Lessons Learned from Analysis of the New Orleans Hurricane Protection System

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ABSTRACT

This report, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, is the final report of a series concerning the in-depth analysis of the New Orleans and Southeast Louisiana Hurricane Protection System conducted by the Interagency Performance Evaluation Task Force (IPET). The IPET was established by the Chief of Engineers determine the facts concerning to the performance of the hurricane protection system in New Orleans and Southeast Louisiana during Hurricane Katrina. The analyses conducted by the IPET and the information presented in this report are designed to answer five principal questions that comprised the IPET mission:

• The System: What were the pre-Katrina characteristics of the hurricane protection system (HPS) components; how did they compare to the original design intent?

• The Storm: What was the surge and wave environment created by Katrina and the forces incident on the levees and floodwalls?

• The Performance: How did the levees and floodwalls perform, what insights can be gained for the effective repair of the system, and what is the residual capability of the undamaged portions? What was the performance of the interior drainage system and pump stations and their role in flooding and unwatering of the area?

• The Consequences: What were the societal-related consequences of the flooding from Katrina to include economic, life and safety, environmental, and historical and cultural losses?

• The Risk: What were the risk and reliability of the hurricane protection system prior to Katrina, and what will they be following the planned repairs and improvements?

The knowledge gained in answering these questions 1) was applied directly to the design and construction of immediate and longer term repairs, 2) was used to assess the integrity of and plan remedial actions for the sections of the hurricane protection system not severely damaged, 3) is being used in the ongoing efforts to enhance the capabilities of the system to achieve 100-year levels of protection, and 4) provide analytical methods and a body of knowledge to assist in planning and designing more effective protection measures in the future. The IPET analytical tools and information bases are being transitioned to the Louisiana Coastal Protection and Restoration Study (LaCPR), to assist in developing effective approaches for higher levels of protection.

The nine volumes of the final report provide a detailed documentation of a broad, multidisciplinary analysis of the hurricane protection system and its performance during Hurricane Katrina. The frequent professional interaction and review comments provided by the American Society of Civil Engineers (ASCE) External Review Panel and the strategic oversight of the National Research Council (NRC) Committee on New Orleans Regional Hurricane Protection Projects have made substantial contributions to the conduct of the analysis and development of the results described in this report. This volume, Volume I, Executive Summary and Overview, provides an overview of the IPET and its efforts, a synopsis of the performance of the hurricane protection system during Katrina and a summary of the principal findings and lessons learned. All are described in more detail in Volumes II-IX.

Since the hurricane protection system is only designed to manage flooding in the metropolitan New Orleans basin, wind-based consequences and any direct consequences exterior to the hurricane protection system are excluded from this report. In addition, the IPET did not examine organizational and jurisdictional issues that impacted the effectiveness of the physical hurricane protection system. These issues are being examined by a separate team in the Hurricane Performance Decision Chronology Study whose results will be reported separately.

This report and all other IPET-produced documents are available on the IPET Web site, *https://IPET.wes.army.mil.*

1.0 HURRICANE KATRINA AND ITS IMPACT

In 2005 the world watched Hurricanes Katrina, Rita, and Wilma devastate portions of the Gulf Coast of Louisiana and Mississippi. The Corps of Engineers, in conjunction with other federal, state, and local partners, mounted an unprecedented, multi-faceted effort to assist in the recovery and rebuilding of the areas affected by these massive storms. The devastation from Hurricane Katrina in New Orleans and vicinity was particularly unprecedented. Because of the extent of the damage to the HPS itself and the consequences of the subsequent flooding, it was imperative to understand what happened and why. Only through this knowledge could the levees and floodwalls be repaired and rebuilt to provide more effective protection in the future. This report provides a detailed accounting of the IPET work to determine why the hurricane protection measures performed as they did and how to provide more effective protection for the future. The area of principal study is shown in Figure 1 and represents the bulk of New Orleans and Southeast Louisiana. This overview includes a brief historical perspective of hurricane protection in New Orleans, a description of the IPET organization and its activities, and an overview of what happened during Katrina in the context of the five IPET mission questions and the analyses accomplished to answer those questions.

2.0 HISTORICAL PERSPECTIVE

Geologic History and Setting: The following is a brief overview of the geologic setting in New Orleans and its influence on the HPS. A more detailed summary of the geologic history of the New Orleans region and the implications of the geologic conditions on the HPS is provided in Appendix I-5. There is also significant discussion of geologic issues on the HPS in Volume III and extensive information on geology presented in Volume V.



Figure 1. Principal area of analysis.

The geologic history of the New Orleans area significantly influences the engineering properties of the foundation soils beneath the levees. Geologic and engineering data gathered from the different levee failures identify a spatially complex geomorphic landscape, caused by Holocene sea level rise, development of different Mississippi River delta lobes, and the distributary channels associated with delta development. Overlying the Pleistocene surface beneath the New Orleans area are predominantly fine-grained, shallow water depositional environments and related sediments associated with bay sound (or estuarine), nearshore-gulf, sandy beach, lacustrine, interdistributary, and paludal (marsh and swamp) environments. These environments define the New Orleans area

history during the Holocene, and comprise the levee foundation for the different failure areas. A relict barrier beach ridge is present in the subsurface along the southern shore of Lake Pontchartrain. This relict beach blocked the filling of the lake with fluvial-deltaic sediments, impacted the supply and texture of sediment being deposited by advancing distributary channels, and influenced the engineering properties of these soils. Marsh and swamp soils beneath the failure area at the 17th Street Canal are much thicker than those beneath the London Avenue Canal because of the influence of the beach complex, and are thickest in the Inner Harbor Navigation Canal area.

Additionally, man's activities in New Orleans during historic time contributed to the spatial complexity of this area and affected the engineering properties of the foundation soils. Man's activities included construction of drainage and navigation canals, pumping groundwater drainage, hydraulic filling of the Lake Pontchartrain lake front, and construction of levees to prevent the river from flooding lowlying areas. Man's activities, combined with the geologic setting and subsidence in this region are responsible for the unique landscape that created the New Orleans area. Historic settlement and subsidence in the New Orleans area has been most severe on the back barrier side of the relic Pine Island Beach (along the south shore of Lake Pontchartrain).

Subsidence did not contribute materially to the foundation failures of the I-wall/levee structures on the outfall canals. However, subsidence has impacted the datum of many of the benchmarks in the city upon which engineering decisions and design were based and affected levee and floodwall height and the level of flood protection. This did influence the amount of overtopping that occurred, which contributed to erosion behind floodwalls and on the back sides of levees that eventually led to their breaching.

Geographic History and Setting: Located in the low-lying Mississippi River delta in Louisiana, large portions of New Orleans lie near or below sea level, which has posed

complex flood management problems since the city's founding in 1718. Historically, the greatest natural threat posed to residents and property in the New Orleans area has been from hurricane-induced storm surges, waves, and rainfall. Until the early twentieth century, construction was largely limited to the slightly higher ground along old natural river levees and bayous, since much of the rest of the land was low, swampy, and subject to frequent flooding. In 1899, the Sewerage and Water Board of New Orleans was created; it remains responsible for draining the city. The topography of New Orleans makes drainage a major challenge, with the same natural and artificial levees designed to keep water out having the unintended effect of confining rainwater and sewage in the city. This led to perhaps one of the most sophisticated and comprehensive drainage systems in the world.

The drainage system created by the Sewerage and Water Board allowed the city to expand outward from the higher ground close to the river into the lower elevations towards and near Lake Pontchartrain. The development of these areas in the early 1900s caused the water table to drop dramatically, which in turn enabled development of additional new neighborhoods such as Lakeview. In addition to the lakeside portions of the city, development in the other areas surrounding the metropolitan area led to a seven-fold total increase in urban acreage during the twentieth century.

The Sewerage and Water Board today drains over 61,000 acres in New Orleans and neighboring Jefferson Parish of almost 13 billion cu ft (cubic feet) of water per year. The drainage system includes 90 miles of covered canals, 82 miles of open canals, and a multitude of pumping stations. However, pumping of groundwater from underneath the city has accelerated the subsidence that the area was already prone to because of its natural alluvial floodplain geology. The subsidence increases the flood risk, should the levees be breached or precipitation exceed pumping capacity, because the New Orleans bowl is becoming deeper as time and subsidence progress. The geographic location of New Orleans makes the city particularly vulnerable to hurricanes. Fortunately, New Orleans has been impacted by only a few large storms. New Orleans was hit by major storms in the 1909 and 1915 Atlantic hurricane seasons. Much of the city flooded in September 1947 due to the Fort Lauderdale Hurricane. The next major threat came in the 1960s with Hurricanes Betsy and Camille.

In 1965 the city was severely damaged by Hurricane Betsy. The catastrophic flooding of the city's Lower 9th Ward, 75 fatalities and substantial loss of property, made Betsy the nation's first billion dollar storm. Although Camille came close to New Orleans, it had much more impact in Mississippi and caused relatively minor damage in New Orleans proper. There has not been severe flooding in New Orleans from a hurricane since Betsy. The city did experience severe flooding May 8, 1995, when heavy rains suddenly dumped over 12 in. (inches) of water on New Orleans in a short time period, overwhelming the pumps. Betsy was the stimulus for the Flood Control Act of 1965 which was the initial authorization for the HPS in place today.

Hurricane Protection System History: Over time, three hurricane protection projects have been designed and partially constructed in New Orleans and the Southeast Louisiana region: Lake Pontchartrain and Vicinity Project, the West Bank and Vicinity Project, and the New Orleans Venice Project. The Lake to Pontchartrain and Vicinity Hurricane Project is discussed in more detail below because of its central role in Hurricane Katrina. All of these projects are discussed in detail in Volume III of this report.

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

SPH developed for the Corps by the Weather Bureau (now the National Weather Service). 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. It also precludes consideration of the dramatic impact of large storms in generating surge and waves long before they reach landfall. For the initial definition of the SPH used in design of the New Orleans hurricane protection structures, hurricanes were considered that occurred during the period 1900 to 1956. Central Pressure Index (CPI) was the primary intensity criterion and the 1-percent recurrence CPI (100-year) was chosen for the initial SPH definition. When the additional consideration of the likelihood of a storm of that size hitting the area near New Orleans is added, it was estimated to be equivalent a 200- to 300-year recurrence event. The SPH was intended to represent the most severe meteorological conditions considered "reasonably characteristic" for the region. A maximum wind speed was also associated with the SPH: for Lake Pontchartrain and Vicinity, it was assumed to be 100 miles per 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, 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 continued to use the original SPH criteria through the time of Hurricane Katrina.

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 percent of the costs and the state and local interests paying 30 percent. The local interests included the State of Louisiana Department of Transportation and Development, the 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 operation and maintenance of the levees and flood control structures. This was one of the first major costsharing projects for the Corps of Engineers.

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 lake front, concrete floodwalls along the 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 lake front. 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 exact treatment of the outfall canals was not resolved. Based on this study, the Corps recommended shifting to the "high level plan" originally considered in the early 1960s. Follow-on efforts examined the use of butterfly surge gates and pump stations at the lake ends of the canals and the use of parallel protection levees and floodwalls along the length of the canals as the sole protection measure. 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 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.

construction of the HPS The was accomplished in many separate steps over a long period of time. The first major structures constructed were the levee and floodwall structures within the IHNC (late 1960s and early 1970s). The levees and structures along the east side of St. Bernard Parish from Bayou Bienvenue to Bayou Dupre were built in the same time frame with periodic enhancements. The initial levee lifts were placed by hydraulic fill from 1967 to 1970, and subsequent lifts were added from 1972 to 1987. Sheet-pile closures at bayous and pipelines were placed in 1992. Construction of the floodwalls along the outfall canals occurred from 1993 to 1999. There were flood-proof bridges and 4 fronting 10 protections (associated with pump plants along the canals) also included in the effort. At the time of Katrina, nine of the bridges had been constructed. The fronting protection for the London Avenue (number 4) and 17th Street (number 6) pump stations were completed prior to Katrina. The protection for Pump Station No. 7 on Orleans Canal and Pump Station No. 3 on London Avenue Canal remained to be done. The lack of the fronting protection for Pump Station No. 7 left a section of legacy wall significantly lower than the adjacent floodwalls, providing a route for water to enter the city without overtopping adjacent floodwalls. This omission left a weak link which compromised the local level of flood protection. Ironically, work on this area was terminated due to lack of funding.

Some components of the system were not scheduled to be completed until 2015, primarily the West Bank and Vicinity Project. At no time has the entire New Orleans and Vicinity area had a reasonably uniform level of protection around its perimeter. At no time has any individual parish or basin had 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 percent complete Orleans in Parish, 70 percent complete in Jefferson Parish, 90 percent complete in the Chalmette area, and 60 percent complete in St. Charles Parish. In 2002, a pre-feasibility study on whether to strengthen hurricane protection along the Louisiana coast was completed. A full feasibility study was estimated to take 5 years to complete. A major Emergency Response Exercise in July 2004 used the hypothetical Hurricane Pam to examine the ramifications of a storm much like Katrina. The results projected losses in excess of what happened in Katrina, including massive overtopping and breaching of levees.

The history of this HPS has been one of continuous incompleteness. This situation was a product of the overall 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 affordability of protection appeared to be a major issue between local and federal authorities.

3.0 PRINCIPAL FINDINGS AND LESSONS LEARNED

This section presents the principal findings and lessons learned from the IPET efforts. The information here represents a big-picture perspective of an extensive amount of work and does not attempt to include detail or supporting technical data or arguments. More detailed findings and lessons learned are provided in each volume of the IPET report along with extensive supporting information on the analyses upon which they were based.

3.1 PRINCIPAL FINDINGS

3.1.1 The System

Impact of Datum Misinterpretation: Spatial and temporal variations of 0.2 to 3 ft were found

between the geodetic datum (land elevation reference) and local mean sea level (water level reference datum, LMSL). Some flood control structures in the region were authorized and designed relative to a water level datum (mean sea level), but constructed relative to the geodetic vertical datum incorrectly assumed to be equivalent to the water level datum. This resulted, in the case of the outfall canals, in structures built approximately 1 to 2 ft below the intended elevation. Updating of the reference elevation points for the region, although underway, was not completed. The use of outof-date reference elevation points left decision makers without an accurate understanding of the actual elevations of the hurricane protection structures.

Impact of Subsidence: The variable and considerable subsidence in the New Orleans area was reflected in the performance of the system in Katrina. It was well known that the New Orleans area experiences significant subsidence, and structures such as levees had some increases in their initial design elevations as compensation. The amount of elevation loss for critical hurricane protection structures was not well quantified prior to Katrina. The IHNC structures, for example, are more than 2 ft below their intended design elevations, mostly from subsidence over the 35-year life of the project. This resulted in a significant loss of protection capability in areas such as the IHNC. The lack of knowledge of accurate elevations was directly tied to the incomplete update of the geodetic reference datum and LMSL.

The hurricane protection system consists predominantly of levees and levees with cantilevered I-type floodwalls. In locations where the right of way did not permit these options and at gated closure structures, there are segments of T-walls. T-walls are inverted "T" shaped concrete structures supported on pre-cast prestressed concrete or steel H-piles. As with Iwalls, a continuous steel sheet-pile wall is embedded in the bottom of the above ground concrete wall to reduce seepage under the structure. The vast majority of the total miles of structures were conventional levees, the majority of floodwalls were I-wall structures with selected areas, specifically at transitions to major structures such as pumping plants and gated structures, having T-walls.

All of the structures are constructed on weak and compressible soils. Stability and settlement of structures are generally critical design issues. The geology of the area was relatively well known and borings taken were reasonably adequate for characterizing the variety of conditions in the area, but the spacing could miss local anomalies in soil type and strength. See Appendix I-5 and Volume V for more details on the geology of the area and its impact on performance.

The majority of the structures in the HPS were generally built as designed, and design approaches were consistent with local practice. A number of samples were taken of materials used in the construction of the structures, particularly concrete from the floodwalls and steel from sheet piles. These samples were tested by independent laboratories and all test results conformed to accepted standards. Sheet-pile lengths were confirmed by physically pulling them from the ground.

The levee and I-wall structure designs along the 17th Street and London Avenue Outfall Canals and for a portion of the Inner Harbor Navigation Canal (IHNC) were inadequate. Several factors significantly impacted the performance of these structures during Katrina. The 17th Street Canal structures had the most significant issues. First, the foundation soil strengths were derived from widely spaced borings and at times using average values that do not capture the high variability inherent in this type of geology. Second, an assumption of uniform shear strengths for soils, based on the greater strengths under the centerline of the levee, beneath the 17th Street Canal levee and floodwall resulted in an overestimation of the subsurface strength at the levee toe. Third, the shear strength of the clay soils under the 17th Street Canal levee and floodwall assumed for design were higher than warranted from the measured data available at the time. These same soil strength assumptions were not made in other

sections of the system where more conservative strength values were used.

The levee and I-wall designs for the outfall canals and IHNC did not consider deflection of the I-wall to the extent that hydrostatic pressure would reach to the base of the sheet piles. This deflection and pressure basically split the levee into two pieces resulting in the protected side attempting to resist the forces for which the entire structure was designed. This played a major role in all four of the I-wall foundation failures. At London Avenue, the deflections provided a direct pathway for the high hydrostatic pressures for the elevated flood waters in the canals to enter the underlying porous relic beach sands and rapidly propagate to the back side of the levee. The pressure caused massive subsurface erosion of the sand under the levee as well as uplift on the protected half of the levee reducing its ability to resist the forces placed on the floodwall and sheet pile. This resulted in failure of the levee-floodwall system.

The original design criteria developed through use of the Standard Project Hurricane (SPH) in 1965 and used for the outfall canals in the late 1980s, was not representative of the hurricane hazard at the time of the design. The Standard Project Hurricane is defined as a hypothetical hurricane intended to represent the severe combination most of hurricane parameters that is reasonably characteristic of a specified region, excluding extremely rare combinations. In 1979 the National Oceanic and Atmospheric Administration (NOAA), updated the SPH definition by increasing the maximum sustained wind speed to 115 mph from the original 100 mph. The Corps chose to continue to use the original SPH definition developed for the Lake Pontchartrain and Vicinity Project for use on the outfall canals. The 1979 definition of the SPH was used for design of the West Bank and Vicinity protective structures.

The system did not perform as a system. The hurricane protection in New Orleans was designed and developed in a piecemeal fashion, resulting in inconsistent levels of protection. In addition to the use of different SPHs for individual projects, the designs for specific structures were influenced by the local conditions. For example, the levee and I-wall system designed for the Orleans Canal was more conservative than that for the 17th Street Canal. The Orleans Levee was broader and the I-wall freeboard (height above the levee crest) less. Soil strength assumptions were also more conservative, using the weaker values at the toe instead of the stronger values under the centerline as assumed for the 17th Street Levees.

Levee and I-walls were designed to provide protection up to the estimated water elevations for the SPH. They were not designed to withstand overtopping. There was no armoring or uniform use of erosion resistant soils in the levee sections. Levee materials ranged from highly resistant to scour to poorly resistant, resulting in significant variations in the protection levels afforded nearby areas. Similarly, I-walls were not protected against erosion if overtopping occurred. Given overtopping, evacuation was the only alternative to reduce exposure to flooding.

The system was not scheduled for completion until 2015. Sections that are not completed represent anomalously low areas, often accompanied by transitions from one type of structure to another. These ended up being weak spots, more vulnerable to overtopping and then erosion.

A majority of the pump stations are not part of the HPS and were not designed to provide capability during large storms. Most pump operators are routinely evacuated prior to hurricanes striking the area because of a lack of a safe haven to ride out the storm. Many of the larger pumping stations have mechanisms to prevent backflow through the pumps if they are not being operated. In some cases these require manual activation.

3.1.2The Storm

Katrina generated a storm surge and wave environment unparalleled in the history of New Orleans. Hurricane Katrina was a very large Category 3 storm when it passed the New

Orleans area on the morning of August 29th. Twenty-four hours earlier this storm had been the largest Category 5 and most intense (in terms of central pressure) storm on record within the northern Gulf of Mexico. During Katrina, at a location due east of the Mississippi River delta and just offshore in deep water, NOAA Buoy 42040 recorded the highest significant wave height ever measured in the Gulf of Mexico (55 ft). That observation matched the largest significant wave height ever recorded by a sensor within NOAA's buoy network, in any ocean. The large size of Katrina throughout its history, combined with the extreme waves generated during its most intense phase, enabled this storm to produce the largest storm surges that have ever been observed within the Gulf of Mexico (up to 28 feet in Mississippi), as determined from analyses of historical records.

Hurricane Katrina generated water levels that for much of the system significantly exceeded the design criteria. Katrina surge levels were up to 20 ft along the east side of the HPS, substantially higher, up to 5 or 6 ft, than the design levels for all areas along the eastern and southern portions of the HPS. The surge levels were roughly equivalent to design criteria along the southern shore of Lake Pontchartrain. Katrina-generated wave heights were approximately equal to the design criteria with the exception of Plaquemines Parish where Katrina-generated waves were significantly higher. Wave periods, however, especially along New Orleans East, St. Bernard, and Plaquemine Parishes, were approximately three times that estimated for the design criteria. The waves impacting the levees were 15- to 16-second-long period ocean storm waves that caused much more runup and overtopping than shorter period waves.

Local wave generation can contribute significantly to wave conditions within outfall and navigation canals in the New Orleans area. Local wave generation in the outfall canals during Katrina generated higher wave conditions over much of the length of the canal than were associated with the waves entering the canals from primary generation areas (either Lake Pontchartrain or the Gulf of Mexico). In the most extreme case examined here, wave heights of over 4 ft were generated within the GIWW/MRGO canal entering the IHNC from the east. The IHNC design assumed 1-ft waves. Detailed hydrodynamic analyses showed that dynamic forces were a significant portion (20 to 30 percent) of the total forces experienced by many of the levees and floodwalls. The dynamic forces considered in the original design were significantly less.

Overtopping by waves generated very high velocities over the crest and back sides of the levees, leading to a high potential for scour and erosion. Velocities from 10 to 15 ft/sec were calculated for the back sides of the levees along St. Bernard Parish, while the front sides of the levees experienced velocities of about one-third of those on the back side. Since erosion potential is related to the cube of velocities, the erosion potential on the back side of the levees was up to 27 times greater. The exception was in the east/west-trending leg of the GIWW near the I-10 Bridge, where wave energy and currents were almost parallel to the orientation of the levees and while overtopping occurred, the back side velocities were not severe. Examination of these levees that failed due to erosion determined that all failures were caused by erosion of the crest and back face.

The southeast trending leg of the Mississippi River Gulf Outlet (MRGO) had little influence on the water levels in the IHNC during Katrina. The relative size of the channel with respect to the very large flow area available when the marsh areas have been inundated by surge, make the amount of water conveyed through the channel a relatively small part of the total. During Katrina, MRGO was far from the "hurricane highway" moniker with which it has been branded. Model results show that this is the case for very large surge-generating storms in this area. This finding agrees with those of an independent study conducted for the State of Louisiana.

There was no evidence of significantly reduced surge levels and wave heights in areas adjacent to wetlands and marshes. Surge elevations and wave energy along the HPS were

impacted mostly by the relative orientation of structures with respect to the direction of the wind and oncoming surge and wave energy. For example, areas on the south side of St. Bernard Parish were sheltered from the dominant east to west movement of wind and water, resulting in reduced storm water levels and less damage. It is likely that the presence of marshes had an impact on surge and wave conditions during the earlier parts of the storm, but the massive size of the storm and propagation of surge and waves ahead of landfall had inundated the surrounding marshes with significant water long before the peak of the storm hit. The exact impact of surge and waves remains marshes on unquantified.

Measurements of temporal variation in wave and water level conditions, and wind, through the peak of the storm were extremely scarce. Of the few sensors deployed in the high impact zone, nearly all were damaged or malfunctioned. None of the self-recording instruments that were in place to record water levels successfully captured water level changes through the peak of the storm in the high impact zone. All malfunctioned prior to the peak.

3.1.3 The Performance

Of the 50 major breaches experienced by the HPS during Katrina, all but four were due to overtopping and erosion. For floodwalls, the overtopping caused erosion behind the walls that eventually caused instability and wall failure. For levees, the scour eroded the back sides and tops of the levees due to high velocities of the overtopping waves in areas of erosionsusceptible soils creating breaching. Areas with high quality levee materials performed well in the face of water conditions that exceeded their design criteria. Structures at authorized design elevations would have reduced the amount of overtopping.

There was no evidence of systemic breaching caused by erosion on face or water sides of the levees exposed to surge and wave action. The water velocities on the face side were only one-third of those experienced at the crest and back or protected side of the levees. The levees largely performed as designed, withstanding the surge and waves until overtopping, at which time they became highly vulnerable to erosion and breaching, especially those constructed by hydraulic fill.

Four breaches, all in the outfall canals and IHNC and all involving I-walls, occurred before water levels reached the top of the floodwalls. All were caused by foundation failures induced by the formation of a gap along the canal side of the floodwall. All of these structures were built over a layer of marsh sediments, in two cases underlain by clays and in the other two underlain by relict beach sand deposits. Along the outfall canals, the subsurface conditions dictated the specific mechanics that, coupled with the high hydrostatic pressures introduced to depth by the gap along the face of the sheet pile, led to instability and failure. The sites underlain by sand experienced significant uplift pressures, seepage and, in one case, a massive piping of subsurface sand from under the levee to the protected side. This action undermined the floodwall.

In the case of the sites underlain by clays, the formation of the gap to the base of the sheet piles introduced high loads along the depth of the wall which could not be resisted by the weak clays. At the IHNC site, the fact that the ground surface elevations beyond the levee toe were significantly below those in the design cross sections contributed to the failure. Soil strength assumptions used in the design of the 17th Street structures were too optimistic. The formation of the gap and the associated hydrostatic pressures introduced at depth, along with effectively splitting the levee into two parts, resulted in a significant reduction in the factor of safety of the structure. This failure mechanism, in particular the gap formation to the bottom of the sheet piles, was not considered in the original design of these structures.

Three other sites within the IHNC experienced I-wall breaches due to overtopping and scour behind the walls which reduced the stability of the structures. These breaches added to the flooding in Orleans (East Bank) and the Lower Ninth Ward. The storm surge levels in the IHNC exceeded the design levels, and lower structure elevations, reduced over 2 ft by 35 years of subsidence, contributed to the amount of overtopping that occurred.

Transitions between types and levels of protection and between protection structures and other features created vulnerabilities to erosion and breaching and reduced the effectiveness of the protection. Some of the transitions are associated with changes in the organization responsible for the structures, some are due to incompletion of the authorized construction, and others are associated with necessary penetrations through the levee/floodwall system.

In spite of being subjected to designexceeding conditions and forces, many sections of the HPS performed well. These tended to be sections with materials resistant to erosion and more conservative designs. The Orleans Canal levee-floodwalls are similar to those on the 17th Street and London Avenue Canals, yet they did not fail. The northern section of Orleans Canal is underlain by clays similar to the 17th Street breach site and the southern section is underlain by sand similar to the London Avenue breach sites. Investigations showed that the levees were more conservative in design, having broader base and less floodwall freeboard. In addition, more conservative soil strength values were assumed in their design.

Levee sections constructed from quality clay materials were much less susceptible to erosion from overtopping. They performed well in spite of being subjected to conditions significantly beyond their design criteria. There was a direct correlation between the character of the levee materials and their performance.

Flooding from Katrina covered approximately 80 percent of the New Orleans metropolitan area. For Orleans East and St. Bernard Parishes, approximately two-thirds of the volume of flooding can be attributed to water flowing through breaches. The one-third due to overtopping and the very large amount of rainfall would itself have caused a significant level of interior flooding. The three breaches in the outfall canals and I-wall/levee failures along the west side of the IHNC were responsible for approximately 70 percent of the flooding in Orleans East Bank. The remainder was due to the heavy rainfall (up to 14 in. in 24 hr) and overtopping.

Because of inoperability, pump stations played no significant role in the reduction in flooding during Katrina. Sixteen percent of the total pumping capacity was operating during the storm, equivalent to approximately 18,000 cfs. The distribution of operating pumps across four parishes, however, reduced the impact of the pumping. Their inoperability, due to a combination of the necessary evacuation of operators, loss of power, loss of cooling water, and flooding, impacted the ability to unwater the city after the storm. Temporary pumps were useful after Katrina, but provided only a small fraction of the capacity needed. Reverse flow through some pumps added to the flooding in at least one parish. While methods are available to prevent reverse flow, they are dependent on human implementation and electrical power.

The maintained condition of the levees was an additional negative factor in the performance of the system. While the presence of trees and other features on the levees could not be directly related to the failures of the outfall canal structures, it is likely that they were enablers in the overall breaching process. The presence of large trees on the levees was particularly troublesome and could easily have accelerated the failure process.

All features must be included in the performance assessments of a system. There are other features, such as the CSX railroad closure gate, that are not an integral part of the HPS but are sources of vulnerability and require independent action to manage during a hurricane event.

3.1.4 The Consequences

Loss of life was concentrated by age, with 70 percent of deaths being people over the age of 70. There were 727 fatalities in the five parishes examined. The poor were disproportionately affected. Loss of life also correlated to elevation, in terms of depth of flooding, especially with regard to the poor, elderly, and disabled, the groups least likely to be able to evacuate without assistance.

Katrina caused direct property losses (excluding Plaquemines Parish) of over \$20 billion, approximately 78 percent (\$16 billion) of which was attributed to residential losses. The next largest component was the 11.5 percent (\$2.4 billion) attributed to commercial losses. There was an additional \$7.0 billion in losses attributed to public infrastructure, including the HPS itself. The most significant infrastructure impact was incurred by the HPS (\$2.0 billion) followed by roadway networks and assets of the regional distribution\transmission electrical grid. Together, the damages to these categories of infrastructure totaled approximately \$2.0 billion. This estimate is followed by damages to public transit assets of approximately \$700 million, followed by damages to rail lines, airport facilities, gas and water distribution, telecommunications assets, and assets for waterborne transportation totaling an additional \$1.7 to \$1.9 billion.

Approximately half of the direct economic excluding public and utilities losses. infrastructure, can be associated with breaching of levees and floodwalls. The remaining losses alone, attributable to rainfall and overtopping, constitute the largest losses experienced in any disaster in the New Orleans vicinity. Losses and, in many respects, recovery can also be directly correlated to depth of flooding and thus to elevation. In some areas flooded by Katrina, where water depths were small, recovery has been almost complete. In areas where water depths were greater, little recovery or reinvestment has taken place.

Combined with the significant and farreaching impact of Hurricane Katrina regarding initial displacement of population, workforce, and businesses, the impacts to infrastructure and affiliated public welfare and services will contribute to slowed phasing of recovery with regard to return of populace and business activities. Orleans Parish alone is estimated to have lost over 60 percent of its population and St. Bernard Parish nearly 80 percent. On the other hand, St. Charles and Tammany Parishes have increased in population since before the storm.

In terms of the social consequences of the Katrina event specifically, the social organization of the community and region has been compromised by the mass exodus of the population, the structural damage, and the demands to respond and rebuild. The flooding caused a breakdown in New Orleans' social structure, a loss of cultural heritage, and dramatically altered the physical, economic, political, social, and psychological character of the area. These impacts are unprecedented in their social consequence and unparalleled in the modern era of the United States. The flooding disproportionately impacted the poor, the elderly, and the disabled.

The performance of the levees protecting New Orleans is a key to its social, cultural, and historic conditions. The immediate physical damage made large portions of the city uninhabitable, with thousands of residential, commercial, and public structures destroyed. Basic infrastructure facilities, such as power, water, sewer, and natural gas lines, were made inoperable and continued to be out of service for months after the event. Many victims not only lost their homes, but also their schools, health care, places of worship, places of trade, and jobs. The forced relocations disrupted family and friend networks. As a result, the event not only had an immediate impact on the well-being of the population of those living and working in the metropolitan area, but also resulted in basic changes in the social organization of all aspects of that population.

The available information indicates that if environmental harm has come from the Katrina flooding of greater New Orleans, it was associated with past regional land and water development. Like many other cities, the soils and sediments of land and waters in New Orleans and other delta urban areas are contaminated with metals and organics at

concentrations that often exceed health standards in areas of most dense development. The flooding of greater New Orleans removed some contamination from greater New Orleans and transported it to Lake Pontchartrain and Violet Marsh with pumped floodwater where it added a small increment to estuarine sediments. The IPET analysis did not look at local redistribution of contaminants within individual drainage basins. Katrina and Rita resulted in the loss of approximately 300 square kilometers of wetlands and marshes, all independent of the performance of the levees and floodwalls. Loss of wetlands regionally appears to fit a pattern of loss associated with past regional development as well. Overall, any sustained environmental loss from flooding and flood management is indicated to be very small in the context of longterm impacts from development in the region.

3.1.5 The Risk

Risk assessment provides a viable means to understand the relative vulnerability of protected areas. The combination of the likelihood of storm water 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.

Performing a meaningful risk assessment requires an accurate inventory and characterization of all components of the HPS. This includes the information and assumptions used in the design, the physical properties including accurate dimensions and elevations, materials and strengths, and maintained condition. This is a substantial task but provides a foundation for true system-wide analysis.

The effectiveness of the protection system depends on human factors as well as engineered systems. These factors, such as timely gate closures, operating gates, and pumping station operability, must be included in the overall assessment to reach accurate conclusions. 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.

3.2 PRINCIPAL LESSONS LEARNED

The principal lessons learned from the IPET analyses are presented below by mission question. Detailed lessons learned are provided in Volumes II to VIII. In addition to the lessons learned that relate directly to the mission questions, there was a cross cutting topic, knowledge and expertise, that warranted discussion and is presented at the end of this section of the report.

3.2.1 The System

Correct elevations and reference datum are essential. All hurricane and flood control protection structures should be designed, constructed, and maintained relative to an up-todate 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 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. In subsidence-prone areas, designs should consider multiple elevation increases over the life cycle of the structure.

Systems planning and design methods are needed. Planning and design methodologies need to allow for examination of system-wide performance. It is obvious from the IPET analysis that the piecemeal development of the New Orleans Hurricane Protection System

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 greater likelihood of failure. The systembased 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 timedependent challenges hurricane protection systems 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. For any given drainage basin, the protection is only as robust as the weakest component of the system protecting that area and how effectively the various components that are interdependent operate together.

Frequent update to guidance and review of projects is critical. Design methods and designs need frequent review to determine whether they represent best practice 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. Design should be based on a system-wide understanding of the processes affecting the system and the interaction and interdependencies of the system components. This is especially true for the characterization of the hazard where modern probabilistic methods should be used.

The SPH process is outdated. More comprehensive probabilistic methods that consider broader varietv of а storm characteristics and storm generated conditions should be used as a basis for planning and design. The Joint Probability Method -Optimized Sampling approach described in Volume VIII is recommended as a technically credible approach.

3.2.2 The Storm

Surge and waves are the hazard, not the storm. Meteorological designations such as the Saffir-Simpson scale by themselves are not adequate to characterize the distributed surge and wave conditions that a HPS will face. Katrina, a Category 3 storm at landfall, generated surges of 24 to 26 ft at Biloxi, MS. In the vicinity of Biloxi, the surge produced by Camille was 15.8 ft, the highest surge that had ever been recorded at that location prior to Katrina. In other words, Katrina (a Category 3 storm at landfall) generated substantially higher surges than Camille (a Category 5 storm at landfall) in the area where they both made a direct hit.

Sophisticated modeling using physics-based codes with high spatial resolution and accurate windfield input is necessary to depict the variable hydrodynamic environments created by large storms. Similarly, 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 Corps' WAM, STWAVE, and ADCIRC prediction models) provided considerable insight into how water surrounding such a complex physical system responds to an equally complex hurricane wind system. The hurricane protection system in Southeast Louisiana is very long and expansive, having a highly irregular layout. These factors coupled with a translating counter-clockwise rotating wind field about the center of a hurricane produced a complicated pattern of wave and storm surge development and evolution. Propagation of an evolving storm surge wave influences the water depth, which in turn exerts strong influence on the local wave field. The wave field is not only a function of what is locally generated by the wind. It is also heavily influenced by wave conditions generated by the hurricane while it was still well off the coast. Those waves propagated into the region well ahead of the storm's arrival.

Current models have uncertain accuracy in treating the effects of wetland and marsh environments on storm surge and waves. Sensitivity tests showed that wave and surge model computations are somewhat sensitive to the methods used to characterize frictional resistance of wetlands and to the values of frictional resistance assigned to different types of wetland landscape. Results showed that storm surge is reduced in some areas, whereas it is increased in others. Likewise, wave height is reduced in some areas and increased in others. Wave height increases are primarily due to the fact that increased water depths associated with increases in storm surge enable larger local wave heights to be sustained.

Resolution of wave setup is a critical element in the estimation of design levels of levees in this area. Hurricane Katrina produced extremely energetic wave conditions along the entire coast of Louisiana. Significant offshore wave heights along the Southeast Louisiana coast ranged from 55 ft due east from the tip of the Mississippi River delta to 20 to 25 ft just north of the Chandeleur Island chain, with peak wave periods of approximately 15 to 16 sec. Considerable wave breaking took place seaward of the Chandeleur Islands. High resolution (as fine as 300 ft) was added to the ADCIRC grid mesh to resolve areas of intense wave breaking along the barrier islands, the periphery of the coastal wetlands fronting Southeast Louisiana, and along the periphery of Lake Pontchartrain. The STWAVE model was run at fine resolution. The high resolution adopted and the use of coupled wave and surge models were able to capture the contribution of wave setup to storm surge away from coastal structures, а contribution of up to 2.5 ft depending on location. But even though the ADCIRC model contained contributions of both direct forcing and wave-related radiation stresses in its estimates of storm surge heights, local wave setup not resolved by the ADCIRC grid contributed 1.5 to 2 ft of additional setup along exposed levees in St. Bernard Parish, Plaquemines Parish, and New Orleans East, as well as along the south shore of Lake Pontchartrain. This additional setup contribution was estimated using Boussinesq wave modeling applied with much higher resolution.

Only 10 to 15 percent of high-water marks were considered to be reliable measures of peak storm water level. Of the many hundreds of high-water marks collected in Louisiana and Mississippi, a relatively small percentage of high-water marks were rated to be reliable measures of storm surge (the peak still water level that was experienced during the storm). The most reliable marks were those measured in the interior of structures on walls, in places where oscillatory wave motions were minimized.

3.2.3 The Performance

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 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. The unanticipated failure mode defined for the Iwalls from this analysis does not represent the only possible failure mode for these structures. Numerous other modes were considered in their design, and other yet undefined modes are likely to occur at some point in the future. Designers need to consider a broad range of failure modes, including some approaches beyond traditional or standard practice.

Design methods and assumptions need continuous review and update. Design methods should be clearly based on physical behavior of engineering components and systems and should be reviewed periodically to determine if they represent the latest knowledge, practice, and technology. Similarly, existing projects should be periodically reviewed to ensure that their original design has not been compromised by changing hazard or changing knowledge base. Planning methods should facilitate examination of system-wide performance. In addition, hurricane protection systems 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.

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 our 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. Added to this is the savings of the time and funding needed to rebuild the protection system itself, which would accelerate the pace of recovery. Resilience is not a national priority in the development of hurricane protection systems, and resilience was not an element in the New Orleans HPS design.

3.2.4 The Consequences

Losses and recovery are flood depth dependent. Losses from a hurricane event creating water levels that exceed design criteria can be expected to be significant, but could be much less if the HPS can withstand overtopping without catastrophic breaching. While the reduction in direct property losses can be substantial and readily estimated (over \$10 billion for Katrina), it is the more difficult to quantify reduction in the indirect economic and cultural losses that may be most relevant to the ability of the affected area to recover. In addition, the perceived character and expected performance of the HPS itself is a significant factor in the choices people will make with respect to re-population and re-investment.

Damages and loss of life were both directly tied to depth of flooding, which in turn is inversely tied to the elevation of the location or subbasin. Areas with lower elevations experienced the most severe losses and, all else being equal, will harbor the highest probabilities of experiencing flooding into the future.

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. Spatial analysis of consequences and the ability to relate consequences to physical performance are powerful tools for making difficult decisions concerning hurricane protection.

3.2.5 The Risk

The comprehensive risk assessment was ongoing at the time of the release of this edition of Volume I. The following are insights gained in the development and execution of the risk assessment. More specific results and lessons learned will be provided in an amended version of this Volume and a completed Volume VIII when the risk results have been validated and published.

Risk supports system-wide planning. A riskbased planning and design approach would provide a more viable capability to inform decisions on complex infrastructure such as hurricane protection systems. The traditional approach, as used for the New Orleans protection measures, is component-performancebased, uses standards to define performance, and relies on factors of safety to deal with uncertainty. It is difficult to examine the integrated performance of multiple components, and standards are usually limited to past experience. Risk-based planning is system-based, requiring that the entire system be described in consistent terms and explicitly including uncertainty. Component performance is related to system performance as well as the consequences of that performance.

Risk expands the criteria for decision making. The risk-based approach is well suited for consideration of a variety of measures of merit. Factors such as loss of life, environmental losses, and cultural consequences can be included in decision making without reducing everything to one measure such as dollars. As applied for the IPET assessment, it allows aggregation and de-aggregation of information to address issues at different scales, providing a useful tool for collaborative planning between responsible agencies at different levels. It also allows for a more comprehensive consideration of hazards. Instead of a single definition derived from limited historical data, a joint probability approach can consider events that reflect historical information as well as a variety of possible events, providing a more robust basis for considering the spectrum of hurricanes that may occur. Most importantly, risk and reliability allows decision makers to understand the relative levels of vulnerability that specific areas face, the nature of the consequences (e.g., loss of life, economic loss, or environmental loss), and to understand the source of the vulnerability. As such, it is an excellent tool for understanding the effectiveness of alternative approaches to reduce risk, which can be managed by changing the performance of the protection system or changing the nature or degree of related consequences.

Traditional methods of hurricane frequency analysis are not adequate to describe the hurricane hazard for risk assessment. Risk assessment requires a stage (water level)- frequency of occurrence (or exceedence) relationship for a multitude of locations around the HPS, the number depending on the variation of the surge and wave conditions. The SPH, or any design hurricane, is only a single representative storm. having a certain combination of characteristics, with an estimated frequency of occurrence; one storm out of a population of hurricanes that are possible, some of which are more severe than the SPH. Relatively little information regarding risk is available from this treatment of the storm threat. Considering a larger set of historical storms, such as in a strict application of the Empirical Simulation Technique, is an improvement; but it also limits consideration of what might occur in of terms combinations of hurricane characteristics to what has occurred. Using the Empirical Simulation Technique with track variations of historical storms adds some hypothetical storms to the historical record, but also adds the challenge of assigning frequencies to these storms. The Joint Probability Method -Optimal Sampling, coupled with high-resolution surge and wave models, was deemed the most rigorous and tractable means to characterize the hurricane hazard for the New Orleans risk assessment. It most thoroughly considers the spectrum of hurricanes that might occur. The period of record from 1950 to the present was defined as the most accurate interval for assessing hurricane characteristics. One will always be limited to a degree by the length of the historical record.

4.0 KNOWLEDGE AND EXPERTISE

Awareness and exploitation of emerging knowledge are critical. The history of the planning, design, and performance of the HPS in New Orleans points out a dilemma. While new pieces of knowledge were available over time that were relevant to the ultimate performance of the I-walls on the outfall canals, the pieces were not put together to solve the puzzle of the failure mechanism that occurred. The Corps' own testing of sheet-pile stability (E-99) in the mid 1980s was not directed at the behavior of I-walls, but with hindsight, some of the behavior observed was indicative of the deflection of a structure that designers essentially assume to be rigid. Similarly, late in the 1980s, research papers published in part through the Corps laboratories discussed the high hydrostatic pressure issue with regard to a gap forming in conjunction with sheet-pile structures. Work, not directly related to levee or floodwalls, in England discussed the deflection and hydrostatic pressure problem for retaining walls. How do these puzzle parts get pieced together to create knowledge for designers and how do designers and reviewers get access to this information? How does the research or testing community become aware of applications, perhaps different from their original purpose, for their new knowledge?

Constant renewal of planning and design criteria and guidance are critical. Part of the solution to this dilemma relates to the amount of overall effort and resources put into the search for new knowledge and capabilities to deliberately update design criteria and planning capabilities. Awareness and capability are gained best when there is both technology push (research creating new knowledge and capabilities) and requirements pull (designers/constructors seeking and pulling information from the research and professional communities). The solution is not more research or more outreach alone, it is the ability of the design/construction and research communities to work together in an environment enabling collaboration and experimentation with new knowledge and approaches to old and new problems. There has been a distinct loss in energy and resources expended in this area, particularly in the domain of hurricane and flood protection and specifically in the geotechnical fields that are at the heart of the levee and floodwall performance issues in Katrina. The focus on standards may, in fact, also deter this process. Standards imply stability and constancy, when in fact the concept of guidelines may be more appropriate, allowing and encouraging customization and adaptation as new knowledge emerges. In either case, standards and/or guidelines need to be refreshed at a greater frequency as the generation of new knowledge continues to accelerate.

Maintaining expertise is critical. The other dimension to this issue is expertise. As technology accelerates and engineering practice evolves at an increasing pace, it becomes more difficult to maintain the level of technical expertise necessary to cope with the ever more complex issues faced in water resources. This is true for the government and the private sectors. Government agencies are especially challenged in an era of outsourcing and competition for experienced professionals. Significant measures are needed to reemphasize technical expertise and renew that expertise as water resources practice evolves. These measures must be part of the culture of organizations and cover the entire profession to ensure that the total team addressing priority issues such as hurricane protection are working from the latest knowledge and professional practice.