How Hurricane Katrina influenced the design of hurricane protection and risk reduction systems and national approaches to risk and resilience: Part 1. Hurricane Katrina and New Orleans: A forensic assessment, risk and reliability analysis, and key lessons learned

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ABSTRACT

A systems perspective is presented of what happened during and after Hurricane Katrina (2005) and the potential for reducing the likelihood of large losses in the future. This work was the basis for the rapid repair of the damage resulting from Katrina and ultimately the development and construction of a new risk reduction system for the region and a major shift in engineering guidance and practice related to public water infrastructure. The work was primarily accomplished through the Interagency Performance Evaluation Task Force (IPET) established by the Chief of Engineers, US Army Corps of Engineers, to conduct a comprehensive forensic analysis of what happened and why, and to an engineering risk and reliability assessment of the hurricane protection system in place when Katrina struck.

Key words: Flood risk, Forensic analysis, Lessons learned, Hurricane Katrina, Risk and reliability analysis

HIGHLIGHTS

- Hurricane Katrina caused extensive and unprecedented economic damages and loss of life in Southeast Louisiana. An interagency task force was formed to find out what happened and why.
- The resulting forensic analysis of the storm and resulting forces, protective structures and their performance, the resultant flooding, and associated economic and life losses portrays a vivid picture of the consequences of being unprepared.
- The associated risk and reliability analysis conducted for New Orleans and vicinity provided a strategic baseline for understanding why New Orleans was so vulnerable and a foundation for configuring both short-term repairs and a longer-term initiative for a dramatic reduction of flood risk for the future.
- The lessons learned from this effort were the roots of major changes in the approach taken for flood mitigation through the application of risk and reliability and a better understanding of both the hurricane threat and the failure modes of coastal structures.

PART 1: INTRODUCTION

The paper is segmented into three components: the first describing the Katrina event, the impact on the existing infrastructure in New Orleans and Southeast Louisiana, and the losses that resulted in terms of both life and property. This provided the basis for understanding the failure modes and vulnerabilities of the existing infrastructure and led to the design of immediate repairs and upgrades to those structures prior to the next hurricane season.

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The second component describes the risk and reliability assessment made to understand the sources of the structural failures and the losses in both geographical and socioeconomic terms. This analysis became a key input for developing a strategy for the design and construction of a new system to dramatically reduce flood risk in the future, discussed in a separate paper in this volume. The third component is a summary of lessons learned from these analyses that are relevant to other critical weather infrastructures and systems that have exposure to flooding.

The IPET was established (October 2005) to examine the performance of the New Orleans and Southeast Louisiana hurricane protection system (HPS) and provide real-time input to the immediate repairs and long-term rebuilding of the system. The results of the IPET effort were initially published as a draft in June 2006 and in final form in June 2009 following extensive review and augmentation. The IPET Final Report consisted of nine volumes (Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Vols I–IX and a supplemental report on risk) available on the Web at https://biotech.law.lsu.edu/katrina/ipet/ipet.html. In addition, a separate study of somewhat reduced scope was conducted by a team led by the University of California at Berkeley. Their report, ‘Investigation of the Performance of the New Orleans Flood Protection Systems in Hurricane Katrina on August 29, 2005, Independent Levee Investigation Team Final Report’, July 31, 2006, is also available on the Web at http://www.ce.berkeley.edu/projects/neworleans/.

PART 2: HURRICANE KATRINA FORENSIC ANALYSIS

The following section describes the fundamental character of the infrastructure in place when Hurricane Katrina struck, the character of the hurricane itself and the forces the infrastructure experienced, the performance of that infrastructure, and the resulting flooding and related losses.

How the New Orleans HPS was planned, designed, and constructed

Planning and construction

Although federally authorized, the Lake Pontchartrain and Vicinity Project was to be a joint federal, state, and local effort, with the federal government paying 70% of the costs and the state and local interests paying 30%. The local interests included the State of Louisiana Department of Transportation and Development, the New Orleans Sewerage and Water Board, and the local levee boards. The Corps of Engineers was assigned responsibility for project design and construction, and the local interests were responsible for the operation and maintenance of the levees and flood control structures. This was one of the first major cost-sharing projects for the Corps of Engineers and the nation.

During the first 17 years of the project, it was focused on what has become known as the ‘barrier plan’. The barrier plan included a series of levees along the lakefront, concrete floodwalls along the Inner Harbor Navigation Canal (IHNC), and a variety of control structures, including barriers and flood control gates located at the Rigolets and Chef Menteur Pass areas that connect Lake Pontchartrain to Lake Borgne. These structures were intended to prevent storm surges from entering Lake Pontchartrain and overflowing the levees along the lakefront. A number of project delays and cost increases occurred as a result of technical issues, environmental concerns, legal challenges, and local opposition to various aspects of the project.

A December 1977 court decision enjoined the Corps from constructing the barrier complexes and certain other parts of the project until a revised environmental impact statement was prepared and accepted. The Corps conducted a ‘Re-Evaluation Study,’ published in 1984, in response to the court order and examined the feasibility of providing protection mostly by means of raising and strengthening levees and floodwalls. The Energy and Water Development Act of 1992 mandated the use of parallel protection and set the stage for the construction of the levee and I-wall structures that were in place prior to Katrina. Note that the original authorization for protection...
occurred in the 1965 time frame and the final resolution of how to provide protection for a large portion of the metropolitan area of New Orleans was not determined until 1992, over a quarter of a century later.

The construction of the HPS, in place when Katrina struck, occurred over the subsequent 40 years. Figure 1 shows the general layout of the major components of the HPS in the immediate vicinity of New Orleans. Some components of the system were not scheduled to be completed until 2015, primarily the West Bank and Vicinity Project. At no time did the entire New Orleans and Vicinity area have a reasonably uniform level of protection around its perimeter. At no time did any individual parish or basin have the full authorized protection planned for in 1965. As of May 2005, the Lake Pontchartrain and Vicinity Project included about 125 miles of levees, major floodwalls, flood-proofed bridges, and a mitigation dike on the lake's west shore. Progress on the project varied by area: 90% complete in Orleans Parish, 70% complete in Jefferson Parish, 90% complete in the Chalmette area, and 60% complete in St. Charles Parish.

The history of this HPS has been one of continuous fragmented decision-making, funding, and deficiencies. This situation was a product of the overall incremental legislative water resources development process; the magnitude of the investments needed to accomplish such projects; the piecemeal allocation of resources; the time and complex processes required to resolve differences in local and federal priorities; and the traditional step-by-step construction process for structures such as levees in subsidence-prone areas such as New Orleans.

**The hazard**

By 2005, three separate hurricane protection projects had been designed and partially constructed in the New Orleans and the Southeast Louisiana region: Lake Pontchartrain and Vicinity Project, the West Bank and Vicinity Project, and the New Orleans to Venice Project. Each project had a specific hazard as a criterion for design.

![Fig. 1 | Map of structures and features of New Orleans and the pre-Katrina Hurricane Protection System (Source: IPET Report, Vols I and III).](http://iwaponline.com/wp/article-pdf/23/S1/156/979286/023000156.pdf)
The Lake Pontchartrain and Vicinity Hurricane Project was intended to protect areas around the lake (in Orleans, Jefferson, St. Bernard, and St. Charles Parishes) from flooding caused by a storm surge or rainfall associated with a hurricane that would be roughly the same as what is today classified by the Saffir–Simpson scale as a fast-moving Category 3 hurricane. The basis for this was the Standard Project Hurricane (SPH) developed for the Corps of Engineers by the US Weather Bureau (now the National Weather Service; see NOAA Technical Report NWS 23, 1979).

The SPH is a steady-state storm based on an analysis of meteorological parameters of past large hurricanes. The assumption of steady-state precludes the consideration of some of the dynamic behaviors we now know characterize hurricanes such as decreasing in intensity and increasing in diameter as they approach shore. For the initial definition of the SPH used in the design of the New Orleans hurricane protection structures, hurricanes were considered that occurred during the period 1900–1956. The Central Pressure Index (CPI) was the primary intensity criterion, and the 1% recurrence CPI (100 years) was chosen for the initial SPH definition. When the additional consideration of the likelihood of a storm of that description hitting the area near New Orleans is added, it was estimated to be equivalent to a 200- to 300-year recurrence event. Note that the character of the 1% recurrence CPI has changed dramatically between the initial SPH estimates and the time of Katrina occurring.

The SPH was intended to represent the most severe meteorological conditions considered 'reasonably characteristic' for the region. A maximum wind speed at landfall was also associated with the SPH; for Lake Pontchartrain and Vicinity, it was assumed to be 100 miles/hour. Following Hurricane Betsy in 1965, the wind speed criterion was revised but all other characteristics remained the same. The 1965 version of the SPH was used for the design of both the Lake Pontchartrain and Vicinity and New Orleans to Venice Projects. In 1979, NOAA issued a report that significantly revised the SPH criteria, resulting in a more intense storm event (1% recurrence CPI went from 934.6 mb in 1965 to 926.2 mb in 1979, see NOAA Technical Report NWS 23, 1979), and this became the basis for the design of the West Bank and Vicinity Project. All activities with respect to the Lake Pontchartrain and Vicinity project continued to use the original SPH criteria through the time of Hurricane Katrina. After Karina, which had a CPI of approximately 905 mb, a NOAA preliminary analysis revised the 1% recurrence CPI to approximately 901 mb. Hence, from a CPI perspective alone Katrina would be associated with a 1% recurrence event in 2005.

The SPH was a basis for estimating the surge and wave conditions that might exist for the New Orleans area. The storm was assumed to travel a number of paths, and the maximum surge and wave elevation generated from these different scenarios (estimated for each location of interest) was assumed to be the design water conditions for the project.

**Design of the HPS structures**

The HPS includes approximately 350 miles of protective structures, 56 miles of which are floodwalls. The majority of the floodwalls are I-walls with small sections of T-walls and a very small number of L-walls, basically similar to T-walls with a horizontal component on only one side at the base.

An aspect of the HPS is that the designs constructed, with the exception of the few sections constructed with T-walls, do not explicitly include protection against overtopping. The structures were, in effect, designed to perform at water elevations up to overtopping, but not beyond. This is not atypical in flood protection measures when cost/benefit justification is a primary decision factor.

Some sections of levees were constructed with higher quality (from an erosion perspective) materials than others, basically clays hauled in versus lower quality soils dredged (the method termed hydraulic fill) from adjacent areas. Along the outfall canals, I-walls were added to existing levees to gain higher protective elevations. Structures along the 17th Street and London Avenue Canals were designed with less conservative assumptions...
than those for the Orleans Canal. Soil strengths assumed for the clay layer underlying the 17th Street Canal were higher than warranted given the measurements available. For all of the canals, the design analysis used acceptable (at the time) but dated approaches for stability analysis and a factor of safety of 1.3. Failure modes examined were traditional for the time but did not explore other possibilities. The design for the Orleans Canal structures was more conservative than those for the 17th Street and London Avenue Canals. The levee section was wider and the freeboard of the exposed floodwall less. Orleans Canal had fewer real estate access restrictions, being adjacent to open public land. In the end, all of these differences played a large role in the ultimate performance of the structures during Katrina.

It is important to note the complexity of the HPS. Besides the structures considered part of the hurricane protection projects cited above, other features such as the main-line levees of the Mississippi River, levees and walls that form the outer periphery of the HPS, pump stations, bridges, navigation structures, and drainage and control structures are all factors in the ultimate ability to protect New Orleans from flooding. Some of these structures are not part of the HPS and fall under different jurisdictions, making their management during a flood more complicated.

The elevations of the hurricane protection structures in 2005 were significantly below the originally authorized heights, due in part from errors in initially constructed elevations, in part from rapid subsidence, and in part from sections where the authorized hurricane protection structures are not yet in place.

**Hurricane Katrina event**

The path followed by Hurricane Katrina, as shown in Figure 2, caused severe surge and wave conditions on the east side of the HPS, from Lake Pontchartrain to southern Plaquemines Parish. Katrina struck early on the morning of 29 August 2005, after building up water levels to the east of New Orleans for several days. Katrina was a Category 5 storm with up to 139-knot (160-mph) sustained surface winds until it was approximately 170 miles from landfall. When it reached landfall at Buras, LA, surface wind speeds were at about 100 knots (115 mph), but the long path through the Gulf, and its intensity and size, had built up record levels of surge and waves, larger than any previous storm to strike the New Orleans area, or the North American continent.

Katrina (a Category 3 storm at landfall) generated substantially higher surges than Camille in 1969, a Category 5 storm at landfall in the area where they both made a direct hit. Whereas the Saffir–Simpson scale ([https://www.weather.gov/](https://www.weather.gov/mfl/saffirsimpson)) is a good surrogate for wind levels and damage from hurricane winds, it is not a particularly good metric to represent the surge and wave generation potential for hurricanes. Surge and wave levels are particularly sensitive to the width of the storm; the fetch, or distance it travels over water; the path the storm takes, the geometry of the coastline and the continental shelf, and the offshore character of the storm. Hurricane Katrina had far greater wave and storm surge generation potential than the SPH storms used to design the HPS in 1965. Note that both were classified as fast-moving Category 3 storms at landfall, according to the Saffir–Simpson scale for hurricanes.

Katrina swept through the New Orleans area rapidly, making a second landfall at Pearl River, MS with surface wind speeds around 100 knots (115 mph). Over a 24-h period, sections of New Orleans near the intersection of Lake Pontchartrain and the IHNC received over 14 inches of rainfall. This rainfall was approximately 20% of the total volume of water that flooded the New Orleans metropolitan area. The east and south-facing levees of New Orleans East, St. Bernard, and Plaquemines Parishes absorbed the brunt of the storm, experiencing surges and waves significantly beyond their design levels. Overtopping was common and, depending on location, persisted for hours.

Literally, all of the gauging instruments to measure water conditions were destroyed by Katrina. Other than high-water marks, and the devastation, there were few measurements to confirm the actual water-level time histories
resulting from the storm. The IPET used the ADCIRC model (Luettich et al., 1992) with a very high-resolution computational grid to model the storm and predict the time history of the surge levels that occurred at different locations around the region. Figure 3 shows the maximum surge levels predicted for Katrina. The high-water marks were used to confirm the accuracy of the model results, and in most cases, they agree to within a foot or two. Surge levels ranged from about 10–12 ft along the south shore of Lake Pontchartrain to 20 ft along the Plaquemines Levees. Even enclosed areas such as the IHNC experienced water levels above 14 ft, not including waves.

Winds from Katrina generated a record-wave environment. Again, the lack of measurements caused IPET to model the wind-generated waves to determine the conditions created by the storm. IPET applied a nested approach that used the Wave Analysis Model (https://journals.ametsoc.org/view/journals/phoc/18/12/1520-0485_1988_018_1775_twmtgo_2_0_co_2.xml) to generate wind-wave fields for the entire Gulf and the Steady State Spectral Wave model (https://apps.dtic.mil/sti/pdfs/ADA588527.pdf) to model nearshore waves in and around New Orleans. The most significant finding was that the waves along the east side of New Orleans levees were ocean-generated waves, with wave periods in the 15–16 s range, much more capable of overtopping structures than the design-assumed local wind waves with periods of 5–6 s.

Figure 4 presents a simple comparison of the surge generated by Katrina with that used for the HPS design. Note that the surge in Lake Pontchartrain was roughly the same as the design levels assumed for the HPS. On
the east side of New Orleans, Katrina-generated surges were significantly greater than the design criteria, ranging from 17 to 20 ft compared to the 12–14 ft assumed in the HPS design. Wave conditions assumed for the SPH design and those estimated from Katrina have a similar relationship. With the exception of Plaquemines Parish, Katrina-generated wave heights were not much different from the design assumptions. In Plaquemines Parish, Katrina did generate significantly higher waves. Wave periods were a different story. In Lake Pontchartrain, the period of Katrina-generated waves was similar to the design assumptions, in the 6–7-s range. Along the St. Bernard and Plaquemines Levees, however, Katrina generated 14–16-s period waves, approximately three times that assumed for the design wave periods. This is very significant in that the longer period waves were largely generated in the Gulf and propagated to shore and have much greater potential for runup and overtopping of coastal structures.

**Performance of the HPS in place when Katrina struck**

Figure 5 shows the locations of the most severe damage to the HPS. Over 220 miles of the protective structures were damaged by Katrina-generated surges and waves, as well as 34 of 71 pumping stations. Approximately 41 miles of structures were judged to be severely damaged. Initially, there were a total of 50 major breaches identified, causing a dramatic reduction in protective elevation and losing the ability to prevent the inflow of external water. Of the 50 major breaches, four were caused by foundation-induced failures and the remainder from a combination of overtopping and scour. Three of the four foundation breaches occurred in the outfall canals and one in the IHNC. I-wall structures were particularly vulnerable as were levee sections created from hydraulic fill, and...
Transitions were either elevation or strength differences occurred from changes in structure type or capability. Transitions between types of flood protection structures were also vulnerable, especially where the transition included a significant change in elevation between the structures.

The storm surge and waves first attacked the Plaquemines Levees well before Katrina’s landfall, causing significant overtopping and erosion before dawn. The Lake Borgne Levees were soon hit with similar conditions, and eventually, both Plaquemines and St. Bernard Levees would be overtopped by both high surge and high, long-period waves. The persistent east-to-west winds had also built up a significant surge level at the convergence of the Gulf Inter-Coastal Water Way (GIWW) and the IHNC. Wind-generated waves reached at least 4 ft in the IHNC, contributing to very high water and dynamic loading on structures. The surge and waves had a devastating effect on the sections of the levees along the GIWW and MRGO that were constructed with materials dredged from the adjacent channels using hydraulic fill. Even though the levees were capped with clay, they were no match for the energetic environment they experienced. The overtopping waves created very high-flow velocities down the back sides of the levees, reaching 10–15 ft/s. These velocities were two to three times those experienced on the waterside of the levees (4–6 ft/s). The potential for erosion being related to the cube of velocity, it is no wonder that the back sides of the levees, especially where they were comprised of erodible materials, was scoured away leading to, in many cases, complete breaching.

Early in the morning of 30 August, a section of I-wall along the Lower Ninth Ward breached. Underlain by the same marsh deposits and clay as the 17th Street Canal, the rising water and waves caused the wall to deflect enough to open a crack that created a direct avenue for high water pressures to reach the foundation. The weak clays underneath, now only reacting with the mass of soil on the protected side of the levee, could not
withstand the force and displaced backward, a process that would repeat itself on the 17th Street Canal. The water levels in the IHNC were approximately 9.5–10.5 ft when the foundation failure occurred. No overtopping had occurred and the design water elevations had not been reached at either breach location. Note that the factor of safety (1.3) for the canal structures was irrelevant because the failure mode that caused the breaching (deflection of the I-wall and hydrostatic pressure reaching the weak clay layer) had not been considered in the design process. See Figure 6 for a summary of major structural breaches on the outfall canals and IHNC and resulting in maximum flood depths.

Not long after the 17th Street Canal breach started, the south breach on the London Avenue Canal was initiated. As in the case of the 17th Street Canal and IHNC failures, water elevations below the design levels caused a crack to form on the waterside of the floodwall and allowed high pressures to be introduced directly into the foundation materials of the levee, this time relic beach sand. The porous sand quickly conveyed the pressure under the levee and caused significant uplift on the protected side. It also is likely that significant subsurface erosion occurred under the levee and caused a blowout on the protected side through which much sand and water flowed, decreasing the support for the levee and floodwall and causing a narrow failure. The north breach on the London Avenue Canal suffered a similar fate around the same time. This breach was much wider and involved less erosion, failure being caused by a loss of stability from the uplift. Water levels in the London Avenue Canal reached about 9 ft, below the design levels and well below the height of the I-walls.
During mid-morning, the I-walls along the IHNC were overtopped and erosion behind the wall reduced their stability, causing three separate sections to fail. There was also a levee failure along the west side of the IHNC that caused additional flooding into the Upper Ninth Ward. There were no T-wall failures with the exception of a small section in southern Plaquemines Parish.

The flooding resulting from the overtopping and breaching was catastrophic, with almost 80% of New Orleans was inundated. Pumping stations were for the most part not operating due to prior evacuation of operators, loss of power, or loss of clean cooling water for the pumps. The pump stations in New Orleans were not designed to operate during major storms. A few stations, notably in Orleans Parish, may have continued to operate if the flooding had not been so extensive. Had the pumps been able to operate, the extent of flooding may not have been impacted greatly, but the duration of flooding could have been significantly reduced. Using temporary pumps and slowly bringing the permanent pumps on line after Katrina required 53 days to unwater the city.

The consequences of the flooding were enormous, dwarfing the losses from previous disasters. Approximately 78% of the direct property losses from flooding were experienced by residential property. This is in part due to their location in some of the lowest elevations of the city. When coupled with the approximately $4.5–$5.6 billion in public infrastructure damages, the total direct property losses for New Orleans alone reach nearly $25 billion.

Loss of life in the Gulf region was staggering, with almost 1,600 fatalities accounted for and hundreds more missing and presumed dead. The New Orleans metropolitan area suffered over 1,000 storm-related deaths. The majority of deaths in Orleans Parish were caused by drowning and preexisting medical conditions. The deaths in St. Bernard Parish were primarily attributed to drowning. Loss of life was highly and inversely correlated with evacuation. Of those who remained, the elderly were particularly vulnerable with three of every four persons who died being over 60 years old. In fact, the flooding in general was disproportionately cruel to the poor, the elderly, and the disabled, groups least likely to be able to care for themselves.

The flooding and resultant prolonged loss of services caused what became more of a migration than an evacuation, casting long shadows on the region’s ability to recover. Only 8 of 73 neighborhoods did not flood, while 34
were completely inundated. Residential property losses were a staggering 78% of the total. Commercial property losses were approximately 11% of the total, while industrial losses were under 2%. Clearly, the people of New Orleans suffered the most direct losses, and these losses represent perhaps the greatest challenge to recovery, not just in terms of property damages. The extensive flooding caused a breakdown in the area’s social and cultural structure, significantly complicating recovery and redevelopment. Critical social institutions such as schools and hospitals were very slow to reopen.

PART 3: KATRINA RISK AND RELIABILITY ASSESSMENT

To gain a true systems perspective of what happened during Katrina and the potential for reducing the likelihood of large losses in the future required a different type of analysis. One that allowed a broad look at the geographically distributed infrastructure system associated with New Orleans within the context of the complex threat represented by the large variety of hurricane events possible for the region. This required a comprehensive risk and reliability analysis, one of the first attempts for such a complex infrastructure system and equally complex hazard. Risk in this context is the potential for loss (expected losses in terms of economic and/or life) and includes the likelihood of the conditions and forces (by location) generated by the hazard, the performance of structures and measures in place to deal with the forces, the likelihood of level and character of flooding, and the expected losses from that flooding. A key aspect of this is fabricating a hazard definition relevant to the future, not just the past so that alternative approaches to dealing with the hazard can be evaluated effectively.

Risk and reliability analysis approach

The following discussion provides a general overview of the risk assessment performed to determine the vulnerability of New Orleans and vicinity to flooding from hurricanes and to estimate the difference in risk, by location, for the pre-Katrina HPS conditions, the post-Katrina (June 2007) HPS conditions, and ultimately the performance of the planned Hurricane and Storm Damage Risk Reduction System (HSDRRSS) that was completed in 2011. The risk assessment process, its application with respect to the pre-Katrina (2005) and post-Katrina HPS (2007), and a presentation and discussion of results are presented in detail in the IPET Report, Vol. VIII, Engineering and Operational Risk and Reliability Analysis. The analysis of the risk given the construction of the HSDRRS and a comparison of that scenario to the risk existing in 2005 and 2007 are provided in the IPET Supplemental Report, ‘A General Description of Vulnerability to Flooding and Risk for New Orleans and Vicinity: Past, Present, and Future’ (Supplemental Report of the Interagency Performance Evaluation Task Force, 2009).

The risk information provided is focused on hurricanes as the primary source. The surge and wave conditions generated by hurricanes are the principal hazard, although rainfall amounts are also factored into the flood analysis. The reliability or performance of the many components of the HPSs is examined through the individual and collective performance of levees, walls, gates and closures, transitions, and pumping stations. The chance of flooding is estimated based on these factors and the rainfall associated with hurricanes. Losses are estimated based on estimated depths of flooding at different frequencies of occurrence. This analysis did not consider flooding resulting from high flows on the Mississippi River not directly related to hurricane surge.

It is important to note that this effort involved developing and applying a prototype method to estimate risk for a large, complex, and geographically distributed system. In many respects, this was a first effort of its kind. The goal of assessing risk is to facilitate rational decision-making. The decisions that risk assessment supports include:

- Policy-level decisions on how best to expend resources to minimize the risk of flooding from hurricanes.
- Planning-level decisions concerning the relative vulnerability of different areas to focus efforts on areas of greatest risk.
• Understanding the sources of risk to include the least capable structures and the most exposed population or assets.
• Planning-level decisions concerning the value of different alternatives for reducing the chance of flooding and losses.
• Insights for design-level decisions on the location and character of structures where to put gates or raise walls.
• Communicating risk to the public, supporting personal decisions on how to prepare for and respond to the possibility of flooding from hurricanes.

The IPET assessment examined risk for the HPS as it existed before Katrina (2005) and for the short-term repairs and upgrades to the HPS as it existed in June 2007 (HSDRRS Design Guidelines 2007). A follow-on assessment was accomplished for the ‘as planned’ HSDRRS Design Guidelines (2012) to both estimate its ability to reduce risk and for the evaluation of additional structural resilience measures such as armoring the levee surfaces.

Risk assessment for New Orleans and Southeast Louisiana provides a broad picture of the relative chance of a flooding in different areas and the losses that could occur as a result of flooding. Risk assessment in the current context is intended to support planning decisions. It is not intended to support engineering decisions. A risk assessment over a large, complex geography like New Orleans requires many generalizations and assumptions, compared to the details of engineering design. Nonetheless, while risk assessment does not generate design information, it does inform design by defining hazards and suggesting alternative approaches to providing protection. It also provides a means to broadly examine the effectiveness of new design approaches and criteria by factoring in the improvements in system performance through the characterization of the fragility of individual system elements.

Risk assessment methodology

Figure 6 shows the general risk assessment methodology used by IPET. The risk assessment methodology consisted of four steps. First defining the hazard, the forces that can ultimately cause flooding and losses. Second, defining system performance, how the individual structures and mitigation measures would respond to the hazard forces. Third, estimating the amount of flooding that would occur in individual areas. Fourth, examining consequences of flooding in terms of potential loss of life and loss of property.

The hazard is the event or condition with the potential for causing an undesirable consequence. In the present context, the hazard is surge and wave conditions caused by hurricanes; it is not the hurricane themselves. To assess the hazard, it is first necessary to identify the range, character, and frequency of hurricanes that may strike the southern Louisiana coast. IPET used state-of-the-art methods, including supercomputer models, to compute the surge and wave conditions that a wide variety of hurricanes would produce around New Orleans. This analysis led to estimates of the frequency of extreme surges and waves everywhere around the HPS. These estimates are for current climate conditions, and they do not project climate variations into the future. Figure 7 shows the peak surge elevations in feet with respect to the geodetic datum for the 500-year recurrence interval. Of particular importance is the complexity of the surge levels, demonstrating that only sophisticated analytical modeling could reveal this heterogeneity. The analysis resulted in the ability to look at surge and wave conditions for a wide range of recurrence intervals.

System performance is the response of the HPS or HSDRRS to the hazard, that is, to surge and wave conditions generated by the hurricanes. The system performance is assessed by modeling the reliability of the HPS or HSDRRS under loads generated by surge and wave. This leads to an estimate of the likelihood that the HPS or HSDRRS can withstand those loads and, correspondingly, to an estimate of the chance of flooding at various places across the city and region. This chance of flooding is sometimes called the vulnerability.
The reliability analysis starts with a detailed inventory of the engineering characteristics of every section and component of the HPS or HSDRRS. Then, the potential for overtopping and breaching is estimated for the spectrum of surge and wave conditions forecast in the hazard assessment. Combining the potential for overtopping and breaching with the frequencies of the corresponding hazards leads to an assessment of vulnerability to flooding from the spectrum of hurricanes that are possible for the region. The calculation also includes the chance of water entering through open gates and the amount of rainfall associated with hurricanes. Figure 8 shows an example of the resultant flood depth maps generated from these analyses.

The consequences of flooding, measured by the potential loss of life and property damage, are estimated by defining the distribution of people and structures within each sub-basin, the elevations of all structures and the surrounding land, and the value of the properties; and then by applying actuarial information and models to approximate losses. Consequences were estimated for different depths of flooding to determine expected losses across the spectrum of hurricanes. The results are summarized for three chances of occurrence, specifically, the 1/50-, 1/100-, and 1/500-year floods. For loss of life estimation, a sophisticated simulation model was developed using geospatial census databases and evacuation plans. For property damage estimation, historical data from flood control and coastal protection projects across the nation were used to develop flood-depth versus damage relationships.

Risk was calculated by combining the chance of undesirable consequences occurring with the magnitude of those consequences should they occur. This allowed an estimate of risk by area, based on the character of the HPS/HSDRRS and other measures that may influence who and what is exposed to flooding. Risk was calculated by multiplying the chance of flooding to a certain depth by the losses expected by the flooding. Losses can be expressed as potential loss of life or potential loss of property.

Fig. 7 | Spatial character of 0.2% (500-year) surge height from IPET modeling using the JPM-OS process with 76 hurricane data set (Source: IPET Final Report, Vol. VIII).
Risk was estimated for the HPS as it existed (1) prior to Katrina and (2) after the repair and rebuilding of the HPS through June 2007. Risk was also assessed for a projected 100-year HSDRRS design scheduled for 2011. The combined risk assessments for the three scenarios are presented in the IPET Supplemental Report ‘A General Description of Vulnerability to Flooding and Risk for New Orleans and Vicinity: Past, Present, and Future’ (Supplemental Report of the Interagency Performance Evaluation Task Force, 2009).

Figures 9 and 10, respectively, show the expected loss of life and loss of property (in terms of percentage of value) for the 1% or 100-year recurrence level for the 2007 (Repaired HPS) and 2011 (planned HSDRRS) scenarios. Since a principal purpose of the risk assessment was to determine how risk is changing with respect to the capabilities of the HPS, both the pre-Katrina and post-Katrina risks were estimated using the pre-Katrina distribution of population and property. The significant value of the HSDRRS is evident in the dramatic reduction of potential losses for both loss of life and loss of property.

**PART 4: KEY LESSONS LEARNED**

There is a more extensive list of lessons learned published in the IPET Report, Vol. I. The lessons presented below represent those that are deemed big picture issues that all flood protection and risk reduction efforts should consider.

**Correct elevations and reference datum are essential**

All hurricane and flood control protection structures should be designed, constructed, and maintained relative to an up-to-date local sea level reference datum. Areas experiencing variable subsidence, such as New Orleans, are likely to have systematic datum and elevation accuracy issues that need frequent attention. It is important to have
Fig. 9 | Expected loss of life for 1%, 100-year frequency flooding for pre-Katrina HPS and post-Katrina HSDRRS (Source: IPET Supplemental Report 1992).

Fig. 10 | Expected property losses as percent of value for 1%, 100-year frequency flooding for pre-Katrina HPS and post-Katrina HSDRRS (Source: IPET Supplemental Report 1992, Risk).
appropriate monitoring stations (for tide and subsidence) in place and associated up-to-date guidelines for the application of this information to existing and new projects.

**Systems planning and design methods are needed**

Planning and design methodologies need to allow for the examination of system-wide performance. It is obvious from the IPET analysis that the piecemeal development of the New Orleans HPS provided a system in name only. This is especially true of the sections that have not been completed, transitions between types of protection that differ in capability (thereby representing weak points), and differences in the relative levels of reliability that created areas with a greater likelihood of failure. The system-based approach should have a time dimension to allow consideration of the potential changes in requirements or conditions over the life of the project and to examine approaches to build in adaptive features and capabilities. Subsidence, changing population demographics, and the changing patterns of hurricane intensity and frequency are obvious examples of the time-dependent challenges all projects face. All components that contribute to the performance of the overall system must be treated as an integral part of the system; pump stations are one example in New Orleans.

**Frequent update to guidance and review of projects is critical**

Design methods and designs need frequent review to determine whether they represent best practices and knowledge. Designs in coastal flood damage reduction projects need to include the concepts of resilience, adaptation, and redundancy to accommodate unanticipated conditions or structural behaviors.

**Modern hazard characterization approaches are essential**

More comprehensive probabilistic methods that consider a broader variety of storm characteristics and storm-generated conditions should be used as a basis for planning and design. The joint probability method–optimal sampling approach described in Volume VIII is recommended as a technically credible approach. Meteorological designations such as the Saffir–Simpson scale by themselves are not adequate to characterize the distributed surge and wave conditions that an HPS will face. The traditional methods of assessing the frequency of occurrence of hurricanes, dependent primarily on historical data, are too simplistic to capture important characteristics of the hurricane hazard such as time- and space-dependent storm intensity and track patterns. The wave and storm surge modeling (using the best available physics-based spatial prediction models) provided considerable insight into how water surrounding such a complex physical system responds to an equally complex hurricane wind system. It is the surge and wave environment that constitutes the hazard, not the meteorological event. Resolution of wave conditions and wave contributions to surge is a critical element in the estimation of design levels of structures in coastal areas.

The use of central pressure deficit as a metric is not adequate to characterize the storm surge potential of a hurricane. Other factors such as storm size (radius to maximum winds), coastal geometry, coastal bathymetry, and storm path are essential elements to characterize surge levels at a location. Given these additional factors, IPET estimated Katrina recurrence interval to be approximately 400 years.

**Designs need to better consider unknowns**

The design approaches taken for the outfall canals were not conservative enough to deal with the unknowns; in this case, the excessive floodwall deflection was not considered in the design. Floodwall design methods need to consider a broader spectrum of possible behaviors, and resilience to overtopping should be considered as a fundamental performance characteristic. Research is needed to understand the full performance limits of structures and to discover new approaches for creating adaptive designs. Design methods and assumptions need continuous
review and update. Factors of safety are irrelevant if the appropriate failure mode is not included in developing that metric. This was the case for the failure of the outfall canal I-walls.

**Planning methods should facilitate the examination of system-wide performance**

In addition, HPS should be deliberately designed and built as integrated systems to enhance reliability and provide consistency in levels of protection. Components such as the interior drainage and pumping need to be an integral part of the system because of the important role they can play in limiting the amount and duration of flooding. Resilience in pumping capacity is especially important. IPET analyses showed that the pumping systems, if operable, could have significantly reduced the total flooding and its duration.

**Resilience to catastrophic breaching can provide huge benefits in reduced loss of life and property**

It is clear that a resilient HPS can provide enormous advantages. Resilience, in this case, refers to the ability to withstand, without catastrophic failure, forces and conditions beyond those intended or assumed in the design. For IPET purposes, resilience refers to the ability to withstand higher than designed water levels and overtopping without breaching. As demonstrated in this analysis of Katrina, approximately two-thirds of flooding and half of the losses were the result of breaching, i.e., the significant loss of protective elevation in structures. While overtopping alone from Katrina would have created dramatic flooding and losses, the difference is staggering in many regards. Reductions in losses of life, property, and infrastructure; associated reductions in the displacement of individuals, families, and the workforce, coupled with reduced disruption to businesses and social and cultural networks and institutions, would have a dramatic impact on the ability of a community and region to recover.

Even with the structures at lower than desired elevations, if they had been robust enough to not fail catastrophically, the loss of life and loss of property could have been half of what actually occurred.

**System-based planning should include all aspects of hurricane response**

A broad and system-based planning capability can increase the effectiveness of integrating evacuation, recovery, and reconstruction aspects into the HPS. In particular, a risk-based approach can provide an effective means to examine approaches to manage both the probability of an adverse event and the exposure to losses as well as the consequences. The spatial analysis of consequences and the ability to relate consequences to physical performance are powerful tools for making difficult decisions concerning hurricane protection.

**Risk assessment provides a viable means to understand the relative vulnerability of protected areas**

The combination of the likelihood of stormwater levels (surge and waves), the likelihood of structural failure at different water levels and dynamic loadings, the likelihood of flooding based on the expected performance of the system, and the consequences of that flooding provides a comprehensive information set on residual risk. This information defines the relative vulnerability of each area as well as the sources of that vulnerability.

**It is critical to estimate the inherent uncertainty in the individual components of the risk assessment and in the final risk products**

Risk assessment combines a variety of data types and incorporates numerous models. Each of these has an inherent degree of uncertainty, in their values, in the ability of the models to replicate the processes they represent, and in the end products themselves. The level of uncertainty must be estimated and incorporated in an overall uncertainty analysis to understand the variance associated with the risk assessment results. This provides some measure of the confidence one can have in using the risk data. The uncertainty quantification accomplished as a component of the risk and reliability analysis demonstrated that 71% of the overall epistemic uncertainty could be attributed to the hazard estimation process and 29% to structural performance estimation.
Vulnerability and risk are key to assessing the value of options

Having a quantitative estimate of vulnerability and risk is extremely important information for understanding both the current situation and the relative value of alternative risk reduction measures for the future. Both the public at large and public officials at all levels benefit by having a common situational awareness of residual risk. The common picture provides a valuable focus on communication for current risk reduction measures as well as those that should be examined for the future.

There is always risk

No amount of effort will eliminate risk. It is critical to monitor and communicate the residual risk so that individuals and public officials can make effective decisions to manage it. Communicating risk is perhaps the most difficult task of them all. Risk assessments for large and complex systems typically have large uncertainties associated with the results. It is important to understand that these uncertainties are not the result of the risk assessment, but result from the data and models used in the assessment process, which are largely the same fundamental tools and inputs used for non-probabilistic deterministic analyses. The difference is that the deterministic approach does not give the investigator knowledge of either the size or sources of uncertainty. The probabilistic approach provides the statistically most likely values for results, which is the best estimate given knowledge available. It also provides an understanding of the sources of greatest uncertainty that allows subsequent development to focus on reducing the largest sources.

DATA AVAILABILITY STATEMENT

All data referenced or discussed in this paper are available within public domain documents, principally the IPET reports, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, Volumes I–IX and a Supplemental Report on the Vulnerability to Flooding and Risk for New Orleans and Vicinity, available on the at https://biotech.law.lsu.edu/katrina/ipet/ipet.html.

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