Managing Hurricane Surge Risks in the Supercomputing Era, Part I

Bob Jacobsen PE

Joseph N. Suhayda, PhD in 2002 Showing the Potential Depth of Surge Flooding in the French Quarter
Photograph by William Brangham For American Radio Works

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

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Louisianans have always been aware of hurricane surge hazard, and have wanted to reduce surge risk. Community leaders and their agents have thus faced the task of accurately assessing surge hazards and balancing the desire for reducing surge risk against other public interests. Today, the Supercomputing Era (see Sidebar) offers impressive tools for quantifying, evaluating, and communicating flood hazards and risks (probabilities of flood heights and their consequences)—facilitating improvements in rational management decisions. However, these decisions must still confront tremendous uncertainties and the challenge of allocating limited public funds among numerous priorities.

> **<u>Supercomputing</u>**
> A High Performance Computer (HPC), or supercomputer, distributes parallel steps to solve highly complex algorithms among hundreds to tens of thousands of microprocessors. Accelerating microprocessor improvements over the recent decades have enabled the development and adoption of HPC clusters for a vast number of computing needs. The "SuperMike" and "Queen Bee" Supercomputers at LSU were both examples of high-end HPC clusters at the time of their commissioning.

This article reviews the history of estimating surge hazard and providing sustainable surge protection for New Orleans, Louisiana and is presented in two parts:

> Part I reviews the pre-Katrina evolution, which is worth knowing in order to truly understand past mistakes which led to the City's devastation and issues which continue to threaten its future.
>
> Part II provides new details on key Katrina surge events. Part II then describes the post-Katrina progress—as well as limitations—in supercomputer-facilitated surge hazard analysis and risk management, together with important implications for future surge risk reduction.

Appreciating these limitations and acting on the implications is crucial to preventing another surge catastrophe.

Part I: Pre-Katrina Evolution of Surge Hazard Estimation and Risk Management

A. The Record Flood

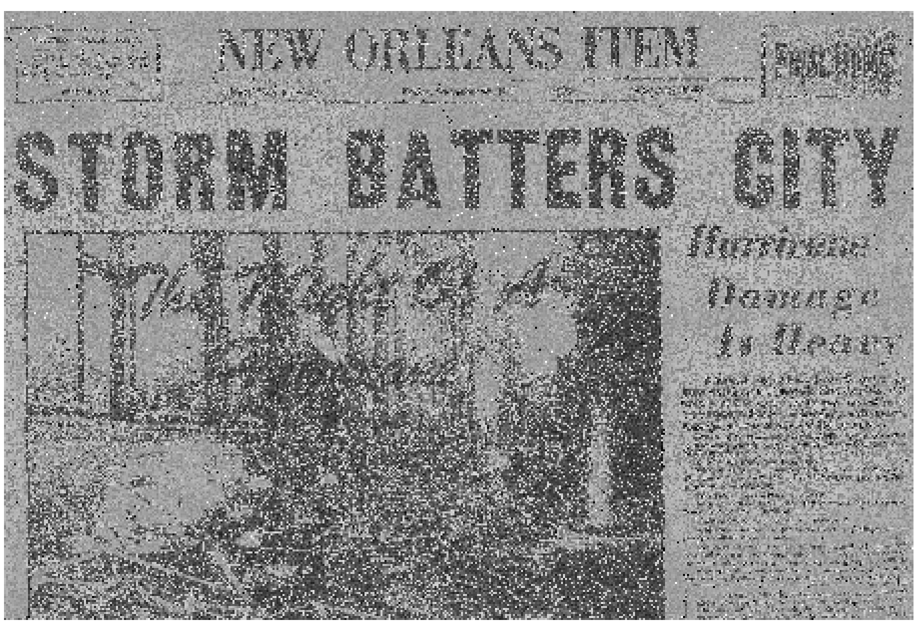
In 1717 Jean-Baptiste Le Moyne de Bienville wrote to his fellow French promoters who were struggling with the decision of where to situate the main settlement of their Louisiana colony. They needed a port location which would optimize their exploitation of local resources and cultivation of cash crops—as well as secure control over the lower Mississippi River and adjacent passages via Lakes Maurepas, Pontchartrain, and Borgne. But they also wanted to minimize exposure to natural disasters that could wipe out their investment. Bienville championed the cusp of a "fine crescent" on the Mississippi River—located strategically at a short portage from the River to Bayou St. John and the south shore of Lake Pontchartrain. Having earlier been granted title to this location, he—not surprisingly—touted it as relatively safe from floods and hurricanes. Thus, from the moment of New Orleans' founding, flood hazards were underestimated and conflicting interests confounded flood risk management.

The French Company of the West was engaged in what today would be called a "cost-benefit analysis." The French likely learned much about regional flood hazards from the natives, including the frequency and magnitude of Mississippi River floods and what they termed *tidal* surges. The region's first human inhabitants undertook a similar tradeoff analysis in choosing locations for their villages. Some tribes—like their European counterparts—may have maintained flood marks spanning generations to supplement their oral history and enhance their chances of staying dry (to say nothing of survival). They may even have recognized how to use the vast, flat, water surface of the swamps during still periods to transfer major flood marks to outlying locations, to enhance their activities in these areas.

Circumstances forced the natives and their European successors to exploit the region's natural resources to the margin of their capabilities—placing a premium on better cost-benefit analyses. Simple reliance on good luck (assuming a run of several easy years would continue) proved an unsustainable risk management practice. Up until the latter half of the 20th Century, keeping track of the historic "record flood" continued to be the State-of-the-Practice (SOP) for defining surge hazard.

Ever since floods have been recorded, the SOP for flood risk management has included placing critical structures—e.g., storage of food reserves, temples, leader dwellings—on the highest available ground, or elevating them. Communities facing frequent floods (dating back to ancient floodplain civilizations in Egypt, China, and Mesopotamia) also adopted the obvious measure of constructing perimeter levees. Within four years of its founding—following the first of many record hurricane surges in 1722—New Orleans leaders required everyone to contribute to building a "back" levee (behind the City, facing Lake Pontchartrain), initially constructed only a few feet above ground. Over the ensuing two hundred years New Orleans experienced many record surges, stimulating the construction of ever higher back levees and improvements in the selection of levee material and construction quality; (the latter particularly during the first half of the 20th Century with advances in geotechnical engineering).

By the early 1960s the City had upgraded its Lakefront levees several times, as had other River communities with their "40 Arpent" levees. (French colonial riverfront land grants had a rear limit of 40 Arpents, equivalent to about 1.5 miles.) The U.S. Army Corps of Engineers (USACE) had begun to assist bourgeoning Jefferson Parish with the design and construction of its back levee (USACE 1955). These latest levees largely were a response to vulnerabilities exposed by the surge associated with the September 1947 hurricane (see Figure 1). Of course, relying on a record flood to manage risk also proved unsustainable.



NEW ORLEANS ITEM

STORM BATTERS CITY

Hurricane Damage Is Heavy

Figure 1. Front Page of the New Orleans Item, September 19, 1947
http://www.old-new-orleans.com/1947_hurricane_frontpage

B. The Standard Project Hurricane

In September 1965 Category 4 Hurricane Betsy produced a new record surge—reaching up to 16 ft NAVD88 in places east of New Orleans. The back levees were not sufficient and there was extensive flooding throughout the New Orleans Lower 9th Ward, St. Bernard Parish, as well as in Gentilly west of the Inner Harbor Navigation Canal (IHNC). The region suffered damages of around $1 billion, making Betsy the most expensive hurricane in the nation at the time. Facing the choice between massive, expensive perimeter protection versus economic stagnation, the City deployed its powerful Senators and Representatives (e.g., Russell Long and Hale Boggs) to persuade a sympathetic President and Congress to fund federal construction (70 percent) of metropolitan New Orleans surge protection (see Sidebar).

To move beyond the record surge, the federal government turned to a concept which had been used in riverine flood control since the 1940s: the Standard Project Flood (SPF). The idea behind the SPF was to determine a "*close* to worst-case" flood height that could reasonably be expected to occur—given regional hydrologic characteristics (regional rainfall extremes, river basin topography, runoff, time of concentration to various tributaries, etc.). Rapid scientific advances in the first half of the 20th Century, coupled with many decades of rainfall data, suggested that a practical extreme flood height reflecting the various physical factors could be directly calculated. As a "close to worst-case" estimate, the SPF was expected to define a hazard more severe than any in the historical record, and to be appropriate for the design of flood controls intended to prevent BOTH the loss of life and destruction of property; (see Sidebar: Worst-Case Flood). The US Weather Bureau (now the National Weather Service under the National Oceanic and Atmospheric Administration, NOAA) was responsible for the SPF estimates.

For protecting both lives and property from surge, the US Weather Bureau similarly provided regional estimates for a Standard Project Hurricane (SPH). The SPH was defined in terms of the barometric pressure deficit (ΔP) associated with the storm core or eye (peripheral pressure minus central pressure, $P_P - P_C$); the core size in terms of radius of maximum winds

<u>Federal Involvement in Louisiana Flood Protection</u>

The federal involvement on the nation's waterways grew during the 19th century, primarily with demands to enhance navigation in support of interstate commerce. Following a record multi-state Mississippi River flood in 1874, Congress created the Mississippi River Commission to take-over the River levees—in large part to ensure that local flood control priorities did not trump navigation interests. However, due to the importance of its Port, protecting the City of New Orleans quickly became a key part of the Commission's river management. Thus, began the substantial and messy federal entanglement in New Orleans flood protection. Record floods again in 1890 and 1912 precipitated levee upgrades. The Great Flood of 1927 forced the Commission (and its agent, the USACE) to re-examine the balance of its River flood control and navigation priorities and to develop new policies and actions that would better address that balance. This, in turn, led to greatly expanded flood control construction and operations and associated long-term funding. Over the course of the 20th Century the USACE became increasingly authorized to lead regional and even local flood control projects—with state and local sponsors assuming a share of construction costs and the operations and maintenance—including several in Louisiana (USACE 1955). These projects all involved the balancing of flood control with competing interests, such as navigation, irrigation, power generation, recreation, and/or environmental preservation.

<u>Worst-Case Flood</u>

The Weather Bureau also developed estimates for the "worst-case" flood—termed the Probable Maximum Flood—based on likely upper physical limits. The Mississippi River levees in Southeast Louisiana are based on a "Project Design Flood," equivalent to the Probable Maximum Flood, with a combined flow of nearly 3 million cubic feet per second from the Upper Mississippi, Ohio, Missouri, and Arkansas Rivers. The Mississippi River Project Design Flood assumes a significant portion of this combined flow is diverted to the Atchafalaya River at the Old River Control Structure. (The Atchafalaya River must also accommodate inflow from the Red River.) Under the flood management plan additional portions are diverted with weir structures at Bonnet Carré (to Lake Pontchartrain) and Morganza (to a floodway east of the Atchafalaya River). The Bonnet Carré weir is opened in phases as needed, followed by Morganza, to keep the River peak flow at New Orleans below 1,250,000 cfs. The Bonnet Carré and Morganza structures have been opened 10 and 2 times, respectively (see Douglas 2011).

(R_{MAX}); and the storm forward translational speed (V_F). A 1959 Report defined the New Orleans regional offshore SPH as having a ΔP of 2.3 inches of mercury (29.92 - 27.6 inches) or about 80 millibars, an R_{MAX} of 30 nautical miles, and a V_F of 11 knots. Offshore, the SPH was estimated to have eyewall winds of about 100 miles per hour (mph), combining with V_F for maximum sustained winds (1-minute average) of about 112 mph. The SPH was estimated to decay modestly as it moved overland, with maximum sustained winds over Lakes Borgne and Pontchartrain of about 100 mph. During the 1970s several slight revisions were made to the New Orleans regional SPH, with a 1978 report identifying a ΔP of 84 millibars, an R_{MAX} of 29 nautical miles, a V_F of 4 knots, and offshore maximum sustained winds of 90 knots, or 104 mph, (NOAA 1972, 1975, 1978, and 1979). (Estimates of the "worst-case" or Probable Maximum Hurricane were also developed and revised, with ΔP increasing from 100 to 125 millibars.)

To estimate SPH peak surge the USACE utilized a few selected landfall/track scenarios and a late-1960s-era one-dimensional (1D) *steady-state* empirical formula. The formula used the maximum local perpendicular wind speed derived from one of the SPH scenarios and computed the surge "setup" at the levee. The estimate of setup also factored in the wind fetch distance, open-water depth, a loss coefficient (e.g., for friction), and drop in barometric pressure. The 1D surge analysis addressed the fact that the higher levees would block, and therefore raise, the incoming surge. Timing of tides was ignored. For Lakes Pontchartrain and Borgne the USACE used mean levels of 1.0 and 0.9 ft above mean sea level (MSL, see Sidebar). Along the south shore of Lake Pontchartrain (the New Orleans Lakefront) the SPH surge was estimated at 11.5 ft MSL and south of Lake Borgne (along the Mississippi River Gulf Outlet, MRGO) at 13.0 ft MSL. The SPH surge setup at the two locations were thus 10.5 and 12.1 ft above the respective mean lake levels (USACE 1966).

Vertical Datum

The USACE frequently used references to MSL and to National Geodetic Vertical (NGVD) interchangeably. The local MSL at Grand Isle is currently estimated at about 0.2 NAVD88, and mean levels in Lakes Borgne and Pontchartrain are about 0.3 and 0.5 ft NAVD88.

For protection features facing open water, SPH peak wave conditions were estimated, along with the wave runup height on levee slopes. To protect against the SPH surge at Lakes Pontchartrain and Borgne the USACE determined that the levee elevation should be set at 16.0 and 17.5 MSL ft, or 4.5 ft above the SPH surge (USACE 1966, 1968, and 1987).

The USACE's recommended SPH surge protection plan for New Orleans is illustrated in Figure 2. As a more cost-effective alternative to a "High-Level Plan" for Lakefront protection (i.e., full exposure to the SPH surge), the USACE incorporated a "Barrier Plan" to reduce surge inflow into Lake Pontchartrain. The Barrier Plan included a levee across what is now known as the New Orleans East Land-Bridge and gates at the Rigolets and Chef Menteur Passes and the IHNC Seabrook entrance. The USACE estimated that the Barrier Plan would reduce the Lakefront levee elevations from 16.0 to 11.0 ft MSL (USACE 1968).

The SPH surge protection project encountered numerous design and construction challenges. Among these were alignment details; adequate buffers; pipeline, utility, and other relocations; availability of suitable levee material; foundation and subsurface variability (affecting levee geometry, soil compaction procedures, and settlement both during and after construction); elevation survey control; and turf establishment. Floodwalls were substituted for levees in reaches with limited rights-of-way, but required extensive subsurface information to specify appropriate sheet pile depth. However, given the USACE's experience with Mississippi River and other flood protection projects these challenges were not that unusual.

Figure 2. Barrier Plan for Protecting the New Orleans East-Bank
USACE 1968

Despite a reinforced sense of urgency resulting from the “near miss” of Hurricane Camille in 1969—which produced a surge of over 20 ft in nearby Waveland Mississippi—the New Orleans SPH Barrier Plan began to confront competing interests and new programmatic hurdles that were not quickly resolved. The Barrier Plan was opposed over concerns that it was likely to alter Lake water quality and fisheries. Environmental interests also opposed the location of a St. Charles Parish levee along the Lakefront, preferring to move it further south and impound much less of the LaBranche Wetlands. Addressing these challenges involved new and evolving—and time consuming—requirements for environmental impact assessments and economic cost-benefit analysis. A final resolution in favor of the High-Level Plan was not reached until the mid-1980s and the St. Charles south alignment was not adopted until the 1990s.

Delays forced by these concerns and processes were then compounded by budget issues (see Government Accountability Office, GAO, 1976):

- Steep inflation of construction costs during the 1970s and 80s meant that annual appropriations covered less and less work, exacerbating delays.
- Annual appropriations for SPH surge protection projects were restricted—as Congress spread USACE funds across many competing demands from across the nation—forcing construction schedules to be greatly extended. New Orleans officials often placed navigation priorities—such as replacement of the IHNC Lock—above surge protection for annual funding.
- The official estimated cost (millions) and completion date of the New Orleans East-Bank SPH surge project (including St. Charles Parish) mushroomed:
    - In 1965 at authorization, $85/1978, (revised in 1968 to $98).
    - In 1976 according to a review by GAO, $352/1992.
    - In 1982 for the re-evaluation and adoption of the High-Level Plan, $760/2008.

Through the 1970s and 80s the region entered an extended period of low hurricane activity, which began to undermine the urgency to complete the SPH surge protection project. As the project dragged on there was an inevitable increasing emphasis on cost control and construction speed-up. This in turn contributed to engineering concessions—e.g., floodwall support conditions, levee materials, elevation control—and to deferring supplemental lifts for levee segments which had undergone significant post-construction settlement.

C. The Surge Hazard Curve

In addition to the SPF, by the mid-20th Century flood protection projects had begun to routinely apply statistical techniques for estimating the probability of extreme events. *Flood hazard* was quantified in terms of the annual probability of a particular flood stage being exceeded. (Each stage has its own discrete *mass probability* so the probability of exceedance is a *cumulative probability* encompassing the mass probabilities of all higher stages.) Quantified flood hazard offered a way (at least in theory) to apply objective, uniform criteria for similar projects across the nation and to gauge the cost-effectiveness of incremental protection alternatives—avoiding suboptimal over- and under-designs. (Subsequent planning developments would incorporate the probability for flood consequences—damages, loss of life, etc.—and seek to compare projects on the basis of quantified *flood risk*.)

Quantified flood hazard is depicted with a *location-specific* curve—graphed with flood stage on one axis and cumulative annual probability, also referred to as annual return frequency, on the other. The annual return frequency has a finite range—from 0 to 1.0 (0 to 100 percent). Instead of annual return frequency the average annual return period is often used—the latter is simply the inverse of the former—e.g., an annual return frequency of 0.01 equals an <u>*average*</u> return period of 100 years.

In the 1960s, the SOP for developing a flood return frequency curve for a location was to plot the series of maximum stages from a local river gauge (or a tide gauge in the case of surge data) versus each observed stage's rank in the record (sometimes slightly adjusted). If river gauge information was limited, additional stage-frequency "data" could be synthesized by estimating the stages associated with regional rainfall events (using the probability of the rainfall event together with hydrologic and hydraulic modeling). Connecting all the plotted points yielded a ragged line. Often a smooth curve was preferred and one would be hand drawn—reflecting what the author thought visually best fit the data. In both cases neither the ragged line nor the hand-drawn curve represented a parametric equation. Given very limited data sets, extrapolation of the hazard curve by hand was very subjective—e.g., to return periods of 100- and 500 years.

In 1966, less than one year after Hurricane Betsy, the USACE developed hand-drawn surge hazard curves to supplement their estimation of SPH surge. Figure 3 depicts a regional hurricane intensity (see Sidebar) return frequency curve prepared with simple visual fitting to a record of central Gulf of Mexico storm P_C observations. The curve—graphed as a nearly straight line on log-linear paper—incudes hand extrapolations. (USACE 1966; an earlier version of this curve appeared in U.S. Weather Bureau Report 1959.) The USACE used the hand-drawn hurricane intensity return curve—together with a few basic track scenarios and the simple 1D steady-state empirical wind setup formula described above to synthesize some limited surge-return data for three main portions of the project: Lake Pontchartrain Lakefront of Jefferson and Metro New Orleans; New Orleans East and the IHNC; and St. Bernard Parish (referred to as Chalmette Loop). The synthesized surge return events supplemented the regional surge return data for nine storms (1893, 1901, 1909, 1915, 1926, 1947, 1956, 1964, and 1965). Figure 4 presents the three 1966 hand-drawn surge hazard curves, prepared on log-linear paper.

<u>Hurricane Intensity</u>

Given more than a century of coastal extreme barometric pressure observations, including from ships, ΔP (or simply P_C, assuming a value for P_P) has long been used to represent hurricane intensity. Given that P_C usually correlates reasonably (though not always) with expected eyewall winds, and surge depends largely on the wind-speed, many hurricane observers came to treat P_C as a short-hand predictor of surge severity for a storm on a given track. In the 1970s, with routine aircraft reconnaissance of hurricane eyewalls and the measurement of maximum sustained winds, the Saffir-Simpson Scale categorizing hurricane intensity from 1 to 5 (based on wind speed) was popularized. For the next three decades, track and Saffir-Simpson category became ingrained in the minds of officials and the public as the overriding factors in surge hazard. Interestingly, the New Orleans regional offshore SPH with maximum sustained winds of 112 mph is a minimal Category 3 storm; however the SPH ΔP of over 80 millibars can be more indicative of a Category 4 storm.

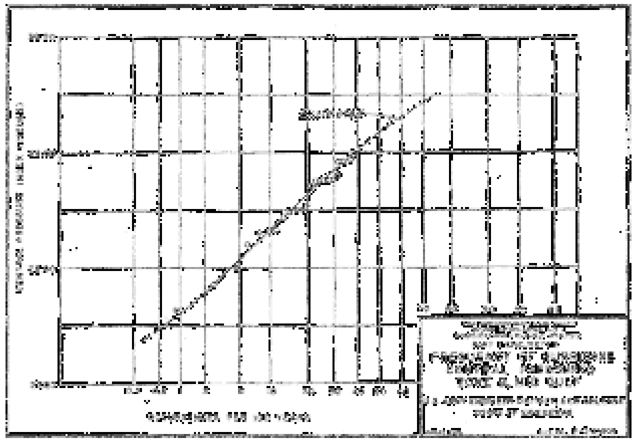


Figure 3. Central Gulf of Mexico Return Frequency for Hurricane Central Pressure
USACE 1966

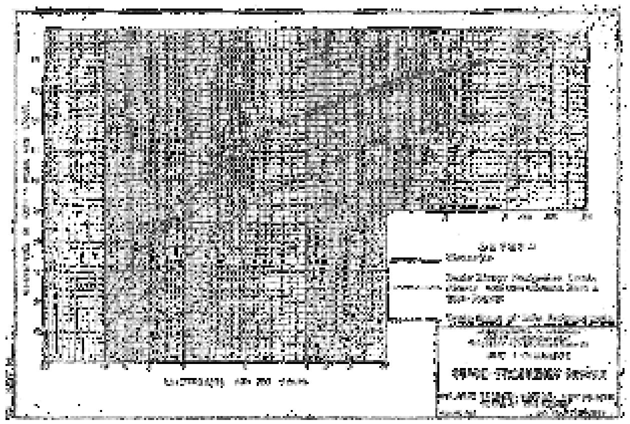


Figure 4. SPH Project Surge Hazard Curves for East Bank New Orleans
USACE 1966

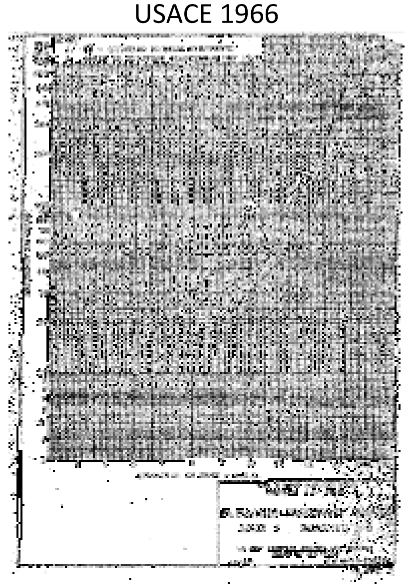


Figure 5. FEMA FIS Surge Hazard Curves for East Bank New Orleans
USACE 1970

During the 1970s the newly established National Flood Insurance Program (NFIP)—which provided insurance coverages and premium costs based on exposure to a one percent annual return frequency, or 100-year (yr) flood—triggered an explosion in hazard analyses for Flood Insurance Studies (FISs) across the country. For coastal Louisiana the predecessor to what is now the Federal Emergency Management Administration (FEMA) turned to the USACE to provide the first FIS surge hazard analysis. The USACE followed a similar procedure to the one described above to create Figure 5, with three surge hazard curves for the New Orleans area: Reach 1, South Shore of Lake Pontchartrain (St. Charles Parish to eastward to South Point); Reach 2, North Shore of Lake Pontchartrain (eastward to the Rigolets Pass); and Reach 3, Lake Borgne (St. Bernard Parish).

The surge hazard curves in Figures 4 and 5 are identical at return periods above 50 years. The SPH protection project and FIS surge hazard analyses apparently used slightly different input information affecting the lower return period values.) Circles on the curves in Figure 5 note that the SPHs for the New Orleans Lakefront and Lake Borgne locations were estimated to be 300-yr and 200-yr events. For the New Orleans Lakefront the 100- and 500-yr surge elevations were 10.3 and 11.9 ft, and for Lake Borgne they were 12.5, and 13.7 ft. Notably, the USACE's hand-drawn curves indicated that the respective increases in surge hazard from 100- to 500-yr return were only a modest 1.6 and 1.2 feet. Both surge hazard curves *excluded* the Barrier Plan.

Extreme Value Functions

When sufficient data were available, the 1970s-era SOP called for the use of parametric equations—termed Extreme Value Functions (EVFs)—in place of hand-drawn hazard curves, eliminating subjectivity in the extrapolation to higher return periods. Five common EVF types were the basic Log-Normal equation, the Log-Pearson Type III equation, and three variants of the Generalized Extreme Value (GEV) equation—the Gumbel, Weibull, and Frechet equations. The plot of cumulative probability data were compared to graphs of several EVF types, with several versions of each EVF type prepared by adjusting equation coefficients. The EVF providing the best general agreement in shape (asymmetry/skew) and suitable tailing properties (especially at the upper return period) was selected. The early SOP relied on special plotting paper customized for each EVF type, which allowed the EVF coefficients to be easily evaluated. Agencies tended to use a particular EVF type for rivers with particular flow characteristics based upon research which suggested a good match—e.g., better fit according to a root mean square error. For example, the Log-Pearson Type III (and corresponding plotting paper) became widely applied for general riverine flood hazard curves. By the 1980s, computers were facilitating the calculation of EVF coefficients and comparison of EVF fits. While the use of an EVF eliminated subjectivity in extrapolating the hazard curve to extreme return periods, some subjectivity still remained in the choice of one EVF type over another. Research efforts on the use of EVFs, particularly the Weibull distribution, to represent hurricane wind and surge hazard were initiated in the mid-1980s but were not applied to New Orleans surge protection prior to Katrina (see Georgiou 1985, USACE 1986, and NOAA 1987.)

At the same time that surge hazards curves were being evaluated for the SPH project and the NFIP, metropolitan New Orleans interior FISs were also defining large areas subject to 100-yr rainfall inundation. These FISs took into account the federally authorized (but incomplete) SPH projects. Thus, for NFIP purposes flood hazard inside the protection was only based on rainfall events. Home mortgagors inside the protection not subject to interior drainage issues were not required to purchase flood insurance—and optional flood insurance was very affordable. Property values in better drained interior areas were greatly enhanced, while those in designated 100-yr flood hazard zones declined, placing a significant economic hardship on whole neighborhoods. Officials in New Orleans (as well as other flood-prone cities across the nation) naturally wanted to accelerate projects that might remove larger, populated, and/or potentially more valuable areas from the 100-yr flood zone. In the 1990s New Orleans area leaders sought and obtained a federal interior drainage construction project under the USACE: the Southeast Louisiana Drainage Project, (SELA). Thus, the NFIP ironically had the inevitable and perverse effect of spurring many local officials to prioritize USACE funding for SELA projects over SPH surge protection. (The NFIP, particularly the arbitrary 100-yr threshold, continues to influence decisions by communities and individuals throughout the nation.)

D. Joint Probability Analysis and Two-Dimensional Modeling

The significance of other storm characteristics in addition to P_C to local wind and surge exposure had long been known and in the 1980s these characteristics—variations in R_{MAX} and V_F, as well as track, including both landfall location (X) and storm approach direction (θ)—began to be more closely re-examined by leading hurricane climatologists (see NOAA 1979 and 1987). Decay in storm intensity with landfall was also studied. Hurricane climatologists determined that a reasonable surge hazard analysis required a larger array of synthetic storms representing the combined joint probabilities of P_C with R_{MAX}, V_F, θ, X, and decay—a so-called joint probability analysis (JPA, see Sidebar).

During this same period surge scientists started applying two-dimensional (2D) hydrodynamic modeling to estimate peak surge for each storm (see Massey et al 2007). 1980s-era 2D hydro*dynamic* modeling began to capture some of the complex *time-varyin*g physical interactions between three phenomena:

1. The shoreward-driven forerunner and main surge.
2. The rapidly shifting local setup driven by the passing wind-field.
3. The impacts on surge caused by coastal landscape features—such as bathymetric conveyances (channels and large, shallow interior bays and lakes) and topographic barriers (levees, roads, dunes, ridges, etc.).

1980s-era 2D transient surge simulation—e.g., FEMA's in-house Coastal Flooding Storm Surge Model—was still coarse in resolving localized interactions. Some important physical processes were not yet represented, such as the setup contribution from wave radiation stress gradients. Often there were debates over whether the 2D model or the earlier 1D steady-state equations (which were simpler, quicker to complete, and less expensive) was more accurate, or more conservative, or more suitable for FISs. One of the first applications of JPA and 2D modeling in coastal Louisiana was performed in 1989 by Joseph N. Suhayda, PhD for a Cameron Parish, Louisiana FIS. Suhayda's JPA/JPM set used 685 storms.

By the 1990s, continued advances in computer capabilities had made JPM and 2D modeling the SOP in surge hazard analysis. The cumulative probability curve was typically left as a non-parametric function covering the wide range of return periods generated by the analysis (perhaps smoothed using an algorithm) and there was no need for extrapolation.

<u>Techniques for Joint Probability Analysis</u>

There are several approaches to developing a synthetic set of storms. Empirical methods emphasize expanding on historical observations to create an artificial record much longer (e.g., an order of magnitude) than the longest return period of interest. The empirical approach produces an artificial record with variability in the combination of hurricane attributes that is consistent with the generally observed joint probabilities in the regional climatology. Coastal wind hazard analysts would later develop an artificial 100,000-yr hurricane record—with tens of thousands of storms—using an empirical approach (Vickery et al 2009).

Surge simulation of an entire empirically-derived artificial record has not been practical. An alternative approach to the storm set, termed the joint probability method (JPM), is to select storms that represent a reasonable sample of the joint-probabilities. Early efforts used a few values for each characteristic—e.g., three values each for five characteristics yields a set of 243 storms.

Figure 6a illustrates a set of 76 storms with their respective *mass probabilities*. In this set several hypothetical storms share the same mass probability (they have common attributes, but different landfall locations). Figure 6b shows a histogram of the combined mass probability by 1-ft bins. The cumulative hazard curve, Figure 6c, is developed by numerically integrating the mass probabilities through each bin.

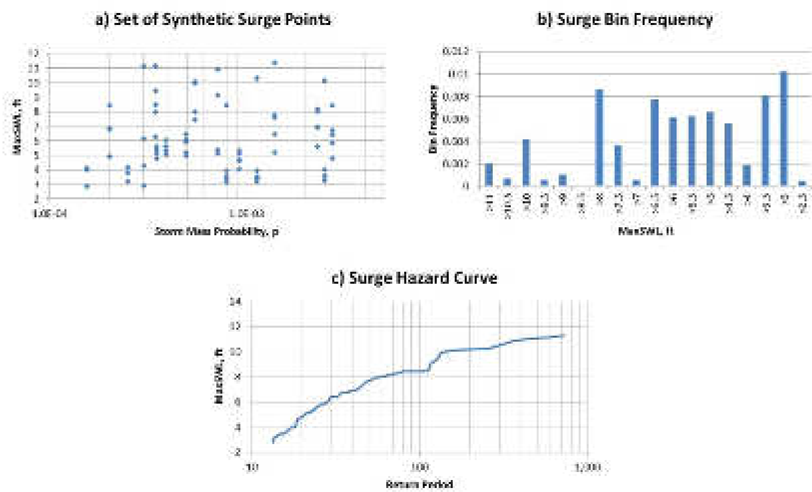


Figure 6 Construction of a Surge Hazard Curve from JPM Results

Despite advances in JPA and 2D modeling, the USACE continued to rely on the original estimated SPH surge and hand-drawn surge hazard curves; (even as the High-Level Plan was only then being finalized and a new surge protection project was being added for the metropolitan West-Bank, USACE 1994). Some of the factors which no doubt influenced the USACE included:

- The New Orleans regional SPH did not change appreciably between 1959 and 1979, and NOAA never revisited the estimate of the regional SPH after that. For new flood control projects the hazard community increasingly preferred estimates of extreme return periods (e.g., 500-yr) over SPFs.
- FEMA had not required a new regional surge hazard analysis for NFIP purposes. If FEMA had, perhaps it might have indicated higher surges at the 200- to 300-yr return period. However, FEMA had a long nationwide backlog for FISs and funded new analyses according to their own priorities.
- The 1966 SPH surge estimates and surge hazard analysis were still thought to be reasonable in light of the relative newness of the JPM/2D approach; some considered the 1966 1D steady-state SPH surge estimates conservative.
- Engineering designs had long been committed the 1966 SPH surge heights. Project momentum using the original 1966 SPH surge analysis was reaching 30 years.
- There was a natural reluctance to re-open the specification of design surge height and a desire to expedite completion of regional SPH protection. At the time of the final selection of the High-Level Plan in the mid-80s an expert review team could have been consulted to determine the reasonableness of continuing to use the 1966 SPH surge as the design surge. However, any change in the design surge likely would have delayed the High Level Plan adoption by many more years.

With prolonged lower hurricane activity and other competing funding priorities—e.g., navigation and drainage—the post-Betsy/Camille urgency was being supplanted in many quarters by complacency. Unfortunately, just like counting on a string of good luck or the record flood, relying on the 1966 SPH surge estimates would also prove to be unsustainable.

E. Extreme Surge Scenarios

Hurricane Andrew came ashore near Homestead, Florida in August 1992 with devastating 150 mph winds, causing $25 billion dollars of damage in Dade County alone. Andrew then crossed into the Gulf of Mexico, re-energized to Category 4, and made landfall with 138 mph winds southeast of Morgan City, Louisiana. Andrew renewed interest in the true nature and impact of extreme hurricanes among both hurricane climatologists and regional wind and surge hazard planners.

By the mid-1990s, state and local emergency operations officials and their federal counterparts (including storm forecasters and disaster planners and responders) had become concerned that the available analyses did not provide sufficient information about potential severe surge events. For the New Orleans area the 1966 estimates of surge hazard were all that was available and these now appeared very rudimentary. If (or when) a major hurricane approached Southeast Louisiana, these officials needed information about surge scenarios associated with that hurricane. They also wanted extreme hurricane scenarios to enhance their annual preparedness drills and "table-top exercises." Information coming from hurricane climatologists made these officials increasingly aware that surge scenarios based on track and Saffir-Simpson category alone were not sufficient. They were also increasingly aware of the effect of the coastal landscape on surge—such as the impact of extended, raised topographic features on blocking and raising surge—and they wanted these better accounted for in the scenarios.

In response to these needs FEMA and the USACE prepared a *Southeast Louisiana Hurricane Preparedness Study* in 1994. The USACE used NOAA's 2D Sea, Lake, and Overland Surges from Hurricanes (SLOSH) computer model to simulate 328 variations for each of the five Saffir-Simpson intensity categories—including 9 variations in θ, each with two different values for V_F and at 15 to 20 landfall locations. A single R_{MAX} of 25 miles was utilized. While the SLOSH model was much coarser than the FEMA's model, simulations were more efficient—allowing more storm variations to be considered. The peak surge results from the various simulations for each combination of Category and θ (e.g., Category 3 on due north heading) were compared, and maximum surge values everywhere throughout the model domain were determined. A composite map showing the maximum envelope of water (MEOW) was thus created, illustrating the maximum surge exposure for a hurricane of given category and general heading many hours before landfall. Five Maximum of Maximums (MOM) maps were then generated further compositing the MEOWs for each category. The MEOWs and MOMs thus provided critical maximum surge exposure throughout the region under extreme hurricane scenarios. (MEOWs and MOMs are not peak surges for a single storm). Figure 7 is a combined MOM for slow-moving Category 4 and all Category 5 hurricanes for Southeast Louisiana prepared by the USACE.

In August 1998 Category 3 Hurricane Georges took direct aim at New Orleans but turned to the east as it approached the Mississippi River Delta. The near-miss of Georges amplified interest in extreme surge scenarios. NOAA subsequently undertook minor refinements of the SLOSH model and updates to the MEOWs and MOMs with additional variations for tide. During this same period the Louisiana Office of Emergency Preparedness tasked Joseph N. Suhayda, PhD with using the higher resolution FEMA model to examine some hurricane scenarios, including Category 5 storms.

The surge estimates developed from these efforts—as illustrated in Figure 7—warned of conditions far in excess of those experienced during the record Hurricane Betsy, and more disquieting, the SPH or even the current (1966) 500-yr surge. Moreover, hurricane climatologists were considering these extreme conditions to have a return frequency estimate of less than 500 years. By the early 2000s national and local news media were increasingly attentive to stories on extreme surge hazard, (New York Times 2002; Times-Picayune 2002; see this issue's Cover), and there was broad dissemination of the extreme surge scenarios among state and local officials and the public.

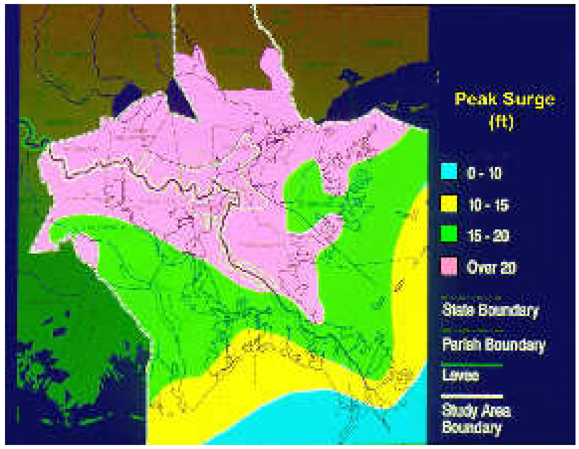


Figure 7. MOM for Slow Category 4 and All Category 5 Storms, Southeast Louisiana
USACE 1998

The new information on extreme surge scenarios precipitated three critical risk management reactions:

1. The directors of SPH surge protection undertook a serious but limited response. Within their authorization and budget constraints the USACE initiated: development of an advanced supercomputer -based (see Sidebar) regional 2D surge model (Westerink and Luettich 2003); preparations with FEMA for a new FIS surge hazard analysis; evaluation of vertical control and settlement issues using modernized GPS-enhanced surveying techniques; and preliminary studies for higher protection. The USACE also prepared an interior "unwatering plan" in the event of catastrophic surge inundation. However, a comprehensive review of structural vulnerabilities throughout the region—given that reaching or exceeding the SPH surge could be more likely than previously thought—was not initiated. USACE and local levee board representatives routinely underscored the need for funding to complete, maintain, and enhance SPH surge protection.
2. New Orleans community leaders emphasized the critical importance of evacuation. Hurricane and local television meteorologists—in conjunction with state and local emergency response officials—significantly improved the quality and communication of hurricane warnings and recommendations for evacuation of low-lying areas over the course of the 70s, 80s, and 90s. Completion of the regional interstate and the explosive growth in travel and accommodations made evacuation more practical to increasing numbers of residents in potentially affected areas. During 1998's Hurricane Georges a large number of New Orleans residents evacuated. In 2004, Category 5 Hurricane Ivan entered the Gulf of Mexico appearing to head for Southeast Louisiana (it also later curved to the east). Authorities urged those capable of leaving New Orleans to do so. A mass evacuation of the City ensued, utilizing the first implementation of a "ContraFlow Plan" that converted some incoming segments of the surrounding interstate to outgoing traffic. (The limitations of the 2004 ContraFlow were subsequently identified and an enhanced plan adopted for the 2005 hurricane season, see Wolshon 2006.)

> **<u>Evacuation and Levees</u>**
> For communities with flood levees, an increasing emphasis on evacuation reduces the priority of levees as a life-saving measure. This in turn fuels greater commitment on the part of leaders to evacuation and leads to levees designed and maintained strictly for mitigating property damage risk (e.g., NFIP purposes). This is especially reasonable if higher levees are not technically or economically feasible. However, when evacuation becomes essential communities must provide for those who have medical, logistical, or financial problems with self-evacuating.

3. Interest increased in coastal protection and restoration to reduce inland surge hazard and risk. Coastal scientists had long been studying the impacts of hurricane surge on coastal wetlands, forests, barrier islands, dunes, cheniers, channels, bays, and other features. With mounting appreciation for Louisiana's rapid loss of coastal wetlands in the 1990s, Hurricanes Andrew and

Georges spurred more investigations of these impacts (for example, see Gunenspergen and Vairin 1996). But, with increasing attention on extreme surge scenarios and associated inland risks, coastal scientists were also encouraged to consider the effect of the various features on surge hazard. Prior to 2000 there was a reliance on overly simplistic explanations: such as the oft-quoted "rule of thumb" that 2.7 miles of wetlands reduce surge by 1 ft. After 2000 the effects of coastal landscapes on surge became a subject for more rigorous inquiries (e.g., Stone et al 2003). While the nuanced influences of various landscape features on surges of various magnitudes had yet to be well-defined, coastal advocates stressed what seemed an obvious link between more coastal wetlands and less surge hazard. State, local and private coastal landowners, resource managers, and supporting scientists began lobbying for federally sponsored coastal protection and restoration not only for ecosystem benefits, but to reduce inland surge risk (see the 1998 Coast 2050 Plan).

As of 2004 most East-Bank protection segments were still incomplete or had inadequate heights (due either to settlement or vertical control issues). However, the USACE's proposed FY2005 budget included less than $4 million for work on the SPH surge protection—substantially less than previous years and a small fraction of the $70 million needed for completion. By comparison, the FY2005 budget was $30 million for SELA and over $200 million for regional navigation and other civil works. In the summer of 2004 (awaiting the FY2005 appropriation) the USACE was forced for the first time in 40 years to temporarily halt work on the SPH surge project.

By the mid-2000s hurricane climatologists noted that the Western Atlantic seemed to be returning to a period of high hurricane activity. At the same time they began urging surge hazard planners to be mindful of the effects of storm size—and not just R_{MAX} but also the extent and strength of the full wind-field. The latter was characterized with a shape parameter (termed "Holland B") and/or the radial span of tropical storm and hurricane force winds. Investigators of extreme surge scenarios took note. In July 2004 researchers at the Louisiana State University (LSU) Hurricane Center—working with the authors of the Advanced Circulation model (ADCIRC, the supercomputer-based model being evaluated by the USACE for updating regional surge hazard analysis)—simulated a large Category 3 storm passing on a critical path just west of New Orleans, which they dubbed "Hurricane Pam." The simulation was prepared for an eight day response exercise attended by over 300 representatives of various federal, state, and local agencies. Figure 8 illustrates the surge just after landfall—in some areas approaching the MOM shown in Figure 7. After the near-miss of Hurricane Ivan a month later, the Hurricane Pam simulation received greater attention during three follow-up workshops, two of which were held in New Orleans. One was conducted in the fall of 2004 and the other, ironically, in late July 2005, one month before Hurricane Katrina struck New Orleans.

Part II (in the August issue of *Louisiana Civil Engineer*) will present:

- A summary of the August 2005 Hurricane Katrina surge event, including new inundation simulations for the various protection failures.
- A review of new developments in—and remaining limitations of—supercomputer-facilitated quantitative hurricane surge hazard analysis and risk management.
- Crucial lessons for providing sustainable surge protection.

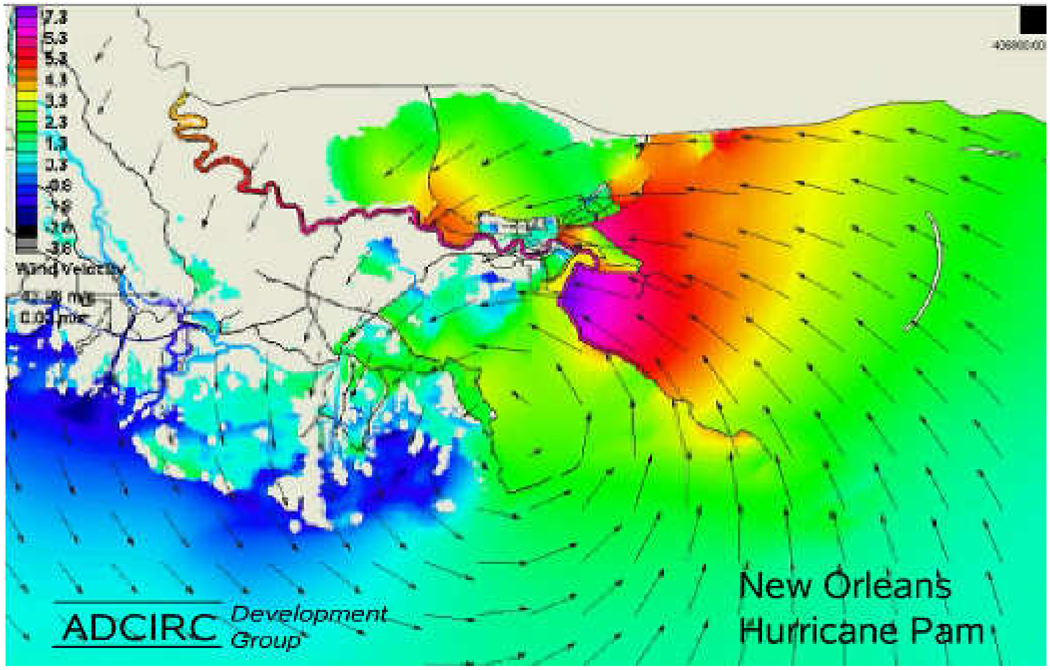


Figure 8. Snapshot of Surge for Large, Category 3 Hurricane Pam
http://www3.nd.edu/~adcirc/pam.htm

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