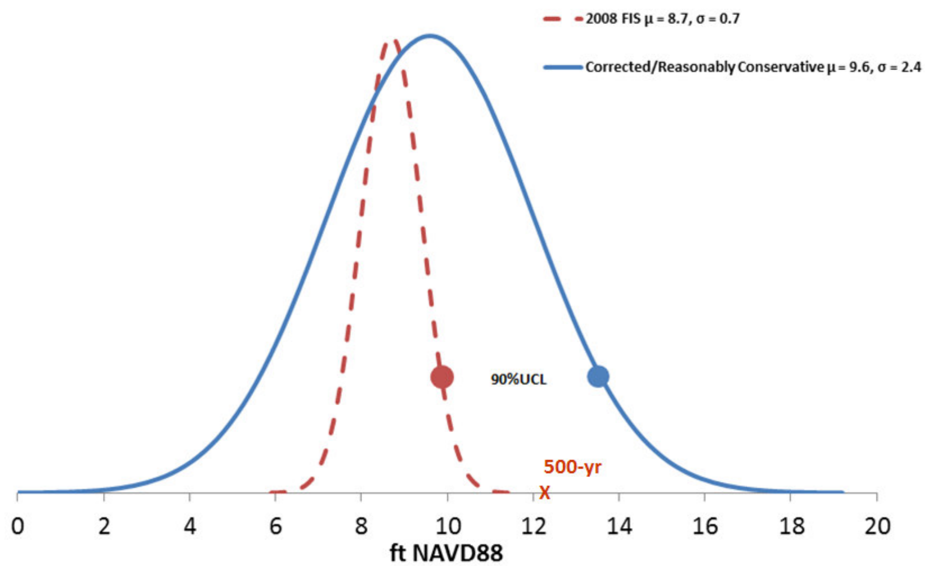


Figure 2.6. Example of East-Bank 100-yr Surge Hazard Uncertainty

2.3 Future Changes in the Hurricane Surge Hazard Estimate

Local/regional agencies like SLFPA-E with grave surge risk management responsibilities must also consider non-stationary issues, including trends for hurricane climatology and coastal landscape which could render current surge hazard estimates obsolete. Potential future increases in hurricane frequency, intensity, and size for the Gulf of Mexico—particularly in light of global climate change—are the subject of research. However, while the effect of atmospheric and ocean temperature *cycles* (such as El Niño and the North Atlantic Oscillation) is widely recognized, there is presently no consensus on long-term *trends* for Gulf hurricane climatology.

Five key landscape trends for Southeast Louisiana include:

1. Regional subsidence. Long-term regional subsidence–which occurs somewhat episodically–is about 0.2 ft per decade in Grand Isle and higher in lower Plaquemines Parish (Reed et al 2009). Farther north, in New Orleans the rate may be closer to 0.1 ft per decade.
2. Sea level rise (SLR). The current long-term "natural or background" SLR is about 0.1 ft per decade. Current observed relative sea-level rise (RSLR)—the combined sea-level rise and subsidence—is 0.3 ft per decade at Grand Isle (9.24 mm/yr, NOAA 2014). Coastal planners expect "anthropogenic SLR" to accelerate in the future, and presently estimate there will be an additional 1 ft of SLR for a 50-yr horizon, or a total SLR of 1.5 ft. *A regional average value for Southeast Louisiana RSLR over a 50-yr horizon is 2 ft (consistent with the Louisiana CPRA 2012 less optimistic value).*
3. Coastal land loss. The combination of RSLR and erosion is converting 16 square miles of sub-aerial land to open water each year.
4. Vegetation changes. Subsidence and salinity increases associated with coastal land loss are causing the conversion of fresh-water swamp forests to brackish water marshes, and other changes in vegetation regimes (see Visser et al 2012).

5. Localized settlement of HSDRRS main and foreshore structures. Structures with well consolidated foundation soils have settlement rates generally less than 1 ft per decade, but which are higher than the regional subsidence rates. Structures recently built or raised over low strength sub-soils (such as levees in St. Charles Parish) can have current settlement rates exceeding 2 ft per decade. (One small segment west of Louis Armstrong Airport has an overall current settlement plus subsidence rate of 3.1 ft per decade.) Settlement rates for these levees should slow down in ensuing decades as the foundation soils consolidate.

Smith et al 2010 examined the combined effect of Trends 1 – 4 and indicated that a complete, widespread devastation of coastal wetlands could result in 100-yr surge increases that are twice RSLR alone. *The increase in 100-yr surge over a 50-yr horizon—due to 2 ft of RSLR plus coastal land loss and vegetation change—can thus be considered to be in the range of 3 to 4 ft.*

Besides landscape trends, 100- and 500-yr East-Bank surge hazards can be affected by proposed projects, especially ones that exacerbate major regional surge confinement. Examples include:

- A surge barrier at NO East Land-Bridge.
- Surge protection levees in Plaquemines, St. Tammany, and St. John the Baptist Parishes.
- Changes to Mississippi River levees in Plaquemines Parish

The height of more frequent surges can also be affected by changes in major conveyance channels. The MRGO closure structure at Bayou LaLoutre has probably changed surge conditions both inside and outside the structure. Part V of the Bob Jacobsen PE May 2013 report included an extensive discussion of how the impact of landscape trends and proposed projects on surge hazard can be assessed.

In addition to non-stationary issues, surge hazard estimates are likely to change with further methodological improvements resulting from more research. The Bob Jacobsen PE May 2013 report also included numerous recommendations for updating the East-Bank surge hazard analysis, as well as key topics for research. While continuing methodological improvements may raise SWL50 estimates, importantly, as depicted in Figure 2.7, these may not appreciably reduce reasonably conservative estimates of upper confidence limits.

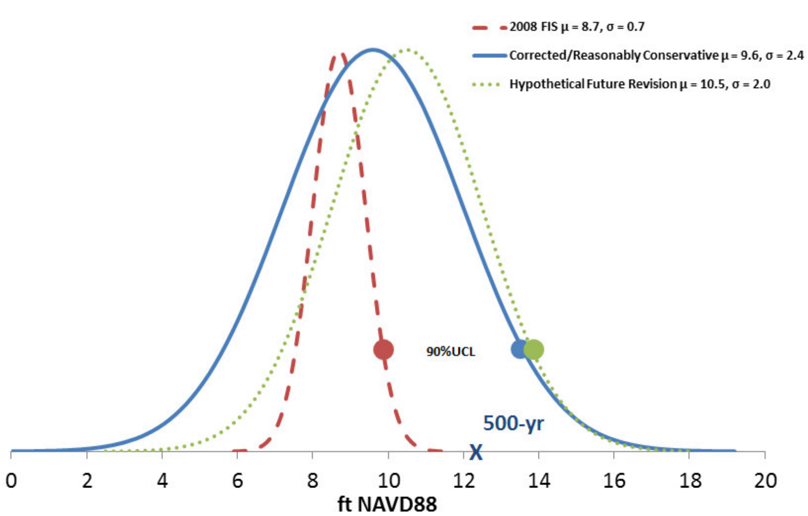


Figure 2.7. Example of East-Bank 100-yr Future Surge Hazard Uncertainty

3. Recent East-Bank Hurricane Surge Events

To enhance understanding of surge phenomena, hazard, and risk, the following sections review key meteorological and peak SWL information—along with some information on surge consequences—for three recent East-Bank surge events: Hurricane Katrina (2005), Hurricane Gustav (2008), and Hurricane Isaac (2012). Data on waves associated with peak surge SWLs adjacent to the East-Bank HSDRRS are available only for one location (Lake Pontchartrain) during Hurricane Katrina.

3.1 Hurricane Katrina

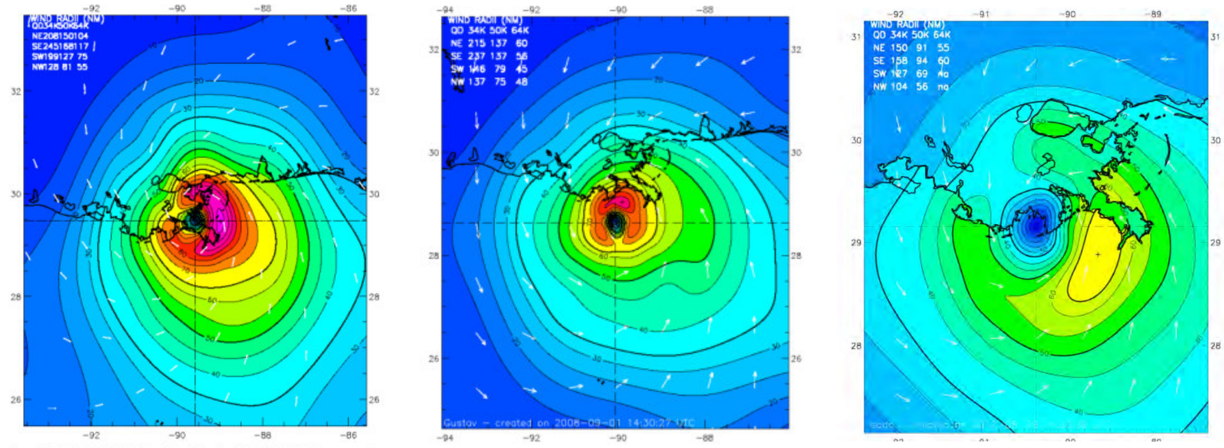
Hurricane Katrina was one of 28 named tropical cyclones, 15 hurricanes, and four hurricanes to reach Category 5 intensity, in the very active 2005 Atlantic hurricane season. It was one of six hurricanes in the Gulf of Mexico that year, and one of three hurricanes to make landfall in Louisiana. Hurricane Katrina intensified to Category 5 as it passed over the Loop Current, becoming the seventh strongest Atlantic hurricane on record (based on its lowest observed central pressure, 902 mb). Maximum wind speeds at the time were 175 mph. The storm's radius of maximum winds and extent of hurricane and tropical storm force winds 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). Hurricane Katrina's peak IKE (over 120 terajoules, TJ) is estimated to be the second highest on record

Hurricane Katrina's Category 5 peak intensity is not a rarity for the Gulf of Mexico: ten hurricanes have reached Category 5 in the Gulf over the period from 1851 to 2013—an observed annual frequency of over 5 percent, or an average return period of less than 20 years. Hurricane Katrina's large size and IKE at Category 5 intensity make it rarer—with an arguable observed return frequency in the Gulf of Mexico at 1/162, or 0.62 percent. Curve fitting to all the observed Gulf of Mexico hurricanes could well produce an estimate of return frequency well above or below this observed frequency.

However impressive Hurricane Katrina was at its peak, more important for surge impact were Hurricane Katrina's characteristics at landfall in Buras, Louisiana (see Figure 3.1). With typical infilling, the storm core decayed to top winds of 126 mph (a strong Category 3), while the central pressure remained very low, at 920 mb. But as is common, the wind-field spread out, with radius of maximum winds and extent of hurricane and tropical storm force winds growing to 40, 135, and 282 miles, respectively. Katrina's landfall IKE was estimated to have remained near its peak value. The storm's forward speed was a rapid 15 mph. Hurricane Katrina retained top winds of 120 mph as it traveled northward on a track east of New Orleans, across Breton and Mississippi Sounds to another landfall near Waveland, Mississippi.

A landfalling Category 3 or higher hurricane is **not** a rare event for Southeast Louisiana, with a recently suggested return period of about 16 years (and 90 percent confidence intervals of ±4 years). A *strong* Category 3 storm with winds at 126 mph has a much longer return period, at about 40 years. (Hurricane Katrina's low landfall central pressure has an even longer return period; however it is more appropriate to base a return period on maximum wind speed than central pressure). It has been estimated that Hurricane Katrina's large *core* increased its return period by at least 42 percent,[12] which would increase

[12] The USACE estimated the landfall central pressure return period at about 340 years, and the overall return period with radius to maximum winds at 398 years, a 42 percent increase.



Hurricane Katrina Hurricane Gustav Hurricane Isaac

Figure 3.1 Hurricane Wind-Fields (H*Winds)
NOAA-HRD (AOML)

the Southeast Louisiana landfall return period to about 60 years. As a comparison, Hurricane Betsy (1965) made landfall in Southeast Louisiana with peak winds approaching 150 mph and a radius of maximum wind of about 80 miles. Two other damaging Category 4 storms made Southeast Louisiana landfalls in 1856, 1893, and 1915. Thus, as a local wind-field event for Southeast Louisiana—dominated by the storm's core characteristics—Hurricane Katrina is not that rare.

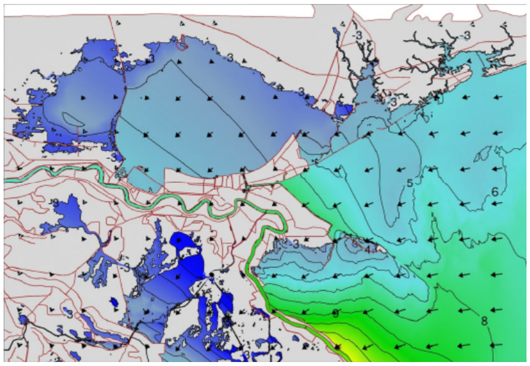
Katrina's large, extended landfall *wind-field*, as evidenced by its IKE, was arguably unique among recorded Gulf hurricanes.[13] Katrina's large wind-field caused significant surge impacts a great distance from the landfall location—as far away as northwest Florida. However, compared to Katrina's core characteristics, the very large IKE, when combined with the fact that Katrina was not a slow-moving storm, played much less of a role in Southeast Louisiana surge conditions.

Hurricane Katrina did not produce a large forerunner.[14] However, the storm's strong, sustained, large core—with eye-wall winds above 120 mph lasting for several hours during its passage east of New Orleans—created massive setup against regional raised topographic features. The evolution of Hurricane Katrina's surge SWL is shown in Figure 3.2. This figure clearly shows the combined influence of the delta and regional levees in confining the surge, and thus dramatically raising surge heights. The role of the levees along the GIWW and MRGO in creating a very high surge at the Funnel is also manifest.[15] Without the current IHNC Surge Barrier, the interior GIWW/MRGO channel conveyed surge into the IHNC Basin. Katrina produced surge peaks of 15 ft NAVD88 in the GIWW east of Paris Road Bridge and 14 ft NAVD88 at the south end of the IHNC, both exceeding local protection system crowns.

[13] Statistical analysis of Katrina's landfalling IKE are not available but could justify a return period of several centuries for a particular track. Estimated wind speeds in Breton Sound may have approached a similar return period.

[14] Hurricane Rita later added more water to Lake Pontchartrain and produced a higher setup on the Lake's west shore.

[15] The impacts of confinement in The Funnel far outweigh those of channel conveyance or declining vegetation resistance. Given the great depth of surge propagating across the entire expanse facing the Funnel, the outer reaches of the GIWW and MRGO played minor roles in conveying surge. The GIWW and MRGO no doubt played a significant role in decades of degradation to the wetlands in the Funnel and eastward to Biloxi Marsh. While loss of these wetlands influences *modest* surge events, as well tides, which in turn are further accelerating wetland loss, their influence on *extreme* surges is small compared to the impact of the regional levees.



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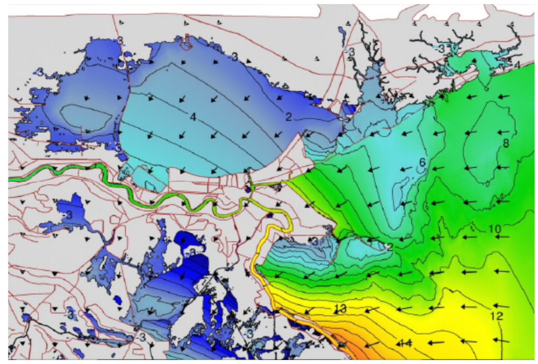

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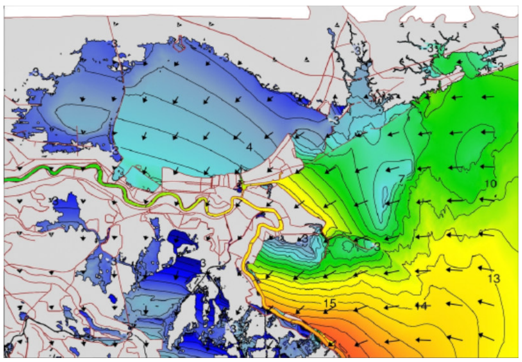

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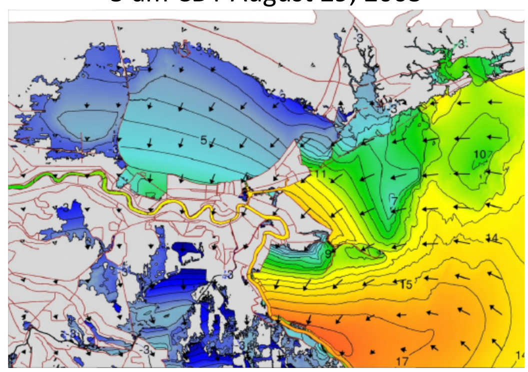

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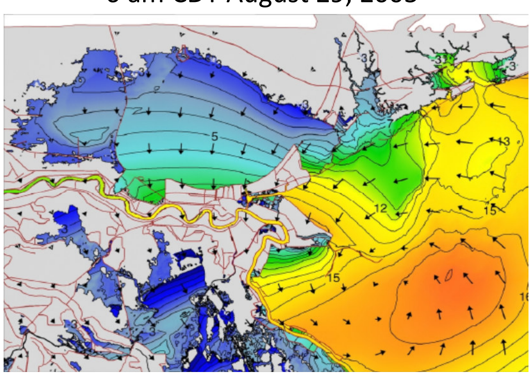

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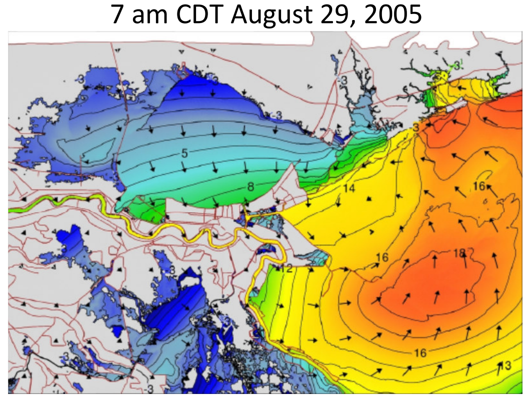

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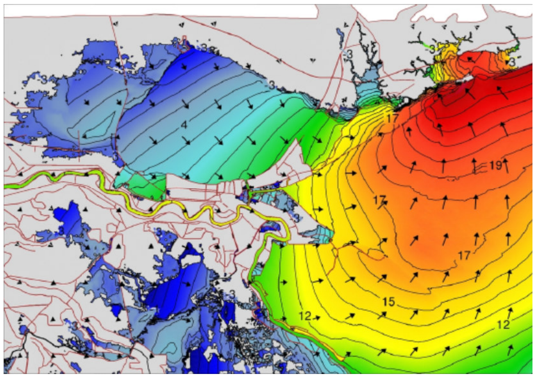
Figure 3.2. Hurricane Katrina Surge SWL

USACE 2008



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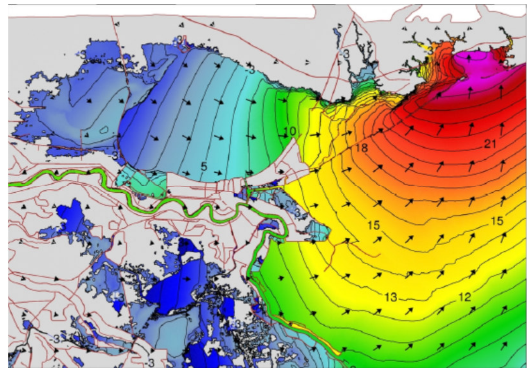

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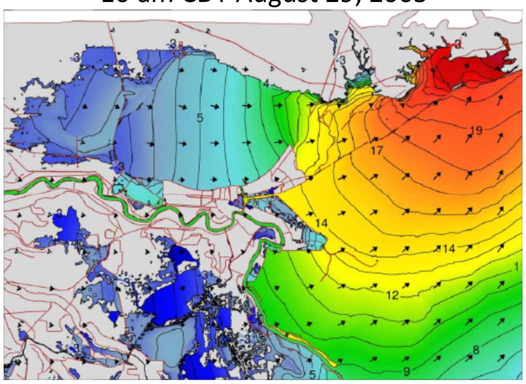

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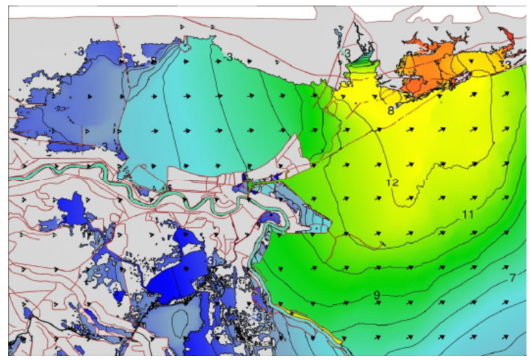

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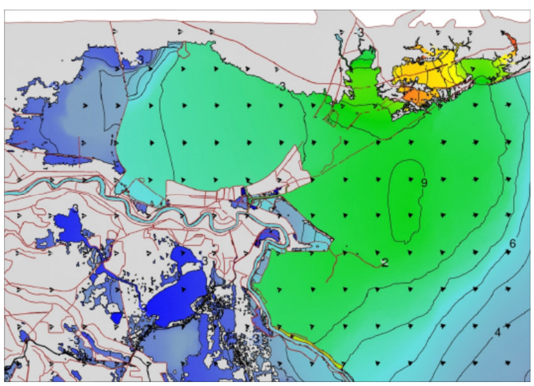

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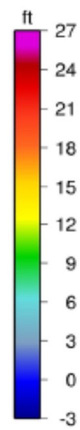

Surge Elevation (NAVD88)

Figure 3.2. (continued) Hurricane Katrina Surge SWL
USACE 2008

Also of note in Figure 3.2 is the pattern in which Lake Pontchartrain is tilted—first to the west, then to the south, and finally to the east. As winds shifted to the east, and surge became confined on the east end of the Lake, and decks on the Interstate "Twin Span" bridge were lifted from the piers.

Table 3.1 presents estimated peak Katrina SWL levels at the 20 locations shown on Figure 2.5, along with the partially corrected values presented in Table 2.1 for 100- and Nominal 500-yr SWL50 and SWL90. Katrina surges exceeded the 100-yr SWL50s at 10 of the 20 locations, including all seven reaches along Lake Pontchartrain in Orleans Parish (NO1, NO10, NE01, NE02, NE30, NE31, and NE10) and three along the MRGO. At four NO East locations the Katrina peak surges exceeded 100-yr SWL90s. These same four locations, plus one along the MRGO, exceeded the Nominal 500-yr SWL50. The post-Katrina surge barriers have no doubt raised SWL hazard values in the Funnel area. However, the issues reviewed in Section 2.2 mean that some SWL hazard values for Lake Pontchartrain may be significantly underestimated. Katrina clearly produced a more extreme return period surge event along the Funnel than in Lake Pontchartrain.

Using partial data from two temporary buoys and wave modeling, the USACE estimated Katrina peak H_s in Lake Pontchartrain (off the south shore) at 10 ft. For an estimated total depth of nearly 20 ft (bathymetry at -12 and surge at +8 ft NAVD88), this equates to 50 percent of depth (Smith 2007).

Overtopping and breaching of the East-Bank regional hurricane surge protection system during Hurricane Katrina caused disastrous flooding in the three major polders.[16] Figure 3.3 illustrates the maximum extent of polder flooding (wetland areas are excluded). The following six perimeter segments (and their associated polders) all experienced heavy overtopping:

1. MRGO Levee, St. Bernard.
2. GIWW Levee and I-Walls west of Michoud (Citrus Back Levee), NO East.
3. GIWW Levee east of Michoud (Back Levee), NO East.
4. IHNC Western I-Wall and Levee, Metro
5. IHNC Eastern I-Wall and Levees, St. Bernard.
6. IHNC Eastern I-Wall and Levees, including behind Lakefront Airport. NO East.

These six segments all included locations with major "erosion breaches" associated with the overtopping.[17] Five perimeter segments had major "collapse breaches"—all at I-Wall structures[18]—which occurred prior to surge levels reaching wall crowns due to design defects. These segments and affected polder were:

1. IHNC Eastern I-Wall just south of Pump Station 5, St. Bernard.
2. IHNC Eastern I-Wall, NO East.
3. London Avenue Canal (North), Eastern I-Wall, Metro.
4. London Avenue Canal (South), Western I-Wall, Metro.
5. 17th Street Canal, Eastern I-Wall, Metro.

[16] See three detailed forensic investigations by IPET, 2006 – 2009; Team Louisiana, 2006; and Independent Investigation Levee Team, 2006.

[17] Some wave erosion prior to overtopping may have occurred on MRGO levees constructed from hydraulic fill.

[18] See Section 4.2 for description.

Table 3.1. Comparison of Recent East-Bank Peak Surge SWLs and Partially Revised Surge Hazards at Twenty East-Bank Locations

All SWLs in NAVD-88

	Estimated Peak SWL			100-yr		Nominal 500-yr	
Location	**Katrina[19]**	**Gustav[20]**	**Isaac[21]**	**SWL50**	**SWL90**	**SWL50**	**SWL90**
SC02-A	5.5	5.0	7.5	12.1	15.97	15.6	21.59
SC02-B	6.0	4.8	7.0	11.6	15.31	15.1	20.90
JL01	7.0	4.6	6.5	9.7	12.80	12.2	16.88
NO01	11.8	4.6	6.0	9.6	12.67	12.2	16.88
NO10	11.0	4.6	6.0	9.8	12.94	12.3	17.02
NE01	13.0	4.5	6.2	9.4	12.41	11.7	16.19
NE02	13.7	4.7	6.3	9.4	12.41	11.7	16.19
NE10	14.0	5.0	6.0	11.2	14.78	14.2	19.65
NE11A	14.2	8.0	7.0	14.7	19.40	18.2	25.19
NE11B	14.7	10.0	8.5	16.2	21.38	19.9	27.54
NE12A	15.0	12.0	7.0	17.2	22.70	21.1	29.20
NE12B	16.0	14.0	6.3	18.2	24.02	22.3	30.86
NE30	13.5	4.6	6.4	9.3	12.28	11.6	16.05
NE31	13.8	4.8	6.3	9.5	12.54	12.0	16.61
SB11	18.0	14.0	5.0	18.8	24.82	23.1	31.97
SB12	19.0	12.5	6.0	17.6	23.23	21.7	30.03
SB13	19.5	11.3	8.0	17.6	23.23	21.7	30.03
SB15	19.0	8.0	10.5	14.9	19.67	18.2	25.19
SB16	15.0	8.0	11.3	17.3	22.84	21.2	29.34
SB17	11.5	8.2	13.5	18.2	24.02	22.6	31.28

[19] These values are estimated based on regional HWM data compiled by FEMA; reported surge peaks in the IPET Report, and interpretation of Hurricane Katrina surge simulation results.

[20] These values are estimated based on regional surge data compiled by USGS the http://pubs.usgs.gov/of/2008/1373/ and interpretation of Hurricane Gustav surge simulation results.

[21] These values are estimated based on regional surge data compiled by USGS the http://wim.usgs.gov/isaacstormsurgemapper/isaacstormsurgemapper.html# and interpretation of Hurricane Isaac surge simulation results.

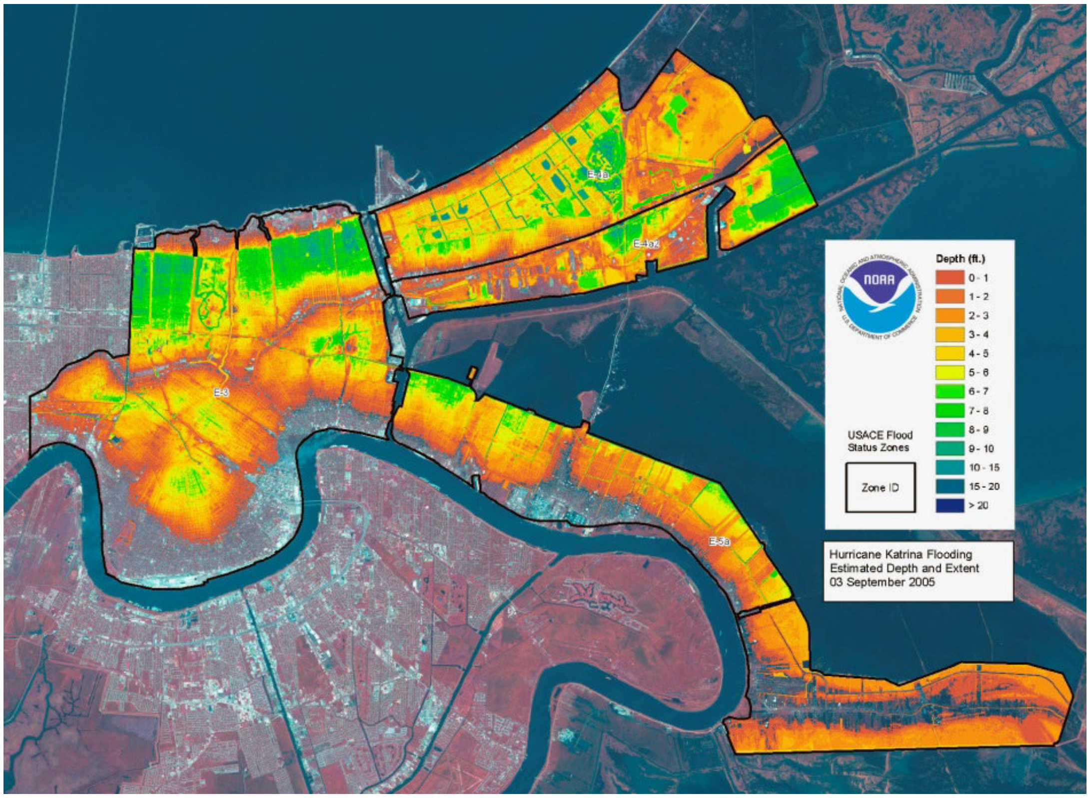

Figure 3.3. Hurricane Katrina Polder Flooding from Protection System Failures
NOAA

Table 3.2 provides estimates, taken from IPET and URS 2006 reports, of the peak interior SWL and inundation volume for each polder by major sub-basins (shown in Figure 3.4). The IPET Report also provided an estimate of the percent of volume from breaching, overtopping, and rainfall Inundation. The inundation volumes for the sub-basins were also verified using the SWL peak and available LIDAR topographic digital elevation models (DEMs).

Hurricane Katrina surge flooding in the East-Bank constituted one of the worst catastrophes in the history of the United States. Over 1,400 Southeast Louisiana residents died directly or indirectly as a result of Hurricane Katrina.[22] 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 the devastating flood's effects on their healthcare (e.g., inability to obtain insulin, dialysis, etc.). Figure 3.5 shows the location of the New Orleans Katrina fatalities.

[22] See Boyd, Fatalities Due to Hurricane Katrina's Impacts in Louisiana, 2011 and Jonkman et al, Loss of Life Caused by the Flooding of New Orleans After Hurricane Katrina: A Preliminary Analysis of the Relationship Between Flood Characteristics and Mortality, 2006.

Table 3.2. Hurricane Katrina Inundation of New Orleans Regional Polders
IPET 2006, Volume VI Tables 7 and 8, and URS 2006[23]

Polder	Sub-Basins	Inundation Peak			Source of Inflow %		
		Time	SWL Ft NAVD88	Volume Acre-Ft	Breaching	Over-topping	Rainfall
Metro	OM1, 2, 3, 4 &5	Mid-Day 8/30	2.5 to 3	88,000 to 99,000	66	13	21
St. Bernard (Inside 40 Arpent Levee)	SB1, 3, &4	Before Noon 8/29	10 to 12	153,000 to 192,000	63	29	8
NO East (Inside Maxent Levee)	NOE3	High Water Marks Not Available					
	NOE4	Before Noon 8/29	2 to 2.5	4,000 to 5,000	17	70	13
	NOE5	Afternoon 8/29	-1.5 to -1	42,000 to 46,000			

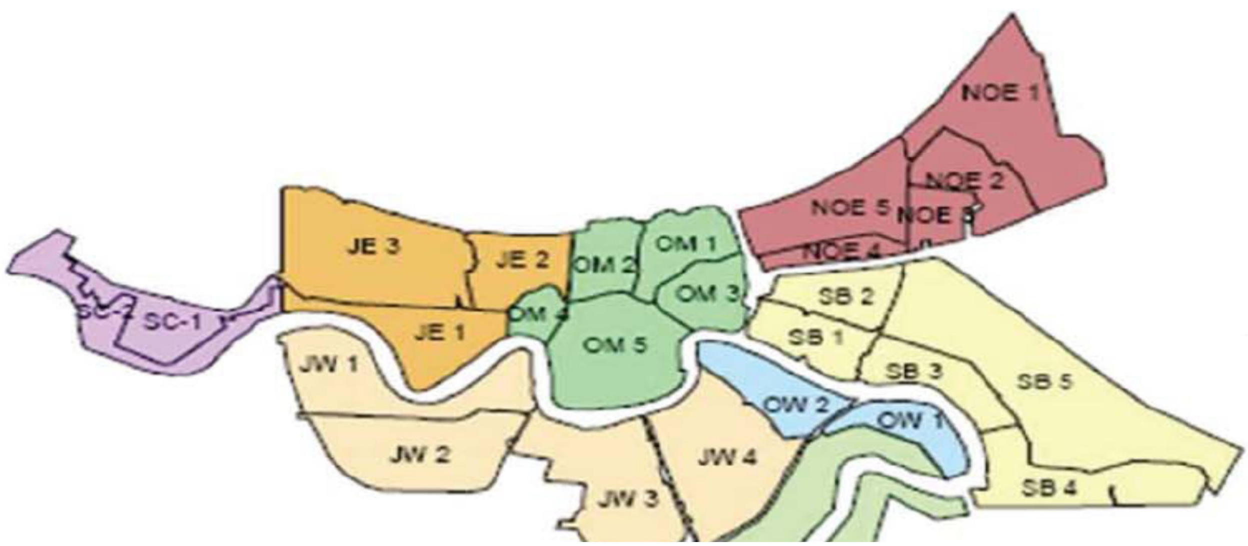

Figure 3.4. East-Bank Polder Sub-Basins
IPET 2009

[23] IPET stage-storage data for the sub-basins was not available and therefore volumes were computed using the regional LIDAR DEM. Slight differences may occur due to sub-basin delineation

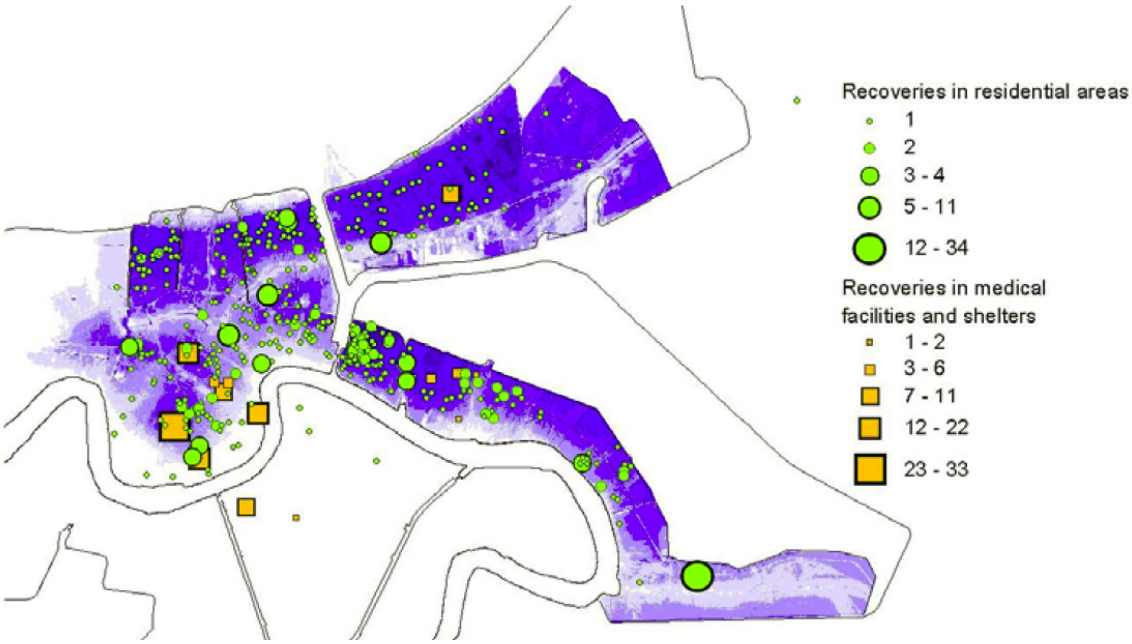

Figure 3.5. Location of Hurricane Katrina Fatalities
Jonkman et al

Other impacts in the initial years following Hurricane Katrina included:[24]

- 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.

[24] Sources include, The Greater New Orleans Community Data Center, Insurance Information Institute, U.S. Census Bureau, and FEMA.

3.2 Hurricane Gustav

2008 also proved to be a very active season for the Atlantic basin, with 16 named storms, eight of which became hurricanes, including five major and four Category 4 hurricanes). Seven of the named storms traversed the Gulf of Mexico, three as Category 2 hurricanes. Hurricane Gustav attained Category 4 intensity prior to passing over western Cuba but decayed to Category 2 while in the Gulf due to persistent wind shear. Had the storm not passed over warm Gulf waters it might have weakened more.[25]

Figure 3.1 includes a depiction of Hurricane Gustav's landfall wind-field. Gustav made landfall near Cocodrie, Louisiana with 105 mph winds, a central pressure of about 952 mb, and a forward speed of about 16 mph. Gustav's wind-field had impressive size, with a radius of maximum winds and extent of hurricane forces winds of about 29 and 70 miles. At landfall Hurricane Gustav's IKE (about 80 TJ) was about two-thirds that of Hurricane Katrina—similar to Hurricane Ivan which struck Florida in 2004.

Hurricane Gustav generated strong sustained south-easterly to easterly winds over the East-Bank coast, creating a significant surge. Figure 3.6 illustrates the peak surge elevations. The figure shows that Hurricane Gustav's East-Bank surge was—like Katrina's, though much lower—largely controlled by the region's major topographic features. Surge was again stacked against the combined delta and regional levee system, dramatically at the Caernarvon Corner and the Funnel. Lake Pontchartrain was tilted up by several feet to the west.

Table 3.1 provides estimates of peak Gustav SWL levels at the 20 locations shown on Figure 2.5. None of Gustav's peak SWLs exceeded the 100-yr SWL50s.

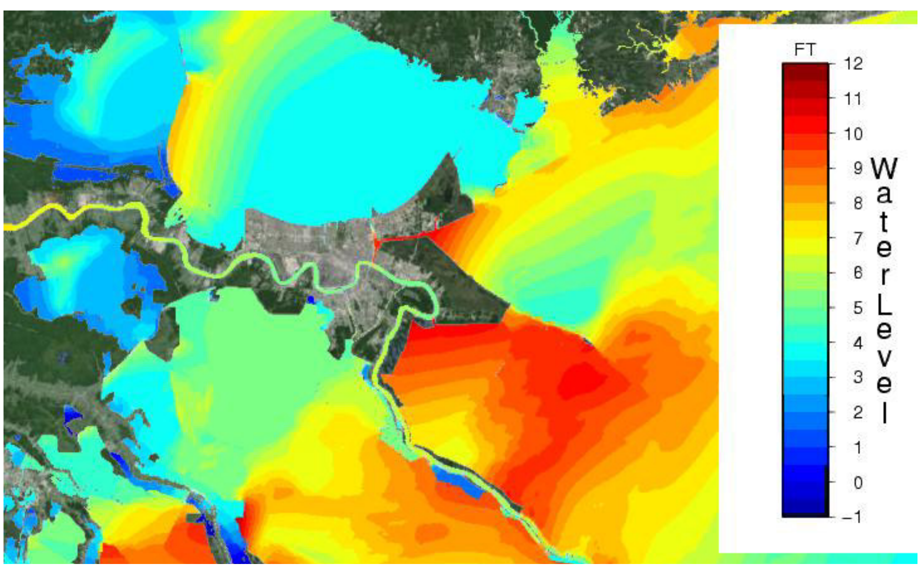

Figure 3.6 Hurricane Gustav Peak Surge SWL
http://adcirc.org/home/news/hurricane-storm-surge-forecasts/hurricane-gustav-storm-surge/

[25] Two weeks after Gustav, Hurricane Ike—like Hurricane Rita following Katrina—strongly impacted southwestern Louisiana at landfall. Hurricane Ike had also attained Category 4 status but weakened prior to entering the Gulf. Both Hurricanes Rita and Ike had strong forerunner effects on the East-Bank. Like Rita relative to Katrina, Ike also produce a higher setup on Lake Pontchartrain's west shore than Gustav.

There were no major failures of the East-Bank perimeter system during Hurricane Gustav. However, Gutav's strong easterly winds produced a remarkable 11.5 ft surge peak in the IHNC (just reaching the floodwall crown is some places). This surge peak combined with local wind-driven waves to cause dramatic wave overtopping of the western side of the IHNC, as depicted in Figure 3.7.[26] As a result, there were serious concerns for floodwall breaching along the western IHNC during the storm, somewhat mitigated by the presence of temporary reinforcement along some reaches (see Figure 3.8).

Figure 3.7 Hurricane Gustav Peak Surge SWL Overtopping the IHNC Western Floodwall
Eliot Kamenitzd Times Picayune

Figure 3.8 HESCO Baskets along IHNC Floodwall.
http://content.usatoday.com/_common/_scripts/big_picture.aspx?width=490&height=332&storyURL=&imageURL=/news/_photos/2008/08/28/gustav-packx-large.jpg

[26] The current HSDRRS IHNC Surge Barrier was under design in 2008.

3.3 Hurricane Isaac

With 19 named storms and ten hurricanes, 2012 was the third most active Atlantic hurricane season on record (tied with four other seasons). However, persistent atmospheric conditions in the far western Atlantic Basin suppressed activity in the Gulf of Mexico to three named storms, two of which, both minimal tropical storms, only grazed the southern Bay of Campeche. Tropical Storm Isaac entered the Gulf after an extended traverse over Haiti, Cuba, the Bahamas, and the Florida Straits, with maximum winds degraded to less than 45 mph, but exhibiting a large wind-field. Isaac's tropical storm force winds had extended 180 miles just after it emerged from Cuba.

The storm advanced northwest across the Gulf to the Southeast Louisiana coast in about 48 hours—passing over the Loop Current and intensifying, but very gradually in part due to its large size. Isaac reached Category 1 hurricane status just 12 hours before initial landfall, with its center less than 90 miles southeast of the mouth of Mississippi River. Hurricane Isaac's wind-field peaked with maximum winds of 80 mph and a central pressure that dipped to 965 mb. However, Isaac's radius of maximum winds, and extent of hurricane and tropical storm force winds were 29, 100 and 160 miles, respectively, and its IKE was significant at 45 TJ. Interestingly, the hurricane winds extended further than for Hurricane Gustav. Following its initial landfall over the Mississippi River mouth, Isaac wobbled westward over coastal waters for eight hours, and then came ashore permanently near Port Fourchon. Figure 3.1 includes a depiction of Isaac's post-landfall wind-field. Isaac then crossed Timbalier Bay and continued to move slowly inland, at less than 6 mph. Isaac maintained peak winds at Category 1 while over land for another 10 hours, *exposing Southeast Louisiana to a 30-hr hurricane wind-field!*

Although a weak Category 1 at its core, Isaac's large wind-field, combined with its very slow forward speed, was able to put a significant amount of East-Bank coastal water in motion, again pushing a surge against regional topographic barriers. Figure 3.9 shows Isaac's East-Bank maximum surge. Table 3.1 provides estimates of peak Isaac SWL levels at the 20 locations shown on Figure 2.5. None exceeded the 100-yr SWL50.

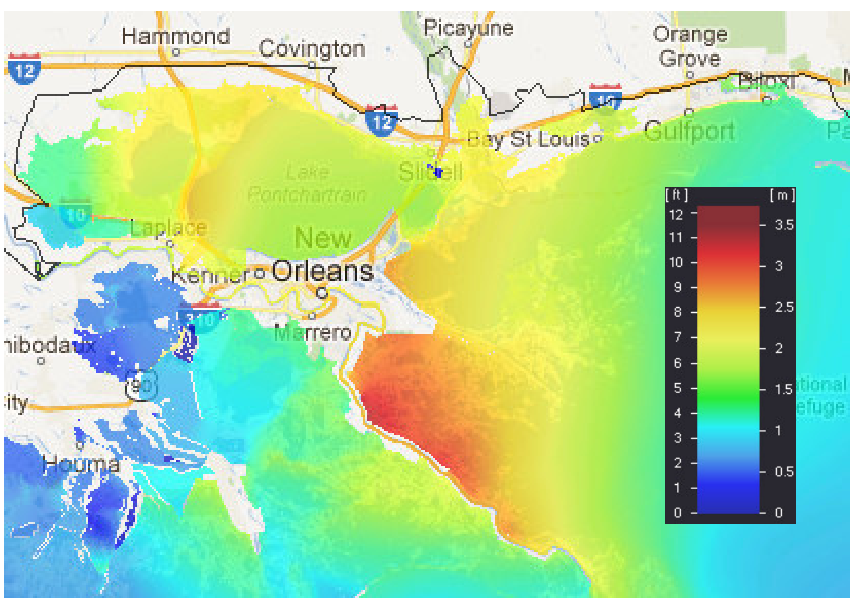

Figure 3.9 Hurricane Isaac Peak Surge SWL
CERA 2012

The combination of Hurricane Isaac's size, slow forward speed, track, and also banding (see Figure 3.10) caused very strong shoreward winds to persist across Breton Sound for an extend period of time—approaching 24 hours. These winds caused an extreme setup along eastern Plaquemines Parish. At the Caernarvon Corner surge levels reached approximately 14 ft NAVD-88, exceeding the surges of Hurricane Katrina and Gustav. The surge overtopped the nearby Plaquemines Parish levee, flooding the community of Braithwaite.

Isaac's wind-field also produced a high setup across Lake Pontchartrain, with peak surge possibly approaching 10 ft NAVD-88 and wave heights reaching 5 ft at Frenier on the west shore.[27] Just to the southeast, near Laplace in St. John the Baptist Parish, the Lake Pontchartrain surge high water marks reached 8.4 ft NAVD-88. The surge impact of Hurricane Isaac on western Lake Pontchartrain was much higher than any of the 2005 or 2008 hurricanes.

There were no overtopping events or failures of the East-Bank HSDRRS during Hurricane Isaac. However, local officials in Plaquemines and St. John the Baptist Parishes were concerned that extreme surge in Braithwaite and LaPlace, respectively, were attributable to post-Katrina HSDRRS enhancements adjacent to these areas (e.g, the Caernaron to Verret segment of the HSDDRS just east of Caernarvon, and the St. Charles Parish segments east of the Bonnet Carre Spillway). They questioned whether these projects had overly confined Isaac's surge, causing it to be higher.

In response to these concerns the USACE conducted surge simulations to assess the impact of the post-Katrina enhancements to the HSDRRS (USACE 2013). They found that the system as it existed prior to Hurricane Katrina would have confined Isaac's surge in a similar manner, and produced similar surge levels in Braithwaite and LaPlace. The USACE assessment did **not** investigate the role of the pre-Katrina system itself (the original authorized projects) on Hurricane Isaac's surge. There is no doubt that surge heights in Braithwaite would have been markedly lower absent the adjacent Caernarvon to Verret segment altogether. Unconfined, the surge at Caernarvon would have spread northward across St. Bernard. The community of Braithwaite was devastated by the local high surge, with most of the residences severely flooded. Two drowning fatalities occurred in the community.

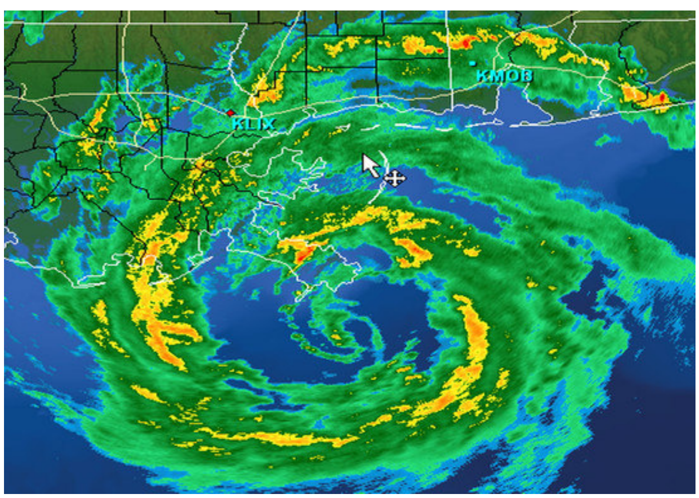

Figure 3.10 Hurricane Isaac Wind-Field Banding
NOAA Radar 2012

[27] Official USGS high water marks were not obtained in Frenier and these values are based on anecdotal reports of local residents.

The LaPlace surge inundated neighborhoods east and west of US Highway 51, damaging several thousand homes. Some areas were not located in the 100-yr flood zones effective at the time and owners did not have flood insurance. The LaPlace surge was probably affected by the Bonnet Carre Spillway western levee (not associated with the HSDRRS). The St. Charles Parish HSDRRS levees are east of the Spillway and well inland from the Lake Pontchartrain shore.

4. East-Bank HSDRRS

This section reviews important *hydraulic* design information for the East-Bank HSDRRS based on the 2011 *DER* (Version 4a)[28] and 2013 *Levee System Evaluation Report* (*LSER*), including its purpose, the components, the overtopping allowance for 100-yr return periods, and the plans for structural resiliency. This section concludes with a discussion of critical challenges to the HSDDRS performance and sustainability.

4.1 <u>HSDRRS Purpose</u>

Prior to Hurricane Katrina Congress authorized the USACE to build a perimeter system to protect the East-Bank from a standard project hurricane (SPH).[29] According to the National Oceanic and Atmospheric Administration (as stated in the 1970s) the SPH has a return period of several hundred years and:

> *is intended as practical expression of the maximum degree of protection that should be sought as a general rule in the planning and design of coastal structures for communities where protection of human life and destruction of property is involved.*

By 2005—given many advances in hurricane climatology and surge hazard analysis—a rigorous updated description of the SPH and related surge estimates for the East-Bank were both needed. The USACE was working with experts in these areas (under very limited budgets) at the time of Katrina. Following the devastation of the system during Hurricane Katrina, Congress authorized expedited repairs and improvements that refocused efforts on achieving NFIP accreditation—removing the interior area from the FIS 100-yr surge hazard. The USACE completed this more limited mission in seven years, with the 2013 publication of the formal *LSER* per NFIP requirements. Congress has not funded a resumption of pre-Katrina Congressional authorizations for East-Bank SPH surge hazard protection.

Given the specific language of the Congressional authorization, it is important to appreciate that the HSDRRS was designed essentially as an NFIP project. As such the USACE has formally re-designated the perimeter system as the *Hurricane and Storm <u>Damage Risk Reduction</u> System*. Thus, while HSDRRS reduces surge damage risks for East-Bank property—and has achieved the goal of restoring post-Katrina property values—there are major residual risks which are not the focus of the HSDRRS.[30] To be sure, the NFIP HSDRRS does reduce more than residential property damage risks. However, the key fact is that *the HSDRRS was not designed or intended to mitigate these risks—even at the 100-yr return period*. The East-Bank must still be evacuated with the approach of a hurricane threatening any overtopping of the HSDRRS NFIP 100-yr design—which might include some slow moving Category 1 and 2 storms. Given the discussions in Section 2.2 (and the *Supplement*), it important to appreciate NFIP limitations in estimating the 100-yr surge hazard.

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[28] The USACE issued a new draft version of the hydraulic design, retitled *Elevations for Design of Hurricane Protection Levees and Structures* to SLFPA-E and CPRA in July 2014; and a finalized version in December 2014. However, Section 4 was largely completed prior to this new version and reflects information from the 2011 version.

[29] SPH is similar in concept to a standard project flood, which was used by the National Weather Service and the USACE for evaluating riverine flooding as early as the 1940s.

[30] Furthermore, 100-yr flood risks remain in many areas inside the polders due to limitations of the interior drainage system.

4.2 HSDRRS Components

The *DER* and supporting information identify 92 component structures in the East-Bank HSDRRS, covering 111 miles, featuring a wide range of structure types. Table 4.1 lists all the components and Appendix B provides figures illustrating their locations.[31] The components include:

- 27 Earthen Levees (82.0 miles). Levees are comprised of well compacted clay fill and typically covered with grass. Prior to Katrina some levees were constructed of poorly compacted hydraulic fill (obtained from the nearby dredging of the navigation channels, e.g. the GIWW and MRGO). Following Katrina such levees were reconstructed using imported clay. New levee lifts on existing clay levees have also used imported clay.
- 32 Floodwalls (24.0 miles). I-Walls consist of a vertical sheet pile in an earthen embankment, (with a concrete cover of the exposed vertical sheet pile). A concrete splash pad is often included on the protected-side. T-Walls include an integrated, reinforced horizontal cross-member and supporting batter piles. T-Walls have replaced I-Walls on perimeter reaches and have also been installed on several former levee reaches to achieve new design heights. T-Walls provide much higher resistance to several of the major I-Wall failure mechanisms during Hurricane Katrina. HSDRRS I-Walls remain along sections of the IHNC Basin.[32]
- 11 Major Dry Gates (0.6 miles) at major road and railroad traffic openings (not including maintenance gates).
- 7 Major Channel Closures (1.5 miles). These include sector and major lift gates and adjacent batter pile reinforced wall abutments (e.g., the IHNC Surge Barrier).
- 15 Pump Stations (2.9 miles, including adjacent abutments) located at the intersection of interior drainage canals with the perimeter system.

Figure 4.1 provides a depiction of each of these structure types. The total number by polder is:

- Metro Polder—38 components covering 32 miles (13 and 7.7 in Orleans Parish; 9 and 10.4 in Jefferson Parish; 16 and 13.4 in St. Charles Parish).
- NO East Polder—21 primary components and 25 miles (all in Orleans Parish).
- St. Bernard Polder—10 primary components and 23 miles (all in St. Bernard Parish).
- IHNC Basin—23 primary components and 31 miles. All the IHNC Basin components are in Orleans Parish with the exception of the southern part of the IHNC Surge Barrier and the levee along the MRGO east from Bayou Bienvenue to the IHNC Surge Barrier.

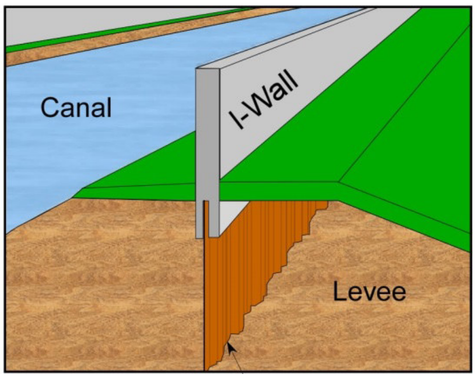
Figures showing the structure locations can be found in the *DER*. The 20 HSDRRS reaches which correspond to the 20 locations shown on Figure 2.5—with the estimates for 100- and Nominal 500-yr surge hazard in Table 2.1—are noted on Table 4.1 in **bold**. The 2011 *DER* designates all 20 reaches as levees. However, nine of the levee segments (noted with a *****) have been constructed with T-Walls mounted on top. (A 2014 revision of the 2011 *DER* revised their classification.)

[31] The USACE does not include the East-Bank Mississippi River levee in the East-Bank HSDRRS.

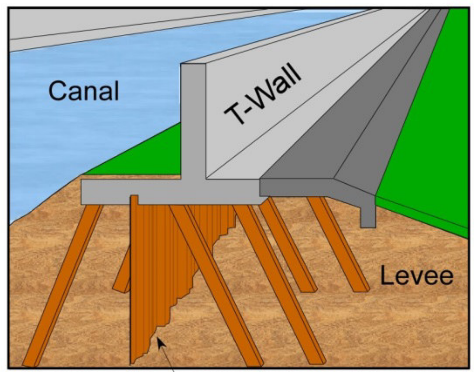
[32] Some I-Wall components have been upgraded to "L-Walls" with thicker splash pads, buttresses, and batter piles. I-walls also remain along the 17th Street, Orleans Avenue, and London Avenue interior outfall drainage canals that connect the interior pump stations to post-Katrina system of perimeter pump stations. These canals are not part of the HSDRRS but are under the jurisdiction of the SLFPA-E.

a. Levee

b. Gate

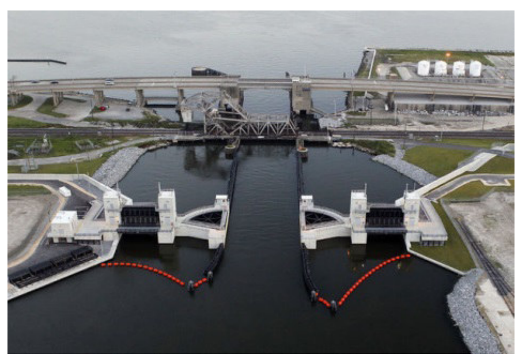


c. I-Wall



d. T-Wall

e. Barrier



f. Channel Gate

Figure 4.1. Examples of HSDRRS Components[33]

[33] Figures a, e, and f. nola.com;

Figures c and d: Stephen A. Nelson, Tulane University, http://www.tulane.edu/~sanelson/New_Orleans_and_Hurricanes/New_Orleans_Vulnerability.htm
Figure b: Linfield, Hunter, and Junius, http://www.lhjunius.com/flood-protection.html

Table 4.1. List of East-Bank HSDRRS Components

ID	Description	Type	Length (ft)
Metro Polder			
JL01	**Lakefront levee**	Levee	47,426
JL02	Pump station 1	Pump Station	1,054
JL03	Pump station 2	Pump Station	1,369
JL04	Pump station 3	Pump Station	704
JL05	Pump station 4	Pump Station	2,206
JL06	Causeway Crib wall	Floodwall	535
JL07	Williams Blvd Floodgate	Gate	191
JL08	Bonnabel Boat Launch Floodgate	Gate	216
JL09	Return wall	Floodwall	1,007
NO01	**New Orleans Lakefront Levee**	Levee	21,116
NO06	NO Marina	Floodwall	2,509
NO07	Bayou St. John	Floodwall	2,374
NO08	Pontchartrain	Floodwall	2,970
NO09	American Std FW	Floodwall	798
NO10*	**Topaz St. Levee**	Levee	1,197
NO11	London Ave Outfall Canal Pump Station	Pump Station	4,698
NO12	Orleans Ave Outfall Canal Pump Station	Pump Station	3,184
NO13	17th St. Outfall Canal Pump Station	Pump Station	184
NO14	Type I Floodgate Similar to Marconi Drive	Gate	361
NO15	Type II Floodgate similar to Canal Blvd	Gate	588
NO16	Lakeshore Drive near Rail St FG	Gate	131
NO17	Leroy Johnson	Floodwall	687
SC01-A	St. Charles Return Levee/Wall	Floodwall	14,639
SC02-A	**St. Charles Parish Levee west of I-310**	Levee	33,185
SC02-B	**St. Charles Parish Levee east of I-310**	Levee	11,989
SC04	St. Rose Canal Drainage Structure T-Wall	Floodwall	510
SC05	Good Hope Floodwall	Floodwall	475
SC06	Gulf South Pipeline T-Wall	Floodwall	228
SC07	Cross Bayou Canal T-Wall	Floodwall	444
SC08	Bayou Trepagnier Pump Station	Pump Station	428
SC09	Almedia Drainage Structure	Floodwall	163
SC10	Walker Drainage Structure	Floodwall	168
SC11	Bonnet Carre Tie-in Floodwall	Floodwall	107
SC12	I-310 Floodwall	Floodwall	1,647
SC13	ICRR Floodgate	Gate	512
SC14	Armstrong Airport Floodwall	Floodwall	2,514
SC15	Shell Pipeline Floodwall	Floodwall	161
SC30	Transition	Floodwall	3,412
		Count	**38**
		Feet	**166,085**
		Total Miles	**31.5**

Table 4.1. List of East-Bank HSDRRS Components

ID	Description	Type	Length (ft)
NO East Polder			
NE01*	**Citrus Lakefront Levee**	Levee	20,982
NE02	**NO East Lakefront Levee**	Levee	31,705
NE03	NO Lakefront Airport East	Floodwall	6,858
NE04	NO Lakefront Airport West	Floodwall	2,581
NE05	Lincoln Beach	Floodwall	1,550
NE06	Collins Pipeline Crossing	Floodwall	464
NE07	Citrus Pump station	Pump Station	174
NE08	Jahncke Pump station	Pump Station	126
NE09	St Charles Pump station	Pump Station	127
NE10	**South Point to Highway 90 Levee**	**Levee**	**26,750**
NE11-A	**Highway 90 to CSX RR Levee**	Levee	11,690
NE11-B	**CSX RR to GIWW Levee**	Levee	3,879
NE12-A	**NO East Back Levee from PS15 East along GIWW**	Levee	12,279
NE12-B	**NO East Back Levee from Gate to PS15**	Levee	10,324
NE13	Highway 11 Floodgate	Gate	296
NE14	Highway 90 Floodgate	Gate	306
NE15	CSX RR Floodgate	Gate	152
NE16	NO East Pump Station 15	Pump Station	671
NE30*	**Transition Reach NE01 to NE02**	Levee	1,005
NE31	**South Point transition reach**	Levee	990
NE32	Transition Levee	Levee	1,017
		Count	**21**
		Feet	**133,925**
		Total Miles	**25.4**
St. Bernard Polder			
SB11*	**MRGO levee**	Levee	8,961
SB12*	**MRGO levee**	Levee	5,004
SB13*	**MRGO levee**	Levee	28,338
SB15*	**MRGO levee**	Levee	24,489
SB16*	**Caernarvon levee**	Levee	27,751
SB17*	**Caernarvon levee**	Levee	21,365
SB19	Bayou Dupre Sector Gate	Closure	686
SB20	St Mary Pump Station (PS#8)	Floodwall	241
SB21	Caernarvon to Mississippi River Floodwall	Floodwall	4,461
SB21	Caernarvon Sector Gate	Closure	
		Count	**10**
		Feet	**121,296**
		Total Miles	**23.0**

Table 4.1. List of East-Bank HSDRRS Components

ID	Description	Type	Length (ft)
IHNC Basin			
GATE-A1	Closure gate at MRGO - GIWW intersection		6,697
	GIWW Sector Gate	Closure	
	Barge Gate	Closure	
	Bayou Bienvenue Lift Gate	Closure	
GATE-A2	Seabrook Sector Gate	Closure	2,095
GI01	Levee Section GI02 to IHNC	Levee	24,818
GI02	Paris Road to levee section GI02	Levee	23,038
GI03	Michoud Canal to Michoud Slip	Levee	17,710
GI03-W	Floodwall under Paris Rd Bridge	Floodwall	1,004
GI04	Michoud Canal and Slip	Floodwall	25,426
GI05	Amid Pump Station (PS#20)	Floodwall	52
GI06	Elaine Pump Station	Pump Station	133
GI07	Grant Pump Station	Pump Station	23
GI08	Bienvenue Sector Gate	Closure	927
IH01-W	IHNC South of I-10	Floodwall	18,794
IH02-W	IHNC North of I-10	Floodwall	21,393
IH03	IHNC Levee South from I-10	Levee	10,131
IH04-W	IHNC Lock to Pump Station (PS#5)	Floodwall	6,710
IH05-W	Dwyer Pump Station	Pump Station	200
IH10	Orleans Pump Stations #5 to Pump Station #19	Floodwall	1,426
IH30	Transition Reach	Levee	300
LEVEE-A1	Closure levee at MRGO - GIWW intersection	Levee	5,700
NE20	NS Railroad Gates near Seabrook East	Gate	120
NO20	NS Railroad Gates near Seabrook West	Gate	414
		Count	**23**
		Feet	**167,112**
		Total Miles	**31.65**
Overall East-Bank HSDRRS		**Total Count**	**2**
		Total Feet	**588,418**
		Total Miles	**111.4**

4.3 Design Elevation and Overtopping Allowance

Levee and floodwall embankment overtopping can readily lead to protected side erosion and breaching. Hughes (2010) and USACE (June 3013) together provide a recent, comprehensive discussion of overtopping limits. *Steady* flow on grass slopes has been the subject of extensive research and it is generally accepted that steady overtopping of embankments with good clay construction and grass cover in the range of 0.1 cfs/ft can occur for many hours without significant erosion. A rate of 0.1 cfs/ft is equivalent to a 45 gallons pouring over every minute along every foot—a little bit less than a 5-gallon bucket every six seconds. Steady overtopping at 1 cfs/ft can even be tolerated for a few hours.

The acceptable limits for an average (over several minutes) overtopping flow with major wave contribution are the subject of research, as added shear and cavitation forces associated with a pulsing overflow must be considered. Figure 4.2 presents an estimate of average overtopping rates for a levee facing a large interior water body as a function of freeboard. In this figure the average overtopping at rates below 1.0 cfs/ft actually reflect very unsteady flows associated with wave overtopping.

According to FEMA regulations, NFIP accredited flood protection systems should be designed to minimize overtopping at the estimated 100-yr SWL height. To this end FEMA regulations (44 CFR 65.10) establish a dual default crown requirement for coastal systems of 2 ft of freeboard above the 100-yr SWL50 and 1 ft above the maximum expected wave runup. Estimation of the maximum runup factors in the SWL50 depth, H_s, T_p, and the embankment slope and material. Maximum wave runup elevations can exceed the significant wave crest elevation by 50 percent of H_s. Thus for a 100-yr SWL50 of 12 ft NAVD88 (with say depth of 12 ft and H_s of 6 ft, or H_s crest at 15 ft NAVD88), the maximum wave runup elevation could exceed 18 ft NAVD88. FEMA's criteria for maximum wave runup essentially try to eliminate wave overtopping of the type seen in Figure 3.6.

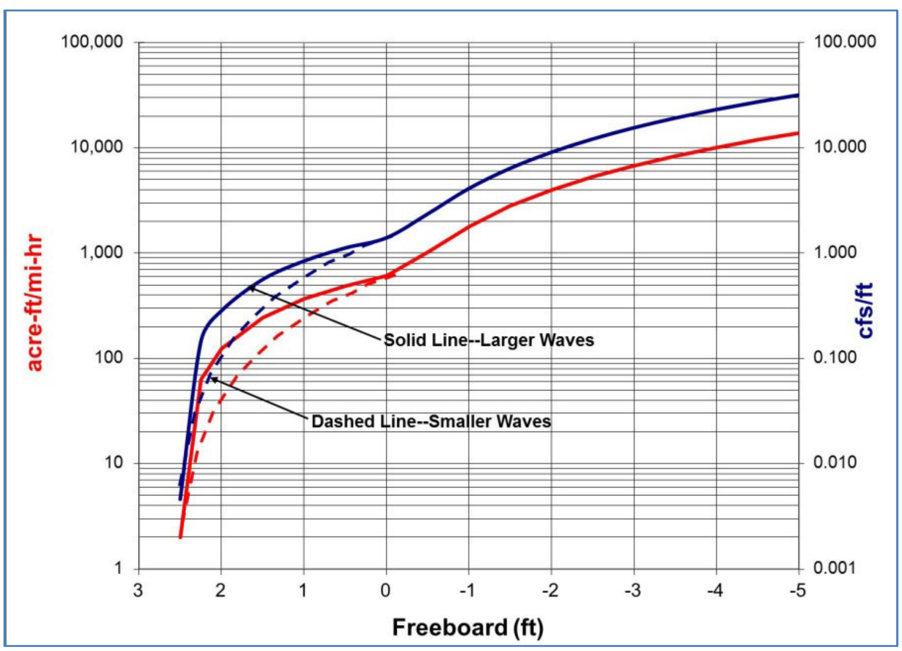


Figure 4.2 Estimate of Levee Overtopping Rate as a Function of Freeboard
based on Lynett et al 2010

FEMA regulations provide an alternative to this dual default. Levees can allow a minor amount of wave overtopping if supported by a detailed engineering analysis addressing the wave overtopping rate, volume, duration, erosional threats. The analysis must also address uncertainty in overtopping.

As previously noted, peak wave conditions with extreme surge are expected to last only a few hours. Thus, rather than using the FEMA default requirements, the USACE developed a set of alternate criteria to prevent protected-side erosion from surge wave overtopping consistent with the purposes of the NFIP. For the HSDRRS design the USACE specified that the crowns be high enough to prevent peak wave overtopping above 0.01 cfs/ft using an estimate of median 100-yr overtopping (Q50). To address uncertainty they specified that crowns should be high enough to prevent peak wave overtopping above 0.1 cfs/ft using an estimate of the 100-yr 90 percent non-exceedance overtopping (Q90). Thus, the Q90 height is essentially the NFIP design elevation FOS for the HSDRRS.[34]

Wave overtopping is estimated with established empirical equations, such as the Van der Meer equation for levees. These adapt traditional exponential (3/2 power) weir equations by incorporating freeboard (crown minus SWL), H_s, T_p, levee slope, and empirical coefficients. The wave overtopping uncertainty distribution—including Q50 and Q90 values—are determined with a special Monte Carlo analysis, which incorporates estimates of standard deviation for the key parameters and coefficients.[35] The overtopping uncertainty distribution is asymmetric—as it reflects the exponential equation and is affected by asymptotic limits that apply as the SWL rises (e.g., reductions in friction, approach to free flow). Thus, the Q50 can differ from the deterministic overtopping.

The USACE's limits for 100-yr Q50 and Q90 (0.01 and 0.1 cfs/ft) were based on limited empirical data for wave overtopping erosion.[36] During the hydraulic design the USACE adjusted levee crowns to achieve **both** the 100-yr Q50 and Q90 limits. Depending on the location, the controlling limit was different and the estimated wave overtopping rate for the non-controlling limit could be substantially below the allowable limit. For those reach conditions where the Q50 and Q90 values are relatively close, the Q50 tends to be the controlling limit and the Q90 limit does not add any elevation to the design.

The USACE considers the design base year to be 2007. The USACE added 1.5 ft to the 2007 hydraulic design height of new T-Walls to account for estimated average regional 50-yrs of RSLR (i.e., through 2057). The USACE increased the hydraulic design elevation only for T-Walls due to the practical difficulties and disproportionate costs of deferring T-Wall height increases to the future. Additional RSLR height for levees was not included in the 2007 hydraulic design elevations. (Recognition of complications with armoring, however, is re-raising this issue—see Section 4.4 below). The final elevations for some components were further augmented during subsequent design steps to address additional structural (superiority), geometry, and construction considerations.

[34] A lower FOS (Q80), or none at all, could be appropriate for a system which has minimal residual risks, e.g., where the whole population is assured of evacuating. However, 95 percent non-exceedance has been used for Midwest regions of the Mississippi River levees.

[35] The Monte Carlo analysis procedure is described in Bob Jacobsen PE May 2013 and March 2015.

[36] The USACE, through Colorado State University, has conducted a small number of wave erosion tests which cannot be regarded as conclusive. More testing is needed of a range of wave and armoring conditions. See USACE *Greater New Orleans Hurricane and Storm Damage Risk Reduction System Levee Armoring Research and Recommendations Report* (LARRR) June 2013 and Bob Jacobsen PE, Review of *Greater New Orleans Hurricane and Storm Damage Risk Reduction System Levee Armoring Research and Recommendations Report*, USACE June 2013.

Table 4.2 presents re-computed 100-yr deterministic, Q50, and Q90, for the locations shown in Figure 2.5. The re-computed overtopping rates use the USACE's 2011 *DER* elevation information for the 20 locations—all levees and thus not designated for higher crowns to allow for RSLR through 2057. Consistent with the objectives of comprehensive surge risk management, the levee overtopping rates reflect the partially revised values for SWL50, SWLσ, H_s and $H_s\sigma$, given in Table 2.1. They also reflect a revision to the Monte Carlo procedure discussed in the Bob Jacobsen PE LLC March 2015 Report (see Appendix C). (The previous procedure included a cap on H_S which reduced both the Q50 and Q90, the former to significantly less than the deterministic overtopping value.) The Table 4.2 values are based on levee design information in the 2011 *DER*.

It is important to note that changes to the SWL50 and SWLσ have a significant—nonlinear—impact on both Q50 and Q90—and therefore on levee height. As Q is proportional to the 3/2 power of freeboard (the crown minus the SWL), increasing SWL50 raises Q50 exponentially. Increasing SWLσ further contributes to drastically increases Q90—as the probability of free overflow increases. Figure 4.3 illustrates that Q50 can increase by a factor of 5 for a 20 percent increase in SWL50 and Q90 can increase by a factor of 10 for a 3-fold increase in SWLσ.

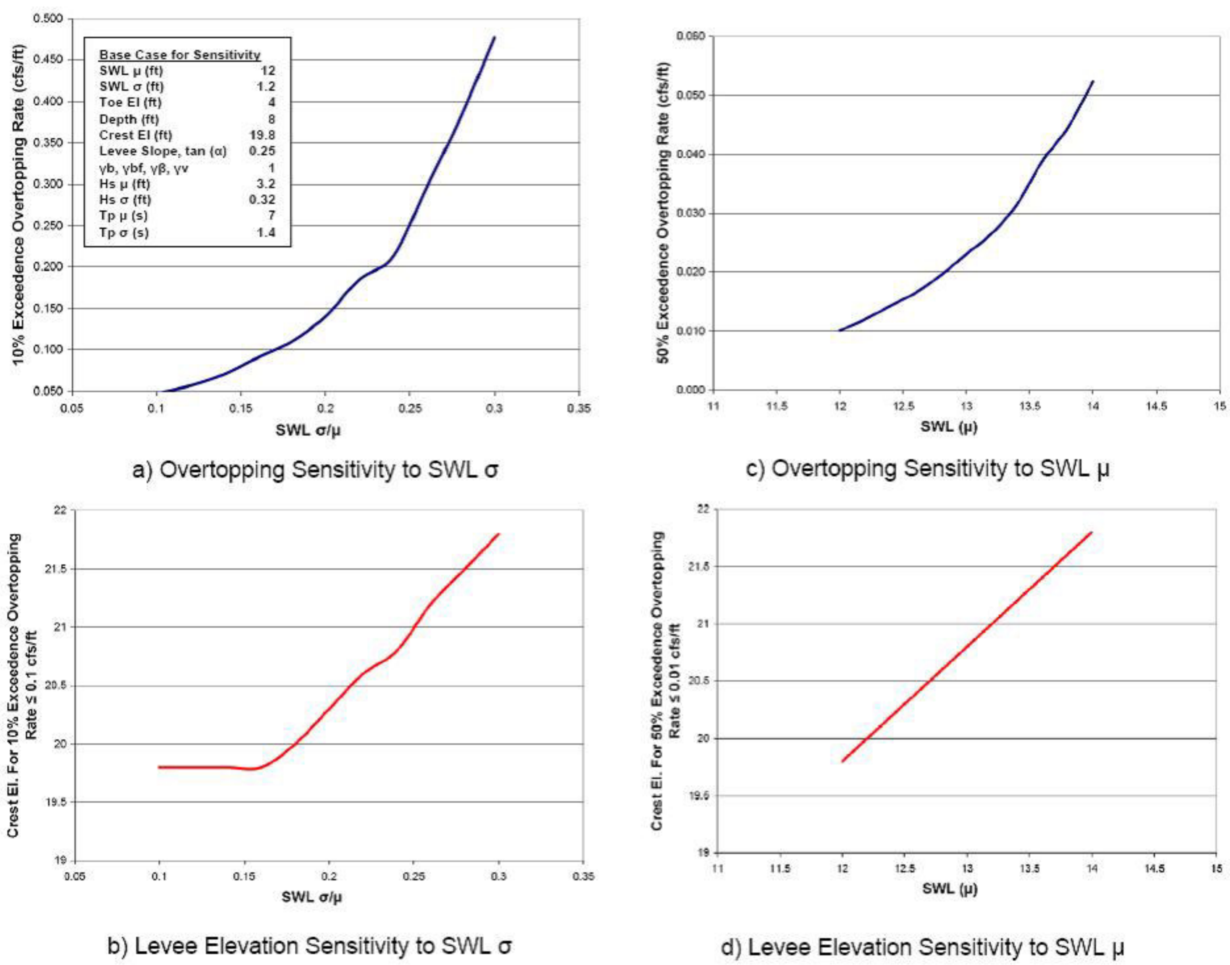


Figure 4.3. Sensitivity of Levee Overtopping Rate and Design Elevation to SWL50 (μ) and SWLσ

The recalculated 100-yr Q50 values are reasonably similar to the deterministic values, averaging about a 10 percent difference. The Table 4.2 100-yr Q50 rates range from 0.002 to 0.60 cfs/ft and the Q90 rates from 0.38 to 8.22 cfs/ft. The uncertainty band for overtopping (normal distribution) is extremely wide—with Q90s one to two orders of magnitude greater than Q50s. This is much wider than for SWL90 versus SWL50. Of the revised 100-yr Q50s and Q90s, 9 and 20, respectively, exceed the USACE specified limits (0.01 and 0.1 cfs/ft). The highest East-Bank 100-yr Q50 and Q90 rates by far are along the St. Charles Parish levees.

Importantly, because levee crowns were set according to 100-yr wave overtopping limits and reaches face different 100-yr wave conditions, the design produces differing 100-yr freeboard (F). Table 4.2 includes both 100-yr F50 and F90 based on the partially corrected estimates of 100-yr SWL50 and SWL90. The 100-yr F50 range from a high of 11.6 ft at SB15 to a low of 2.4 ft at SC02-B.
The 100-yr F90 range from a high of 6.8 ft at SB15 to a low of -1.3 ft at SC02-B. *The low 100-yr freeboard for the St. Charles Parish levees correlates to the high 100-yr overtopping uncertainty.*

Table 4.2 also provides freeboard information for the Nominal 500-yr hazard. The USACE 2011 *DER* provided for an elevation *check* of the 500-yr F50. Table 4.2 shows that for all 20 locations, the Nominal 100-yr F90 is less than the 500-yr F50. ***Thus, the 100-yr F90 is actually a more rigorous elevation check, consistent with the previous discussion of SWL uncertainty.***

Table 4.2. Partially Revised* Overtopping Rates and Freeboard at 20 East-Bank HSDRRS Locations

Location	Design Crest (ft NAVD88)	100-yr					Nominal 500-yr				
		Overtopping (cfs/ft)			Freeboard (ft)		Overtopping (cfs/ft)			Freeboard (ft)	
		Det	Q50	Q90	F50	F90	Det	Q50	Q90	F50	F90
SC02-A	15.5	0.20	0.22	5.55	3.40	-0.47	1.14	6.46	66.21	-0.10	-6.09
SC02-B	14.0	0.60	0.66	8.22	2.40	-1.31	6.00	8.83	79.37	-1.10	-6.90
JL01	16.5	0.01	0.01	0.23	6.80	3.70	0.32	0.36	7.08	4.30	-0.38
NO01	16.0	0.02	0.03	0.66	6.40	3.33	0.88	0.96	10.69	3.80	-0.88
NO10	15.0	0.04	0.04	0.78	5.20	2.06	1.23	1.22	14.05	2.70	-2.02
NE01	13.0	0.05	0.03	1.50	3.60	0.59	1.22	1.14	26.05	1.30	-3.19
NE02	15.5	0.01	0.01	0.30	6.10	3.09	0.16	0.18	6.21	3.80	-0.69
NE10	17.0	0.01	0.01	0.76	5.80	2.22	1.01	1.06	20.14	2.80	-2.65
NE11A	22.0	0.04	0.05	1.82	7.30	2.60	1.90	1.76	26.27	3.80	-3.19
NE11B	25.0	0.01	0.01	0.85	8.80	3.62	0.65	0.73	20.61	5.10	-2.54
NE12A	28.0	0.01	0.01	0.58	10.80	5.30	0.43	0.48	14.83	6.90	-1.20
NE12B	29.0	0.01	0.01	0.70	10.80	4.98	0.49	0.55	18.47	6.70	-1.86
NE30	14.5	0.03	0.03	0.74	5.20	2.22	0.54	0.58	9.56	2.90	-1.55
NE31	16.5	0.01	0.01	0.21	7.00	3.96	0.15	0.18	5.41	4.50	-0.11
SB11	29.0	0.01	0.02	1.23	10.20	4.18	0.85	0.94	26.20	5.90	-2.97
SB12	27.5	0.002	0.002	0.38	9.90	4.27	0.31	0.36	19.51	5.80	-2.53
SB13	26.5	0.01	0.01	1.05	8.90	3.27	6.89	4.86	31.41	4.80	-3.53
SB15	26.5	0.005	0.01	0.24	11.60	6.83	1.15	0.88	10.39	8.30	1.31
SB16	26.5	0.02	0.02	1.32	9.20	3.66	1.42	1.42	25.64	5.30	-2.84
SB17	26.5	0.01	0.01	1.83	8.30	2.48	1.79	1.67	46.21	3.90	-4.78

* Estimates have been revised from those reported in the USACE 2011 *DER* to better support ***local comprehensive surge risk management*** (see *Supplement* and Bob Jacobsen PE March 2015 Report, included as Appendix C).

All 20 reaches would require crown increases to meet the current established design limits ***IF*** partially revised surge hazard values (Table 2.1) and changes to the Monte Carlo procedure are employed, reflecting comprehensive surge risk management goals. Sixteen reaches would require increases of 2 ft or greater, and six increases of 4 ft or greater. Importantly, these elevations could be mitigated if:

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

However, as previously noted the NFIP may not require revision of 100- and Nominal SWL50 and SWLσ—indeed the NFIP may not undertake a new FIS to revise these values for many years. The NFIP may also not require revisions in the overtopping analysis—apart from changes to the HSDRRS conditions themselves. This may be especially true if revised 100-yr overtopping volumes present a negligible interior flood hazard.

4.4 Breach Resiliency

Congress' post-Katrina authorization to the USACE provided for adding some resiliency to the HSDRRS not required under the NFIP. Given uncertainty in surge SWL, H_s, and T_p—and accelerating rates of overtopping as conditions become more extreme—resiliency has been prioritized on resisting breaching from overtopping erosion during worse-than-design conditions through armoring of the protected-side of HSDRRS levees.[37] The USACE considers the new T-Walls, with added reinforcement and height for future RSLR, and structural superiority, to be inherently more resilient than levees.

The USACE is employing estimates of Nominal 500-yr Q50 and Q90 to evaluate suitable levee armoring alternatives.[38] The calculation of Nominal 500-yr Q50 and Q90 are done with the same Monte Carlo analysis used in 100-yr Q50 and Q90. Table 4.2 includes revised estimates for Nominal 500-yr Q50 and Q90 at the 20 selected levee locations based on partially corrected values for 500-yr SWL50, SWLσ, H_s and $H_s\sigma$, given in Table 2.1, and the changed Monte Carlo procedure. The Nominal 500-yr Q90 ranges from 5.4 to 79 cfs/ft. Nine locations have Nominal 500-yr Q50 rates above 1 cfs/ft, and sixteen have Nominal 500-yr Q90 above 10 cfs/ft.

The USACE's current levee armoring proposal based on Nominal 500-yr Q50 includes:

If Q50 is	Armoring
≤1 cfs/ft	unreinforced Bermuda grass
>1 and ≤ 2.7 cfs/ft	high performance turf reinforcement mat (HPTRM) reinforced Bermuda grass
≥2.7 cfs/ft	slope paving

[37] The USACE interpretation of resiliency precludes raising crown elevations beyond the NFIP design. HSDRRS resiliency includes some measures to reduce potential collapse breaching (structural superiority). SLFPA-E and CPRA have also proposed the need for more detailed investigations to address other resiliency issues, such as uncoated sheet piles and flood-side erosion.

[38] The USACE armoring proposal states that time averaging will be used for the *Nominal* 500-yr Q50 and Q90 (and specifies a 6-hr average for the Q90). This has the potential to lower estimates from peak Q50 and Q90 estimates. The USACE has not specified how the Q50 and Q90 estimates are to be modified for a longer averaging period.

The USACE also provides for upgrading the levee armoring depending on the Nominal 500-yr Q90:

If Q90 is	Upgraded Armoring
≤1 cfs/ft	unreinforced Bermuda grass
>1 and ≤ 1.8 cfs/ft	enhanced watering and fertilizing of Bermuda grass
>1.8 and ≤ 4.0 cfs/ft	HPTRM reinforced Bermuda grass
>4.0 cfs/ft	HPTRM reinforced Bermuda grass or slope paving depending on further analysis of overtopping velocity on slope

4.5 Challenges to HSDRRS Performance in Comprehensive Surge Risk Management

SLFPA-E—along with the CPRA and other federal, state, and local agencies—faces many critical HSDRRS performance challenges in order to protect lives and crucial economic and cultural assets. These include issues with the 100-yr elevation design, breach resiliency, and operations and maintenance (O&M). The addition of 1.5 ft for future RLSR to the new T-Walls, plus structural superiority, means that the near-term elevation design and resiliency issues tend to bear hardest—though not exclusively—upon the HSDRRS *levee* components.

100-yr Elevation Design Issues

Table 4.3 summarizes ten major HSDRRS levee sustainability issues for the 100-yr surge, together with their magnitude and timing—***from the perspective of comprehensive surge risk management*.** Eight issues relate to the specified design elevation. Issue Nos. 1 and 2 address the partial revision of surge hazard and overtopping estimates discussed above and in Appendix C. Issue No. 3 is updating design elevations for improvements in the surge hazard analysis SOP since the 2005-09 study—e.g., in hurricane climatology, modeling, and JPA. Issues Nos. 1, 2, and 3 combined could increase levee elevations by several feet.

Issue Nos. 4, 5, and 6—SLR, coastal erosion and vegetation change, and implementation of other proposed regional surge protection projects, see Section 2.3—would also be addressed in an updated surge hazard analysis. Issue Nos. 4 and 5 could raise elevation requirements by 0.4 ft by 2017 (versus 2007), and by as much as 3.5 ft by 2057. Note that this latter “worst-case” impact is 2 feet higher than the RLSR adjustment incorporated by the USACE for T-Walls. *Less drastic coastal change could still result in 0.2 and 2.5 ft of impact by 2017 and 2057, respectively—with the latter 1 ft greater than the T-Wall overbuild.*

Another design elevation issue, No. 7, is the acceptable limits for 100-yr Q50 and Q90—0.01 and 0.1 cfs/ft, respectively. If these are lowered or raised in the future based on more wave overtopping erosion research, then upward or downward adjustments could be made to design elevations. Similarly, Issue No. 8 is the Q90 FOS, which if it were reduced or increased would also affect elevations.

Finally, design Issue No. 8 involves possible modification of future overtopping analysis to allow for foreshore wetland (especially forested swamp) reduction of wave heights associated with 100-yr SWLs—which could *reduce* design elevations.

The combination of Issues 1 through 8 will seriously challenge the sustainability of minimizing the HSDRRS 100-yr surge overtopping, from a comprehensive surge risk management perspective.

Table 4.3. Ten Major HSDRRS Levee Sustainability Issues

Issue	Estimated Magnitude[39]	Timing
*Design Issues**		
1. Revise SWLσ and Q90 Per Appendix C Reasonably conservative treatment of uncertainty/FOS	**1 to 2 ft Increase**	**Now**
2. Revise SWL, H_s, and Q50, Median Estimate Per Appendix C	**0.5 to 2 ft Increase**	**Now**
3. Update Surge Hazard Analysis: Improvements in Hurricane Climatology, Modeling, JPA	**1 ft Decrease to 2 ft Increase**	**2020**
4. Update Surge Hazard Analysis: Sea Level Rise	**0.1 ft Increase** **1.5 ft Increase**	**2017** **2057**
Current Rate of Sea Level Rise	0.1 ft Increase 0.5 ft Increase	2017 2057
Additional Anthropogenic Sea Level Rise	<0.1 ft Increase 1 ft Increase	2017 2057
5. Update Surge Hazard Analysis: Coastal Erosion and Vegetation Change**	**0.1 - 0.3. ft in Increase** **1 - 2 ft Increase**	**2017** **2057**
6. Update Surge Hazard Analysis: Other East-Bank Surge Projects	**2 ft Increase**	**At Construction Completion**
7. Acceptable Overtopping Limits	**Could Increase or Decrease > 1 ft**	**If Hydraulic Design is Modified**
8. Foreshore Swamp Forest Reduction of Wave Heights and Overtopping	**>2 ft Decrease**	**If Hydraulic Design is Modified**
Maintenance Issues		
1. Post-Construction Settlement Plus Subsidence	**<1 to 3.1 ft**	**2025**
Reach Settlement	<1 to 3 ft	2025
Regional Subsidence (can be episodic so may be greater in some decades than others)	0.1 ft	2025
2. Height Survey Improvements	**0.4 ft Increase**	**As Technology Improves[40]**
Revisions of GEOID model	0.2 ft Increase	
Better ellipsoid height surveying	0.2 ft Increase	

* These issues for earthen levees only, and are from a comprehensive surge risk management perspective.

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[39] Magnitudes for each issue are reasonable *planning-level* estimates that could be applicable at some HSDRRS reaches. **All issues do not necessarily apply at all reaches at the same magnitude**. Changes to HSDRRS levee design elevations are likely to also entail other key design issues, including geometric (and right of away acquisition), geotechnical, structural, etc. For some levees, significant height increases may require a total re-design, e.g., addition of a T-Wall.

[40] While relatively small on their own, height survey errors greatly affect the monitoring and evaluation of other HSDRRS elevation issues.

Assessing the impact of these eight design issues from an NFIP perspective is beyond the scope of this Report. Parish NFIP Administrators are required under the terms of the NFIP to advise FEMA should they become aware of any significant issues with the surge hazard analysis or HSDRRS design which might affect the accuracy of parish FIRMs. SLFPA-E—in conjunction with the CPRA and the USACE—should coordinate with the local Parish NFIP Administrators and FEMA to make them aware of the eight design issues listed in Table 4.3. The HSDRRS is scheduled for a formal NFIP re-evaluation and re-accreditation in 2023, requiring an update to the LSER. Absent an update to the 2008 NFIP FIS, SLFPA-E—in conjunction with the CPRA, the USACE, and FEMA—would need to determine if/how issues with the surge hazard and overtopping analyses should be addressed in the NFIP re-accreditation of the HSDRRS. Depending on NFIP priorities, FEMA may not fund another FIS for many years (perhaps decades).

Breach Resiliency Issues

A critical performance and sustainability concern is the resiliency of the 100-yr components to withstand more extreme conditions without breaching. Five key resiliency topics are:

1. Appropriate armoring measures for overtopping rate estimates. The partially corrected Nominal 500-yr Q50 and Q90 overtopping rates indicate many levees should receive the higher levels of armoring than currently contemplated. Future revision of the surge hazard analysis will raise these overtopping estimates.
2. Constructability and maintenance problems influencing the effectiveness of enhanced grass and HTRM.
3. Future research modifications to overtopping limits associated with grass and HTRM.
4. The resiliency of the remaining I-Walls along the IHNC Basin.
5. The timing of levee resiliency implementation for each reach. SLFPA-E, CPRA, and the USACE recognize that many levee reaches require future lifts as discussed above. Armoring these levees prior to stabilizing levee settlements could result in costly removal and replacement of armoring. In these cases armoring might actually impede timely construction of new lifts. On the other hand, delays in armoring could result in catastrophic breaching if an overtopping event were to occur. Timing may be further complicated by the need for additional alternatives analysis per Topics 1, 2, 3, and 4.

O&M Issues

Proper O&M is crucial to the intended NFIP performance of the HSDRRS—it is a key element of NFIP accreditation—as well as in reducing residual risks. The East-Bank O&M is complicated by three layers of management and sub-regional fragmentation of O&M funding and execution. The HSDRRS O&M is overseen by the State CPRA—the official HSDRRS local partner with the USACE. HSDRRS O&M duties in St. Bernard, Orleans, and Jefferson Parishes are assigned to SLFPA-E. O&M of the East-Bank St. Charles HSDRRS is the responsibility of the Pontchartrain Levee District (PLD). The O&M duties of SLFPA-E must be carried out by three parish-level subsidiary agencies using their respective staffs and resources: the Lake Borgne Basin Levee District (LBBLD) in St. Bernard Parish; the Orleans Levee District (OLD) in Orleans Parish; and the East Jefferson Levee District (EJLD) in Jefferson Parish. The activities of each of these parish-level districts must be funded by the voters of the separate parishes. Recently the voters of St. Bernard Parish have twice declined to raise taxes required by the LBBLD to carry out its duties (necessitating cut-backs in some of LBBLD's drainage activities).

Table 4.3 lists two elevation O&M issues which affect the implementation of levee lifts to maintain required design elevation. The first issue—additional levee lifts to address post-construction settlement and regional subsidence—is extremely important to the continued performance of the HSDRRS. As noted in Section 2.3, settlement rates are much higher than the regional subsidence rates. Levees with well consolidated sub-soils generally experience overall settlement plus subsidence rates of less than 1 ft per decade. Levee reaches with sub-soils that are not well consolidated experience overall settlement plus subsidence rates approaching 3 ft per decade. These levee lifts—as well as elevation maintenance of breakwater features—must be implemented for continued accreditation of the HSDRRS under the NFIP. Figure 4.3 shows the current schedule for East-Bank levee lifts.

The second issue noted in Table 4.3 is improved vertical surveying, which could determine that some locations require additional lifting on the order of 0.4 ft.

To perform as designed, the HSDRRS requires mechanical operation of the 11 main road and railroad gates, together with the 7 channel gates. The latter include five gates in the IHNC Basin—IHNC Surge Barrier Sector, Seabrook Surge Barrier Sector, Barge, Bayou Bienvenue Lift, and Bayou Bienvenue Sector—and two additional sector gates at Bayou Dupre and Caernarvon. In addition, the system includes numerous other minor mechanical structures. Operation plans and requirements are detailed in water control manuals prepared by the USACE.

Operation of the channel gates is complicated by many factors, including:

- The amount of advance notice provided by NOAA that a storm surge may occur.
- Maintaining water levels inside the Central Wetlands below limits (typically necessitating early closure of the sector gates at Bayous Bienvenue and Dupre).
- Providing time to allow water craft throughout the East-Bank to utilize the GIWW and IHNC to move to safety.
- Operation of gates prior to wind speeds reaching specified thresholds.
- Operation of gates below required water velocity caps; gate closures can be difficult to coordinate given the effects of possible forerunner conditions.
- Mechanical difficulties (e.g., clearing debris obstructing gate closure).

Due to these difficulties, in some cases exacerbated by design limitations, the SLFPA-E and CPRA have made requests that the USACE assume responsibility for operating four of the five gates in IHNC Basin (excluding the Bayou Bienvenue Sector Gate). Failure to properly close the four gates in IHNC Basin could result in excessive interior IHNC Basin levels. The IHNC Basin still includes over 13 miles of I-Walls, similar to those which failed during Hurricane Katrina.

An additional operational concern is the presence of poorly restrained vessels, tanks, and other structures inside the IHNC Basin. Anticipated flood levels in the IHNC Basin, coupled with winds and waves, could cause these items to become buoyant and to damage an I-Wall or gate, leading to a catastrophic breach.

Ongoing maintenance challenges that can affect the integrity of an HSDRRS component include:

- Ensuring the integrity of designed and designated wave breakwater structures (including railroad embankments along the NO East Lakefront).
- Keeping a healthy grass cover over the 80-plus miles of earthen embankments.
- Controlling traffic on levee crowns.
- Controlling nuisance animals which burrow and damage embankments.
- Repairing crown and embankment damage and erosion.
- Preventing and repairing corrosion of steel components.
- Preventing and repairing significant cracks and other damage to concrete components.
- Repairing and/or replacing worn or damaged mechanical items.

Major maintenance activities and repairs often occur after storm surge events, including lesser storms. Examples include flood-side erosion of embankments, damage from unrestrained items, wind damage, etc. SLFPA-E procedures and checklists for routine and special inspections, maintenance, and repairs—including documentation—are detailed in dozens of project-specific Operations, Maintenance, Repair, Replacement and Rehabilitation Volume III Manuals prepared the USACE. Altogether SLFPA-E and its subsidiaries budget over $25 million annually for HSDRRS O&M. SLFPA-E costs for O&M can fluctuate drastically with special major periodic maintenance and repairs.

An important, polder inundation O&M issue is interior drainage. O&M for gravity systems and pump stations in St. Charles, Jefferson, and Orleans Parishes are the responsibility of separate parish-level departments. The drainage departments in Jefferson and Orleans Parishes are not overseen by SLFPA-E. The SLFPA-E subsidiary LBBLD is responsible for drainage O&M in St. Bernard Parish.

A special concern is coordinated pumping for the interior and Lakefront stations on the 17th Street, Orleans Avenue, and London Avenue outfall canals to ensure that the water levels remain below safe limits—8 to 10 ft NAVD88 depending on location—as dictated by USACE evaluations of their embankments and I-Walls. The interior pump stations are the responsibility of the New Orleans Sewerage and Water Board (NOS&WB), while the Lakefront pumps are currently operated by the USACE. However, the outfall canal embankments and I-Walls, while not technically a part of the HSDRRS, are the responsibility of SLFPA-E.

A complete discussion of East-Bank HSDRRS and drainage O&M technical and funding challenges that bear on reducing comprehensive surge inundation risks is beyond the scope of this Report.

5. East-Bank Surge Inundation Hazard

This section discusses fundamental aspects of surge inundation of polders and the special vulnerabilities of the three East-Bank polders (Metro, NO East, and St. Bernard). Previous planning-level efforts to assess inundation hazard and risk for these polders are summarized, along with general considerations of accuracy and uncertainty, and potential future changes. Finally, the significance of surge inundation risks is compared to other polder flood risks.

5.1 Fundamentals of Polder Surge Inundation Hazard and Risk

Hurricane surge inundation hazards for the East-Bank polders—and their associated consequences and risks—can be divided into five general classes:

Class A Minor, occasional wave overtopping occurs along a limited portion of the perimeter, with peak overtopping potentially exceeding 0.01 cfs/ft (4.4 acre-ft of water per mile per hour). Overflow volumes will be very small (possibly approaching 100 acre-ft) relative to overall polder rainfall quantities. Some minor accumulation may occur in low interior locations near the point of overtopping.

Class B Wave overtopping increases to above 0.1 cfs/ft, (44 acre-ft/mi-hr)—requiring some resiliency to withstand breaching. As freeboard is reduced and/or wave heights increase the rate of wave overtopping increases. Impacts to the polder sub-basin receiving the overflow volume (possibly exceeding 1,000 acre-ft) are still likely to be less than rainfall quantities, though localized impacts near the point of overtopping will increase.

Class C Regular, prolonged heavy wave overtopping, potentially exceeding 1 cfs/ft (436 acre-ft/mi-hr) as the SWL nears the crown. Absent sufficient armoring, erosion could create shallow breaches, and thus higher inflows. Figures 5.1a-c illustrate erosion from overtopping at two locations that nearly resulted in shallow breaches. A limited breach has the potential to introduce significant flood volume, approaching 10,000 acre-feet. The sub-basin which receives the inflow will experience significant inundation and damage to residential property, businesses, and infrastructure, as well as economic disruption. If low areas become rapidly flooded there is a risk of fatalities to those unable to evacuate. *Class C inundation hazard poses the first level of significant residual risk exposure.*

Class D Prolonged surge SWLs above crowns cause longer, deeper breaches unless the highest levels of armoring are present. Sub-basin inundation is extensive and deeper, exceeding 10,000 acre-feet, increasing the risk of fatalities. The sub-basin receiving breach inflow will experience a devastating flood, with inundation extending to adjacent portions of the polder via any gaps in sub-basin boundaries and other interior barriers.

Class E Catastrophic breaching, as occurred in all three polders during Hurricane Katrina. Severe erosional and possibly collapse breaching leads to widespread inundation. Interior water levels rise very fast and buildings near the breach location may be destroyed by rushing water. Deep breaches cause water levels inside and outside the polder to equalize. Polder flooding is only limited by continuous, high interior barriers. Remaining residents may not be able to react in time to save their lives. This inundation class has the greatest risk of fatalities.

a. North Bank of GIWW at Paris Rd During Hurricane Katrina

b. Same as a., After Hurricane Katrina

c. NO East Lakefront Levee, After Hurricane Katrina

Figure 5.1 Examples of Levee Overtopping That Nearly Produced Shallow Breaches

The inundation classes do NOT correspond to hurricane intensity categories. A large stalled Category 2 hurricane could produce a Class D inundation event.

Given the functional intent of the HSDRRS, the levee and floodwall reaches should have inundation Class A, B, and C return periods on the order shown in Table 5.1 (100 years, 100 – 500 years, and >500 years). However, for inundation hazard it is crucial to consider the return period for the *whole polder*; (see the *Supplement* for a discussion of *independent* surge hazards).

Each of the three East-Bank polders may have two independent exposures for extreme surge events:

- For Metro polder extreme events along the Orleans Parish lakefront are likely to be different from those for St. Charles Parish.
- For the NO East polder, events producing extreme surge along the GIWW are likely to be different from those producing extreme surge along Lake Pontchartrain.
- Similarly events producing extreme surge along the Caernarvon to Verret segment of the St. Bernard polder will be different from those affecting the segment along the MRGO.

If it is the case that a polder has two independent exposures, then the *polder return periods* for surge inundation are half those for the individual reaches, as indicated in Table 5.1. Furthermore, if the East-Bank as a whole has at least three independent exposures, then *regional return periods are one-third of the reach return periods!* The East-Bank could be facing a return period of 166 years for a 500-yr event occurring somewhere along the HSDRRS perimeter.

Moreover, given the issues detailed in Table 4.3, the polder return periods for the various class inundations could be even less. And over the coming years, these return periods will get shorter—i.e., worsen—with RSLR and coastal wetlands loss.

From the perspective of the East-Bank region as a whole, the future return period for a Class A event will reach 20 years, and 200 years for a Class D event. *For a 20-yr regional planning horizon, the probability of a Class D inundation could approach 10 percent.*

Table 5.1. Reach, Polder, and East-Bank Inundation Hazards

Inundation Class	Description	Return Period (years)			
		HSDRRS Reach Design Basis	Equivalent for Polder	Equivalent for East-Bank	Future for East-Bank
A	Minor/occasional wave overtopping	100	50	33	20
B	Wave overtopping above 0.1 cfs/ft; <1,000 acre-ft	100 - 500	50 - 250	33 - 166	20 - 100
C	Overtopping above 1 cfs/ft; <10,000 acre-ft	>500	>250	>166	>100
D	Prolonged free flow, >10,000 acre-ft	>1,000	>500	>333	>200
E	Equalization with exterior, approaching 100,000 acre-ft*	>2,000	>1000	>666	>400

*roughly equivalent to the breach inundation volume for the Metro Polder during Hurricane Katrina.

Estimating the actual polder surge inundation hazard at a particular inside location (probability of a peak interior SWL) is much more complicated than for the exterior surge hazard.[41] Unlike exterior surge hazards, polder surge inundation hazards cannot be readily assessed with a Surge-Response Function and Surge-Response OS. Instead, a JPM-OS is required to represent the local probabilities for a wide range of very extreme hurricanes. Then the following must be identified:

- The exterior surge condition (SWL, H_s, and T_p) at points along the polder perimeter throughout each JPM-OS storm event.
- The overtopping locations and inflows occurring throughout each event.
- The probability of various breach scenarios (lengths and inverts), resulting from various breach mechanisms (erosion and collapse), occurring at a range of perimeter locations and a range of times, together with the inflows for each breach scenario.
- The routing of overtopping and breach inflows within the polder, including contributions of rainfall and the influence of interior drainage and winds.

The inundation for each JPM-OS hurricane coupled with every applicable combination of breach scenarios is then analyzed, together with the full joint probabilities of each combination of hurricane and breach scenarios. The inundation CDFs are then constructed for each interior location. For "planning-level" hazard analysis the JPM-OS, number of breach scenarios, number of interior locations, and routing can be greatly simplified. For example, routing may be simplified to determining interior peak SWL at limited number of interior sub-basins using one-dimensional level-pool (reservoir) calculations.

5.2 Special Vulnerabilities of East-Bank Polders

According to five separate forensic studies of Hurricane Katrina's devastating inundation,[42] a major contributing factor was the absence of planning for the polder protection "as a system." In response, the USACE rebuilt the East-Bank protection as a "Hurricane and Storm Damage Risk Reduction System," with a primary design objective of having all components meet a consistent overtopping standard for NFIP accreditation—i.e., the chain would contain no under-designed or over-designed links.[43]

However, the recomputed 100- and 500-yr overtopping rates shown in Table 4.2 (based on a comprehensive surge risk reduction perspective) differ drastically among levee segments within each system. Table 5.2.a compares the 100- and Nominal 500-yr Q50 and Q90 for two reaches in each polder, and provides the factor by which they differ. The Metro Polder has the greatest overtopping differences—with exposures along SC02-B higher than along JL01by a factor of over 100 for the 100-yr Q50. NO East and St. Bernard also have differences between components, but with somewhat lower multiples— ranging between 2 and 10. These differences mean that each polder has a particular overtopping vulnerability:

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[41] See Bob Jacobsen PE Report, April 2013 for a full discussion of polder surge hazard analysis methodology.

[42] IPET, 2006 – 2009; Team Louisiana, 2006; Independent Investigation Levee Team, 2006; American Society of Civil Engineers Hurricane Katrina External Review Panel, 2007; National Academy of Engineering and National Research Council of the National Academies, 2009.

[43] Two major exceptions were the addition of 1.5 ft to T-Walls for RSLR and 3.5 ft to certain gates (1.5 for RSLR and 2 ft for "structural superiority").

Table 5.2. Levee Overtopping Vulnerabilities in East-Bank Polders
(Based on revised overtopping estimates in Table 4.2)

Location	100-yr		Nominal 500-yr	
	Q50	Q90	Q50	Q90
a. Comparison of Overtopping Rates for Two Locations in Each Polder				
Metro				
JL01	0.006	0.23	0.36	7.08
SC02-B	0.66	8.22	8.83	79.37
SC02-B/JL01	**107.53**	**35.97**	**24.65**	**11.21**
NO East				
NE31	0.006	0.21	0.18	5.41
NE11A	0.05	1.82	1.76	26.27
NE11A/NE31	**7.07**	**8.68**	**9.95**	**4.86**
St. Bernard				
SB15	0.005	1.05	0.88	10.39
SB17	0.015	1.83	1.67	46.21
SB17/SB15	**2.82**	**1.74**	**1.91**	**4.45**
b. Comparison of Polder Levee Overtopping Exposures				
Metro				
SCO2-B/SB17	**43.9**	**4.5**	**5.3**	**1.7**
NO East				
NE11A/SB17	**3.1**	**1.0**	**1.1**	**0.6**
St. Bernard				
SB17/SB17	**1.0**	**1.0**	**1.0**	**1.0**

- Metro Polder—along St. Charles Parish.
- NO East—near where US90 crosses the levee.
- St. Bernard—near the Caernarvon Corner.

The special vulnerability of the Metro Polder to overtopping in St. Charles Parish is further highlighted by the disparity in 100- and 500-yr F90s shown in Table 4.2.

Overtopping exposures also differ markedly between polders. Table 5.2.b shows the factor by which the higher overtopping rate in each polder (from Table 5.2.a) differs between polders. Table 5.2.b reveals that the Metro Polder is much more vulnerable to a Class C inundation hazard than either NO East or St. Bernard. SC02-B 100-yr Q50 is much higher than SB17, by a factor of 44—though the former still represents wave overtopping. Perhaps even more alarming is the five-fold factor in Nominal 500-yr Q50—with the St. Charles location at nearly 9 cfs, indicating significant continuous free flow. *The higher population and critical infrastructure and economic assets of the Metro Polder mean that there is a significant disparity in residual surge inundation risk between the three polders.*

In addition to the above overtopping vulnerabilities, all three East-Bank polders have major breach exposures associated with the remaining I-Walls along the IHNC Basin. The IHNC Basin I-Walls may not provide adequate FOSs for comprehensive risk management purposes at higher IHNC Basin surge SWLs. High IHNC Basin SWLs can occur with extreme overtopping at the IHNC Surge Barrier or due to malfunctions at the IHNC or Seabrook Surge Barrier Gates. (Note, unlike adjacent HSDRRS reaches, the USACE's design for the IHNC Surge Barrier allows substantial 500-yr overtopping. For the 9,400 ft barrier an overtopping rate of 10 cfs/ft equates to more than 1 ft of rise in the IHNC Basin rise every 30 minutes.) The I-Walls are also vulnerable to impact loading. An IHNC Basin I-Wall failure at any of the three polders would likely result in a Class D inundation.

For Metro Orleans Parish there is a potential for an Outfall Canal I-Wall failure in the event pumping at the interior and Lakefront stations, between the NOS&WB and the USACE, is not coordinated. An Outfall Canal failure (assuming the Lakefront station prevents backflow from Lake Pontchartrain) might release up to 1,000 acre-ft of water. While not insignificant, this is a much lower risk than an I-Wall failure for the IHNC Basin.

5.3 The Current Polder Surge Inundation Hazard Estimate

To date, there have been three efforts to examine East-Bank surge inundation hazard: IPET's Volume VIII Report (2009), the *LACPR Report* (2009), and work by ARCADIS/RAND in support of the Louisiana's *Comprehensive Master Plan for a Sustainable Coast* (2012). The following paragraphs discuss these efforts, their accuracy and uncertainty, and future changes in surge inundation hazard estimates.[44] All three efforts are "planning-level" exercises involving simplifications noted previously. The hazard estimates were intended to aid in the relative comparison of different alternative conditions (perimeter systems, coastal restoration, etc.) and not to provide absolute indications of interior hazard.

Given the HSDRRS accreditation, the East Bank FISs have not investigated polder surge inundation hazard. However, the information presented above suggests that St. Charles Parish could have a notable 100-yr surge inundation hazard.

IPET

IPET analyzed polder flood hazards to compare the effect of pre-Katrina protection, post-Katrina repairs, and the HSDRRS. The IPET analysis made extensive use of the simplifications listed previously, including:

- A small JPM-OS, in this case adapted from the 2005-09 Surge-Response OS
- Very limited number of breach scenarios.
- One-dimensional, level-pool, routing.
- Limited number of pumping scenarios.
- Ignoring the effects of interior wind setup and waves
- Interior level-pool routing by sub-basins.

[44] A detailed description and evaluation of these efforts are presented in Bob Jacobsen PE May 2013.

IPET determined 50-, 100-, and 500-yr SWL50 hazards by sub-basin. IPET also produced maps of depth hazard such as the one shown in Figure 5.2.[45] The IPET results, including the maps, are noted as *Nominal**—as the approach relies on less rigorous estimates of exterior SWL hazards than those Nominal 500-yr estimates used in the HSDRRS resiliency design.[46] For example, the *Nominal** 500-yr inundation hazard for Metro Orleans Parish is likely to be significantly underestimated. Also, several final features of the HSDRRS were not included in the analysis. The IPET report did not estimate confidence intervals for the polder inundation hazard.

LACPR
In 2009 the USACE also produced the *LACPR Report*. The study looked at inundation levels for three "makeshift" cases involving exterior 100-, 400-, and 1,000-yr SWL50s at *all points on the HSDRRS perimeter*. To examine polder inundation the LACPR study considered HSDRRS overtopping but no breaching. The LACPR used these "makeshift" cases because they were convenient for "planning-level" comparisons of protection and restoration alternatives. A case with the same return period SWL all points around the HSDRRS is rarer than that return period indicates. Actual inundation hazards require a more detailed joint probability analysis using hundreds of storms and numerous combinations of exterior surge and breaching scenarios.

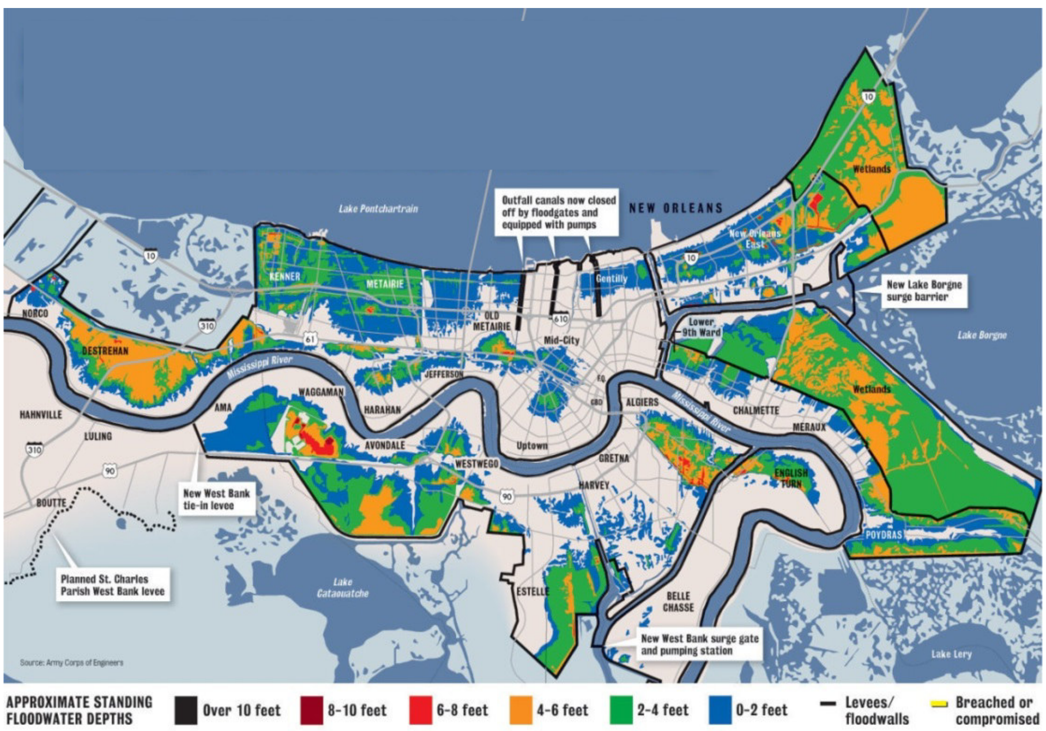

Figure 5.2. *Nominal 500-yr Surge Inundation**
Times-Picayune 2012 (from IPET 2009)

[45] Figure 5.2 is a reproduction of the original IPET 2009 map by the Times-Picayune in 2012. The map and accompanying article discussed residual East-Bank surge inundation hazards. The article does confuse the estimated return frequency of the inundation event shown on the map with the return frequency of a hurricane.

[46] For example, the adapted JPM-OS does not include any landfalling Category 5 hurricanes. The adaptation of the JPM-OS was a very reasonable approach at the time given IPET's purpose, schedule, and resources.

Master Plan
ARCADIS/RAND developed a regional scale comparative surge hazard/risk analysis tool for supporting Master Plan evaluation. The tool used a simplified ADCIRC model and JPM-OS to compute exterior surge hazards. Interior inundation associated with each storm was computed in an approach very similar to IPET. Current (2012) East-Bank polder hazards were not reported. However, the tool was employed in ranking alternative proposed coastal protection and restoration projects.

Future Changes in the Hurricane Surge Inundation Hazard Estimate
The regional trends and other factors noted in Section 2.3—RSLR, coastal erosion, HSDRRS settlement, new projects—that will cause future increases in exterior surge hazard (and which affect overtopping estimates and the adequacy of the HSDRRS levee designs) will also raise polder inundation hazard. The polder hazard can also be reduced in the future depending on changes to the HSDRRS itself—e.g., augmenting levee heights or resiliency. As with exterior surge hazard, improvements in the State-of-the-Practice for undertaking the analysis itself are likely to significantly change 500-yr inundation hazard estimates from the *Nominal** ones provided by IPET.

Bob Jacobsen PE (May 2013) recommended revision of the polder inundation hazard analysis as soon as possible and investments in further method improvements. One method that should receive significant attention in the coming years is the treatment of breach scenarios and probability—as well as uncertainties. For Class C inundation, equalization of interior and exterior SWLs obviously serves as an upper bound.

5.4 <u>Hurricane Surge Inundation Versus Other Flood Hazards</u>

In addition to inundation from hurricane surge, the three East-Bank polders face flood hazards associated with rainfall and the Mississippi River. Rainfall hazards include

- Severe tropical rainfall only, i.e., without surge-driven inundation. Rainfall only accumulations with tropical cyclones can easily exceed the commonly referenced 25-year return period, 24 hour duration magnitudes—on the order of 9 to 11 in for Southeast Louisiana (Faiers et al 1997). During Tropical Storm Allison (2001) a location in Southeast Louisiana received over 15 in of rainfall in one 24-hr period, and nearly 30 in over the course of the storm.[47]
- Severe non-tropical rainfall events. A series of storms on May 7-8, 1995 produced up to 20 inches of rainfall in Southeast Louisiana, inundating some low areas inside the Metro Polder by several feet (NOAA NWS 2005).

Polder interior drainage systems are typically sized for 10-year events—subjecting some low-lying areas to frequent flooding. Table 5.3 presents the volume of rainfall by polder sub-basins (Figure 3.4) for 10- and 100-yr 6-hr rainfall events, and a 100-yr 24-hr event. For those not familiar with rainfall hazards, these volumes may come as a surprise. The Metro 100-yr 24-hr volume is about 1/3rd the volume of the Katrina inundation. This highlights the importance of robust drainage and pumping design and O&M for the East-Bank polders.

[47] at Thibodaux Louisiana (NOAA NWS 2001).

Table 5.4 compares the IPET *Nominal** 100- and 500-yr "planning-level" surge inundation hazard volumes polder with the 100-yr 6-hr rainfall event, both with pumping. While the IPET report may understate the surge inundation hazards, the comparisons do give an indication of the relative importance of rainfall hazard. For example, in the Metro Polder, sub-basins OM-1, 2, 3, 4 and 5 have very similar volumes for the *Nominal** 500-yr surge inundation and 100-yr 6-hr rainfall, with the latter actually being a bit higher.

The Mississippi River levees protecting the East-Bank—together with upriver flood control structures at Bonnet Carre, Morganza, and Old River—are generally reported as sufficient to contain an 800-yr flood.[48] There are no recent studies analyzing the joint probabilities for various conditions in the Mississippi, Red, and Atchafalaya Rivers that update this estimate. However, there are potential factors to suggest that the return period could be lower—such as siltation of the Atchafalaya Basin, RSLR and reduced river gradients, changes in runoff and tributary flow frequencies throughout the Mississippi River basin, and changes in estimates of precipitation return periods.

A Mississippi River flood impacting the East-Bank could potentially involve an overtopping or collapse breach. In either case the entire adjacent polder could be filled to elevations well above 15 ft. Such an event would be much worse than Hurricane Katrina—more so as the high flooding would likely last for many days. Besides the known seepage locations that are typically well controlled during high river stages, the East-Bank may have some special vulnerabilities to Mississippi River flood—e.g., the river cut-bank near Ochsner Hospital or insufficiently supported I-Walls—that have not been well-studied.

The 2013 Bob Jacobsen PE report recommended that a comprehensive, rigorous assessment of all major East-Bank flood hazards be undertaken. Given the recurring public and private property and infrastructure damage associated with rainfall flood events, and the catastrophic devastation of a Mississippi River flood, the relative risks of the various inundation threats need to be understood.

[48] During and after the 2011 Mississippi River flood the 800-yr return period was cited in many news reports, see http://swampland.time.com/2011/05/13/cliches-levees-and-federal-funds/

Table 5.3. Volume for Rainfall Hazards
Acre-Ft of Accumulation Excluding Losses and Pumping (Faiers et al 1997)

Polder	Sub-Basin	Area Acres	6-hr Duration 10-yr 6.5 In	6-hr Duration 100-yr 10 In	24-hr Duration 100-yr 13 In
NO East	NOE1 Bayou Sauvage	14,233	7,710	11,861	15,419
	NOE2 Maxent Wetland	5,683	3,078	4,736	6,157
	NOE3	2,866	1,552	2,388	3,105
	NOE4	2,338	1,266	1,948	2,533
	NOE5	9,588	5,194	7,990	10,387
	NOE3, 4, 5	***14,792***	***8,012***	***12,327***	***16,025***
	Total Polder	***34,708***	***18,800***	***28,923***	***37,600***
St. Bernard	SB2 Central Wetland	5,066	2,744	4,222	5,488
	SB5 Central Wetland	24,340	13,184	20,283	26,368
	SB1	5,115	2,771	4,263	5,541
	SB3	5,485	2,971	4,571	5,942
	SB4	9,415	5,100	7,846	10,200
	SB1, 3, 4	***20,015***	***10,841***	***16,679***	***21,683***
	Total Polder	***49,421***	***26,770***	***41,184***	***53,539***
Metro	SC1 (mostly swamp)	5,906	3,199	4,922	6,398
	SC2	7,364	3,989	6,137	7,978
	SC1 & 2*	***13,270***	***7,188***	***11,058***	***14,376***
	JE1	7,784	4,216	6,487	8,433
	JE2	5,510	2,985	4,592	5,969
	JE3	15,395	8,339	12,829	16,678
	JE1, 2, 3	***28,689***	***15,540***	***23,908***	***31,080***
	OM1	5,041	2,731	4,201	5,461
	OM2	4,176	2,262	3,480	4,524
	OM3	4,720	2,557	3,933	5,113
	OM4	2,063	1,117	1,719	2,235
	OM5	11,268	6,104	9,390	12,207
	OM 1, 2, 3, 4, 5	***27,268***	***14,770***	***22,723***	***29,540***
	Total Polder*	***69,227***	***37,498***	***57,689***	***74,996***

Table 5.4. Comparison Surge Inundation versus Rainfall Hazard [49]

100% Pumping

Polder	Sub-Basin	Acres	IPET *Nominal** Surge Inundation				6-hr/100-yr Rainfall Minus 6-hr Pumping Acre-ft
			100-Yr		500-Yr		
			Elev NAVD88	Vol Acre-ft	Elev NAVD88	Vol Acre-ft	
NO East	NOE1 Bayou Sauvage	14,233	0	7,975	3	47,635	
	NOE2 Maxent Wetland	5,683	-4	6,206	-2	14,718	
	NOE3	2,866	-4	1,244	-3	2,104	
	NOE4	2,338	-1	1,058	0	1,756	
	NOE5	9,588	-9	2,625	-6	10,598	
	NOE3, 4, 5	***14,792***		***4,927***		***14,458***	***12,327 - 1,930 = 10,397***
Lower 9th Ward/ St. Bernard	SB2 Central Wetland	5,066	2	2,475	3	5,462	
	SB5 Central Wetland	24,340	3	21,764	5	62,814	
	SB1	5,115	-12	0	0	35,397	
	SB3	5,485	-3	593	-1	1,706	
	SB4	9,415	1	1,480	4	14,639	
	SB1, 3, 4	***20,015***		***2,073***		***51,742***	***16,679 – 4,518 = 12,161***
Metro	SC1 (mostly swamp)	5,906	3	8,057	5	18,654	
	SC2	7,364	3	2,175	5	6,041	
	SC1 & 2	***13,270***		***10,232***		***24,695***	***11,058 - 1,017) = 10,041***
	JE1	7,784	2	1,995	4	6,366	
	JE2	5,510	-12	45	-4	3,185	
	JE3	15,395	-5	6,721	-3	25,322	
	JE1, 2, 3	***28,689***		***8,761***		***34,873***	***23,908 – 10,289 = 13,619***
	OM1	5,041	-6	964	-5	2,276	
	OM2	4,176	-12	14	-12	14	
	OM3	4,720	-12	1	-12	1	
	OM4	2,063	-2	468	1	2,361	
	OM5	11,268	-12	16	-2	2,638	
	OM 1, 2, 3, 4, 5	***27,268***		***1,463***		***7,290***	***22,723 – 12,724 = 9,999***

[49] The surge inundation elevations are from IPET; IPET stage-storage data for the sub-basins were not available and therefore volumes were independently computed using the regional LIDAR DEM. Polder totals are presented for information purposes but a single 500-yr event would not produce the entire polder volume

6. Approaches to Surge Inundation Hazard Reduction

As discussed in Section 5, the East-Bank polders face significant residual inundation threats from hurricane surge. The return period for the FIS Nominal 500-yr surge occurring somewhere around the East-Bank HSDRRS perimeter could well approach 100 years, factoring partial correction of the 2008 FIS, a reasonably conservative assessment of uncertainty, and changing conditions. The East-Bank return period for a Class D surge inundation event—with over 10,000 acre-ft of inflow—could well approach 200 years (with a 10 percent probability during any 20-yr time-frame), or worse if HSDRRS O&M is not well-funded and effective.

This section reviews eight approaches to reduce inundation risks for the East-Bank polders:

1. Evacuation
2. Broadening Participation in Flood Insurance
3. Flood Proofing
4. Enhancing the HSDRRS
5. Improving Interior Drainage
6. Coastal Restoration
7. Removing West-Bank Levees in Lower Plaquemines Parish
8. Compartmentalization

All eight approaches are capable of providing some measure of risk reduction. Given that the East-Bank faces several flood threats and numerous infrastructure needs, and limited funding and other resources, investments in surge risk reduction should be directed at the most cost-effective strategies.[50]

As noted in Section 5.4, the polders also face serious flood threats from rainfall and the Mississippi River. Thus, it is crucial that flood risk mitigation agencies, not "over-invest" in reducing surge risks at the expense of rainfall and river flood risks. Bob Jacobsen PE (May 2013) recommended that surge and other flood risk management agencies work together to institutionalize such evaluations and prepare plans to implement the most cost-effective measures. The New Orleans metropolitan area also has many other infrastructure, social, cultural, educational, health, and welfare funding needs.

Formal risk assessment methodologies can assist in rational decision-making. IPET's 2009 *General Description of Vulnerability to Flooding and Risk for New Orleans and Vicinity: Past, Present, and Future* stated:

[50] Bob Jacobsen PE (June 2013) in a review of the USACE's Levee Armoring Research and Recommendations Report, (June 2013) recommended that SLFPA-E work with the CPRA and the USACE to develop a comprehensive *Hurricane Surge Residual Risk Management Program.* Key actions should include:

- Establish a permanent, ongoing effort, for continuous improvement of surge hazard and risk estimates and risk management planning.
- Include all sources of residual risk and all potential risk reduction measures.
- Address both HSDRRS and non-HSDRRS plans for residual risk reduction.
- Evaluate and prioritize HSDRRS armoring recommendations within an appropriate matrix of all residual risk reduction alternatives, including measures that reduce the need for maintenance.
- Provide for future research to support continuous improvement of surge hazard and risk reduction estimates and risk management planning.

> It is imperative that that level of (residual) risk be quantified and made available to the public and public officials. In addition, a 100-year system such as that planned for 2011 in New Orleans, should be considered a baseline, not an end-state, for an urban area.... (R)isk reduction (from the HSDRRS) must be coupled with additional measures.... This may be more effective evacuation … or flood proofing, compartmentalization or land-use zoning to reduce property damages.

A detailed evaluation of benefits and costs for the range of surge risk reduction measures is beyond the scope of this Report. The overview in this Section includes only a general consideration of each approach—a summary of goals and challenges for each approach is presented in Table 6.1. Most of these approaches have been anticipated since well before Hurricane Katrina.[51] Following Katrina, the concept of a "multiple lines of defense" (MLOD) strategy to reducing surge risk received new emphasis and more rigorous examination, as exemplified in Figure 6.1 from Lopez (2008).

The responsibilities for implementing the eight approaches are highly fragmented, and include a variety of federal, state, and local agencies. For example, the NFIP related elements are typically administered in the East-Bank region by the parish governments. The Louisiana Department of Transportation and Development, Public Works and Water Resources Division, is the State NFIP Coordinator. The SLFPA-E and CPRA are not responsible for East-Bank NFIP administration. Parish participation in the NFIP is contingent upon local regulation of development in the 100-yr floodplain. FEMA, in cooperation with the parishes, conducts the FISs to assess the regional surge hazard and to update Flood Insurance Rate Maps (FIRMs) depicting the height and extent of the 100-yr flood (the 100-yr flood zone or floodplain).

Thus, coordinating cost-effective risk reduction is a daunting task. As the local agency most familiar with residual surge risk, SLFPA-E can evaluate issues and provide recommendations for all eight approaches. However, SLFPA-E only has direct responsibility for Enhancing the HSDRRS, in conjunction with CPRA; Improving Interior Drainage in St. Bernard Parish; and a few potential compartmentalization features.

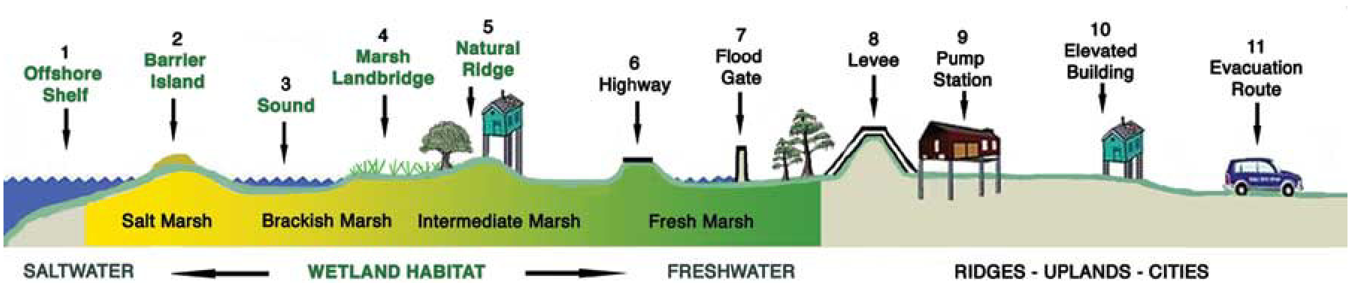

Figure 6.1. Multiple Lines of Defense
Lopez 2008

[51] See the special five-part series "Washing Away" published by the New Orleans Times-Picayune in June 2002.

Table 6.1. Summary of Polder Inundation Risk Reduction Approaches

Goal	Challenges
All Approaches • Reduce Class C, D, and E inundation risks to life, health, property, and polder assets. • Slow the rising cost of flood insurance. • Enhancing the regional attractiveness for economic investment.	 • Fragmentation of responsibilities among various federal, state, and local agencies. • Escalating costs for greater increments of flood risk reduction. • Other governmental priorities can outweigh flood risk reduction.
1. Evacuation • No. 1 Priority. Protect lives when NFIP HSDRRS overtopping is threatened.	 • Improving surge forecasts. • Capacity and maintenance of evacuation routes. • Pick-up, transportation, and sheltering for those with health, financial, or logistical challenges to self-evacuation.
2. Broadening Flood Insurance Participation • No. 2 Priority. Facilitate quicker, more cost-effective recovery. • Fairness; reduce “free riders.”	 • Large number of residential properties not required to have flood insurance. • Political opposition to monetary incentives or mandates.
3. Flood Proofing • Phase in greater elevation and flood proofing requirements for residences, commercial property, public facilities, and infrastructure. • Obtain NFIP CRS credits.	 • Gain acceptance for cost-effective requirements by public and property interests; overcome anti-regulation sentiment. • Funding for flood proofing public facilities.
4. Enhancing the HSDRRS <u>i) Upgrade Design for NFIP Re-Accreditation (As Required)</u> • Revise design as needed to continue meeting NFIP requirement for negligible 100-yr overtopping. • Carefully consider whether or not to undertake any “voluntary” revisions.	 • Determining NFIP requirements for revised surge hazard and overtopping analysis; and what are SLFPA-E/CPRA responsibilities. • Federal funding for revised FIS and overtopping analysis and NFIP required HSDRRS upgrades. • FEMA may not undertake/fund revision of Southeast Louisiana FIS. Other parishes may not want a revision. • SLFPA-E/CPRA voluntary revision of NFIP surge hazard and overtopping analysis may trigger extensive/expensive HSDRRS upgrades but without federal support. • Potential SLFPA-E/CPRA liabilities if new analyses are not undertaken.
<u>ii) Upgrade Design Beyond NFIP Requirements</u> • Revise the design to reduce overtopping hazard beyond requirements for NFIP re-accreditation. • Achieve a greater inundation risk reduction, e.g., using a SOP 500-yr Q90 overtopping limit.	 • Revise surge hazard, overtopping, and residual risk analysis to evaluate alternatives. • Analyses beyond NFIP requirements not likely to be funded by FEMA. • Major upgrades will cost tens of billions of dollars, require lengthy studies, property and environmental impacts. • USACE may require new authorization to support new engineering investigations and upgrades; federal funding likely difficult to obtain; *2009 LACPR Study* found upgrades may not be cost-effective. • Cost escalations over decadal construction schedules and erosion of political commitment. • Adverse effects on neighboring surge hazard. • NO East Surge Barrier option does not reduce HSDRRS overtopping hazards associated with “tilting” scenarios.

Table 6.1. Summary of Polder Inundation Risk Reduction Approaches
Continued

Goal	Challenges
iii) Upgrade Breach Resiliency • Optimize reduction of catastrophic breaching/inundation risks with more robust armoring of NFIP system.	• Full, state-of-the-practice surge hazard, overtopping, and residual risk analysis to optimize reach-by-reach armoring. • Alternatively, maximize armoring level under current authorization with greater FOS and tighter overtopping limits; identify vulnerable reaches for upgrades from turf to HPTRM and from HPTRM to paving. • Supplement federal funding with additional state/local funding. • Coordination of levee lifts and armoring. • Maintenance issues.
5. Improving Interior Drainage • Better diversion of overtopping to drainage system and removal via pump stations.	• Drainage improvements reduce flood risks mostly in sub-basin; less so over whole polder. • Pumping and conveyance upgrades can be very expensive. • For some sub-basins, rainfall flood risk may be more cost-effectively reduced initially through detention and re-use (see GNO Urban Water Plan). • Likely to require a high percentage of local funding. • Upgrades typically focused on rainfall events and not surge inundation. • Operational reliability and resiliency is required for surge inundation risk reduction. • Likely to be more effective in reducing Class C inundation, than more extreme Class D and E inundation hazards.
6. Coastal Restoration • Reduce 100-yr surge hazard at HSDRRS and flood risks for outlying communities.	• Modest projects have limited impact on East-Bank polder inundation hazard. • Significant inundation hazard reduction requires special considerations for restoration elevation, footprint, and resiliency. • Massive projects may lower forecasted increases to 100-yr HSDRRS elevations due to RSLR and coastal erosion; but may be impractical to optimize large-scale ecosystem/habitat projects for surge hazard reduction. • Fronting forests may be cost-effective way to reduce HSDRRS wave overtopping—but requires changes to USACE wave estimates to allow for vegetation effects.
7. Removing West-Bank Levees in Lower Plaquemines Parish • Reduce surge pile-up on east flank of the delta; also facilitate delta building processes.	• Compensation/mitigation may not prove sufficient to overcome local opposition.
8. Compartmentalization • Use existing man-made and/or natural topographic features to provide redundancy in protection of critical sub-basins or neighborhoods.	• Identifying projects with broad support; fairness of reducing flood risks inside the compartment but increasing flood risks outside the compartment. • Identifying projects with high benefit-to-cost, including opportunity cost of not investing in ways to reduce risk over large polder area. • Difficult acquisition of property or servitude/RoW/use. • May require modifications to drainage systems to avoid rainfall flooding impacts.

6.1. Evacuation

Hurricane evacuation of coastal residents has been formally implemented in Southeast Louisiana for many decades. Besides Katrina (2005), over the past 20 years evacuations have occurred for Hurricanes Georges (1998), Isadore (2003), Lili (2003), Ivan (2004), Rita (2005), Gustav (2008),[52] and Isaac (2012). The region as a whole can expect to experience hurricane evacuations at a return period of less than 5 years, and more often during active hurricane periods in the Gulf of Mexico.

The thousands of deaths which occurred during Hurricane Katrina dramatically demonstrated that protecting lives is the number one hurricane surge responsibility of federal, state, and local government. Effective evacuation—encompassing the needs of those with health, financial, and logistical challenges to self-evacuation—is the top surge risk management priority. For the East-Bank polders, hurricane evacuation is the responsibility of St. Charles, Jefferson, Orleans, and St. Bernard Parish emergency management departments, working in conjunction with the Louisiana Governor's Office of Homeland Security and Emergency Preparedness (GOHSEP), state and local transportation departments, and state and local law enforcement.

As noted in Section 5.1, a Class A inundation (associated with an NFIP 100-yr overtopping event) has an expected return period of about 20 years for the East-Bank as a whole—perhaps 10 years for the combined East- and West-Banks. Thus, given the design limitations of the HSDRRS, evacuation notices for the East-Bank polders can be expected at this average frequency—and more frequently a) during decades of greater hurricane activity, and b) if hurricane forecasters and evacuation officials act more conservatively. Recall that surge hazards, and thus overtopping risks, are not a function of hurricane intensity alone. A large stalled Category 2 hurricane is capable of producing a Class D inundation event.

As reviewed in Section 4.1, the HSDRRS design function is limited to reducing flood damage to residential and small business property. The HSDRRS was not intended for—and was not designed with FOSs for—protecting the population. The critical role of evacuation as a necessary complement to the HSDRRS in managing surge risk was clearly stated in the USACE 2009 *LACPR Report*.

Thus, although evacuation is rarely 100 percent effective—and is itself not without risks to life and health—for the purposes of this Report the *residual* hurricane surge inundation risk for the East-Bank polders does not encompass threats to life and health and is instead limited to uninsured damages to public and private assets and the associated economic, cultural, and personal losses.

While SLFPA-E has no direct role in hurricane evacuation, it can support improvements by:[53]

- Continually reminding evacuation officials and the pubic of the limitations of the HSDRRS.
- Working with CPRA to advance regional hurricane climatology, surge science, and HPC/High-Resolution modeling, and thus timelier and more accurate hurricane surge forecasts and evacuation notices.

[52] See Wolshon 2006 and Campanella et al 2012.

[53] SLFPA-E does operate gate structures on Louisiana Highways 39, 46, and 300 which effect evacuation of outlying coastal areas in Plaquemines and St. Bernard Parishes. SLFPA-E officials can also be advocates for a) improved coastal roads, highways, and interstates to meet peak evacuation demands of residents and businesses; b) optimal "Contra-flow" plans; and c) adequate funding for pick-up, transportation, and sheltering contingencies to meet the needs of thousands of residents with health, financial, and logistical challenges to self-evacuation.

6.2. Broadening Participation in Flood Insurance

An NFIP levee is to surge what firefighting is to wildfires—no more than a complement to evacuation and property insurance.

Broad flood insurance participation facilitates more rapid, wide-spread, and efficient flood recovery.[54] Thus, expanding property flood insurance for a full range of residential, commercial, and industrial damages—through the NFIP (with subsidized premiums for basic residential coverage) and commercial underwriters (for remaining coverages)—is a very cost-effective flood risk management component.[55] For most floodplain communities, expanding flood insurance participation is the logical second flood risk reduction priority, after effective evacuation. By substantially lowering the 100-yr flood hazard for the East-Bank polders, the NFIP HSDRRS facilitates expanded flood insurance participation and makes it an even more attractive for surge risk management.

While SLFPA-E (with the CPRRA) is responsible for maintaining HSDRRS NFIP accreditation it is not responsible for NFIP administration. SLFPA-E can coordinate with the parishes, FEMA, and other federal, state, and local surge risk management agencies to broaden flood insurance participation by:

- Supporting parish officials in promoting participation in flood insurance. A useful mantra is: “An NFIP levee is to surge what firefighting is to wildfires—no more than a complement to evacuation and property insurance.”
- Working with parish officials to consider incentives for flood insurance participation, such as tying participation in flood insurance to property tax rates for local drainage and HSDRRS O&M. While monetary incentives—much less mandates—can be politically controversial, all risk reduction measures deserve to be on the table for fair consideration. Broadening flood insurance participation can remedy the unfairness of “free-riders.” In addition, over the long-term, broadening participation can reduce increases in premiums.

6.3. Flood Proofing

Flood proofing is the oldest technique for mitigating flood damage risk, as well as one of the most cost-effective and reliable. Floodplain communities across the nation are increasingly committed to flood proofing public facilities (hospitals; shelters; schools; and police, fire, and key governmental buildings); commercial facilities; infrastructure (roads, natural gas, electricity, water, sewer, communications), and other community resources, as well incentivizing flood proofing of private residences. Under the NFIP, residences in the 100-yr floodplain are subject to basic flood-proofing requirements, and the parishes are encouraged to develop greater requirements. The NFIP provides credit for enhanced flood proofing—in the form of lower premiums—through its Community Rating System.

A big advantage of flood proofing is that significant reductions of flood damage risk are often achievable at a modest public expense. Flood proofing can be implemented in phases—by type of facility, by

[54] A large amount of New Orleans area housing stock (and small business property) is not under a mortgage, and many owners do not opt to carry flood insurance.

[55] An exception is those areas where repetitive flood damage is experienced. For such areas the NFIP requires that residences also be elevated the 100-yr flood or else removed.

degree/type of improvement, and according to the local ground elevation/inundation hazard. Building codes can address reasonable flood proofing schedules for residences and private facilities. Flood proofing for many public and commercial facilities and utilities can be addressed during normal replacement and renovation cycles.

Flood proofing can be quicker to implement and more cost-effective than public flood control projects, such as enhancing the HSDRRS or upgrading interior drainage. For the East-Bank (and West-Bank) polders, flood proofing has the added benefit of reducing risks for rainfall flood hazards.

Again, SLFPA-E can coordinate with the parishes, FEMA, and other federal, state, and local surge risk management agencies to achieve greater flood-proofing, particularly:

- Greater elevation. New residences and other buildings can be required to have higher foundations or piers, exceeding minimal NFIP requirements. Multi-story buildings can be designed to place non-critical components (e.g., parking) on the lower floors. Where feasible, renovation of older homes and buildings can also require greater elevation.
- Expanding requirements to place crucial building components (backup power, communications, etc.) on higher floors.
- Use of resilient waterproofing for building and infrastructure components that must remain at or below key flood hazard levels

6.4. Enhancing the HSDRRS

The HSDRRS can be enhanced to reduce inundation risk in three ways: upgrade for NFIP re-accreditation as required, upgrade to reduce overtopping beyond NFIP requirements, and upgrade breach resiliency.

i. Upgrade Design for NFIP Re-Accreditation (As Required)

SLFPA-E, together with the CPRA and USACE, are responsible for the current HSDRRS design objective of meeting NFIP requirements for negligible 100-yr overtopping (see Section 4.1). A formal revision of the HSDRRS LSER is required for the 2023 NFIP re-accreditation. The LSER revision *may be required to modify key design elements such as*:

- The 2008 FIS 100-yr surge estimates to a) correct errors (see Section 2.2); b) update for changes in surge conditions (e.g., RLSR, coastal erosion, etc.), and c) incorporate the latest practices in surge hazard analysis (hurricane joint probability, Surge-Response, surge modeling, etc.).
- 100-yr Q50 and Q90 overtopping estimates with new estimates of SWLσ and other uncertainties,[56] foreshore wave height conditions, as well as changes to the Monte Carlo analysis procedure.
- Overtopping Q50 and Q90 acceptable limits to reflect the latest overtopping erosion research.

[56] Consistent with NFIP purposes, not necessarily to be reasonably conservative for local comprehensive risk management.

Such revisions could lead to upgrades in the HSDRRS design,[57] such as higher crown elevations, changes to foreshore and embankment slopes, and the addition of wave breaking features. For some reaches innovative methods of raising crowns might be considered (e.g., installing gravity walls atop levees). For reasons discussed in Sections 4 and 5, levee reaches are likely to require NFIP upgrades sooner than perimeter T-wall reaches. In the East-Bank, the levees in St. Charles Parish (overseen by the PLD) have the lowest 100-yr freeboard and may need NFIP design upgrade soonest.

Importantly, revisions to the FIS 100-yr surge estimates, the Q50 and Q90 overtopping estimates, and the overtopping limits are complicated by questions of what revisions are actually required under the NFIP and who is responsible for funding and undertaking which revisions. FEMA typically assumes responsibility for FIS revisions—in which case they would likely fund the USACE or a contractor to revise the 2008 FIS. However, FEMA may not require a full—or even a partial revision—of the FIS, as they may not have this revision as a funding priority. If this is the case, SLFPA-E and CPRA will have to decide whether they should undertake a FIS revision. The CRPA and SLFPA-E are responsible for the 100-yr Q50 and Q90 overtopping estimates, as well application of the latest information on acceptable limits, assuming the USACE has officially transferred "ownership" of the HSDRRS to the CPRA.

It could be argued that for strictly NFIP re-accreditation purposes, the CPRA and SLFPA-E should not "volunteer" any revisions of the 2008 FIS surge hazard estimates or the USACE's Q50 and Q90 overtopping estimates. Doing so could lead to the CPRA and SLFPA-E being responsible for implementing expensive design changes. On the other hand, if the CPRA and SLFPA-E undertake a 2023 LSER without full revision of the FIS 100-yr surge estimates, the Q50 and Q90 overtopping estimates, and the overtopping limits, they should carefully assess their (and the parishes') potential liabilities under the NFIP, as well as under Louisiana civil law.

ii. Upgrade Design to Beyond NFIP Requirements

An HSDRRS upgrade beyond NFIP requirements could entail revising the surge hazard and overtopping analyses consistent with comprehensive surge risk management. At a minimum this would include the partial revisions discussed in Sections 2.6 and 4.3(see Appendix C), but could extend to a complete new analyses addressing updates to the state-of-the-practice for rigorous evaluation of extreme hazards. Any significant HSDRRS redesign would likely involve a joint effort of SLFPA-E, CPRA, and the USACE. A redesign could consider one or more of the following:

1. **Updated Surge Hazard Analysis.** Surge hazard CDFs could be revised to correct errors, update for changes in surge conditions, and/or incorporate the latest practices in hurricane climatology, Surge-Response, and HPC/High-Resolution surge modeling. New estimates would be developed for SWL, H_S, and T_P at a range of return periods: 100-, 200-, 500-, 1000-yr, etc.
2. **Reasonably Conservative Uncertainties at Each Hazard Level.** Appropriate values for SWLσ and other uncertainties at the 100-, 200-, 500-, 1000-yr, etc. levels would be developed for FOS considerations. (Recall—see Sections 2.4, 2.5, and 2.6—that the assignment of uncertainties to the CDF using epsilon is an important issues in determining SWLσ.)

[57] HSDRRS design changes are above and beyond the requirements for maintenance lifts to meet current design. Regardless of design changes, the 2023 re-accreditation must show that maintenance lifts are being performed.

3. **Updated Q50 Overtopping Limits.** The redesign would review the latest overtopping erosion research and update the acceptable limit for Q50 at selected hazard levels of interest, e.g., 100-, 200-, 500-, and 1000-yr, etc.
4. **Updated Q90 Overtopping Limits/FOS.** The redesign would also update the acceptable limit for Q90 for the hazard levels of interest. Changing the FOS from Q90 could also be considered, e.g., to Q95.
5. **Revised Overtopping Monte Carlo Analysis.** The estimations of Q50 and Q90 (or other FOS) could be based on new reasonably conservative uncertainties, new estimates of the foreshore wave heights, and revised Monte Carlo analysis procedures.

New reach elevations, geometry, wave breakwaters, etc. would then be determined for the preferred hazard level and FOS. At a minimum this could continue to be the 100-yr Q90 but determined with revised surge hazard estimate, reasonably conservative uncertainties, and a revised overtopping analysis (see Appendix C). For some reaches, a major upgrade could include addition of T-Walls.

The HSDRRS levees in St. Charles Parish have the lowest 100-and 500-yr freeboard and pose a high relative overtopping breach hazard in the East-Bank, including an inundation risk to East Jefferson. Upgrading this segment is under the jurisdiction of the PLD but is strongly in the interest of SLFPA-E.

A systematic HSDRRS upgrade to reduce overtopping would involve detailed investigations and evaluation of design alternatives. Recall from Section 5 that inundation volumes from Class A, B, and C overtopping alone (without major breaching) can be modest relative rainfall flood hazards. Therefore, modest upgrades may not be worthwhile, especially relative to improving breach resiliency, (see below).

An HSDRRS upgrade to substantially reduce overtopping—e.g., 500-yr Q90 to 0.1 cfs/ft—would face many serious hurdles:

- A rigorous surge hazard and overtopping analysis for comprehensive risk management purposes addressing 500- and 1000-yr hazards is beyond the scope of the NFIP and not likely to be funded by FEMA. New state-of-the-practice analyses would likely take at least two years to complete and cost several million dollars.
- The USACE may require new Congressional authorization to support engineering and construction of a HSDRRS upgrade to reduce overtopping. The USACE's 2009 *LACPR Study* recommended against 400- and 1000-yr upgrades to the HSDRRS as not cost-effective versus other risk reduction alternatives.
- The cost of upgrading the HSDRRS to substantially reduce inundation risk will run into the tens of billions of dollars; federal funds for engineering, much less constructing, an upgrade will be difficult to obtain.
- SLFPA-E and CPRA may have to take the lead on investigations for an HSDRRS upgrade. This may not be a funding priority given O&M responsibilities.
- Upgrades may require extensive property acquisition, as well as mitigation of impacts to adjacent properties and the environment.
- Major upgrades could increase nearby extreme surge hazards, in which case they would be opposed by these communities.
- Major upgrades would have very lengthy construction schedules, subjecting the project to great cost uncertainties and the loss of political will.

An East-Bank project augmenting the HSDRRS that has received considerable attention is the addition of a barrier across the NO East Land-Bridge. A NO East Land-Bridge Barrier could reduce filling of the Lake Pontchartrain/Lake Maurepas Basin. In addition to the East-Bank polders, surge hazard from Lakes Pontchartrain and Maurepas affects the western and northern shores of the Lakes. However, a substantial barrier will raise surge hazard in The Corner and along The Funnel. A barrier with gates and abutments across Rigolets and Chef Menteur Passes may also impact the water quality and fisheries of the Lakes. Importantly, a NO East Land-Bridge Barrier would not affect tilting of the Lakes.[58]

iii. Upgrade Breach Resiliency

Upgrading the designated armoring for levee reaches (see Section 4.4) may be a more cost-effective strategy to reducing residual surge risks than redesign for lower overtopping. Some armoring improvements may not require significant design changes to the reaches themselves (e.g., upgrading from enhanced turf to HPTRM, or HPTRM to paving). Unlike upgrading the HSDRRS design, improved armoring may not require expanded right-of-ways, property and environmental impacts, or lengthy construction schedules.

Determining the optimal level of armoring requires a revised surge hazard and overtopping analyses consistent with comprehensive surge risk management. Furthermore, it requires a state-of-the-practice inundation hazard analysis and risk assessment for armoring alternatives. This inundation hazard analysis also requires advanced methods for addressing breach probabilities.

However, short of a new effort to optimize armoring, some practical armoring improvements could be planned under the USACE's current authorization. For example, the USACE could consider a larger FOS for its Nominal 500-yr overtopping rate (which it is using for armoring decisions), as well as more stringent 500-yr overtopping limits. If current USACE appropriations are not sufficient to fund armoring upgrades, SLFPA-E and CPRA could consider contributing a larger cost share.

In addition to increased funding, an important challenge associated with stronger armoring measures (HPTRM and paving) is coordination with levee lift schedules and potential armor maintenance and replacement issues associated with levee lifts.

Besides improved armoring for overtopping erosion, HSDRRS breach resiliency can be increased by:

- Armoring flood-side slopes for reaches exposed to significant wave erosion.
- Enhancing the stability of any levee reaches and floodwalls shown to have the lowest FOS through monitoring and design reviews.
- Investigating and addressing potential subsurface weaknesses which could expose reaches to seepage related failures.

[58] The USACE (2009) and SLFPA-E (Ben C. Gerwick 2012) have both conducted evaluations of a NO East Land-Bridge Barrier—including options for limited barriers with overtopping and without closure of the Rigolets and Chef Menteur Passes. The options do not appear to significantly reduce the East-Bank HSDRRS overtopping hazard.

6.5. Improving Interior Drainage

The three East-Bank polders include 32 primary forced drainage pump stations which transfer interior accumulated water to outside the HSDRRS. These "perimeter" pump stations are listed in Table 6.2, along with their capacities. (The pump station locations and drainage sub-basins are addressed in Section 7.) Table 6.2 also summarizes total perimeter pumping capacities within the three East-Bank polders, with the Metro and St. Bernard polders subdivided by parish.

Perimeter pump stations are designed to work with interior conveyance networks consisting of open and covered canals, pipelines, and interior "lift" stations, which aid in draining low-lying areas to major canals. Interior lift stations are not listed in Table 6.2. The combined sub-basin pumping and conveyance systems are designed to accommodate a 10-yr rainfall event. This design means that many interior areas retain significant risk of rainfall flooding. FEMA flood hazard maps for the East-Bank parishes show interior areas that have 100-yr rainfall flood exposure.[59] The federal government supports parish drainage projects through the USACE Southeast Louisiana (SELA) Program, which provides design and construction, at 25 percent local match.

Table 6.2 includes the Orleans Parish pump stations which discharge into the 17th Street, Orleans Avenue, and London Avenue outfall canals. The three stations which re-pump water from the outfall canals to Lake Pontchartrain are not listed. The Gentilly Pump Station includes a siphon which drains the area west of London Avenue Canal.

Improving interior drainage to acceptable retention areas and increasing the rate of flood water removal has the advantage of simultaneously reducing both Class B/C surge inundation risks and rainfall flood risks. The latter are of much higher probability and improvements could provide significant reduction of fairly high frequency flood consequences. Disadvantages of these improvements in regards to reducing surge risk include:

- Projects may only affect flood risks in their respective sub-basin.
- Projects may require improvements to both perimeter pumping capacity and interior conveyance and lift stations.
- Incremental pumping and conveyance improvements can be very expensive.
- For some sub-basins, rainfall flood risk may be more cost-effectively reduced initially through run-off detention and reuse (see GNO Urban Water Plan, 2013). Projects are likely to require a high percentage of local funding.
- Operational reliability and resiliency is required for surge inundation risk reduction.
- Drainage improvements are much less effective in reducing Class D and E inundation hazards.

[59] http://www.lsuagcenter.com/en/family_home/home/design_construction/Laws+Licenses+Permits/Getting+a+Permit/Your+Flood+Zone/flood_maps/

Table 6.2. Capacities of East-Bank Polder Perimeter Pump Stations

Pump Station	Capacity		Sub-Basins Drained
	cfs	acre-ft/day	
Metro Polder			
St. Charles Parish			
Bayou Trepagnier (Engineers Canal)	800	1,587	Far Western SC2
Cross Bayou	1,250	2,479	Portions of SC1/2
Total	**2,050**	**4,066**	
		-	
Jefferson Parish		-	
Canal St (at 17th St Canal)	160	317	Southeastern JE2
PS 1 (Bonnabel Canal)	3,750	7,438	Eastern JE1/2
PS 2 (Suburban Canal)	5,440	10,790	Eastern JE1/3 and Western JE1/2
PS 3 (Elmwood Canal)	5,700	11,306	Central JE1/3
PS 4 (Duncan Canal)	4,800	9,521	Western JE1/3
PS 5 (West Return Wall)	900	1,785	Far Western JE1/3
Total	**20,750**	**41,157**	
		-	
Orleans Parish		-	
PS 3 (London Avenue)	4,260	8,450	Eastern OM5, Western OM3, and OM1 west of London Avenue Outfall Canal and south of NS Railroad
PS 4 (Gentilly to London Ave Canal);	3,720	7,378	OM1 north of Gentilly Ridge
PS 6 (17 St. Canal)	9,480	18,803	Western OM5 and Far Western OM2
PS I-10 (Railroad Underpass to 17th St. Canal)	860	1,706	OM2
PS 7 (Orleans Avenue)	2,690	5,336	Central OM5 and most of OM2 west of Orleans Avenue Outfall Canal
PS 12 (Lakeview at Harbor)	1,000	1,983	Northern OM2, west of Orleans Avenue Outfall Canal
PS 19 (Florida Avenue at IHNC)	3,650	7,240	Most of OM3
Total	**25,660**	**50,896**	

Table 6.2. Capacities of East-Bank Polder Perimeter Pump Stations

Pump Station	Capacity		Sub-Basins Drained
	cfs	acre-ft/day	
	NO East Polder		
Inside Maxent Levee			
PS 10 (Citrus)	1,000	1,983	NOE5
PS 14 (Jahncke)	1,200	2,380	NOE5
PS 16 (St. Charles/Lakefront Airport)	1,000	1,983	NOE5
PS 18 (Maxent)	60	119	NOE3
PS 20 (Amid)	500	992	NOE4
PS 22 (Grant)	192	381	NOE4
Elaine St.	90	179	NOE4
Dwyer	120	238	NOE5
Total	**4,162**	**8,255**	
Maxent Lagoon Area			
PS 15 (GIWW)	750	1,488	NOE2 (Maxent Lagoon)
	St. Bernard Polder		
Orleans Parish			
PS 5 (Florida Avenue at Bayou Bienvenue)	2,260	4,483	SB1
		-	
St. Bernard Parish		-	
PS 1 (Fortification)	1,245	2,469	SB1
PS 2 (Guichard)	350	694	SB1
PS 3 (Bayou Villere)	500	992	SB3
PS 4 (Meraux)	1,245	2,469	SB3
PS 5 (E J Gore)	660	1,309	SB4
PS 6 (Jean Lafitte)	1,000	1,983	SB1
PS 7 (Bayou Ducros)	1,017	2,017	SB3
PS 8 (St Mary)	834	1,654	SB4
Total	**6,851**	**13,589**	

6.6. Coastal Restoration

Coastal features exert a fundamental role in surge SWL confinement, conveyance, and frictional energy loss, as well as in wave dampening and breaking (see *Supplement*). Five key coastal MLOD features which affect surge hazard are depicted in Figure 6.1—barrier islands, coastal marsh, forested ridges (or cheniers), reinforced embankments for roads/railroads, and coastal channel closures. Figure 6.2 highlights eight crucial East-Bank coastal landscape features which are the subject of restoration planning:[60]

1. LaBranche Wetlands
2. The NO East Land-Bridge
3. Funnel (or Golden Triangle) Wetlands
4. Bayou La Loutre Ridge, including the MRGO Closure
5. Biloxi Marsh
6. Bayou Terre aux Boeufs Ridge
7. Delacroix/Caernarvon Marsh
8. Chandeleur Islands

Reduction of Class C and higher inundation risks (>500-yr return) to the East-Bank polders requires large-scale and sustainable restoration of these features. However, management of these features to reduce extreme surge hazard poses special considerations, such as:

Figure 6.2. Eight Crucial East-Bank Coastal Landscape Features

[60] As of a 2014 CPRA presentation to SLFPA-E: http://www.slfpae.com/presentations/2014%2002%2020%20-%20Coastal%20Restoration%20&%20Protection%20Projects%20-%20CPRA.pdf

- Feature Elevation. Most East-Bank coastal defense features are relatively low-lying, with many below elevation 5 ft NAVD88. Their influence on surge thus rapidly diminishes as they and the surrounding landscape become significantly drowned during extreme events, and more so if the surge is slow moving. In order to reduce extreme surge, coastal features may need to be elevated several feet. Such surge reduction elevation requirements may be much higher than ecological requirements might dictate.
- Feature Footprint (size and orientation).   Fragmented defense features lose their effectiveness, especially at extreme surge depths. Ridges and embankments are effective when they impose a long, continuous cross barrier. Frictional features (e.g., coastal marsh) also require continuity for miles along the flow path. To be effective, channel closures need to be tied to coastal ridges. Footprint requirements for surge reduction may also be much larger than for ecological benefits.
- Feature Resilience. Many coastal features cannot be relied upon to reduce extreme surge risk. Marsh grasses that are bent down offer much less resistance than woody plants. Bare dunes and berms comprised of fine soils can be rapidly eroded with the rising surge. However, adding resilience (e.g., rock armoring) may be inconsistent with ecosystem design goals.

In principal, East-Bank coastal features can be restored to maximize reductions of polder inundation risk. However, these features serve critical ecosystem (habitat) functions and therefore projects funded through ecosystem restoration programs must be optimized for those objectives and not reducing the risks of East-Bank polder inundation. In some cases optimizing a project for extreme surge risk reduction may actually be counterproductive for ecosystem restoration. The additional costs to meet extreme surge reduction goals (e.g., fill elevation) can overwhelm other key restoration budget items. Importantly, the impacts of restoration projects on surge are difficult, time-consuming, and costly to analyze. For example, “tipping points” for fragmentation and complex channel hydrology require very detailed study of a range of storms as well as tides.

Although they may not necessarily be optimized for extreme surge reduction, ecosystem restoration projects can reduce less severe surges hazards.[61] They may help to counteract future increases in 100-yr HSDRRS elevations (and associated Class A and B risks) for regional RLSR, coastal erosion, and coastal vegetation change. Table 4.3 indicates that the combination of these trends could require HSDRRS elevation increases of 3 to 4 ft by 2057 at some locations. *However, it is not reasonable to expect ecosystem restoration projects to address the entire future increase*.

Importantly, large-scale ridge restoration projects, like the expansion of hurricane protection levees, have the potential to increase surge risks in adjacent areas. Improvement of the land-bridge between Lakes Pontchartrain and Maurepas could increase 100-yr surge hazards in St. Charles Parish.

One notable cost-effective element of coastal restoration for reducing Class C polder inundation risk is the reconstruction/enhancement of heavy forests and woody vegetation fronting HSDRRS reaches. Such forests, which could include ridges, could reduce wave overtopping by dampening and breaking waves prior to their reaching the HSDRRS. Effective forest margins may only need to extend 1,000 ft or less from the HSDRRS. Forest margins along the HSDRRS could be included in restoration plans for the

[61] Restoration projects not optimized for extreme surge risk reduction may significantly reduce more frequent modest surges and high tides—such as a 10-yr return event. Reducing more frequent surges could lower HSDRRS O&M requirements, as well ameliorate modest flood hazards in outlying communities—e.g., Lake Catherine, Venetian Isles, Shell Beach, Reggio, Hopedale, and Delacroix—and resources.

LaBranche, Funnel, and Delacroix/Caernarvon Marshes. SLFPA-E and CPRA would have to work with the USACE and FEMA to allow sustainable forests to be included in the HSDRRS hydraulic design *DER*. *Currently the DER requires vegetation impacts on waves to be ignored.* While fronting forest margins can reduce wave overtopping, they may not significantly reduce SWLs or assist in meeting freeboard requirements and reducing Class D and E risks.

Table 6.3 provides a brief description for each of the above eight East-Bank features, related projects, and potential advantages and disadvantages. In addition to these exterior coastal features, two that lie *inside* East-Bank polders are also the subject of restoration planning: the Bayou Sauvage National Wildlife Refuge (BSNWR) at the east end of the NO East Polder and the Central Wetlands in the St. Bernard Polder. These areas are discussed in Section 7.

6.7. Removing West-Bank Levees in Lower Plaquemines Parish

A roughly 30 linear mile narrow strip of land on the west bank of Plaquemines Parish is protected by parallel federal levees—one along Mississippi River and second hurricane protection “back” levee—offset in many places by less than ½ mile. Researchers have recognized that these levees (federal work on these levees dates back to the 1960s) significantly block surge from moving east to west across the lower Mississippi River delta and raise extreme East-Bank surge events, as depicted for Hurricanes Katrina, Gustav, and Isaac in Figures 3.2, 3.6, and 3.9. The USACE’s 2009 CPR Study included very preliminary analysis of two levee removal options. Figure 6.3 shows a reduction in “pseudo-100-yr” surge SWL for one levee removal alternative. In addition to lowering East-Bank inundation risk, a major advantage of removing these levees is that it could also work synergistically with coastal restoration of the lower Mississippi River delta by providing corridors for renewed distributaries and/or modified navigation channels.

Given that much of the enclosed land is agricultural or undeveloped, removal/reduction of some/all of these levees could be a feasible approach to reducing East-Bank polder inundation risks. Levee removal would have to be mitigated by other projects to allow continuation of economically important activities in the lower West-Bank delta—e.g., port, oil and gas, commercial and recreational fishing.[62] However, a significant disadvantage is that some private land and business interests may not be satisfied by mitigation and/or compensation and could force lengthy legal delays.

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[62] Elevated causeway roads could be used to cross spillway easements and small ring levees could be retained for important areas. Farming could continue on easements, subject to surge/restoration management needs.

Table 6.3. Coastal Protection and Restoration Projects for Reducing East-Bank Polder Surge Risks

Feature Description	Projects	Advantages	Disadvantages
LaBranche Wetlands including the CN Railroad Embankment Of the 43 miles of Lake Pontchartrain exposure, over 10 miles in St. Charles Parish lie behind the LaBranche Wetlands. The LaBranche Wetlands, including the CN Railroad Embankment, likely provide some reduction of fast rising surges, but may have a greater benefit in wave reduction. Roberts et al (2008) conducted a preliminary evaluation on the influence of the LaBranche Wetlands on the St. Charles Parish surge SWL hazard.	CPRA currently maintains 300 acres of restored marsh on the northern fringe of the wetlands (built in 1994).	Wetlands offer some protection to the CN Railroad embankment—the more critical surge reduction feature. This embankment is effective in modest surges.	Wetlands have minor effect on extreme surge. Embankment is subject to deterioration during extreme surges. Requires periodic re-building of marsh platform.
	Large-scale sediment, diversion/management to nourish interior forested swamps, as well as canal closures, are in preliminary planning.[63]	Enhancement of continuous, sustainable forested swamp area fronting the HSDRRS could reduce wave heights associated with extreme surge.	Substantial filling and forest restoration may be required to reduce extreme surge SWL.
NO East Land-Bridge, Wetlands Only[64] The NO East Land-Bridge is key part of the regional "Corner" described in Section 2.1. It separates Lakes Borgne and Pontchartrain and includes the US Highway 90 and CXS Railroad embankments. The nearly continuous, slightly elevated highway and railroad are the controlling elements of the NO East Land-Bridge on Lake Pontchartrain surge hazard. The adjoining wetlands protect the embankments from erosion during small events (reducing maintenance). Together, Highway 90 and the CSX Railroad reduce the "filling" of the Lake but have no impact on its "tilting." The Metro and NO East Polders have 43 miles of HSDRRS fronting Lake Pontchartrain, about 39 percent of the total East-Bank HSDRRS. Of this, 33 miles directly faces open water, with no natural fronting surge defenses.	CPRA currently plans and maintains shoreline armoring.	Wetlands offer some protection to the US Highway 90 and CSX Railroad embankments—the more critical surge reduction features. These embankments are effective in modest surges. They are also crucial to regional evacuation and recovery.	Wetlands have minor effect on extreme surge. Embankments are subject to deterioration during extreme surges. Requires funding for periodic maintenance.

[63] See the LaBranche Wetlands presentation given to the SLFPA-E Board on December 15, 2011, http://www.slfpae.com/presentations/2011%2012%2015%20-%20PLD%20LaBranche%20Wetlands.pdf

[64] The USACE (2009) and SLFPA-E (Ben C. Gerwick 2012) have both conducted evaluations of a NO East Land-Bridge *Barrier*—including options for a limited raised barriers with overtopping and without closure of the Rigolets and Chef Passes.

Table 6.3. Coastal Protection and Restoration Projects for Reducing East-Bank Polder Surge Risks

Feature Description	Projects	Advantages	Disadvantages
Funnel Wetlands The NO East and St. Bernard Polders include 18 miles of HSDRRS in The Funnel. The reaches are paralleled by large channels (the GIWW along the north and the closed MRGO along the south). The near banks are fairly narrow and include some minor vegetation. The far banks, which extend to the southwest shores of Lake Borgne, consist of fragmented marsh. Detailed studies on the influence of specific sub-features and vegetation types have not been undertaken.	CPRA currently plans and maintains shoreline armoring for Lake Borgne. There is no current shoreline armoring activity along the GIWW and the closed MRGO.	Woody vegetation helps to reduce surge waves and their potential erosion of flood-side of HSDRRS embankments.	Minor effect on extreme surge SWLs.
	Large-scale restoration and protection of shoreline and marsh are in preliminary planning.[65]	The addition of continuous, sustainable forests fronting the HSDRRS could reduce wave heights associated with extreme surge.	Substantial filling and forest restoration may be required to reduce extreme surge SWL.
Bayou La Loutre Ridge, including LA Highways 46/624 & MRGO Closure The Bayou La Loutre Ridge is the natural bank of an old Mississippi River distributary channel. LA Highways 46 and 624 are located on the ridge between the HSDRRS and Hopedale. The eastern portion of the ridge extends into the Biloxi Marsh. Together the Bayou La Loutre Ridge and the Biloxi Marsh offer some protection to the NO East Land-Bridge and The Funnel area of the HSDRRS. The recent closure of the MRGO at Hopedale reconnected the eastern and western portions of the ridge. There are no published studies on the influence of the Bayou La Loutre Ridge on regional surge hazard.	CPRA projects for re-elevating and re-vegetating portions of Bayou La Loutre Ridge are in a very early stage.	The existing Bayou La Loutre Ridge provides a stable base for an elevated coastal defense and helps protect the surrounding marsh.	Substantial elevation of ridge may be required to reduce extreme surge SWLs at the NO East Land-Bridge and The Funnel.
Biloxi Marsh The Biloxi Marsh lies north of the MRGO and separates Lake Borgne from Chandeleur Sound. The marsh reduces surge in regional Corner—including NO East Land-Bridge—and The Funnel. Detailed studies on the influence of specific sub-features and vegetation types have not been undertaken.	CPRA currently plans and maintains shoreline armoring.	Protecting marsh, in turn, helps to protect the Bayou La Loutre Ridge during more frequent surges.	Apart from the Ridge, the marsh has limited effect on extreme surge SWLs. Extremely large area to maintain.
	Large-scale sediment, diversion to nourish marsh, as well as canal closures, are in a very early stage. (See Footnote 10)	Need pockets of stable marsh from which to expand. Supported in part by occasional opening of Bonnet Carre Spillway, Pearl River, and Mississippi River sediments.	Substantial additional filling and marsh restoration may be required to reduce extreme surge SWLs at the NO East Land-Bridge and The Funnel.

[65] See the USACE MRGO Ecosystem Restoration Plan Feasibility Study, July 2012.

Table 6.3. Coastal Protection and Restoration Projects for Reducing East-Bank Polder Surge Risks

Feature Description	Projects	Advantages	Disadvantages
Bayou Terre aux Boeufs Ridge, including LA Highway 300 The Bayou Terre aux Bouefs Ridge is the natural bank of an old Mississippi River distributary channel. LA Highway 300s is located on the portion of the ridge north of Delacroix. The ridge extends well into the Delacroix Marsh. Together the Bayou Terre aux Boeufs Ridge and the Delacroix/Caernarvon Marsh offer some protection to the Caernarvon-Verret portion of the HSDRRS. There are no published studies on the influence of the Bayou Terre aux Boeufs Ridge on regional surge hazard.	CPRA projects for re-elevating and re-vegetating portions of Bayou Terre aux Bouefs Ridge are in a very early stage.	The existing Bayou Terre aux Bouefs Ridge provides a stable base for an elevated coastal defense.	Substantial elevation of ridge may be required to reduce extreme surge SWLs at the Caernarvon-Verret portion of the HSDRRS.
Delacroix/Caernarvon Marsh The Delacroix/Caernarvon Marsh lies south of the MRGO and separates Breton Sound from the Caernarvon-Verret portion of the HSDRRS. Detailed studies on the influence of specific sub-features and vegetation types have not been undertaken. [66]	CPRA operates the Caernarvon Diversion (build in 1991) which can divert up to 8,000 cfs of Mississippi River water into the adjoining marsh. The diversion was designed for salinity control.	Management of wetland salinity and nutrients facilitates a gradient of marsh types and habitats. Protecting marsh, in turn, helps to protect the Bayou Terre aux Boeufs Ridge during more frequent surges.	Freshwater diversion may not enhance sustainability of this particular marsh for surge events. Apart from the Ridge, the marsh has limited effect on extreme surge SWLs. Extremely large area to maintain.
	Large-scale sediment, diversion to nourish marsh, as well as canal closures, are in preliminary planning.[67]	Need pockets of stable marsh from which to expand. Supported in part by regular Mississippi River overflow at Bohemia and regional suspended sediments. Enhancement of continuous forested swamp fronting HSDRRS could reduce wave heights associated with extreme surge.	Substantial additional filling and marsh/forest restoration may be required to reduce extreme surge SWLs at the Caernarvon-Verret portion of the HSDRRS[68]

[66] Walmsley et al (2009) provided a preliminary assessment. Further work is needed to distinguish the relative impacts of size, orientation, elevation, and Manning's *n* friction for various ridges, marsh, and open water—for different storms.

[67] These include measures to sustain Mardi Gras Pass and enhance river overflows in the Bohemia Spillway; see http://www.saveourlake.org/coastal-projects-bohemia.php.

[68] A preliminary analysis showed that the Delacroix/Caernarvon Marsh reduces surge and wave levels; see Wamsley et al, 2009.

Table 6.3. Coastal Protection and Restoration Projects for Reducing East-Bank Polder Surge Risks

Feature Description	Projects	Advantages	Disadvantages
Chandeleur Islands			
The Chandeleur Islands chain forms an arc separating the northern Gulf of Mexico from Breton Sound. The islands have undergone extensive erosion and increasing fragmentation in recent decades, especially since Hurricane Georges (1998). Many portions have converted to shallow bars and shoals. The Chandeleurs reduce westward forerunner and surge propagation toward the Delacroix/Caernarvon and Biloxi Marshes.	CPRRA mined crucial sand sources to create fronting “sand berms” along portions of the Chandeleur Islands in response to the BP oil spill. (Sand placement was not optimized for habitat or surge protection). The long-term fate of the sand used in the berms is subject of ongoing study	For the near term, sand may be available in areas which facilitate reconstruction of effective islands	Time to reuse the sand in an effective way may be limited. Without protective re-vegetation (and possibly armoring) islands will have limited life. Chandeleur Island restoration may be better optimized for habitat than surge risk reduction. Substantial elevation of island dunes may be required to reduce extreme surge SWLs.

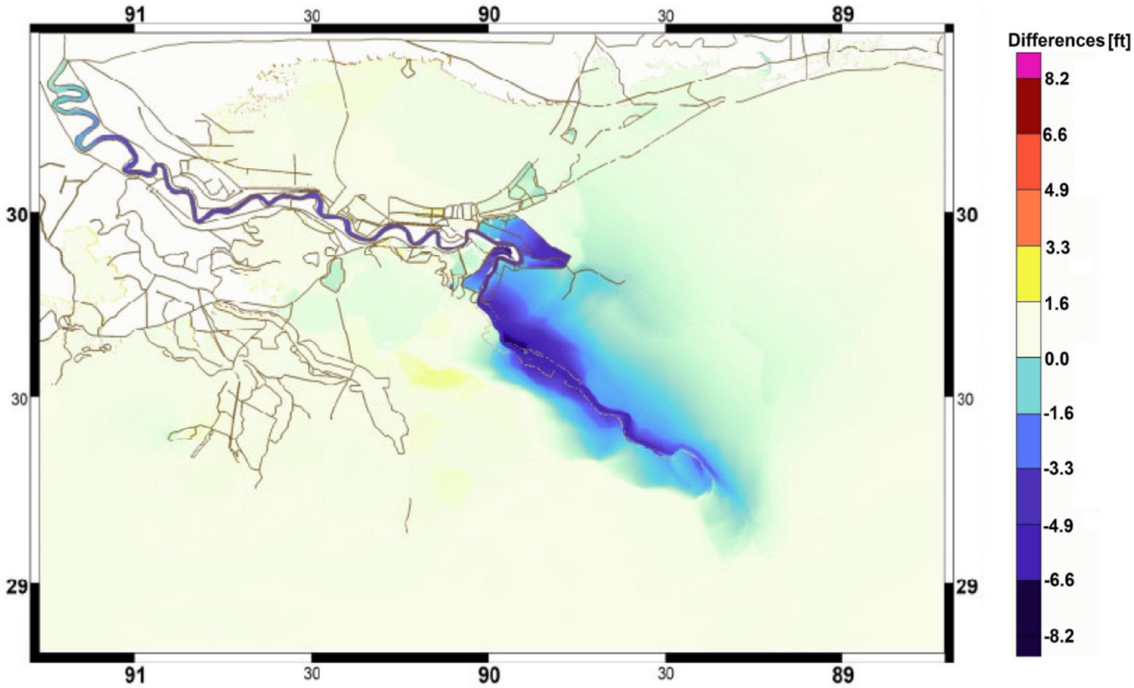

Figure 6.3. Difference in a "100-yr" SWL with West-Bank Plaquemines Levees Removed
de Jong et al 2007

6.8. *Compartmentalization*

Besides the MLODs shown in Figure 6.1, polder flood risks can be reduced with the use of additional internal structural lines of defense—as demonstrated by the Dutch developers of polders:

> The polder system was first applied in the 1500s to recover agricultural land from swamps and river backwaters. The Land von Maas en Waal (Walled Land from the Meuse River) is an example of early polder design. A primary dike separated the land from the river, *and secondary dikes created compartments inside the polder*. Each compartment had windmill-driven pumps, drainage canals, sluice gates and flood gates. If a major flood breached or topped a dike, the compartments each filled separately as a delaying action that allowed residents of the polder to evacuate. http://www.ehow.com/about_5386764_history-polder.html

The rationale behind compartmentalization of a polder has an analogy in shipbuilding with the use of bulkhead partitions to reduce the risk of sinking in the event of a hull breach. Ship compartmentalization likely predates the development of polders by several centuries.

During Hurricane Katrina many natural and man-made raised features within each of the three East-Bank polders strongly influenced the inundation depicted in Figure 3.3. As the region recovered, making use of these features for internal compartmentalization became an obvious subject for future risk reduction. Example features include interior levees and floodwalls, natural ridges, railroad embankments, and road embankments.

Potential advantages of polder compartmentalization include:

- Redundancy in protecting selected areas/sub-basins within a polder.
- Compartments can be focused on critical sub-basins—e.g., key infrastructure, business and employment districts, shelters, and hospitals, etc.
- Compartments can be used to isolate particular weaknesses in perimeter protection.
- Existing features may make some compartmentalization relatively easy and inexpensive to achieve.
- Design (e.g., height) for enhancing/expanding compartmentalization can be adjusted to meet desired level of risk reduction: modest heights for Class C surge inundation; greater heights for Class D and E surge inundation; even higher to reduce risks from Mississippi River flooding (Metro and St. Bernard Polders).
- Compartmentalization implementation timetable can be relatively short. For example, local funding and construction of compartmentalization may be achievable on schedule of a few years, while federal funding and construction of HSDRRS improvements may take much longer.

Potential disadvantages of compartmentalization include:

- Compartmentalization only reduces flood risks for those areas inside the compartment.
- Compartmentalization can increase the flood risks for those areas outside the compartment, requiring expensive mitigation.
- Upgrade of compartmentalization features also may require expensive mitigation of drainage impacts.
- Issues of fairness can make compartmentalization politically difficult to achieve.
- Servitudes/rights-of way/use agreements or actual property acquisitions for compartmentalization projects may be very difficult to secure—e.g., railroad and highway embankments.

The main challenge with compartmentalization is to find projects that have broad support and a relatively high benefit-to-cost, including the opportunity cost of not investing in other risk reduction options.

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