

Hurricane Surge Hazard Primer



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About the Author

Bob Jacobsen is a professional engineer with over 35 years of experience addressing environmental and water resource challenges in South Louisiana. He received a master's degree in civil engineering from Louisiana State University in 1996 and has completed additional coursework in coastal engineering towards a doctorate. Since 2001 he has specialized in Louisiana *Coastal Hydrology*, particularly the application of High Performance Computing/High-Resolution hydrodynamic modeling to wetland hydrologic restoration and hurricane storm surge protection. In the field of *Coastal Hydrology* he has:



- Worked with authors of the leading HPC/High-Resolution model ADCIRC since 2004.
- Attended every ADCIRC User's Workshop since 2007 and has been a frequent presenter.
- Led and authored HPC/High-Resolution hydrologic modeling studies for the Maurepas Diversion (2007) and Lake Pontchartrain Tidal Circulation (2007).
- Led and authored HPC/High-Resolution surge modeling studies for the MRGO (2006) and Alliance Refinery (2007).
- Supported review of surge-landscape interactions for the USACE's LaCPR Study (2007).
- Led and authored detailed planning studies for the Northeast Florida/Georgia Coastal FIS (2010).

Since 2011 Bob has worked for both the Southeast Louisiana Food Protection Authority, East and the Louisiana Coastal Protection and Restoration Authority on hurricane surge issues. In this capacity he authored *Hurricane Surge Hazard Analysis: The State of the Practice and Recent Applications for Southeast Louisiana* (May 2013), *Four Priority Issues with the USACE Surge Hazard and HSDRRS Overtopping Analysis* (March 2015), and *New Orleans East-Bank Hurricane Surge Residual Risk Reduction Report* (February 2016). He has also recently authored:

- *Hurricane Surge Hazard Uncertainty in Coastal Flood Protection Design*, Journal of Dam Safety, Vol 13 No 3, 2015.
- *Managing Hurricane Surge Risks in the Supercomputing Era, Part I Pre-Katrina Evolution of Surge Hazard Estimation and Risk Management*, Louisiana Civil Engineer, May 2015.
- *Managing Hurricane Surge Risks in the Supercomputing Era, Part I Post-Katrina Progress and Limitations in Surge Hazard Estimation and Implications for Surge Risk Management*, Louisiana Civil Engineer, August 2015.
- *The Hurricane Katrina 10th Anniversary Test* (see www.bobjacobsenpe.com).

Bob has given numerous presentations on HPC/High-Resolution coastal hydrodynamic modeling and hurricane surge at professional meetings and has provided expertise to several news organizations, including the Times-Picayune, the Lens, the Weather Channel, and CNBC.

Bob recently served as President of the Louisiana Section of the American Society of Civil Engineers. He enjoys surf-fishing along Louisiana's coast. His mother and sister still live in the Metairie house the family moved into in 1965, two weeks before Hurricane Betsy struck.

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Abstract

This *Hurricane Surge Hazard Primer* summarizes important basic technical information about surge phenomena, hazard, and risk.

It provides an overview of surge hazard analysis, including uncertainty in surge hazard estimates.

Importantly, this *Primer* describes the limitations of hurricane surge hazard analysis and risk management under the National Flood Insurance Program.

The reader is encouraged to refer to other reports listed in the References for a more detailed explanation of many key concepts.

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Special Note: New Orleans (Louisiana) East-Bank and Lake Okeechobee (Florida)

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1. Hurricane Surge SWL and Waves

As shown in Figure 1, hurricane surge includes both rising still water level (SWL) and wind waves. The SWL represents a short term (few minutes) average of the water level—i.e., without wind waves. The maximum SWL that occurs in inundated areas is often estimated by surveying high water marks (HWMs) inside flooded buildings unaffected by waves. Along open coasts, peak surge SWL conditions are usually sustained for a period of only an hour or two. Along inland bays, lakes, and inland wetlands and in flooded polders* surge waters can become trapped and peak conditions may remain for many hours.

The surge SWL elevation is typically compared to the long term average SWL, which is the Local Mean Sea Level (LMSL). The elevation of LMSL and surge SWLs (and wave crests) must be considered in a well-established vertical reference system, such as the latest epoch of the North American Vertical Datum of 1988 (NAVD88). Regional coastal SWLs will normally fluctuate with astronomical tides, seasonal expansion of the water with warming (steric effects), and other meteorological events (seasonal wind patterns, rainfall, river floods, etc.).

Surge waves heights (crest to trough) are traditionally described using the average of the one-third highest waves which occur over a short time, referred to as the significant wave height (H_s). Wave heights are limited by wind speed and duration, fetch (open water distance over which the wind blows), and water depth. For a large shallow bay or lake the H_s upper limit ranges from 40 to 60 percent of depth, depending on bottom conditions. Wave heights for inundated areas are further limited by natural and man-made terrain variations and vegetation. Features which sufficiently reduce depth can break waves. Wave energy is affected by the period (time between peaks or troughs, T_p), which is typically longer for the open ocean and shorter in bays and lakes. Along large inland lakes and bays the duration of peak surge SWL may encompass 2,000 waves, with several hundred exceeding the H_s associated with peak SWL.

An important wave phenomenon is the contribution that the nearshore breaking of large open ocean waves makes to a shoreline increase in SWL, termed wave setup. Wave setup can contribute over ten percent of the SWL surge along the open ocean coast.

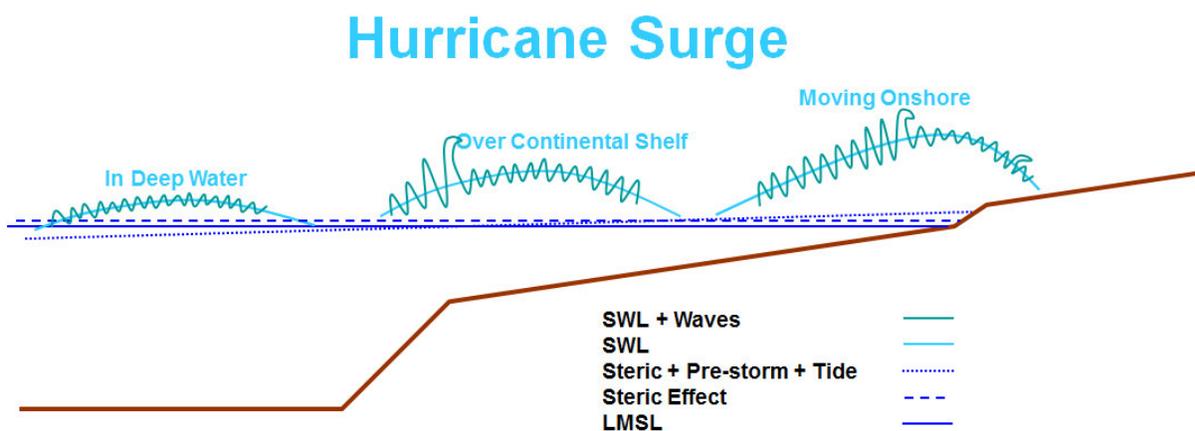


Figure 1. Components of Hurricane Surge
(scale exaggerated)

*Polder is a Dutch word for an area completely surrounded by levees usually requiring forced drainage.

2. The Dozen Hurricane Conditions Contributing to Surge

Tropical cyclones (Figure 2) consist of winds circulating counter-clockwise around a core of low atmospheric pressure, which extends from the ocean surface up through the troposphere. Wind speed varies dramatically with the radial distance from the storm center—from mild within a storm’s central core, or eye, to a maximum at the eye-wall, and then generally declining outward from the eye-wall. While the low central pressure contributes somewhat to surge (about 4 inches of SWL rise for every 10 millibars of pressure drop), the winds acting on the ocean surface are the far more significant surge force. When maximum sustained (1-minute average) winds reach 74 mile per hour (mph) the cyclone is referred to as a *hurricane*.

There are *eight* major conditions associated with the hurricane storm itself that contribute to surge at a location of interest:

1. The hurricane *core intensity* at landfall, indicated by the storm’s central pressure deficit and maximum wind speed. The central pressure deficit tends to be proportional to wind speed squared. Hurricane core intensity is the basis for the Saffir-Simpson Scale, with five category rankings based on hurricanes reaching sustained winds of 74, 96, 111, 130, and 157 mph.
2. Landfall core (eye) size, or radius of maximum winds, with larger cores containing substantially more energy capable of pushing larger amounts of water and driving higher surges.
3. The forward velocity of the hurricane during landfall. The observed hurricane wind speed is increased on the right-hand side of the storm by the forward velocity of the storm—as with a ball thrown forward from a vehicle versus one thrown from a standstill. But more importantly, slow moving storms allow a longer time for surge build-up.
4. The track angle with the coast line at landfall. The landfall approach angle affects the direction of the main surge push—which builds-up in the forward right-hand quadrant.

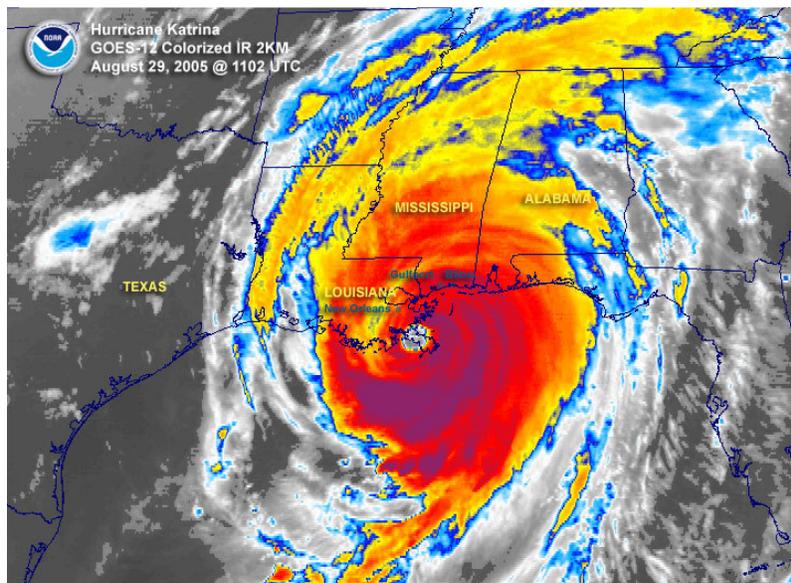


Figure 2. Hurricane Katrina at Landfall
NASA/NOAA 2005

5. Landfall location with respect to location of interest. Wind speed and direction, and surge, vary greatly with the distance and direction to landfall. Coastal locations exposed to the forward right-hand quadrant of the core will often experience the greatest surge.

Until recently, the popular media tended to simplify the threat of hurricane surge as primarily associated with the Saffir-Simpson Scale. However, surge scientists have known for many decades that Conditions 1 through 5 all affect the potential surge associated with a hurricane scenario (NOAA 1959 and 1975). Three additional factors are now also understood to be important:

6. Landfall wind-field size and distribution beyond the core. These are described with the radial extent of hurricane force and tropical storm force winds and the Holland B shape parameter.
7. The asymmetry and irregular concentration of outer winds at landfall. The radial extent of hurricane force and tropical storm force winds and the Holland B shape parameter are typically given separately for storm quadrants. The radial decline of wind speed is not smooth, with wind energy concentrated in spiral bands and sometimes secondary eye walls.
8. Pre-and post-landfall track variations and wind-field dynamics. Pre-landfall variations can influence early surge effects, while post-landfall track can influence wrap-around/back-side wind-driven surges impacts occurring after eye passage. During the 48 hours prior to landfall a storm's core and wind-field can undergo a range of changes—from rapid strengthening to rapid decay—depending on the ocean temperature and atmospheric conditions it encounters. Just prior to and following core landfall, hurricane strength usually falls due to overland disruption of the wind and pressure fields and the intrusion of drier air. Landfall decay is particularly common in high intensity storms, while low intensity slow moving storms sometimes retain their strength for many hours.

Advances in surge science are continuing to improve understanding of how Conditions 6, 7, and 8 contribute to hurricane surge. Hurricane meteorologists are studying snapshots of storm integrated kinetic energy (IKE) as well as indicators of accumulated energy to gain a better sense of the full effect of a hurricane wind-field and its history on surge.

In addition to the above eight storm characteristics, surge is affected by four hydrologic conditions:

9. Astronomical tides. Depending on the timing of the hurricane landfall, the astronomical tide can add or subtract to the surge—as much 1.5 feet along the open Southeast Louisiana coast.
10. Seasonal steric increases to LMSL. Southeast Louisiana coastal LMSL increases by about 0.5 ft in the late summer and early fall with thermal expansion of the sea water and generally lower atmospheric pressure.
11. Pre-storm meteorological conditions. Regional pre-storm winds, rainfall, and coastal currents can further modify the LMSL along the open coast and in coastal sounds, bays, and lakes. In addition, coastal river levels can be affected by pre-storm floods.
12. Rainfall associated with the storm. Although hurricane rainfall has a minimal effect on surge heights along open coasts, substantial rainfall can influence surge flooding around interior coastal sounds, bays, and lakes, particularly for slow moving storms.

3. The Three Phases of Hurricane Surge

The specific characteristics of a hurricane event shape three phases of surge:

1. The *forerunner*. A large, slow-moving hurricane can produce a slow steady rise (inches per hour) in coastal and interior water SWL beginning more than a day before storm arrival. Depending on the direction of winds and wind-induced currents relative to the coastline, this rise can also be enhanced by the Coriolis force (associated with the Earth's rotation) in an oceanographic phenomenon known as Eckman Setup.
2. The main surge or push of water just in advance of landfall, which results in a rapid rise (feet per hour) of SWL along the open coast and *filling* of interior bays and lakes.
3. The rapid local *tilting* (feet per hour) of coastal sounds, bays and lakes that occurs as the wind-field passes overhead. The tilting direction rotates with a passing hurricane's shifting wind direction—determined by the storm track with respect to the water body. West of the track winds shift from westward to southward to eastward, while east of the track they shift from westward to northward to eastward. Major tilting impacts can occur with some storms in susceptible locations hours after the passage of a hurricane's eye.

Three important facts regarding hurricane wind driven surge (a very distinct ocean phenomenon from a tsunami) should be noted:

1. The wind's force on the water is proportional to the square of the wind speed—so all other things being equal, a 60 mph steady wind exerts four times the force on the ocean surface as a 30 mph steady wind.
2. The downwind rise in SWL (or setup) is proportional to the length of the open water fetch over which the wind is blowing—again, other things being equal, a 50-mile fetch will produce twice the setup compared to a 25-mile fetch.
3. The wind-driven setup is *inversely* proportional to the depth of the open water fetch over which a steady wind is blowing—so a steady wind blowing over a bay or lake with a depth of 10 ft deep will produce twice the setup versus one with a depth of 20 ft.

Severe *tilting* of coastal bays and lakes can occur with very little *filling*. A 60 mph steady wind blowing for several hours across 50 miles of open fetch with a depth of 10 ft is capable of producing a downwind surge in excess of 10 ft. Thus, prolonged exposure to sustained winds in large radial band from a slow moving Category 1 hurricane can produce more setup than the more intense but short duration main surge from a higher category fast-moving storm. This was demonstrated by the fact that Hurricane Isaac produced a greater surge than Hurricane Katrina at Braithwaite in Plaquemines Parish, despite Katrina passing directly over Braithwaite and Isaac tracking over 40 miles away. A good analogy which provides a physical sense of these factors is to consider the effect of blowing soup across a bowl of varying size and depth with varying strength and duration.

4. Important Landscape Factors

Surge height depends not only on the twelve hurricane conditions, but also on how the moving water interacts with the regional landscape. Three landscape factors are important: *confinement, conveyance, and friction.*

The impact of confinement can be easily understood with an analogy of dumping a drum full of water on a room with a hard floor: if the drum is tipped over in the center of the room the water will spread out evenly in all directions (assuming the floor is level) with the perimeter depths being small in all directions. However, if the drum is spilled near the side of the room directly towards a wall two things will happen: the depth of the spill will be much higher at the wall and the wall will direct the flow of the spill. The depth and control of the spill will be higher still if the drum is tipped over facing a corner. Confinement does two things to surge: it a) “dams up” surge, converting kinetic energy into SWL height (potential energy) and b) routes (redirects) the surge. Another common example of these effects occurs when a river’s floodplain is restricted. Landscape surge confinements include both natural topographic ridges and man-made embankments and walls.

Conveyance features provide preferential terrain flow paths—usually also with lower frictional resistance—especially during low SWLs. Examples include coastal passes, coastal rivers and their estuaries and floodplains, and man-made navigation, drainage, and oil-field canals.

The conversion of surge kinetic energy to potential energy is affected by the presence of friction features which can dissipate kinetic energy. Frictional dissipation of surge energy is caused by terrain “speed bumps” such as shoals, reefs, submerged ridges and cheniers;” bottom roughness—e.g., a shallow surge flow over thick marsh versus bare ground; and dense vertical obstructions—e.g., heavy forests. In the case of the spilled drum in the room center, the spill would extend farther if the floor had a smooth versus a very rough surface. Similarly, the height of a confined spill would be higher with lower frictional conditions (and just as a dampened pendulum reaches a lower height versus an undampened one).

Importantly, the impact of landscape features on surge depends on:

- Feature footprint and elevation. Expansive surges are relatively unaffected by small features.
- Feature orientation with respect to the direction of surge flow. Features can have different impacts on surges moving from different directions. For example, a channel may increase some surges but reduce others, with closure of the channel having the opposite effect.
- Feature resilience. With more extreme surges, features can become deformed and more easily drowned, and thus have much less impact. Embankments can be eroded; vegetation flattened or uprooted; and channels can be silted in or obstructed.
- The surge depth. A feature’s influence on surge may be significant when depths are a few feet, but may be much less so when depths reach double digits. For a small spill on the floor, subtle undulations, bumps, seams, etc., can affect depth and routing, while with larger spills the subtler features become much less influential.
- The surge velocity. Frictional effects also depend greatly on surge velocity, with slow surges experiencing negligible frictional impacts.

5. Hurricane Surge Modeling and Surge-Response Functions

In recent years, improved atmospheric models of hurricane wind and pressure have been coupled with *hydrodynamic models*—such as models prepared with the ADvanced CIRCulation, (ADCIRC) code—and run on high performance computers (HPC)—or supercomputers. The combined *hurricane surge models* depict the regional surge confinement, conveyance, and friction landscape details in high resolution and can simulate the particular dynamic movement of surge waters from a specific storm in a given landfall region. Progress in hurricane surge modeling has improved surge forecasting and warnings, facilitating greater public recognition of the complexity of surge threats.

Regional HPC/High-Resolution surge models have both accuracy (bias) and precision (scatter)¹ limitations. These are typically assessed with a *hindcast* of peak SWL and comparison to post-storm HWMs and tide gauge data. A regional, model-wide hindcast bias is given by average positive/negative error to indicate if the model generally over-/under-predicts the peak SWL. Regional hindcast precision is indicated by the standard deviation of local errors in predicting peak SWL. Dietrich et al 2011 performed hindcasts of Hurricanes Katrina, Rita, Gustav, and Ike with a high resolution ADCIRC model, illustrated in Figure 3. Discounting issues with wind and surge data, regional bias was found to be up to ± 15 percent of the SWL, and the precision was found to be up to 15 percent. Within regional models, worse bias and scatter can be present in places with complex wind and wave setup, and at lower surges due to greater influence of local topography, bathymetry, and friction issues.

Advances in HPC/High-Resolution surge modeling have also improved quantifying *Surge-Response Functions*.² For any particular hurricane scenario, a location within a given coastal region will exhibit particular peak surge SWLs that reflect the combination of forerunner, filling, and tilting physics. Along smooth open coasts, changing Surge Response is a smooth, nearly linear function of changing hurricane characteristics—e.g., double the central pressure deficit and *all other things being equal* the surge will double. This allows for straightforward interpolation and extrapolation of surges for a wide range of storm combinations based on HPC/High-Resolution modeling of a modest sized, optimized sample (OS) of storms. However, for locations within complex coastlines—particularly those near large sheltered water bodies—the Surge-Response Function is likely to be much less linear and smooth, requiring a much larger Surge-Response OS.

Currently, many developers of Surge-Response Functions do ***not*** calibrate their HPC/High-Resolution surge models to remove bias noted in the hindcast. They maintain that limited understanding of Surge-Response means that tuning a model for a better hindcast might make it a worse model for some key Surge-Response OS storms. Future improvements in Surge-Response science may soon facilitate acceptable methods for calibrating surge models.

¹ A common analogy comes from target practice with a rifle: the discrepancy between the general center, or “average,” of a shooter’s results and the target bulls-eye illustrates accuracy, while the spread of shots around the average illustrates precision. A discrepancy in accuracy is termed “bias” and it may be attributable to poor alignment of the rifle sight, or a consistent shooter error. Precision, on the other hand, reflects factors which randomly alter the result.

² A Surge-Response Function for a coastal region is analogous to a Stage-Discharge Function for a river. River stage is often considered as a curvilinear function of *one* condition—flow (discharge)—given a floodplain’s geometry and friction attributes. Surge SWL can be thought of as a function of the eight hurricane conditions together with the four hydrologic conditions, plus a given coastal region’s geometry and friction attributes. The Surge-Response is dictated by surge physics including: local conservation of mass, atmospheric pressure deficit, wind drag, wave radiation stress, water pressure, astronomical tide, Coriolis force, lateral bed reaction, friction drag, and turbulent stress. HPC/High-Resolution models mimic Surge-Response using mathematical formulations for these physics.

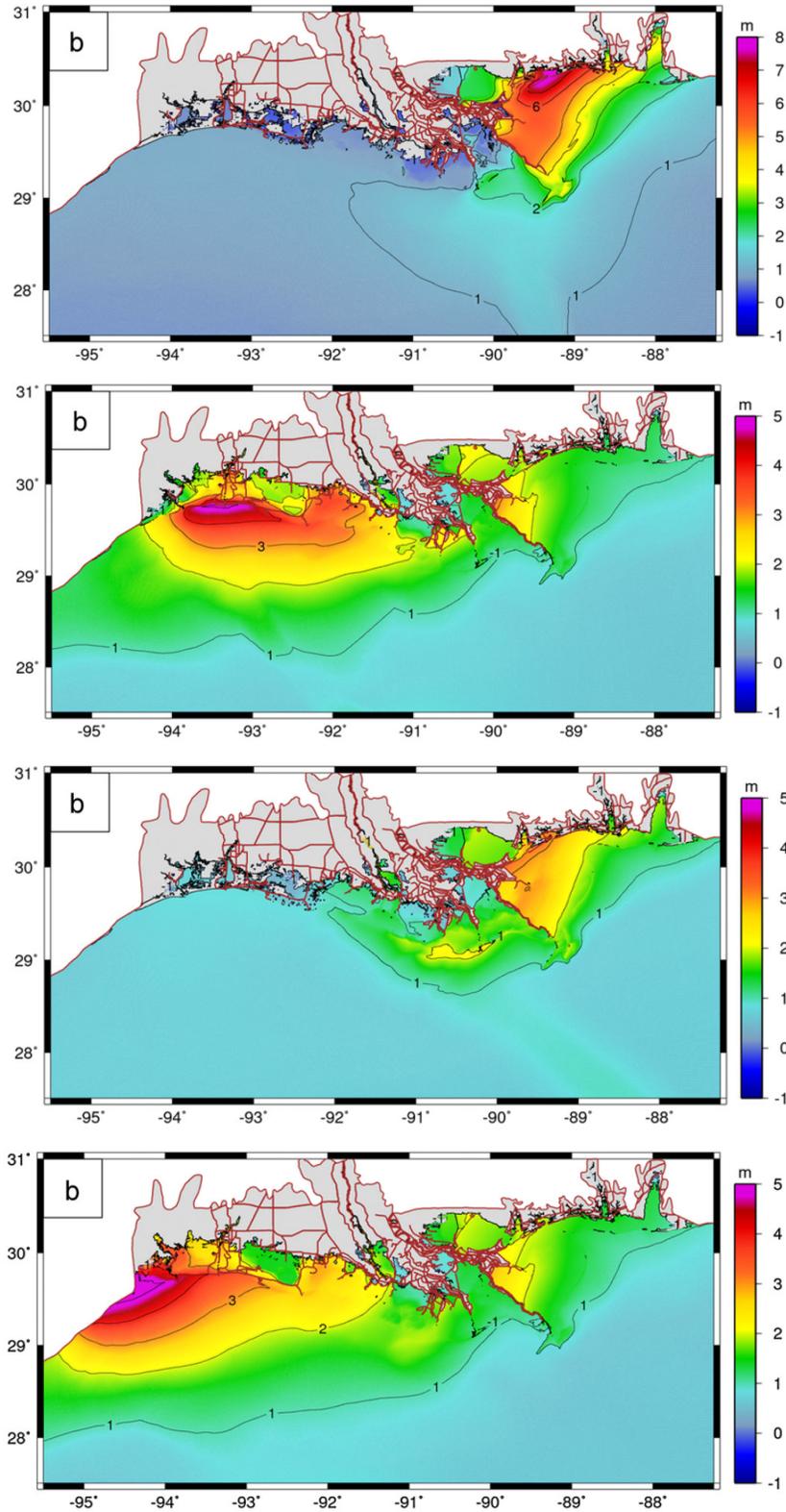


Figure 3. ADCIRC Models of Peak SWL for Hurricanes Katrina, Rita, Gustav, and Ike
Dietrich et al 2011

6. Hurricane Surge Hazard and Risk

Hurricane surge hazard is a probability, expressed as a decimal number between 0 and 1 (or as a percent), that a particular surge SWL can be reached at least once in a time-frame, typically a year, for a specific location. For example, at a given point a surge SWL of 10 ft NAVD88 may have a one percent chance of occurring in any year. This probability is also called a one percent *return frequency*, and is equivalent to the expectation that the 10 ft SWL will be reached at least once every 100 years, *on average*. This 100-yr duration is referred to as an *average* recurrence or return period. A two percent return frequency is equivalent to a 50-yr return period; a 0.2 percent chance to a 500-yr return period; and a 0.1 percent chance to 1,000-yr return period. Over any time-frame, a 100-yr surge SWL is five times as likely to occur as a 500-yr surge. The surge hazard has increasing SWL magnitude with increasing return period, i.e. rarity.

Surge hazards—probabilities—are an *average expectation*. The 1 percent/100-yr surge is expected to recur on average once every 100 years over a very long time frame—e.g., 10 times over 1,000 years. Probabilities for a particular SWL can be computed for other time frames than one year, as well as for multiple occurrences over various time frames. For example, the 10-ft SWL with a 100-yr return period has a 26 percent probability of occurring at least once during the course of a 30-yr mortgage.

Surge hazard at a location is affected by three things:

1. The particular regional hurricane climatology—the regional frequency of hurricanes with various combinations of the eight storm conditions previously discussed in Section 2. This frequency based on combined conditions is referred to as *joint probability*. Hurricane climatologists have been refining *Hurricane Joint Probability Functions* for various stretches of coast along the Atlantic Ocean and Gulf of Mexico since the 1950s.
2. The additional joint probability of the four hydrologic conditions discussed in Section 2.
3. The local *Surge-Response Function* discussed in Section 5—the regional landscape and the exposure condition of the location—proximity to coast, large inland water bodies, sheltering, or surge confinements, etc.

The *climatological* probability of a particular hurricane making landfall (with some combination of the eight conditions) is ***not*** the same as the probability of the peak surge SWLs associated with that storm. The surge SWLs for a given storm will vary across a region. A severe (regionally rare) hurricane may produce an extreme surge at one point and a modest surge a few miles away. Thus, the surge hazard associated with a given storm will also vary across the region.

For a given location, a 10-ft SWL can potentially be produced under a number of different storm scenarios. Thus the probability of a 10-ft SWL at that location has to reflect the sum of all those scenario probabilities—referred to as the *cumulative* probability.

It is important to recognize that surge hazard is defined at a location or point. The SWL associated with a particular surge hazard level can differ greatly between two locations in the same region: the 100-yr surge might be 10 ft at one point, but 20 ft at much more vulnerable point. This is equivalent to also saying that the hazard level associated with a particular SWL can differ greatly across a region: the less vulnerable point might expect a 20-ft SWL at a 1,000-yr return period.

If the scenarios for surge hazard are sufficiently different for two locations they are considered *independent*. For two totally independent locations, the probability of one or the other location experiencing the one percent surge in any year approaches two percent—i.e., the average return period for one or the other to experience a 100-yr surge becomes close to 50 years. For five independent exposures the annual probability of a 100-yr surge is close to five percent, or an average return period of close to 20 years that one location will experience a 100-yr surge. (Just as the more people that flip a coin, the more the odds go up that someone will get tails.) With three independent exposures, the probability of a 100-yr flood becomes 26 percent during any 10-yr time-frame. Over concurrent 30-yr mortgages on three properties with independent exposures, there is a 60 percent probability that one will experience a 100-yr flood.

Hurricane surge risk is the product of the surge hazard and the expected consequence of that surge. In addition, surge risk also reflects the probability of failure for any applicable protection measures. Estimates can be developed for a *comprehensive* range of consequences that can occur with each local surge hazard level. These can include but are not limited to:

- Direct and indirect fatalities;
- Injuries and illnesses;
- Residential and commercial property damages;
- Wind and flood damage insurance claims;
- Local temporary and permanent declines in economic activity (GDP), employment, personal income, sales tax revenue, etc.;
- Regional and national economic impairments; and
- Impacts to historical and cultural assets and local ways of life.

In theory, quantitative risk assessment provides a rigorous way of comparing between types of disasters at a given location (e.g., a surge flood event versus a rainfall-only flood event), disasters at different locations, and risk reduction alternatives. In the latter, potentially feasible alternatives (levees, evacuation, flood proofing, expanding flood insurance participation, etc., combinations of alternatives, versus no action) are compared for the *mitigated risk*, the *residual risk* left to be borne (and by whom), and the costs. In practice, risk assessment may need to be semi-quantitative, or even qualitative, due to the lack of well-developed hazard and/or consequence models.

7. Hurricane Surge Hazard Analysis

A surge hazard analysis determines the surge SWLs (and associated wave H_s) over a range of return periods at a coastal point of interest. The location-specific surge hazard is depicted with a *cumulative distribution function* (CDF), which is graphed as illustrated in Figure 4. The return period is presented logarithmically. The CDF in Figure 4 is for the tide station located at the eastern tip of Grand Isle Louisiana. The CDF was tabulated from tide records and is shown by the dots on the graph. The tabulated CDF dots have been fitted with an Extreme Value Function (EVF, heavy black curve). EVFs (such as log-normal, log-Pearson, Gumbel, Frechet, Weibull, to name a few) provide a useful way of smoothing, interpolating, and extrapolating a tabulated CDF—but have many issues. The selection of an EVF type is somewhat subjective—and preference for fitting a different EVF could produce different interpolated/extrapolated hazard values.

A tide-gauge based CDF is only applicable within a very small, nearby area. Furthermore, a tide gauge record may not represent a reasonably wide array of storm scenarios. To provide a more representative CDF, surge hazard analyses are usually conducted using *Joint Probability Analysis* (JPA). This approach quantifies the Surge-Response and Hurricane Joint Probability Functions, together with probabilities for the additional four hydrologic conditions, for all points of interest. For reasonably smooth coastlines recent Surge-Response OSs have utilized only two or three values for hurricane storm Conditions 1, 2, 3, 4, and 6—together with numerous variations for Condition 5—yielding a very manageable storm set for modeling.³ For complex coastlines a very large Surge-Response OS may be required. The Surge Response Function is then applied to a large number of hypothetical storms representing the range of hurricane joint probabilities. The set of peak storm SWLs for any location, and the associated probability of each storm's peak SWL, then becomes the basis for determining the surge hazard CDF.⁴

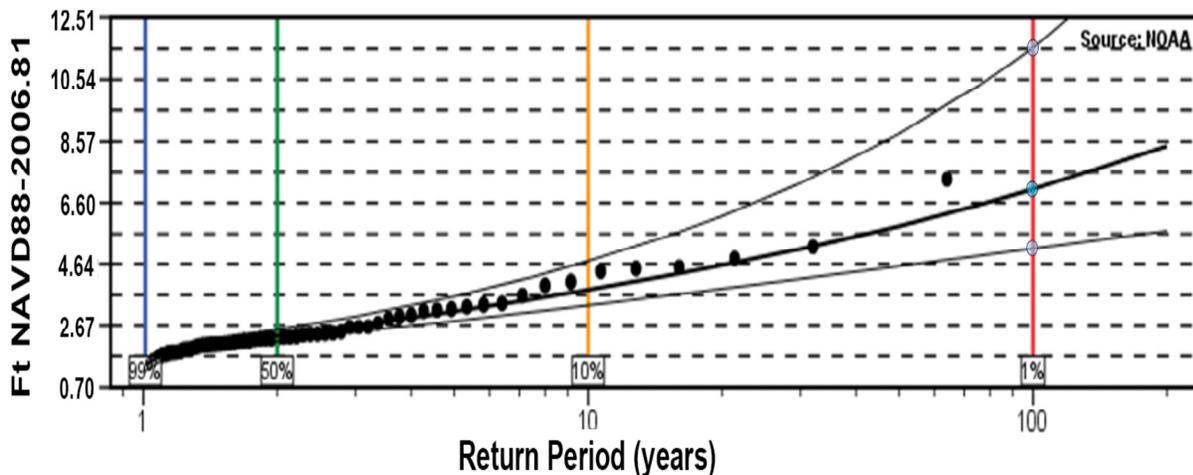


Figure 4. Grand Isle LA Tide SWL CDF with 95 Percent Confidence Interval
NOAA (http://tidesandcurrents.noaa.gov/est/est_station.shtml?stnid=8761724)

³ If certain storm and/or hydrologic conditions are not addressed directly in the JPA functions they must be considered part of the hazard uncertainty, see Section 8. In some cases an explicit Surge-Response Function is not developed and instead a storm set is selected (and simulated with the HPC/High-Resolution surge model) to represent the joint probabilities in the hurricane climatology (or an initial approximation of the surge hazard CDF).

⁴ A *surge risk analysis* presents the magnitude of flood consequences as a function of return probability—e.g., CDFs for estimated deaths; property damage; declines in population, personal income, tax revenue; etc.

8. Uncertainty in Surge Hazard Estimates

Surge hazard estimates for any location have several important sources of *stationary* uncertainty (not including long-term trends such as climate and landscape changes). For convenience, each can be represented as normally distributed,⁵ with standard deviation (σ) expressed either as a percent or a fixed increment of peak surge SWL50.

Two sources are for the Hurricane Joint Probability Function—i.e., defining the hurricane climatology for the location of interest:

1. The *hurricane sampling uncertainty*—the length of the observed record to adequately characterize the joint probabilities.
2. Representativeness of the historical record for various climatological cycles, such as El Niño.

Three sources relate to the adequacy of the HPC/High-Resolution surge model in simulating all the Surge-Response OS scenarios for the specific location of interest:

3. The model hindcast residual error (bias and precision).

⁵ Uncertainties are often described with a normal (Gaussian, “bell-shaped”) distribution. The assumption of a normal distribution should be considered carefully and may be inappropriate for representing uncertainties with “fat” distribution tails; see Nassim Taleb, *The Black Swan*, and Nate Silver, *The Signal and the Noise*. The normal distribution is defined with the *median* estimate (μ) and a standard deviation (σ) for that particular estimate. Multiples of σ are used to define symmetric “confidence intervals” within which the “true” value is expected to be found. For example, 80, 90, and 95 percent confidence intervals—with corresponding confidence limits of ± 40 , ± 45 , and ± 47.5 percent, respectively—fall within $\pm 1.28\sigma$, $\pm 1.65\sigma$, and $\pm 1.96\sigma$, respectively. A “non-exceedance level” corresponds to an upper confidence limit and includes the interval below the lower limit. A SWL median estimate and the 90 and 95 percent non-exceedance SWLs (which correspond to the upper limits of 80 and 90 percent confidence intervals) are noted as SWL50, SWL90 and SWL95. Figure 5 presents a series of normal distribution curves around a SWL50 estimate. The series of curves illustrates that for higher relative standard deviations (σ/μ), the confidence interval becomes much wider. As σ increases from 0.1μ to 0.5μ the SWL95 increases from 1.17μ to 1.83μ .

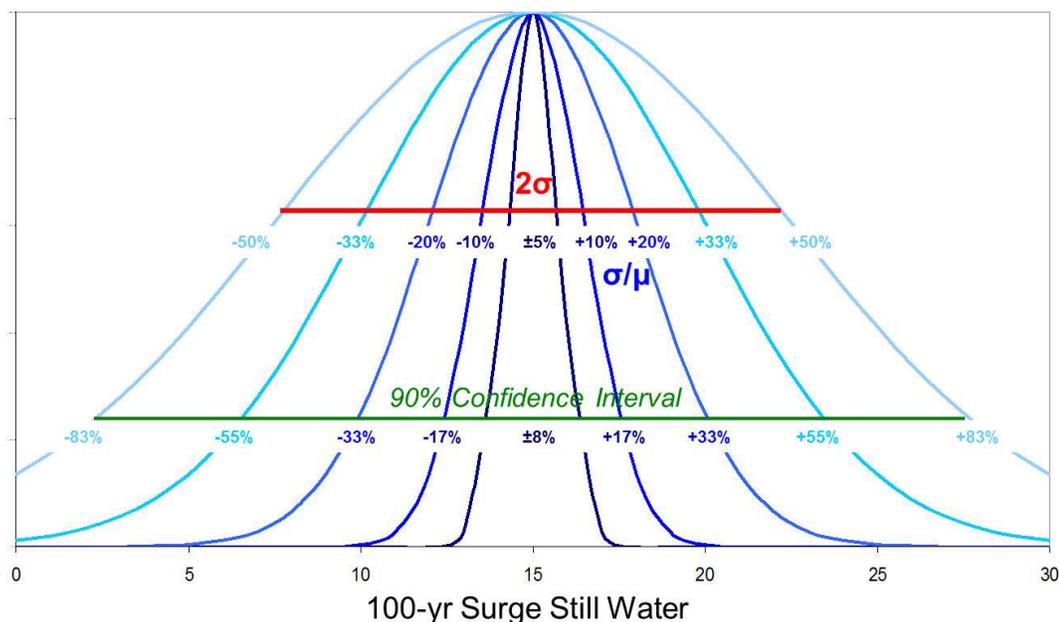


Figure 5. Example of the Effect of σ on Normal Distributions

4. Uncertainty in the empirical formulations used in the surge physics and the coefficients—e.g., wind-water drag, landscape wind reductions; hydrodynamic drag.
5. Plus additional variability in surge SWL associated with storm and hydrologic conditions if they are not included directly in the JPA, such as:
 - The size and strength of the general wind-field (Condition 6).
 - Additional wind-field structures and track/dynamic variations (Conditions 7 and 8).
 - Tides and steric effects (Conditions 9 and 10); a normally distributed uncertainty has typically been used in regions with small tide amplitudes such as the central northern Gulf of Mexico; an estimate of the seasonal steric effect is often included in the Surge Response model.
 - Other meteorological conditions (Conditions 11, and 12).

Two sources relate to construction of the Surge-Response Function itself:

6. Adequacy of the Surge-Response OS to capture local non-linear surge response for the full range of hurricanes.
7. Interpolation from the results of the OS.

The σ values key uncertainty factors can potentially exceed 10 percent of the SWL50. The σ values are combined by *adding in quadrature*.⁶

Given limited hurricane records, hurricane sampling uncertainty, the first factor, is perhaps the least reducible. Ideally, a data record five to ten times the return period of interest—with a variety of storm surge events even more extreme than the return period of interest—is needed to substantially reduce this uncertainty. Hurricane sampling uncertainty is often approximated using the residual error in the fit of an EVF to the surge CDF. Figure 4 shows the confidence interval for the EVF fit to the Grand Isle tide gauge CDF—which is based on a record length of 60 years. The EVF in Figure 4 provides a 100-yr SWL estimate of about 7 ft. However, the 95 percent confidence limit for the EVF shows this SWL could have a return period of less than 30 years.

The hurricane sampling uncertainty σ is inversely proportional to the square root of record length. JPA is used in order to reduce this uncertainty by augmenting a short hurricane record with a broader range of storm scenarios based on probabilities taken from a wider geographic region. For example, hurricane probabilities based on storm data for a region six times larger than the actual record for a location being studied might be thought of as artificially increasing the actual record by a factor of six—thereby reducing the sampling uncertainty σ by a factor of $6^{1/2}$, or 2.45. However, the choice of geographic region and the degree it really expands the record length and reduces sampling uncertainty is a matter of significant professional judgment.

When any of the above surge hazard uncertainties are included directly as part of the JPA they are then reflected in the surge hazard CDF. Aleatory factors—inherent variability in the natural event, such as those under Factor 5—may be appropriate for incorporating into the CDF, and thus estimates of 100-yr, 500-yr, and other surge hazards. An obvious example is accounting for tide timing directly in the 100-yr surge estimate.⁷

⁶ Ten uncertainty factors each with σ values of 10 percent would combine to $\sqrt{10 * 0.10^2}$ or 32 percent.

⁷ An economical alternative to explicitly incorporating more factors into the JPA (which can then require a much larger OS) is to simply apply a lumped σ value, referred to as the *epsilon* σ , during the numerical integration of the CDF.

Epistemic factors—uncertainties associated with limitations of data or models, such as Factors 1 – 4, 6, and 7—may be more appropriate for use in defining confidence intervals *around the CDF*, as opposed to incorporating *into the CDF*. Notably, while incorporating uncertainty factors into the CDF slightly *increases* the 100-yr and greater surge hazards, it *reduces* the upper limit of a confidence interval for these surge hazards by a much greater amount. Hence, incorporating more uncertainties directly into the JPA and thereby into the CDF may not be appropriate when confidence intervals are a key surge risk management tool.

A reasonably conservative treatment of uncertainties in surge hazard estimates, such as the 100-yr surge, and the assignment of typical uncertainties to the confidence interval—and not assigning them to the CDF—can produce a SWL95 value (upper limit of a 90 percent confidence interval) significantly greater than the SWL50 estimate. In the case of a 100-yr surge estimate of 10 ft, a reasonable Factor of Safety (FOS) for comprehensive surge risk management might be a value of 14 ft. *Importantly, the 100-yr SWL95 value can be much higher than the 500-yr SWL50 value, and thus may be more suitable for a surge risk management FOS.*

When reasonably conservative confidence intervals are considered for the return period the magnitude of uncertainty is also great. The true return period for the 10 ft SWL could easily be between 50 and 200 years.

Thus, while they can be very useful for some risk management purposes—such as for very broad-based (regional national) actuarial assessments of property damage risks under the Federal Emergency Management Agency (FEMA) National Flood Insurance Program (NFIP)—local surge hazard estimates have so much uncertainty that they should really be regarded as

Scientific Guesstimates!

9. NFIP Surge Hazard Analysis

FEMA's NFIP offers flood insurance to residential (and small business) property owners and is a major institutional tool for managing hurricane surge flood damage risk. The NFIP premium rates are based largely on exposure to single hazard level: the 100-yr flood. NFIP insurance for property with exposure to the 100-yr flood is typically required by mortgagees. Flood insurance premium costs have risen in recent years but continue to be heavily subsidized. FEMA, in cooperation with the local communities conducts Flood Insurance Studies (FISs) to regionally assess 100-yr flood 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). The NFIP is administered by the local communities, with participation in the NFIP contingent upon local regulation of development in the 100-yr floodplain.

The NFIP premium assessments do not distinguish between properties with various hazards within the 100-yr floodplain—or outside the 100-yr floodplain. Since the NFIP's inception, property values have been increasingly affected by NFIP 100-yr flood zone delineations. Not surprisingly, a wide range of federal, state, and local projects have been focused on reducing 100-yr flood zones. The NFIP's single threshold approach is increasingly seen as too simplistic, extremely unfair, and leading to too many inefficient economic outcomes.

Despite the lack of a granular approach to flood hazard and property damage risk, NFIP flood insurance is considered a financial bargain for homeowners—largely due to a tradition of federal subsidies for the program and frequent underestimation of the 100-yr flood zone. NFIP flood insurance is an even greater bargain for residential properties outside the 100-yr flood zone.

NFIP limitations influence the accuracy of FIS estimates of the 100-yr flood. The NFIP accepts programmatic, resource, cost, and schedule constraints on FIS flood hazard analyses consistent with the actuarial aspects of its particular mission: managing a nationwide, federally subsidized, fund for property flood damage claims. Moreover, the NFIP is under political pressure to make flood insurance affordable and to not overly impact community property values.

The regional (multi-county) scope of surge FISs—including determining Surge-Response and Hurricane Joint Probability Functions—means that FISs are not intently focused on the local quality of estimates. FIS HPC/High-Resolution surge models are typically not calibrated to reduce local bias (or minor systemic bias) and Surge-Response OSs are not expanded to address nonlinearities for key local features.

These various constraints lead the NFIP to frequently underestimate the 100-yr surge.⁸

The NFIP is not meant to address the full, *comprehensive* range of flood consequences to commercial, industrial, and uninsured residential property; community infrastructure; cultural and economic assets; as well to lives, health, and livelihoods. Residual flood risks beyond the NFIP must be mitigated through other measures—such as evacuation to reduce risks to lives and health. Urban planners concerned with residual risks often seek to evaluate flood mitigation for a 500-yr hazard.⁹ While FIRMs usually include

⁸ FIS budgets and limited interest in local conditions means that there are also frequently inaccuracies that contribute to over-estimating the 100-yr hazard. Those communities concerned primarily with the impact of FIRMs on real estate values tend to have a one-sided view of FIS quality issues—challenging FIS FIRMs only for the inaccuracies that contributing to over-predicting the 100-yr hazard.

⁹ See American Society of Civil Engineers, Louisiana Section, *2012 Report Card for Louisiana's Infrastructure*.

estimates of the 500-yr flood zone, the NFIP's focus on 100-yr flood estimates and its many critical limitations in addressing that hazard mean that FIS 500-yr flood estimates should be regarded as **Nominal**. Because FISs are not intended to provide rigorous assessments of extreme local hazard, the Nuclear Regulatory Commission does not rely on FISs. Unfortunately, for many communities FISs and FIRMs provide the only estimates of extreme flood hazard.

The NFIP has very limited use for flood hazard confidence intervals; they are not used at all in FIS delineations of 100-yr flood zones. Recent NFIP surge FISs have included some evaluation of regional level uncertainty but have not been concerned with locally important uncertainties, or reasonably conservative treatments of uncertainty for local comprehensive risk management purposes.

Those agencies responsible for comprehensive surge risk management in a local community increasingly appreciate the potential for bias in NFIP surge hazard analyses. They also understand the need to address all important local uncertainties and undertake reasonably conservative assessment of uncertainties—both typically beyond the scope of the NFIP (see Jacobsen et al 2015).

Figure 6 illustrates the potential effect of addressing bias and uncertainty in a 100-yr surge estimate consistent with a local comprehensive risk management perspective versus the NFIP. Note that the 100-yr SWL50 has increased by about 1 ft and the 100-yr σ value has increased by more than a factor of three (2.4 versus 0.7 ft). The result is that the SWL95 has increased by almost 4 ft. Note that the 100-yr SWL95 is about 1.5 ft higher than the 500-yr SWL50.

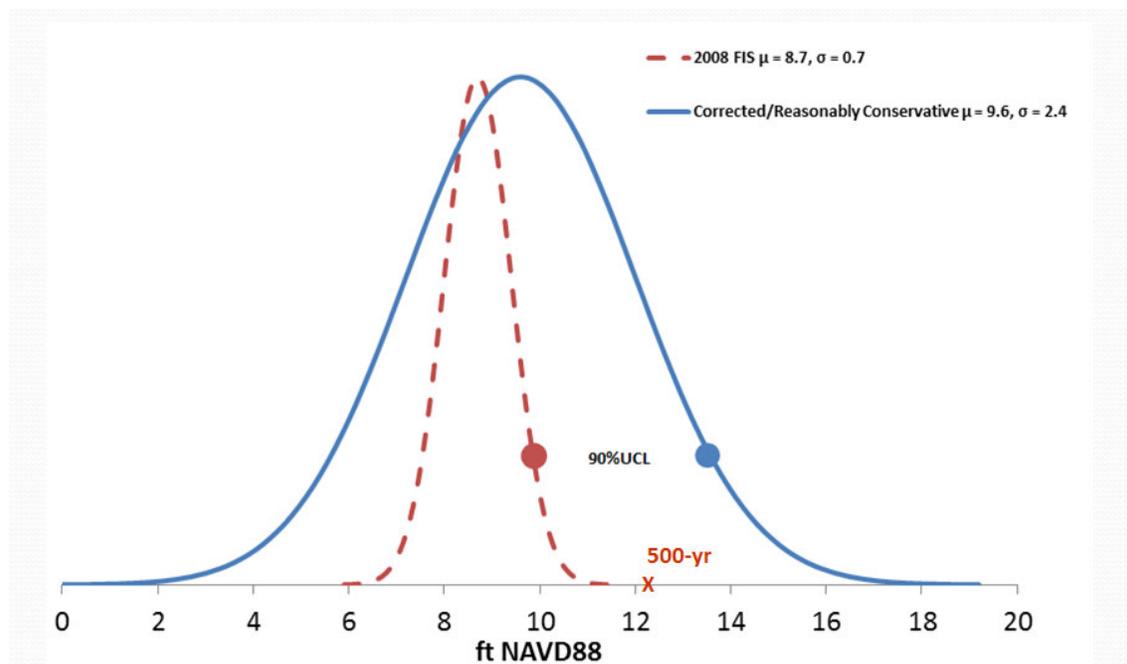


Figure 6. Example of Differences in 100-yr Surge Hazard and Uncertainty Estimates for NFIP versus Local Comprehensive Surge Risk Management

Correcting for bias and properly defining uncertainty are critical for developing local evacuation plans and FOSs for local projects to mitigate residual risks. A critical concern is the FOS for overtopping of local surge barriers. Overtopping rate uncertainty is ***not*** proportional to surge SWL hazard uncertainty—but instead increases drastically (due to greater potential for free flow as opposed to strictly wave overtopping). *When the 100-yr surge σ value is increased by a factor of three (as in Figure 6), the overtopping σ can increase by a factor of ten!*

Thus, polders have a much higher inundation risk than indicated by the NFIP!

Local comprehensive risk management purposes thus require more rigorous (and more frequent) analyses of surge hazards and uncertainties than the NFIP provides. On the other hand, NFIP surge hazard analyses—with all their limitations—may be sufficient for communities not investing heavily in residual surge risk reduction.

Estimates of surge hazard and risk, and associated uncertainties, at a location may not be stable over time. Long-term trends in hurricane climatology, sea level, and coastal landscape, as well as regional coastal projects, will modify local surge hazard and risk. NFIP surge hazard analyses typically do not specify adjustments to address non-stationary issues. In fact, the NFIP does not provide for regular updates to surge hazard analyses. On the other hand, comprehensive surge risk management does require that surge hazard analyses account for non-stationary issues.

10. Comprehensive Hurricane Surge Risk Management

Communities must address comprehensive surge risk management, encompassing the full range of flood consequences. Generally, there are ten measures available.

1. An effective evacuation program. *Eliminating loss of life is the top surge risk management priority.* Community officials must ensure readiness of evacuation plans to address the limits of surge protection systems and their FOS. Unlike the NFIP, they must treat uncertainties in protection system performance reasonably conservatively for loss of life risks. A special challenge is ensuring adequate evacuation plans to address those with health, logistical, or financial problems in self-evacuating. In order to plan local measures aimed at protecting lives, officials can refer to estimates of maximum surges associated with a range of hurricane scenarios—rather than relying on vague surge hazard estimates. NOAA develops and updates maps such as the one in Figure 7 depicting the highest peak SWL from across a wide range of storms of given Saffir-Simpson category—so called “Maximum of Maximums” (MOMs) maps.
2. Expanding flood insurance participation. When (not if) a flood occurs, community recovery is quicker and more widespread if more property damage is covered by insurance. Thus, broadening insurance coverage is the second priority. Communities can consider incentives (and even mandates) to reduce the expense and unfairness of “free riders.”
3. Raising flood-proofing requirements. Increasing minimum elevations for private and public buildings and infrastructure can be a cost-effective risk management measure. Higher flood proofing requirements can also lower NFIP premium rates.

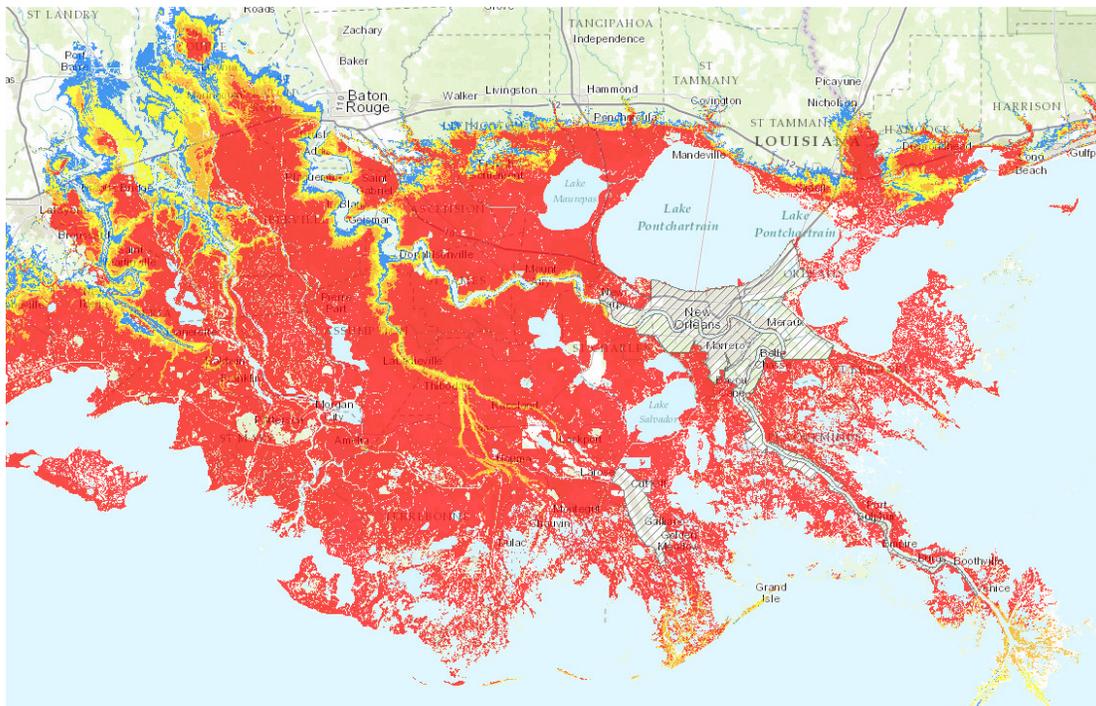


Figure 7. NOAA Maximum of Maximum for Category 3 Hurricane Surge

<http://noaa.maps.arcgis.com/apps/StorytellingTextLegend/index.html?appid=b1a20ab5eec149058bafc059635a82ee>

4. A *Minimal NFIP* accredited levee system (minimal FOSs) to reduce NFIP insurance premiums. Importantly, when surge protection systems are built to complement the NFIP officials must understand the NFIP programmatic goals and its limitations for surge hazard analysis, uncertainty treatment, overtopping analysis and levee FOS, and accreditation. Furthermore, they must ensure that the public understands that NFIP levees leave considerable residual risk to life and property. Communities must address “right sizing” to avoid building systems that are too complex and too expensive to operate and maintain. Importantly, NFIP reaccreditation is required every ten years. [NFIP credit may be available for levees below 100-yr hazard and these may be optimal for some communities.]
5. A *Higher-than-NFIP* surge protection system. This can include higher FOSs to address overtopping and other uncertainties, or explicit design for more extreme surge. Communities may not find higher levees to be cost-effective when compared to enhancing Measures 1 through 3.
6. Adding breach resiliency (e.g., armoring) to a levee system. Resiliency can address a more extreme surge hazard and/or FOS (e.g., 500-yr overtopping at a reasonably conservative estimate of the confidence interval). Resiliency can be a better investment than more height—but there are many factors to consider: residual overtopping, breaching, and polder inundation risks; costs; potential for federal support; long-term performance; O&M; etc.
7. Restoration of large-scale coastal features—i.e., those with sufficient elevation, footprint, and resiliency to reliably reduce extreme surges.
8. Where practical, removal of coastal features that exacerbate surge.
9. Enhanced interior drainage and pumping capacity (for polders).
10. Interior compartmentalization (for polders).

Community leaders should not oversell the benefits of a surge risk reduction option, especially to the detriment of Measures 1 and 2. For NFIP levees, a useful mantra is:

***An NFIP levee is to surge what firefighting is to wildfires—
a complement to evacuation and property insurance!***

All measures should be evaluated as a “system” and components need to function synergistically. Community leaders should note that apparent complementary measures can become competing interests. Local drainage improvement and coastal restoration programs can have their own drivers and projects may need to be optimized for these purposes. For example, coastal restoration projects are usually optimized for long-term coastal habitat and ecosystem productivity, not for surge reduction. Use of limited coastal restoration funds on surge risk reduction may not be prudent, and vice versa. Moreover, it is important to recognize that surge protection systems can have significant adverse impacts on nearby communities and coastal landscapes.

Community leaders must also appreciate that surge risk management is never finished. Communities must invest in continuous improvement in all areas. They must be prepared to address increases in hazard estimates, including non-stationary trends such as sea level rise, to periodically re-evaluate risk reduction measures for gaps and weaknesses, and to fix them. Furthermore, surge risk management for coastal communities usually must be done in the context of needed investments for other flood risks, such as those for rainfall and river flooding—as well as for other natural hazards and local priorities.

Special Note: New Orleans (Louisiana) East-Bank and Lake Okeechobee (Florida)

The major portion of metropolitan New Orleans lies on the East-Bank of the Mississippi River, south of Lakes Pontchartrain and Borgne. This region has a unique vulnerability to extreme hurricane surge due to a combination of the following eight factors:

1. New Orleans is at the heart of the central-northern Gulf of Mexico, which is exposed to a 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 8 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 landfall along a 500-mile region centered on New Orleans—12 made landfall in Southeast Louisiana. Furthermore, and just as important for surge risks, the Loop Current sustains slow moving storms.
2. As illustrated in Figure 9, 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 natural dam contributes to a much greater surge hazard on the eastern versus western flank. Moreover, the intersection of the delta with the Mississippi coast creates a critical “Corner.” 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 are the “Funnel” produced by the junction of the Gulf Intracoastal Waterway (GIWW) and Mississippi River Gulf Outlet (MRGO) levees and the corner at Caernarvon Corner (at English Turn) which includes a combination of HSDRRS, Mississippi River, and local Plaquemines Parish levees. The first experienced massive surge during Katrina. The second saw greater surge during Category I Isaac’s slow passage to the south and west in 2012 than during Katrina, which tracked directly overhead.
4. The major East-Bank coastal sounds, bays, and lakes 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 with hurricane passage.
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 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 10 shows one of two River levee breaches at the ConocoPhillips Refinery near Belle Chase from Hurricane Katrina surge. The two breaches were caused by overtopping of the River levee, exacerbated by conditions at two adjacent loading docks, and resulted in extensive damage to the refinery.

Stalled lower intensity hurricanes can produce SWLs ranging from 9 to 15 ft NAVD88 at exposed points depending on location characteristics, while SWLs with extreme hurricanes can reach 15 to 30 ft. Point return periods for these events are about 60 and 200 yrs, with regional returns of 20 and 67 yrs.

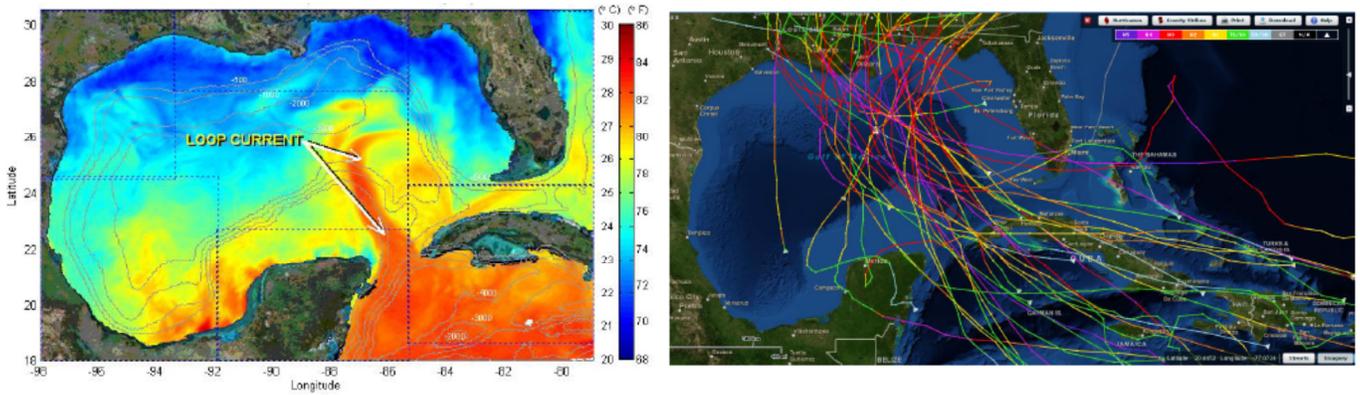


Figure 8. The Loop Current and Major Hurricanes in Central-Northern Gulf of Mexico
WAVCIS, NOAA

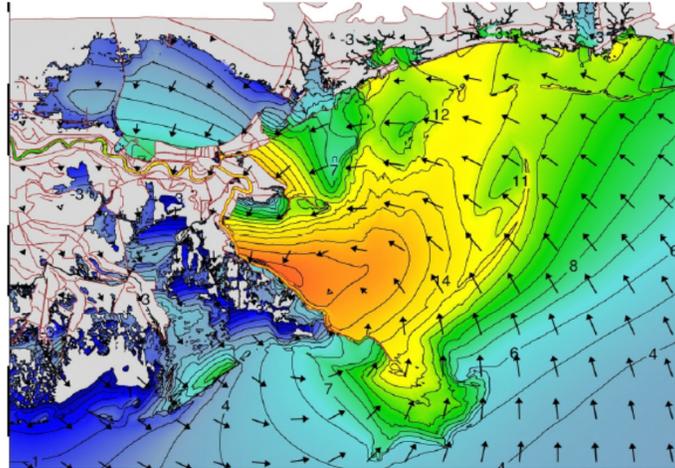


Figure 9. Impact of the Mississippi River Delta and East-Bank Levees on Katrina Surge
USACE 2008



Figure 10. Mississippi River Levee Breach at ConocoPhillips Refinery during Katrina

In the wake of Katrina, Congress authorized funding of an NFIP levee system. With FOS and other limitations, the New Orleans East-Bank has an expected evacuation return period of about 20 years.

A second striking example of complex surge vulnerability is Lake Okeechobee in Florida. Unlike Lake Pontchartrain in the East-Bank, Okeechobee is a freshwater lake, isolated from the ocean and not subject to hurricane surge forerunner or filling. Figure 11 illustrates that the general size and depth of Lake Okeechobee is similar to Lake Pontchartrain.

The Lake Okeechobee Hurricane of 1928 made landfall near West Palm Beach Florida with maximum winds of 145 mph. As the hurricane approached Lake Okeechobee, southward winds tilted the freshwater lake, with a depth reportedly approaching 20 ft. The surge around Lake Okeechobee resulted in over 2,500 deaths, making it the second deadliest hurricane in US history.

To protect Lake Okeechobee residents the perimeter Herbert Hoover Dike was constructed to a height of about 30 ft above the surrounding ground—or at least 10 ft above the 1928 storm surge. The NFIP expected 100-yr SWL along the southern shore of Lake Okeechobee is considered to only be about 10 ft above the normal pool, (or 23 and 13 ft NAVD88, respectively). The crest of the Herbert Hoover Dike (at 40 ft NAVD88) is 17 ft above the expected 100-yr SWL.

The NFIP expected 100-yr SWL at the point shown on the south shore of Lake Pontchartrain is 8.7 ft NAVD88, about 8 ft above the typical LMSL for hurricane season.¹⁰ Hurricane Katrina’s surge at the location was at about 12 ft NAVD88. The design crest for the surge levee along the south shore of Lake Pontchartrain is at 16.0 ft NAVD88, about 7.3 ft above the NFIP 100-yr SWL and 4 ft above the Hurricane Katrina surge.

The NFIP 100-yr freeboard (the levee crown height above the NFIP 100-yr SWL) is much greater for the Herbert Hoover Dike than for the New Orleans Lakefront levee—by almost 10 ft. Unlike the New Orleans post-Katrina levee, the Herbert Hoover Dike design significantly exceeds a basic NFIP risk management purpose.

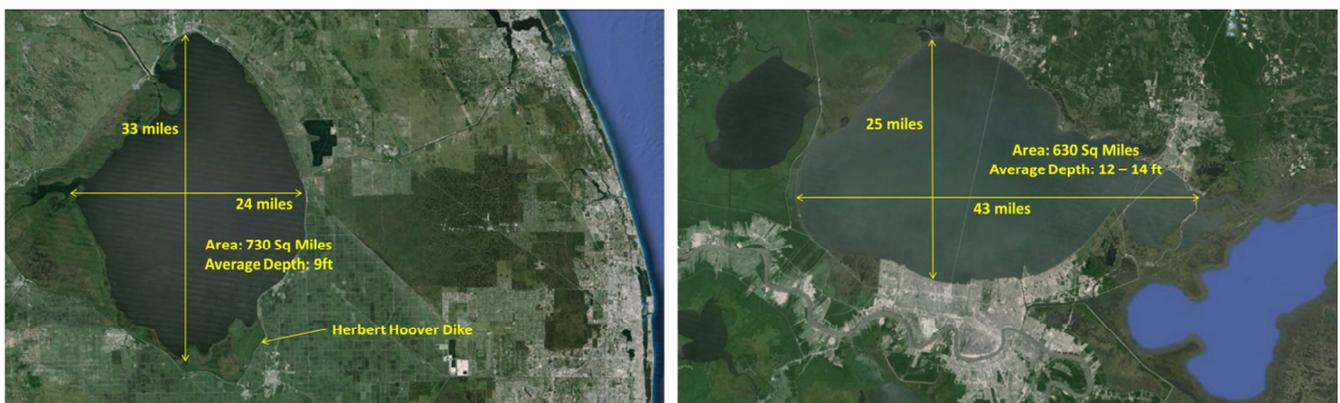


Figure 11. Comparison of Lakes Pontchartrain and Okeechobee (Florida)

Google Earth Imagery (same scale)

¹⁰ A partial revision of the surge hazard analysis for comprehensive risk management purposes raised the 100-yr estimate about one foot, to 9.6 ft; other issues may further raise the 100-yr surge estimate (Jacobsen March 2015).

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