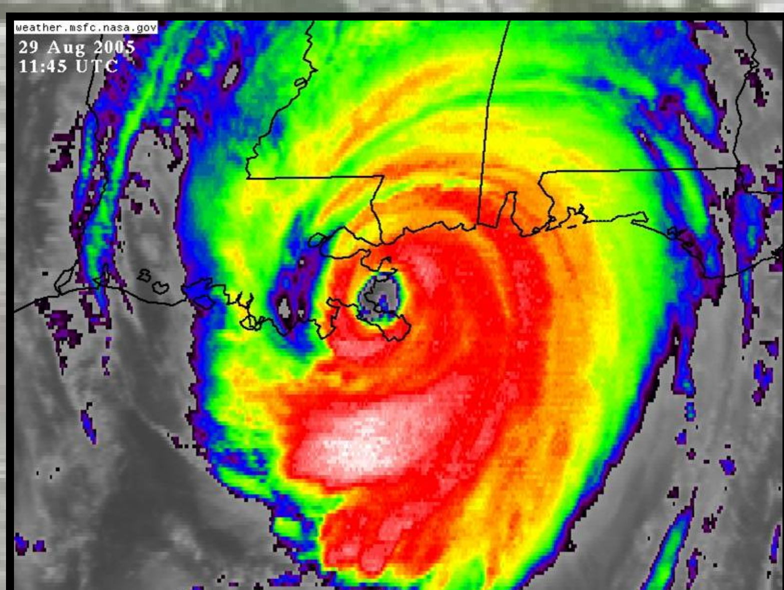
US Army Corps of Engineers

Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System

Draft Final Report of the Interagency Performance Evaluation Task Force

Volume I – Executive Summary and Overview

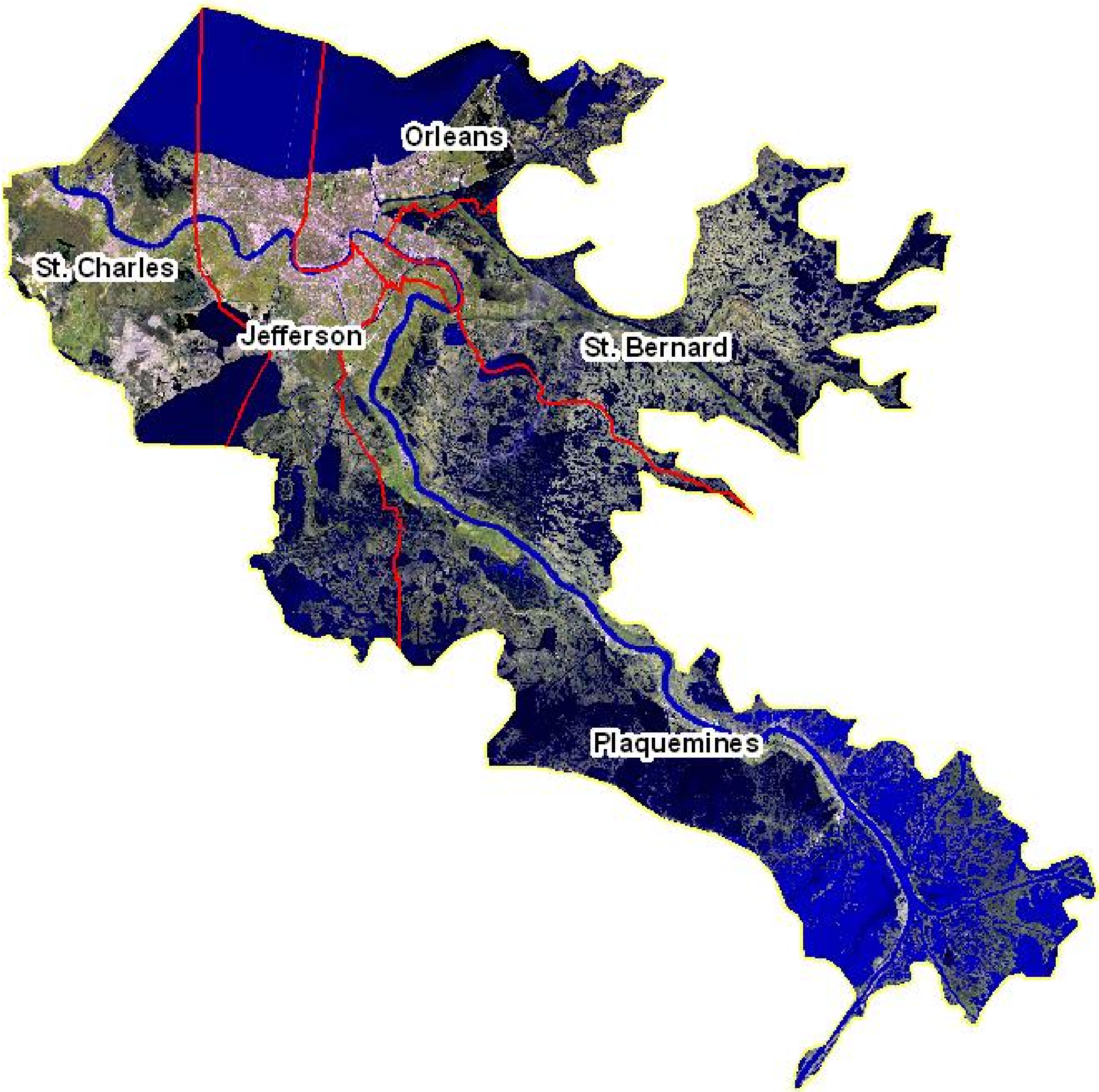
1 June 2006



FINAL DRAFT

(Subject to Revision)

Volume I
Executive Summary and Overview



This report is not intended as a final expression of the findings or conclusions of the United States Army Corps of Engineers, nor has it been adopted by the Corps as such. Rather, this is a preliminary report summarizing data and interim results compiled to date. As a preliminary report, this document and the information contained therein are subject to revisions and changes as additional information is obtained.

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Preface

This report is the result of an intense performance evaluation of the New Orleans and Southeast Louisiana hurricane protection system during Hurricane Katrina. It was conducted by the Interagency Performance Evaluation Task Force, a distinguished group of government, academic, and private sector scientists and engineers who dedicated themselves solely to this task from shortly after Katrina struck through the start of the next hurricane season. Created by the Chief of Engineers, U.S. Army Corps of Engineers and peer reviewed literally on a weekly basis by an equally distinguished external review panel of the American Society of Civil Engineers, the group applied some of the most sophisticated capabilities available in civil engineering to understand what happened during Katrina and why. Their purpose was not just new knowledge, but application of that knowledge to the repair and reconstitution of protection in New Orleans as well as improvement to engineering practice and policies. The results of their work are largely already in the ground, having been transferred and applied prior to the completion of this report. The bulk of the information and documents used or generated by the Task Force has been placed on a public Web site, *https://IPET.wes.army.mil*, as they became available. At the time of the distribution of this draft report, there were well over 4300 documents on this site.

There are nine volumes in the final report, designed to provide a detailed documentation of the technical analyses conducted and their associated findings. They are organized around major technical tasks that together provided an in-depth, system-wide assessment of the behavior of the hurricane protection system and lessons learned that have been incorporated into the immediate repairs and are integrated into the continuing efforts to improve the system and assessing approaches for higher levels of protection. The volumes and their individual focus areas are as follows:

- Volume I: Executive Summary and Overview – Summary of findings and lessons learned. Overview of performance evaluation activities and reports.

- Volume II: Geodetic Vertical and Water Level Datums – Update of geodetic and water level references for the region and determining accurate elevations for all critical structures.

- Volume III: The Hurricane Protection System – Documentation of the character of the hurricane protection system, including the design assumptions and criteria, as built and maintained condition.

- Volume IV: The Storm – Determining the surge and wave environments created by Katrina and the time history and nature of the forces experienced by protection structures during the storm.

- Volume V: The Performance – Levees and Floodwalls – Understanding the behavior of individual damaged structures and development of criteria for evaluation of undamaged sections. Providing input to repairs and ongoing design and planning efforts.

- Volume VI: The Performance – Interior Drainage and Pumping – Understanding the performance of the interior drainage and pumping systems with regard to extent and duration of flooding. Examination of scenarios to understand system-wide performance.
- Volume VII: The Consequences – Determination of the economic, human safety and health, environmental, and social and cultural losses due to Katrina. Examination of scenarios to understand implications of losses and possible recovery paths on future risk.
- Volume VIII: Risk and Reliability – Determination of the inherent risk for all parts of the system prior to and following Katrina. Provision of capability for risk-based decision support for continuing improvement and development of hurricane protection.
- Volume IX: Supporting Appendices – Documentation of information resources and management, program management, and communications.

On behalf of the entire Interagency Performance Evaluation Task Force, the undersigned offer this report and the results therein as a contribution to the well being of the people of New Orleans and Southeast Louisiana and the reconstitution of effective hurricane protection for their future.

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Executive Summary

Introduction

This report, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System, is a draft of the final report in 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 to determine the facts concerning the performance of the Hurricane Protection System in New Orleans and Southeast Louisiana during Hurricane Katrina. This report provides a comprehensive description of the IPET activities and the findings and lessons learned from those activities. 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 1, Executive Summary and Overview, provides an executive summary of the findings and lessons learned and an overview of the IPET efforts described in more detail in Volumes II–IX.

The draft final report provides a detailed documentation of a broad, multi-disciplinary analysis of the hurricane protection system and its performance during Hurricane Katrina. Since the system is only designed to manage flooding in the metro-New Orleans basin, wind-based consequences and all direct consequences exterior to the system are excluded from this report. This report is being provided as a draft, offering provisional final results for the entire spectrum of the work accomplished with the exception of the risk and reliability assessment which is undergoing validation and peer review. Some of this work will continue to be reviewed and validated after the release of this draft. This includes final reviews by the ASCE External Review Panel and the NRC Committee on New Orleans Regional Hurricane Protection Projects. The results of those reviews will be incorporated into the draft prior to final publication, which is expected to be in September 2006. As such, the information provided in this draft report should be considered as provisional and subject to revision. This report and all other IPET-produced documents are available on the IPET Web site, *https://IPET.wes.army.mil*.

The key objective of the IPET is to understand the behavior of the New Orleans Hurricane Protection System in response to Hurricane Katrina and assist in the application of that knowledge to the reconstitution of a more resilient and capable system. As such, the IPET analysis is geared toward determining why certain sections and structures breached and why others did not, using that understanding to assess the integrity of the remaining portions of the system, and providing an analytical and knowledge base to assist in designing more resilient protection measures. IPET is also conducting a risk and reliability assessment of the entire system to aid in understanding the levels of protection that will exist for the future. This methodology will support the Louisiana Comprehensive Protection and Restoration Study. To do this, the IPET Teams have conducted an integrated set of analyses designed to provide a balanced assessment of the performance of all aspects of the physical system. The IPET is not examining organizational and jurisdictional issues that impact the effectiveness of the physical system. These issues are being examined by the Hurricane Katrina Decision Chronology Study being conducted by a separate group of investigators.

The architecture of this report is aligned with the five major questions that comprise the IPET mission. Those questions involve:

- 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, and what insights can be gained for the effective repair of the system, and what is the residual capability of the undamaged portions? This also involved understanding the performance of the interior drainage and pump stations and their role in flooding and un-watering 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 and Reliability: What was the risk and reliability of the hurricane protection system prior to Katrina, and what will it be following the planned repairs and improvements (1 June 2006).

All of these efforts are underpinned by the establishment of accurate elevations for geodetic reference points throughout the region and re-establishing the relationship of local mean sea level to the geodetic datum.

Findings

The IPET findings are presented in three tiers: the first two presented in Volume I and the third in the individual volumes addressing major topical areas of analysis. The first tier is the overarching findings that represent a synthesis of the component analyses. The second tier, presented in Volume 1 as a synopsis of principal findings, is a synthesis of the findings from the component analyses of the hurricane protection system. The detailed findings are presented in Volumes II–VIII. A unique aspect of the IPET work is that the results are in many cases, already "in the ground" in the form of the repairs accomplished. They are also incorporated into the planning and design processes that are the basis for continued work to recover to authorized levels and for completion of the system. The analytical tools and information bases will be transitioned to the Louisiana Comprehensive Protection and Restoration Study, to develop effective approaches for higher levels of protection.

Overarching Findings

The System did not perform as a system: the hurricane protection in New Orleans and Southeast Louisiana was a system in name only. Flood protection systems are an example of a series system—if a single levee or floodwall fails, the entire area is impacted. It is important that all components have a common capability based on the character of the hazard they face. Such systems also need redundancy, an ability for a second tier of protection to help compensate for the failure of the first tier. Pumping may be the sole example of some form of redundancy; however, the pumping stations are not designed to operate in major hurricane conditions. The system's performance was compromised by the incompleteness of the system, the inconsistency in levels of protection, and the lack of redundancy. Incomplete sections of the system resulted in sections with lower protective elevations or transitions between types and levels of protection that were weak spots. Inconsistent levels of protection were caused by differences in the quality of materials used in levees, differences in the conservativeness of floodwall designs, and variations in structure protective elevations due to subsidence and construction below the design intent due to error in interpretation of datums. The presence of closure gates such as those for the CSX railroad that must function as a part of the system, but are separately controlled, add to the inherent risk in the system. Redundancy was simply not included. Continuity of pumping could have significantly reduced at least the duration of flooding and in some areas the extent. Armoring the back sides and crests of levees and the protected side of floodwalls would have added significant redundancy and reduced breaching. Surge gates at the mouths of the outfall canals are an excellent example of providing redundancy. The combination of the surge protection for the canals and resilient levee-floodwall systems will dramatically reduce risk in Orleans East Bank.

The storm exceeded design criteria, but the performance was less than the design intent: sections of the hurricane protection system were in many ways overwhelmed by the conditions created by Hurricane Katrina. This is particularly true for the sections of the Gulf Intracoastal Waterway (GIWW) along New Orleans East, and the levees in St. Bernard and Plaquemine Parishes where the combination of record high surge and long period waves exceeded the design conditions and devastated the levees. This devastation, however, was aided by the presence of incomplete protection, lower than authorized structures, and levee sections with erodible materials. While overtopping and extensive flooding from Katrina were inevitable, a complete system at authorized elevations would have reduced the losses incurred. The designs were developed to deal with a specific hazard level, the Standard Project Hurricane as defined in 1965; however, little consideration was given to the performance of the system if the design event or system requirements were exceeded.

Within two of the three outfall canals in Orleans Parish, and at one site within the Inner Harbor Navigation Canal (IHNC), foundation failures occurred prior to water levels reaching the design levels of protection, causing breaching and subsequent massive flooding and extensive losses. These failures were all associated with I-wall structures and a common failure mode involving the formation of a gap on the canal side of the floodwall that precipitated and accelerated the failure in the foundation materials. The designs for these structures were marginal with respect to practice and the uncertainty inherent in the variable geological conditions and the hurricane hazard for the area. The duration of flooding could have been reduced if the pumping capability had been able to continue, but the pumping systems were not designed to operate in severe hurricane conditions.

Two 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. Reduced protection elevations at transitions between structure types and incomplete sections of the system similarly reduced protection levels and increased flooding. Another site on the west side of the IHNC breached from overtopping and scour of a levee. The elevation of the levee was lower than adjacent areas, which added to its vulnerability.

The flooding and the consequences of the flooding were pervasive, but also concentrated. Consequences of the flooding and the associated losses were greater than any previous disaster in New Orleans and, in themselves, create a formidable barrier to recovery. Loss of life was concentrated by age, with more than 75 percent of deaths being people over the age of 60. 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.

The majority, approximately two-thirds by volume, of the flooding and half of the economic losses can be attributed to water flowing through breaches in floodwalls and levees. 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.

Another concentration of consequences is in the nature of the losses. Twenty five percent of residential property values were destroyed by Katrina and this loss represents 78 percent of all direct property damages. Non-residential properties suffered a 12 percent loss in total value or half the rate of residential. Clearly residential areas were more prone to flooding.

The repaired sections of the hurricane protection system are likely to be the strongest parts of the systems until the remaining sections can be similarly upgraded and completed. Since there are many such areas where the protection levels will be the same as before Katrina, the New Orleans metropolitan area remains vulnerable to any storm creating surge and wave conditions that rival those from Katrina.

Synopsis of Principal Findings

Geodetic Vertical and Water Level Datum (Volume II)

The variable and considerable subsidence in the New Orleans area was reflected in the performance of the system in Katrina in two ways. First, the magnitude of the subsidence and adjustments to the datums were not fully considered in the design and construction of the Hurricane Protection System. Spatial and temporal variations of 0.2 to 3 ft were found between the geodetic datums and water level reference datums. Flood control structures in the region were authorized and designed relative to a water level datum (mean sea level), but constructed relative to a 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. In at least one case, the Corps made a deliberate decision not to re-examine elevations of existing project structures after datum adjustments were made. Second, updating of the reference elevation points for the region, although underway, was not completed and left decision makers without an accurate understanding of the actual elevations of the hurricane protection. 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.

Hurricane Protection System (Volume III)

There was no evidence of government or contractor negligence or malfeasance. With the exceptions noted below, the system was generally built as designed, and design approaches were consistent with local practice. However, several factors described below significantly impacted the system's performance during Katrina. Sections of the system were built below specified design elevations due to the use of an inaccurate relationship between the geodetic datum and mean sea level. While varying across the system, this elevation difference can be as much as 1 to 2 ft. Foundation soil strengths were derived from relatively widely spaced borings and at times using average values that may not capture the high variability inherent in this type of geology. The decision to use uniform soil shear strengths, based on the greater strengths of the soils under the center line of the 17th Street Canal levee, resulted in an overestimation of the subsurface strength at the levee toe. Coupled with the use of average values obtained from widely spaced samples in a geology with highly variable conditions, the structure was left with a marginal factor of safety. This same assumption was not made in other sections of the system where more conservative strength values were used.

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. While updates in original 1959 definition of the SPH for the New Orleans area were made by the National Oceanographic and Atmospheric Administration (NOAA) in 1979, the Corps chose to continue to use the 1965 and 1966 original definitions developed for the Lake Pontchartrain and Vicinity and New Orleans to Venice Projects.

The hurricane protection in New Orleans was designed and developed in a piecemeal fashion, resulting in inconsistent levels of protection. Four slightly different SPH's were used, and 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 less (height above the levee crest). 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.

Sections that are not completed represent anomalously low areas, more vulnerable to overtopping and failure. The majority of the pump stations are not designed to provide capability during large storms. Levee materials ranged from highly resistant to scour to poorly resistant, resulting in large variations in the protection levels afforded nearby areas. Other factors such as the CSX closure gate not functioning and the maintained condition of the levees were additional negative factors in the performance of the system. While the presence of trees and other features on the levees were not obvious causes of breaching, it is possible that they were enablers in the overall breaching process.

Storm (Volume IV)

Hurricane Katrina generated water levels that for much of the system significantly exceeded the design criteria. Katrina surge levels were substantially higher, up to 5 or 6 ft, than the design levels for all areas along the eastern and southern portions of the hurricane protection system, and were roughly equivalent along the south 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 long period ocean storm waves that cause much more runup and overtopping than shorter period 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. For example, the IHNC design assumed 1-ft waves, while at least 4-ft waves were experienced during Katrina.

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 10 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 the levees that failed due to erosion determined that all 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.

Performance (Volumes V and VI)

Of the 50 major breaches experienced by the hurricane protection system 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 erosion-susceptible soils creating breaching. The value of added erosion resistance was clear, an attribute that could also be provided by measures such as armoring. Areas with high quality levee materials performed reasonably 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.

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. 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 seepage and in one case a massive piping of subsurface sand from under the levee to the protected side, undermining the floodwall. The formation of the gap and the associated hydrostatic pressures introduced at depth resulted in a significant reduction in the factor of safety of the structure. This failure mechanism, in particular the gap formation, was not considered in the original design of these structures.

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 design-exceeding conditions and forces, many sections of the hurricane protection system performed well. These tended to be sections with materials resistant to erosion and more conservative designs.

Flooding from Katrina covered approximately 80 percent of the New Orleans metropolitan area. Approximately two-thirds of that 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 foundation failures associated with flooding in Orleans East Bank were responsible for approximately 70 percent of the flooding in that area. The remainder was due to the heavy rainfall (up to 14 in. in 24 hr) and some overtopping-induced breaching along the west side of the IHNC.

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 18000 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 un-water 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.

Consequences (Volume VII)

The most serious direct impact of Katrina was the high number of deaths. While large numbers of people were able to evacuate, the groups least likely to be able to do so on their own, the poor, elderly, and disabled, were hardest hit. This emphasizes the critical need for additional capabilities in this area. The depth of flooding was high correlated to land elevation, and the areas with the lowest elevations were largely residential. This places the residential population who cannot readily evacuate at the greatest risk.

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 $6.0 to $6.7 billion in losses attributed to public infrastructure, including the hurricane protection system itself. The most significant infrastructure impact was incurred by the hurricane protection system (1.8 to 2.08 billion) followed by roadway networks and assets of the regional electrical distribution\transmission 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 $690 to $730 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 losses, excluding public and utilities 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.

Combined with the significant and far-reaching 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 obviously 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 flood-water where it added a small increment to estuarine sediments. The IPET analysis did not look at local redistribution of contaminants within individual drainage basins. 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 long-term impacts from development in the region.

Risk and Reliability (Volume VIII)

The findings for the risk and reliability assessment will be provided upon completion of the ongoing validation of the methodology and products as recommended by the ASCE External Review Panel.

Lessons Learned

Lessons learned are presented in three tiers in compliance with the presentation of findings. Tier one, overarching lessons learned, represents an integration of the major principal lessons learned that are presented here in Volume I. Volumes II to VIII provide a more detailed discussion of lessons learned relevant to the individual topics addressed in each volume.

Overarching Lessons Learned

The IPET analysis provides broad insights into the many aspects of the New Orleans and vicinity hurricane protection system and why the system performed as it did during Hurricane Katrina. Integration of a number of these principal lessons learned provides some strategic insights for the future relevant to the continued reconstitution of protection in Southeast Louisiana and for hurricane and flood protection projects in general. These insights are presented here as overarching lessons learned.

Resilience: It is clear that a resilient hurricane protection system can provide enormous advantages. Resilience in this case refers to the ability to withstand, without catastrophic failure, forces and conditions beyond those intended or estimated 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 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 was not an element in the New Orleans Hurricane Protection System design. While resilience here is referring to the performance of the physical system, there is also a need for resilience in managing consequences. This falls squarely in the domain of emergency preparedness and response.

It is important to view resilience as time-dependent, given changes in requirements for protection (i.e., changes in potential consequence) or changes in the hazard (climate dynamics or changes in the nature of the protection system and subsidence). Resilience must be part of the adaptive nature of a system and be reviewed frequently as a fundamental character of the design and capacity of the system. Three main principles are suggested:

- Designs conservative enough to appropriately account for the unknown and flexible enough to be augmented as hazards or requirements change.
- Performance redundancy such as armoring to prevent scour from overtopping that leads to failure and breaching.
- Integrated systems approach to protection, from design, construction, operation, maintenance, and emergency operations perspectives. Pumping resilience as a component of the system is one example.

Systems Performance: Planning and design methodologies need to allow for an 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 generate areas with greater vulnerability to failure. The systems 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 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.

Risk and Reliability: A risk-based 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-performance-based, 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 systems-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.

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 wide 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.

Knowledge, Technology and Expertise: The history of the planning, design, and performance of the Hurricane Protection System 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 sheetpile floodwalls (E99 Sheet Pile Wall Field Test Report, Technical Report 1, Lower Mississippi Valley Division, June 1988) in the mid 1980s was not directed at the global stability of I-walls, but with hindsight, some of the behavior observed was indicative of the wall deflections that could lead to a gap forming between the pool side soil and the wall. Similarly, late in the 1990s, research published in part by the Waterways Experiment Station (Soil Structure Interaction Effects in Floodwalls. *Electronic Journal of Geotechnical Engineering*, Vol. 2, 1997) discussed the need to include hydrostatic water pressures with regard to a gap forming between the pool side soil and wall in the numerical modeling of sheetpile floodwalls. Work, not directly related to levee or floodwalls, in England discussed the deflection and hydrostatic water pressure problem for earth retaining walls. How do these puzzle pieces get placed 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?

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 and greater frequency as the generation of new knowledge continues to accelerate.

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 re-emphasize technical expertise and renewal of 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. The Corps should be a leader in this area.

Synopsis of Principal Lessons Learned

The principal lessons learned from the primary areas of analyses are presented below by major topical area. These lessons learned are discussed in more detail in the individual volumes cited that provide the full details of the IPET work in each area.

Geodetic Vertical and Water Level Datums (Volume II). 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 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. The relatively recent advent of LIDAR systems will contribute to updating elevations over large areas such as New Orleans.

The Hurricane Protection System (Volume III). Design methods and designs need frequent review to determine whether they represent best practice and knowledge. Designs in coastal hurricane 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 Storm (Volume IV). Meteorological designations such as the Saffir-Simpson scale by themselves are not adequate to characterize the distributed surge and wave conditions that a hurricane protection system will face. Sophisticated modeling using physics-based codes with high spatial resolution is necessary to depict the highly 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 SPH process is outdated. 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 Performance (Volumes V and VI). The design approaches taken for the outfall canals were not conservative enough to deal with the unknowns. Floodwall design methods need to consider a broader spectrum of possible behaviors, and resilience 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 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. Integration of armoring is especially important to provide resilience to erosion. 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.

The Consequences (Volume VII). Losses from a hurricane event causing water levels that exceed design criteria can be expected to be significant, but can be much less if the hurricane protection system has a high level of resilience. While the reduction in direct losses can be substantial and readily estimated, 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 rapidly recover. In addition, the perceived character and expected performance of the hurricane protection system itself is a significant factor in the choices people will make with respect to re-population and re-investment.

If there is one lesson learned from the Consequence analysis, it is the direct correlation of losses with elevation, or lack thereof. 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 sub-basin. Areas with lower elevations experienced the most severe losses and will continue to harbor the highest probabilities of experiencing flooding into the future.

A broad and systems-based planning capability can increase the effectiveness of integrating evacuation, recovery, and reconstruction aspects into the hurricane protection system. 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.

Risk and Reliability (Volume VIII). Risk and Reliability lessons learned will be incorporated into the report after completion of the ongoing validation of the risk methodology and risk products as recommended by the ASCE External Review Panel.

Overview

Introduction

Last year the world watched Hurricanes Katrina, Rita, and Wilma devastate the Gulf Coast. 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 hurricane protection system 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 the evolution of hurricane protection in the New Orleans region, a descriptive synopsis of what happened during Katrina through the eyes of the analyses accomplished, a brief description of IPET, and a synopsis of the organization and content of this report.

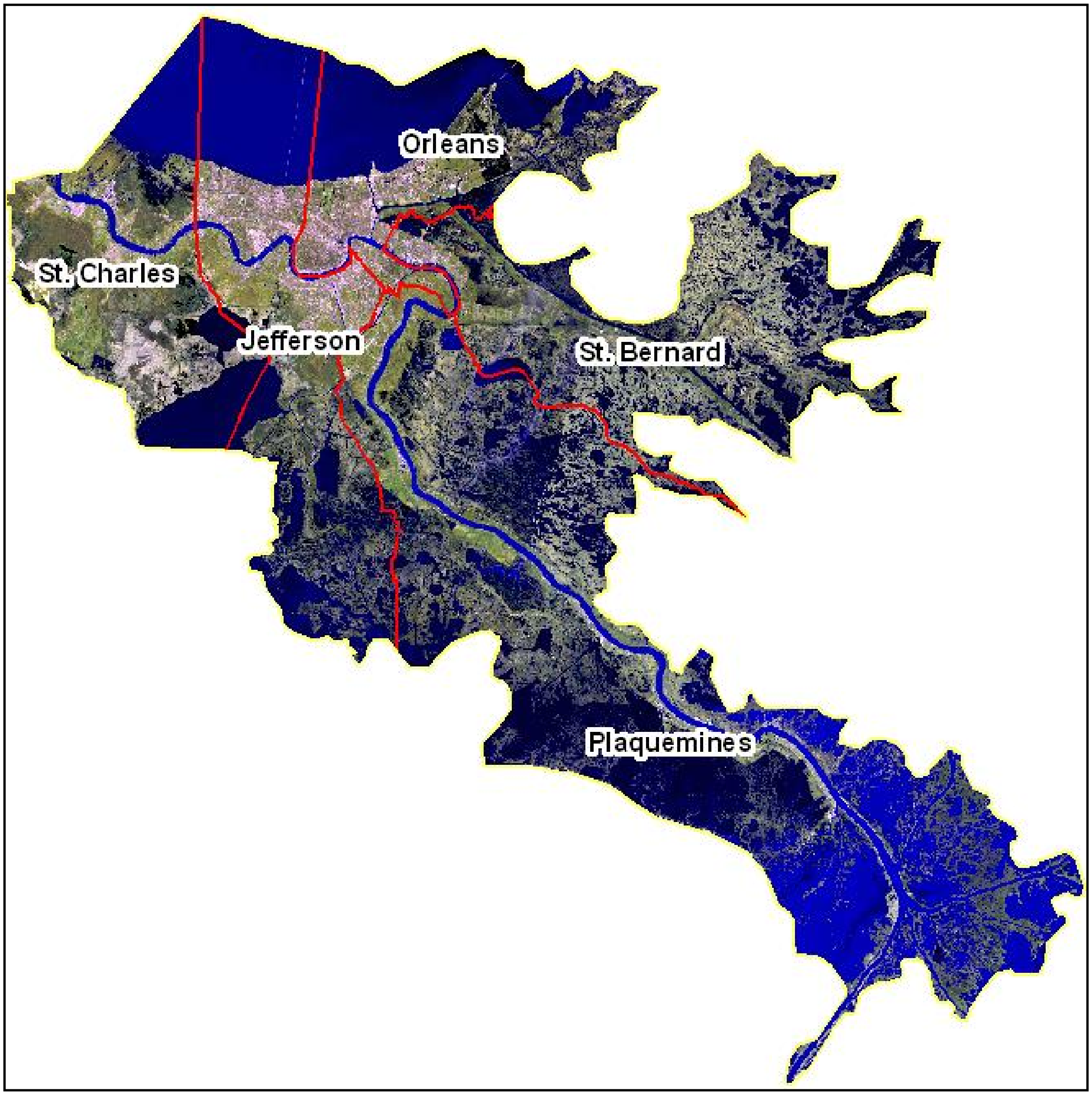

Figure 1. Principal area of analysis

Historical Perspective

Located in the low-lying Mississippi River delta in Louisiana, large portions of the city of New Orleans lie near or below sea level, a fact that 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, Louisiana, area has been from hurricane-induced storm surges, waves, and rainfall, especially those associated with Hurricane Betsy in 1965, Camille in 1969, and Lilli in 2002. Although some hurricane protection had been provided to a few areas of New Orleans, it was not until Hurricane Betsy struck the city, killing 75 people and causing substantial damage and loss of property, that a comprehensive hurricane protection plan was initiated. Over time, three hurricane protection projects have been designed and partially constructed in New Orleans and the Southeast Louisiana region: Lake Pontchartrain and Vicinity, the West Bank project, and the New Orleans to Venice project. The Lake Pontchartrain and Vicinity project is used here to illustrate the events that preceded Hurricane Katrina.

Congress first authorized the Lake Pontchartrain and Vicinity hurricane protection under the Flood Control Act of 1965. The project was intended to protect areas around the lake (in the parishes of Orleans, Jefferson, St. Bernard, and St. Charles) from flooding caused by a storm surge or rainfall associated with a hurricane that would be roughly the same as what is today classified as a fast-moving “Category 3” hurricane. The basis for this was the standard project hurricane (SPH) developed by the Corps with the assistance of the U.S. Weather Bureau (now the National Weather Service). The model (assumed at that time to represent a storm that would occur once in 200-300 years) was intended to represent the most severe meteorological conditions considered reasonably characteristic for that region: winds up to 111-113 miles per hour and that can be expected to cause some structural damage from winds and flooding near the coast from the storm surge and inland from rains. Although federally authorized, the 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 Corps of Engineers was assigned responsibility for project design and construction, and the local interests were responsible for maintenance of the levees and flood controls.

During the first 17 years of construction of what has become known as the “barrier plan,” 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. The barrier plan included a series of levees along the lakefront, concrete floodwalls along the IHNC, and control structures, including barriers and flood control gates located at the Rigolets and Chef Menteur Pass areas. These structures were intended to prevent storm surges from entering Lake Pontchartrain and overflowing the levees along the lakefront. A paradox of these massive levees is that in keeping water from the city, they also prevent Mississippi River sediment--which has historically been important in replenishing deltaic land surfaces--from spreading across the region. As a result of this and other activities such as pumping of groundwater, many areas of the city have been slowly subsiding, which has further exacerbated flood risks.

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. After the court order, the Corps changed course and recommended abandoning the barrier plan and shifting to what became known as the “higher level plan” originally considered in the early 1960s. Local sponsors executed new agreements to ensure their share of the non-federal contribution to the revised project. Even before construction began on the barrier plan, design changes to raise the levees along the three main drainage canals that drain water from New Orleans into Lake Pontchartrain were incorporated to protect against storm surges from the lake. The construction of higher levees has long been an option for reducing risks, but they are expensive to build, require the acquisition of additional lands, and may entail negative aesthetic and environmental consequences.

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 in Orleans Parish, 70 percent complete in Jefferson Parish, 90 percent complete in the Chalmette area, and 60 percent complete in St. Charles Parish. The estimated completion date for the entire project was 2015. In recent years, questions were raised about the ability of the project to withstand hurricanes with intensities greater than those assumed for the original design. 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.

Katrina

The hurricane protection system, outlined on the map in Figure 2, includes approximately 350 miles of protective structures, 56 miles of which are floodwalls. The majority of the floodwalls are I-walls with some sections of T-walls and a small amount of L-walls. Figure 3 provides a schematic of the basic geometry of these structures. The elevation of the current hurricane protection structures are significantly below the originally authorized heights in part from errors in initial constructed elevations and in part from rapid subsidence. Figure 4 provides a general map of the New Orleans metropolitan area and the features of the hurricane protection system that were factors in the system performance during Katrina.

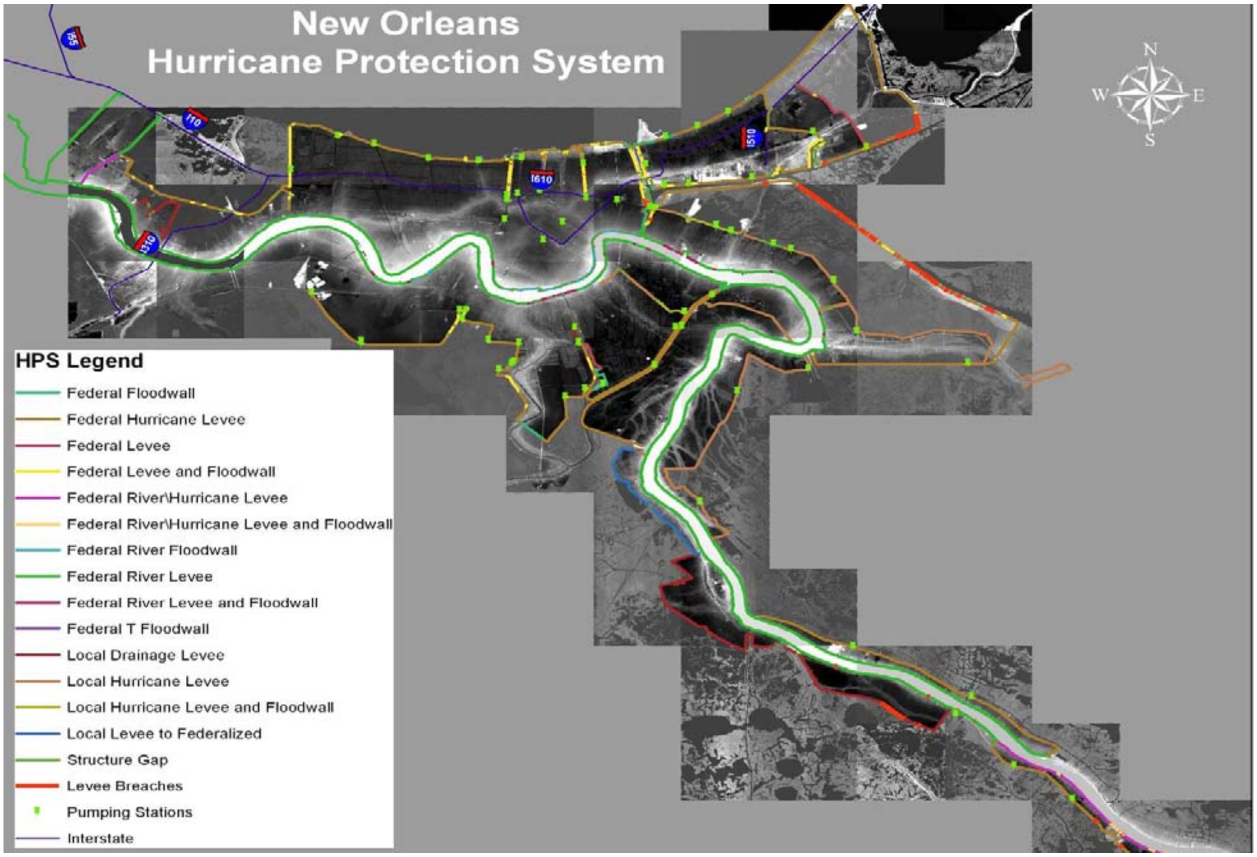

Figure 2. Outline of the New Orleans and Southeast Louisiana Hurricane Protection System

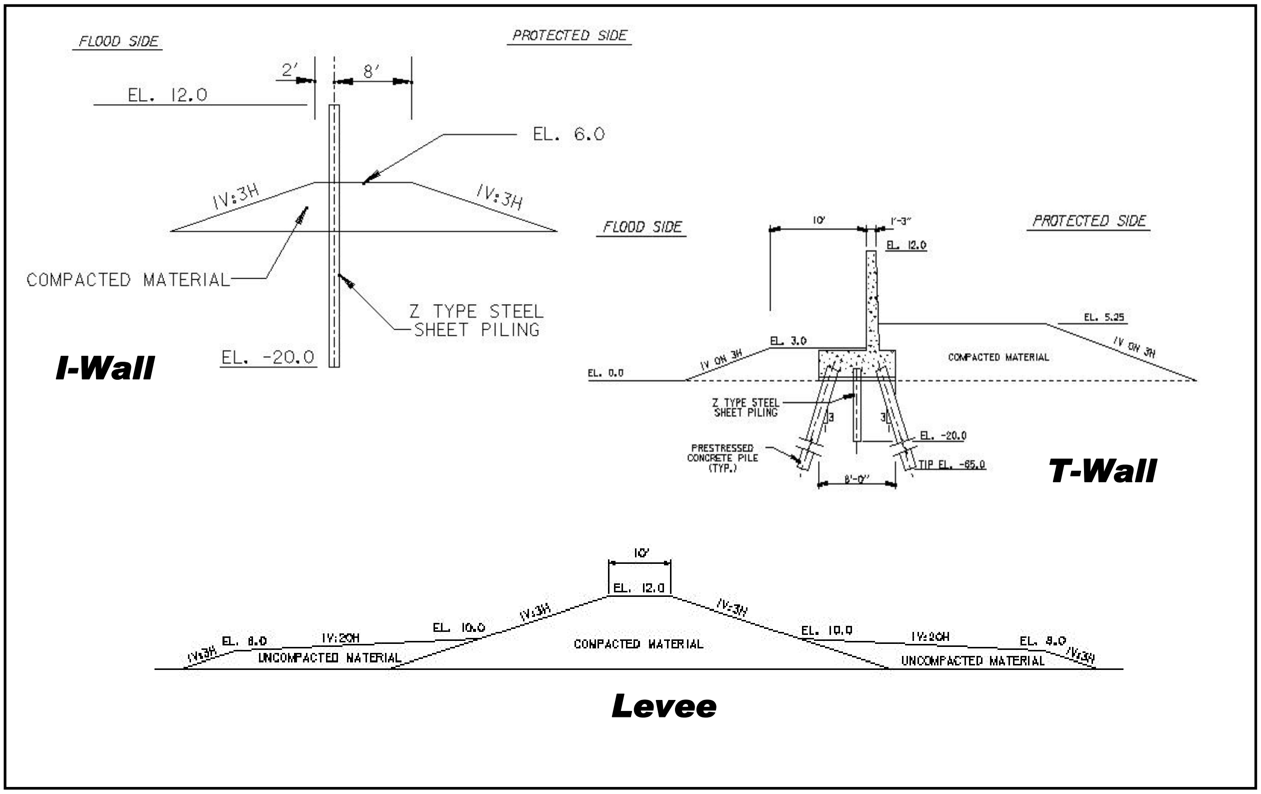

Figure 3. General schematic of major hurricane protection structures used in New Orleans and vicinity

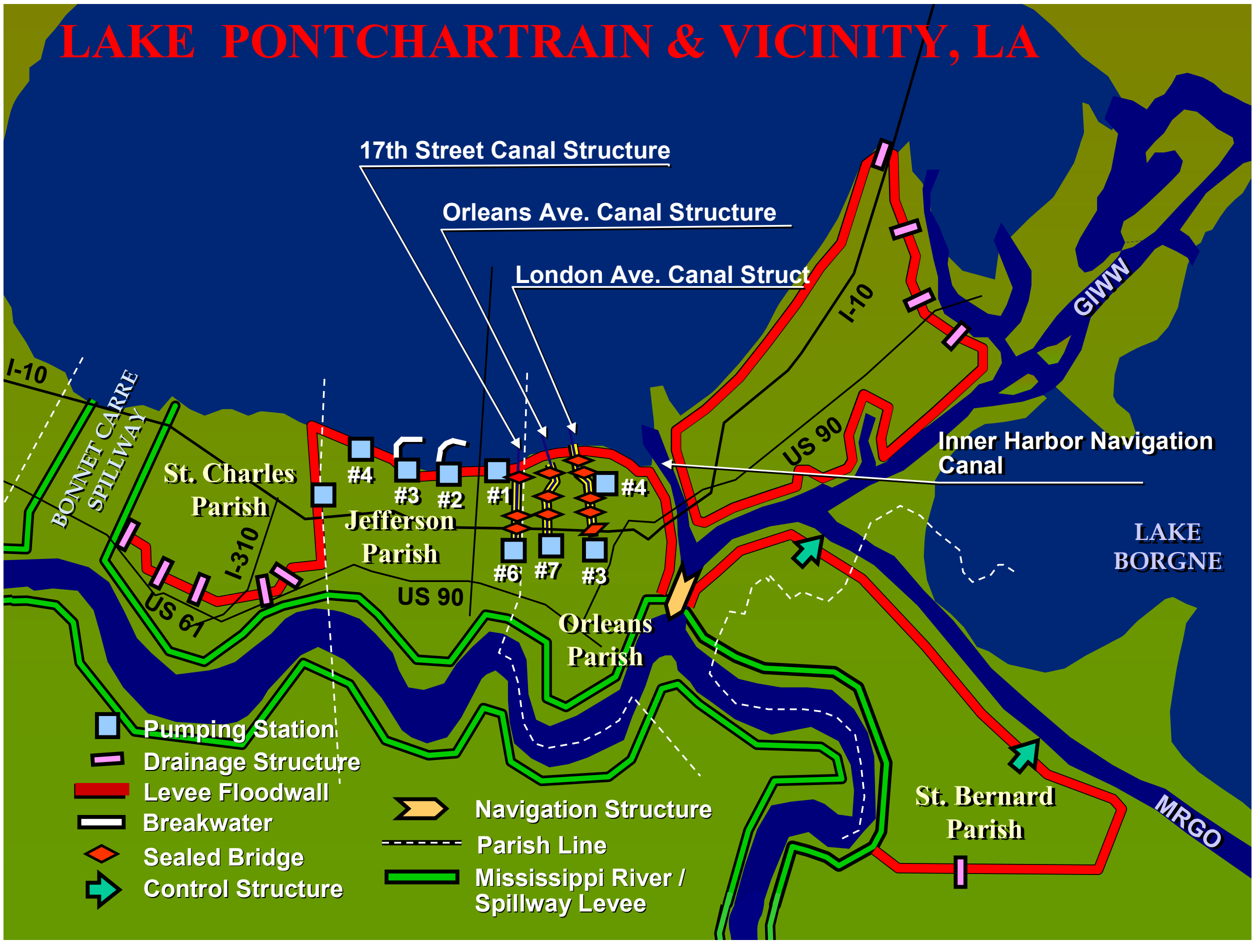

Figure 4. Map showing detailed geometry and features of the New Orleans metropolitan area

The path followed by Hurricane Katrina, shown in Figure 5, caused severe surge and wave conditions on the east side of the hurricane protection system, from Lake Pontchartrain to southern Plaquemines Parish. It 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 175-mph winds until it was approximately 170 miles from landfall. When it reached landfall at Buras, LA, around 0630 hr, wind speeds were at 127 mph, but the long path through the Gulf had built up record levels of surge and waves, larger than any previous storm to strike the area, or the North American continent.

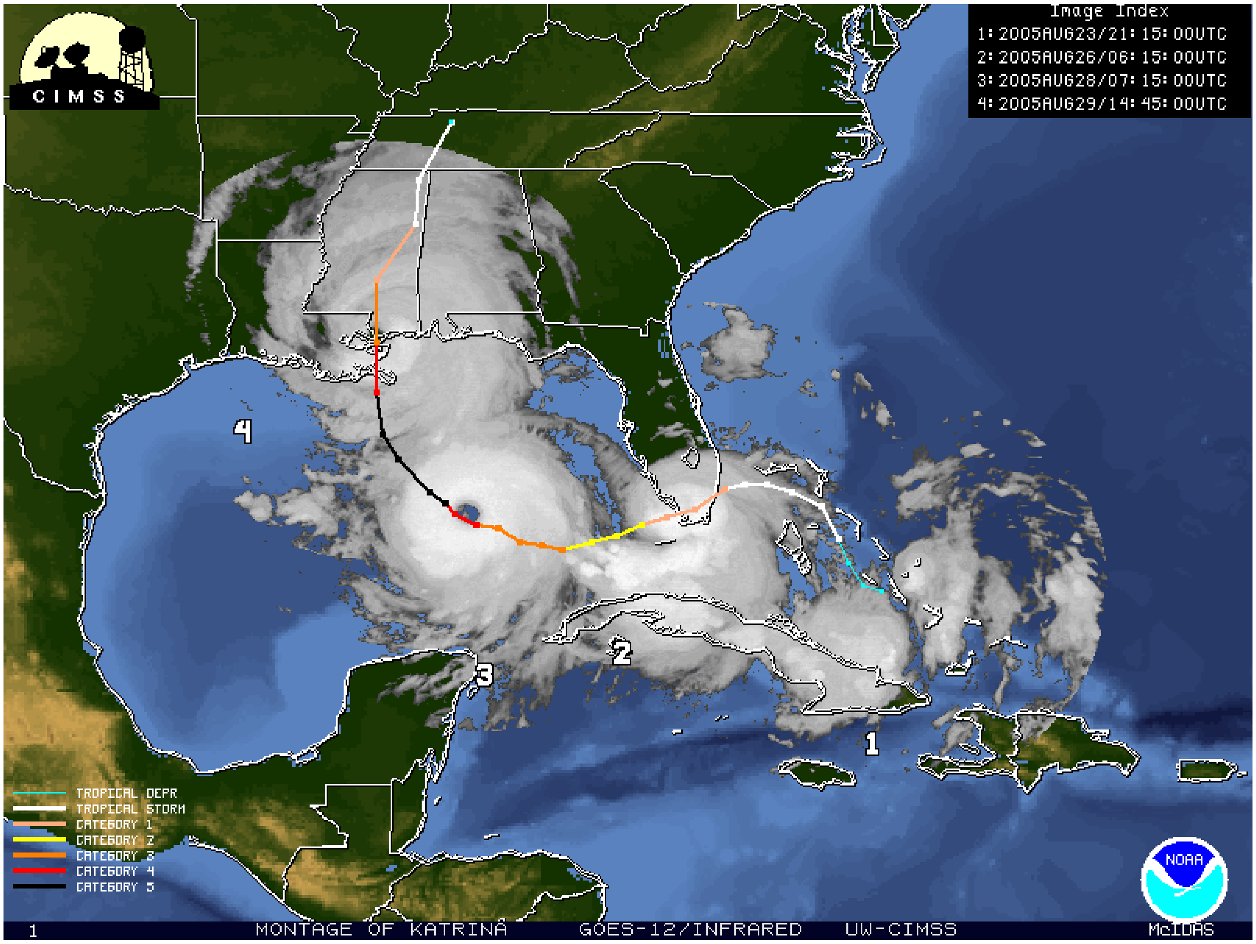

Figure 5. Hurricane Katrina path and intensity history

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. Whereas the Saffir-Simpson scale is a good predictor of wind damage from hurricanes, it is not a particularly good predictor of the surge and wave generation potential for these storms. Hurricane Katrina had much greater wave and storm surge generation potential than the Standard Project Hurricane storms used to design the hurricane protection system.

Katrina swept through the New Orleans area rapidly, making a second landfall at Pearl River, MS, around 0945 hr with wind speeds still around 121 mph. With it came record rainfall as shown in Figure 6. Over a 24-hr period sections of New Orleans near the intersection of Lake Pontchartrain and the IHNC received over 14 in. of rainfall. The previous record was from Hurricane Betsy which dumped up to 7 in. in the same time frame. This rainfall was to become at least 20 percent 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 surge and waves significantly beyond their design levels. Overtopping was common and would persist in some areas for hours.

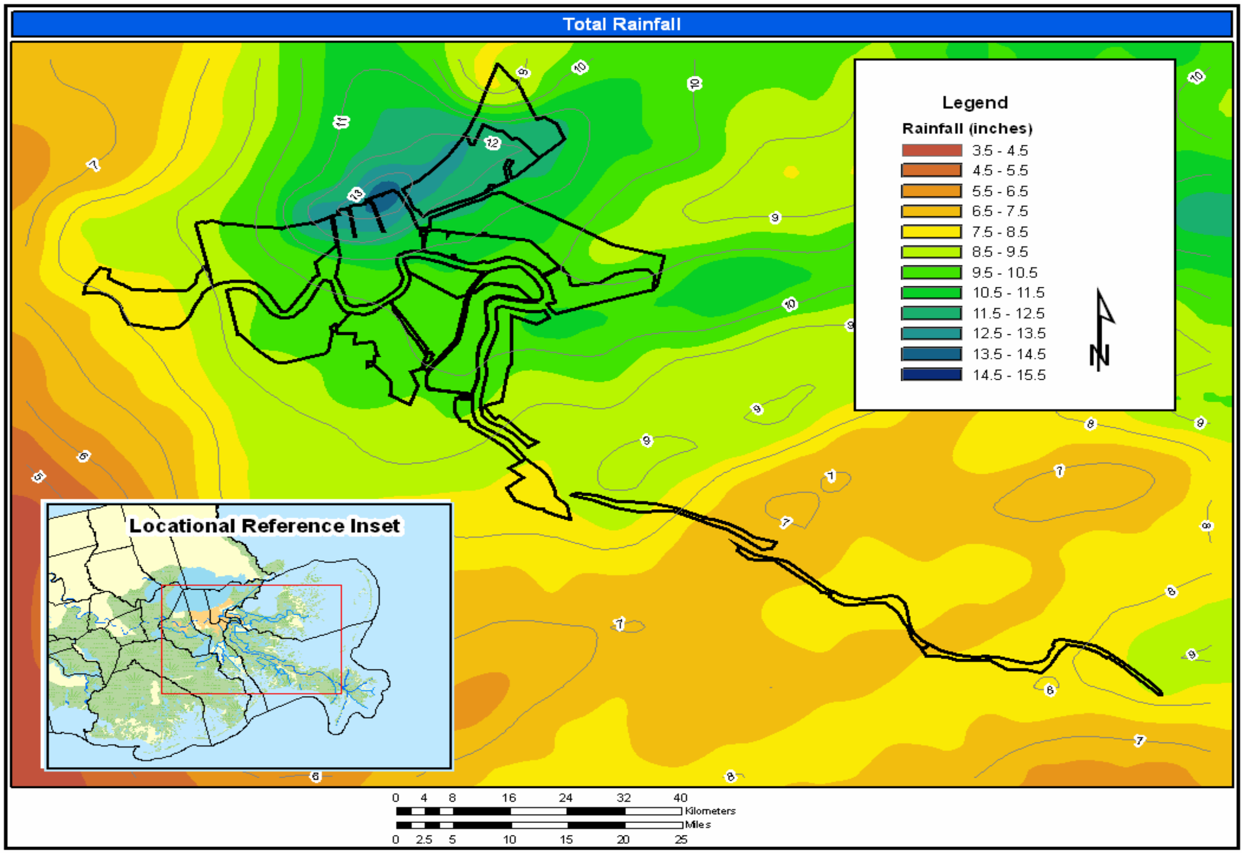

Figure 6. Hurricane Katrina rainfall totals

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 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 7 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. Surge levels ranged from in the neighborhood of 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.

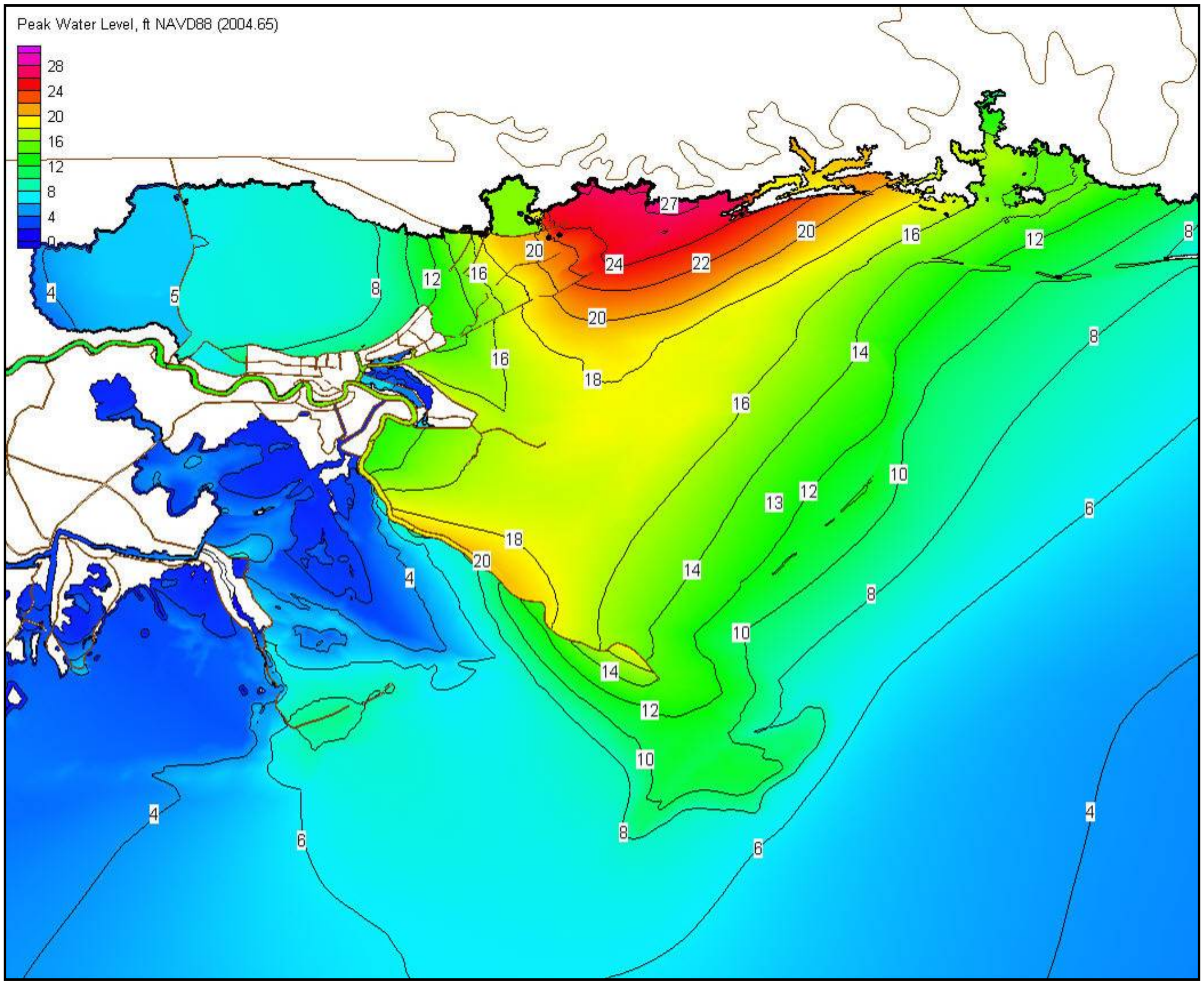

Figure 7. Maximum computed storm water level using the ADCIRC model, Mississippi to Louisiana region, water levels in feet, NAVD88 (2004.65).

Winds from Katrina generated a record-wave environment. Again, the lack of measurements caused the IPET to model the wind-generated waves to determine the conditions created by the storm. IPET used a nested approach that used the WAM model to generate wind wave fields for the entire Gulf, and STWAVE to model nearshore waves in and around New Orleans. The resulting wave heights and wave periods are shown in Figures 8-11. They demonstrate that the Katrina-generated wave environment was severe. The most significant finding was that the waves along the GIWW, St. Bernard, and Plaquemines levees were ocean-generated waves, with a wave period in the 16-sec range, much more capable of runup and overtopping structures.

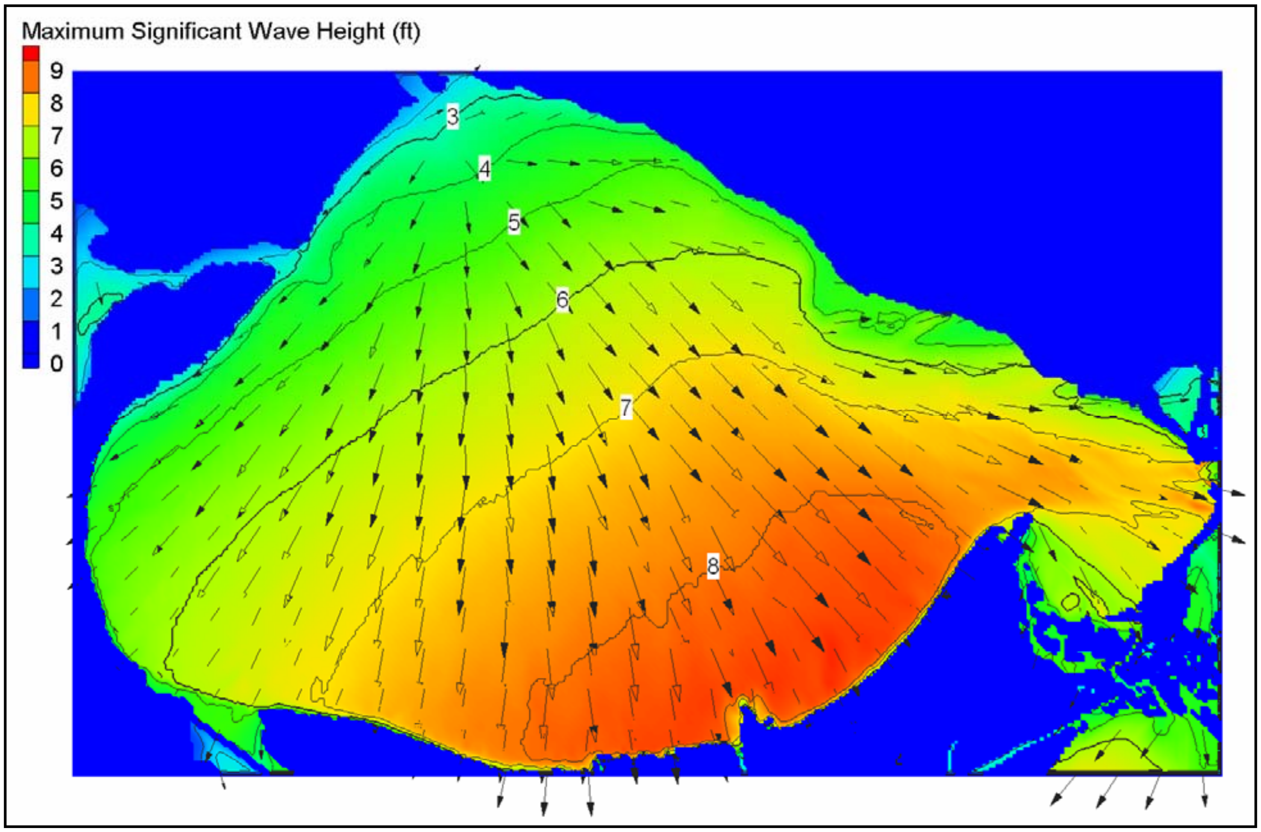

Figure 8. Lake Pontchartrain maximum modeled significant wave height and corresponding mean direction (wave heights in feet)

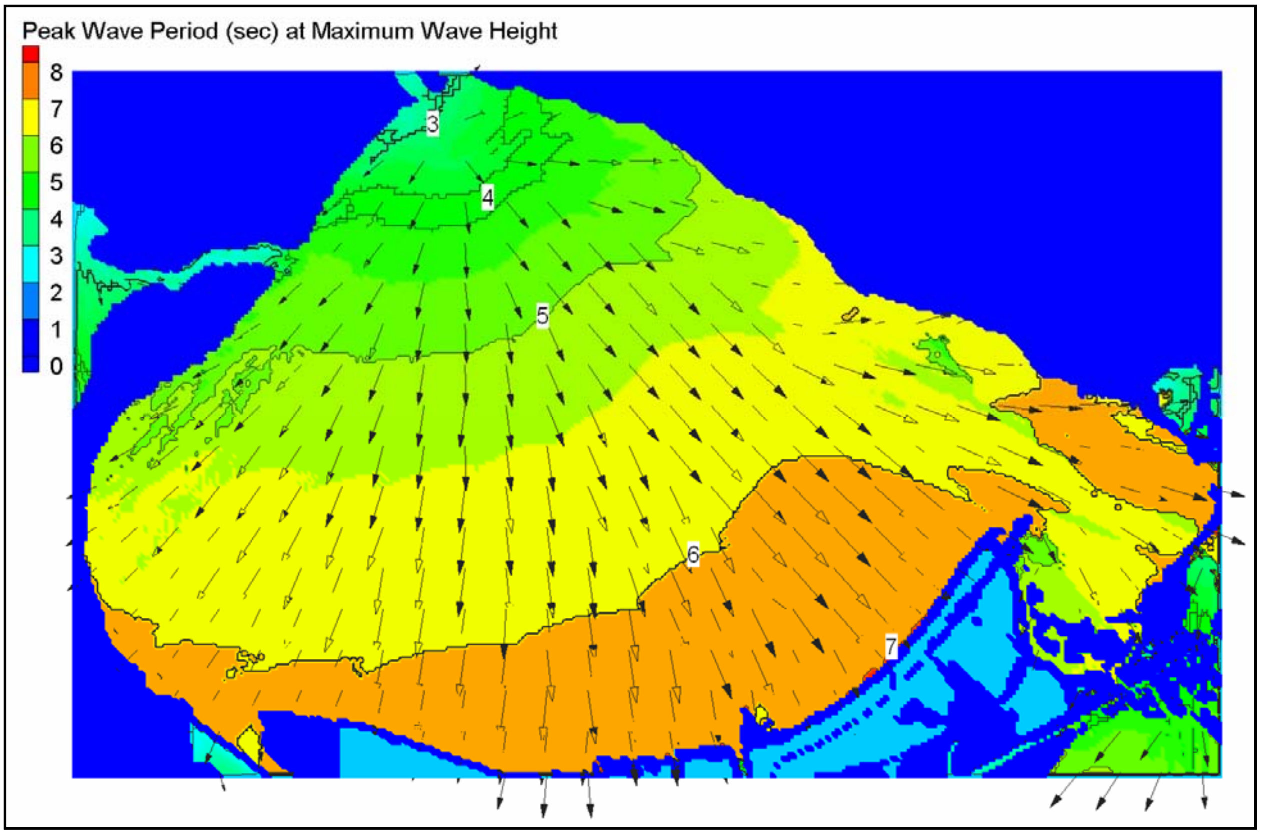

Figure 9. Lake Pontchartrain modeled peak wave period corresponding to the maximum wave height (periods in sec)

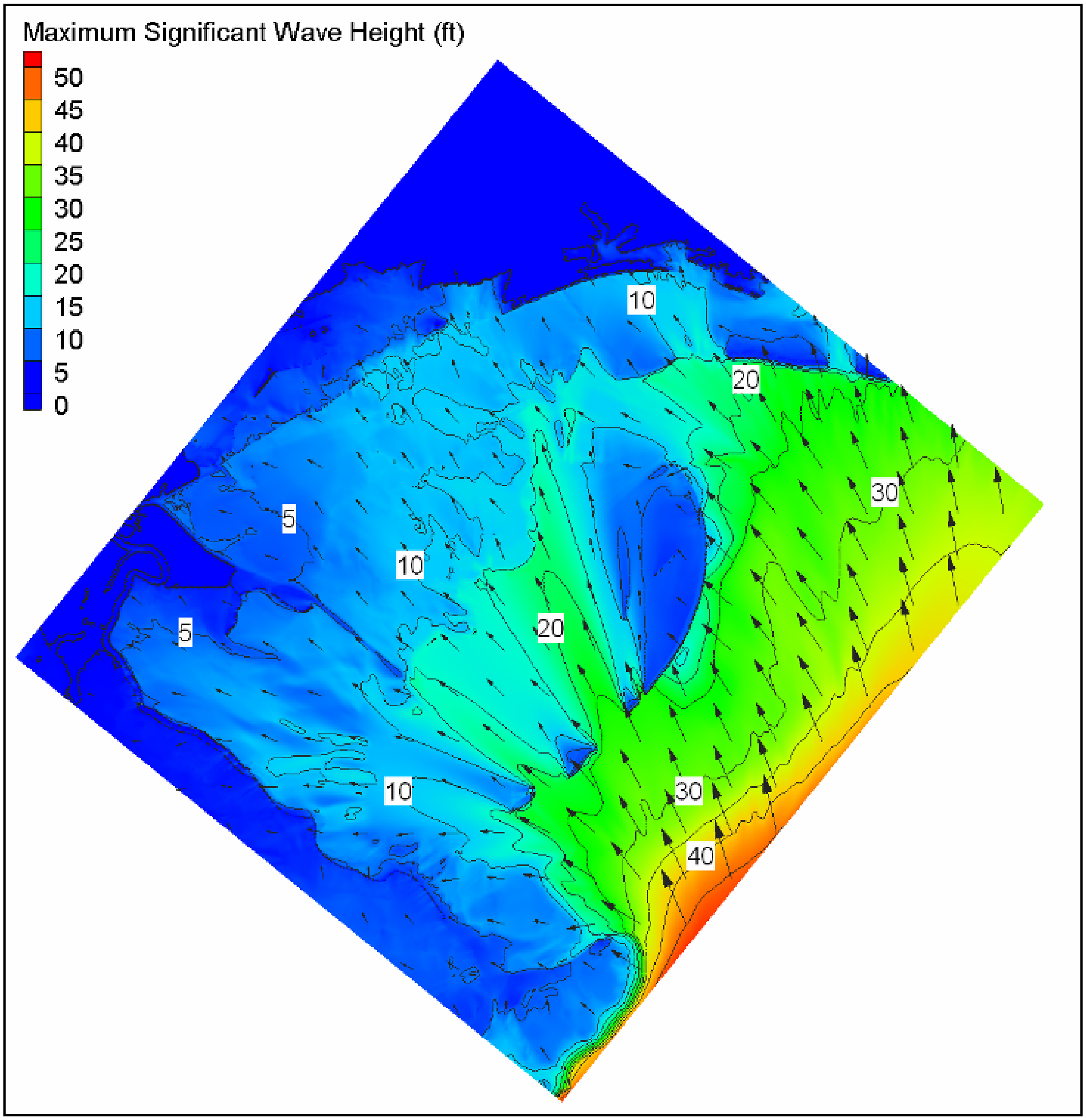

Figure 10. Southeast Louisiana maximum modeled wave height (wave heights in feet)

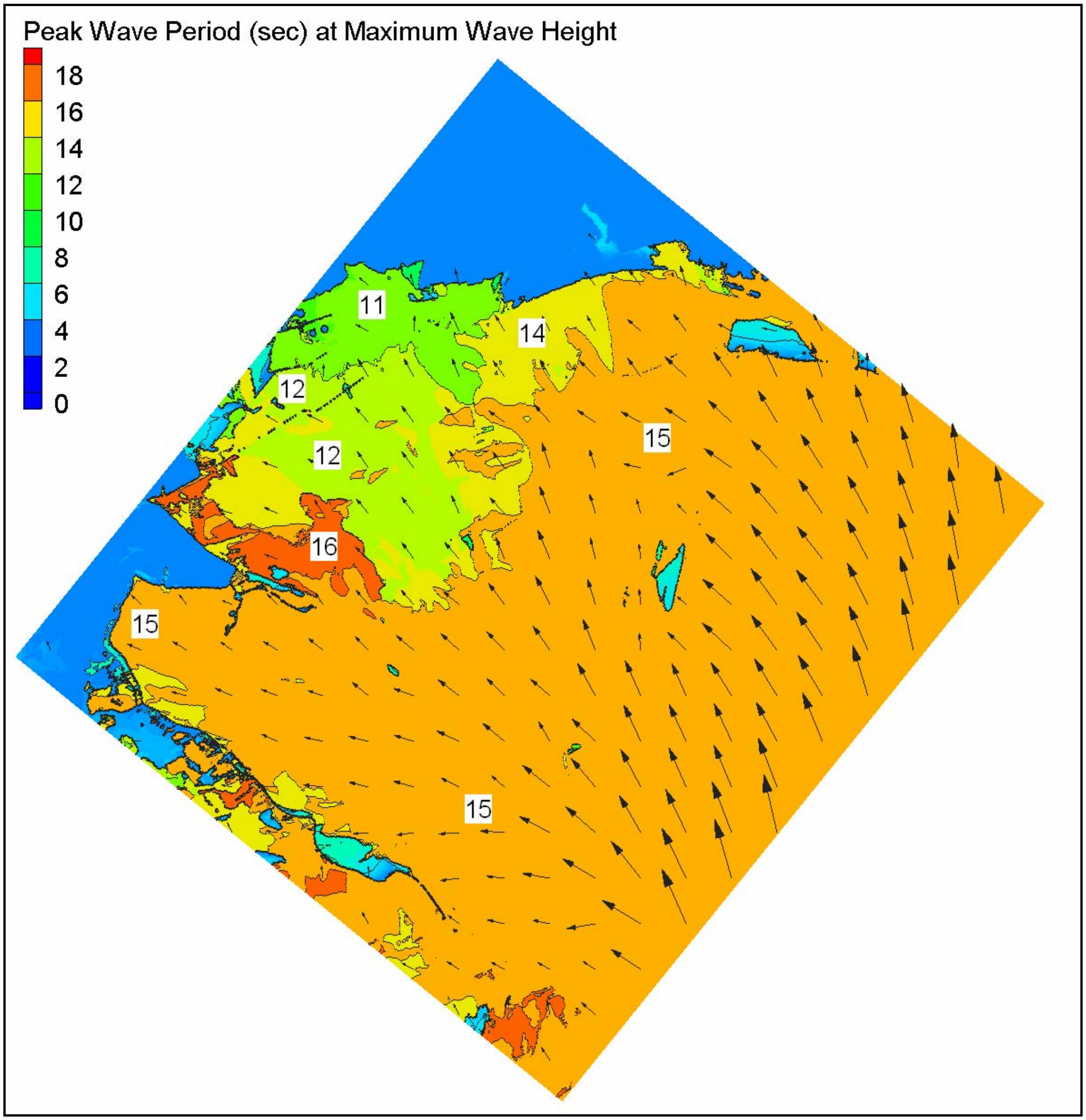

Figure 11. Southeast Louisiana modeled peak wave period corresponding to the maximum wave height (periods in sec)

Figure 12 shows the locations of the most severe damage to the hurricane protection system. Approximately 169 miles of the protective structures were significantly damaged by Katrina-generated surge and waves, as well as 34 of 71 pumping stations. A total of 41 miles of structures was judged to be severely damaged. There were a total of 50 major breaches, areas where the structures failed, 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 where either elevation or strength differences occurred from changes in structure type or capability.

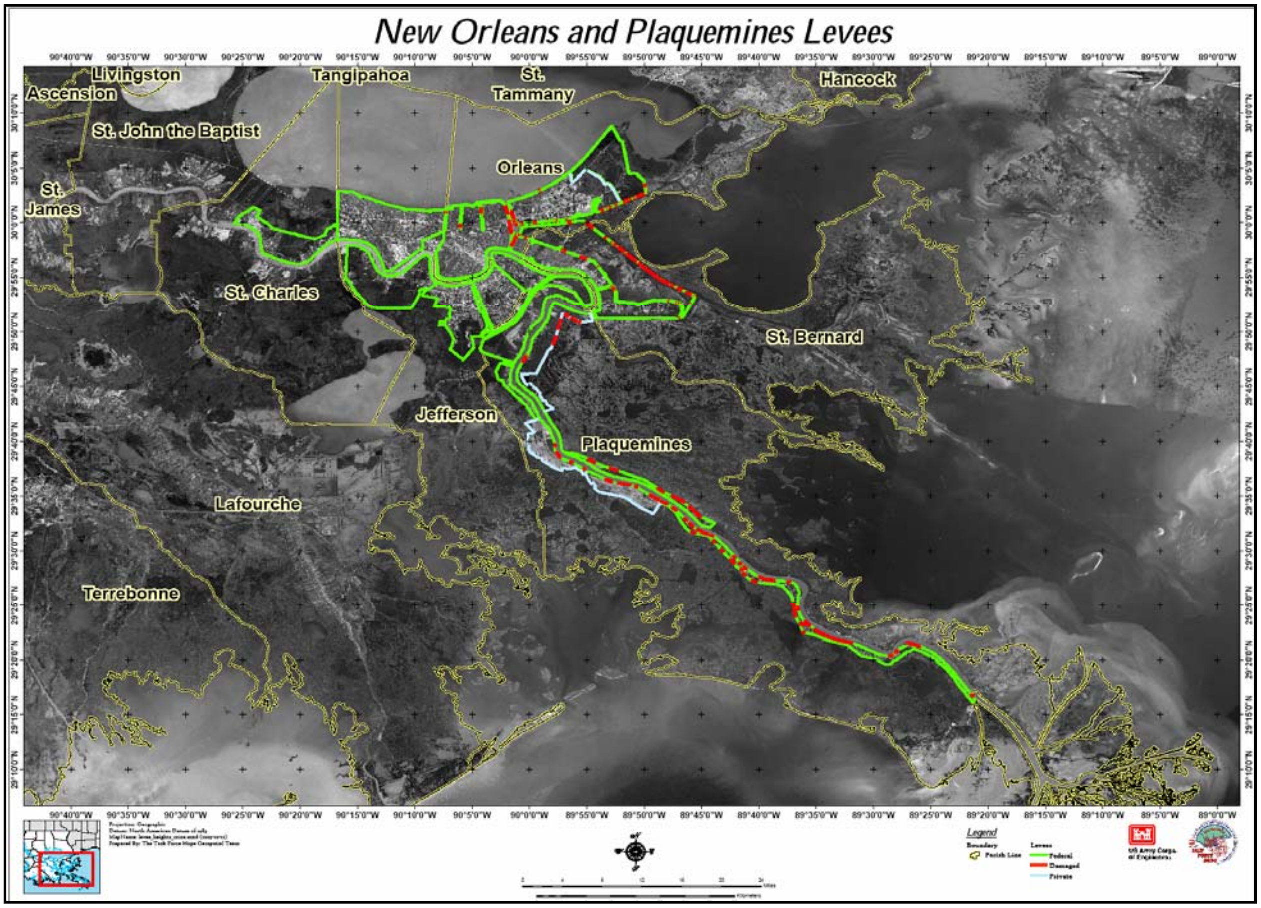

Figure 12. Locations (in red) of severe damage to hurricane protection structures resulting from Katrina

The storm surge and waves first attacked the Plaquemines levees well before Katrina's landfall, causing significant overtopping and erosion before dawn. The MRGO 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 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 (Figure 13) and MRGO (Figure 14) that were constructed with hydraulic fill. The overtopping waves created very high water velocities down the back sides of the levees, reaching 10 to 15 ft/sec. These velocities were two to three times those experienced on the water side of the levees. 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, were scoured away leading to, in many cases, complete breaching. Figure 15 shows the close correlation between the degree of breaching from overtopping and erosion and the types of materials, In this example for New Orleans East, the correspondence of breaching and hydraulic fill constructed levees is obvious.

Figure 13. Example of levee along New Orleans East, GIWW, breaching from overtopping and scour of erodible materials

Figure 14. Example of levee breach along MRGO from overtopping and scour of erodible materials

Figure 15. Correlation of levee breaching with type of levee materials for New Orleans East

Four I-wall failures that resulted in breaches and very significant flooding occurred on the morning of August 29th.

At about 5:00 AM, the Lower Ninth Ward was flooded by a breach in the I-wall on the east side of the IHNC. The failure occurred when the water elevation in the IHNC was 10.5 ft, about 2.0 ft below the top of the wall. The failure was caused by instability in the foundation soils beneath the I-wall and the levee. The failure was aggravated by deflection of the I-wall as the water rose in the canal. This movement of the I-wall caused separation of the wall from the levee fill soil on the canal side of the wall, and formation of a gap extending down to the bottom of the wall. Water entering this crack subjected the wall to high water pressures and greatly increased loads, leading to gross instability and a breach through the wall as the water continued to rise.

At about 6:30 AM, with water at elevation 7.0 ft in the 17th Street Canal, the I-wall on the east side of the canal was breached, flooding the adjacent neighborhoods. The mechanism of failure was the same as at the IHNC – development of a gap between the I-wall and the levee fill, which resulted in increased water load on the wall. The design of the wall at this location had not recognized lower strength beneath the toe of the levee than beneath the crest, and this fact resulted in an I-wall with less capacity than would otherwise have been the case.

At about 7:00 AM a breach occurred on the London Avenue Canal near Mirabeau Avenue. About an hour later a second breach occurred on the London Avenue Canal, near Robert E. Lee Boulevard. Like the 17th Street Canal and the IHNC breaches that occurred earlier, the London Avenue Canal breaches involved formation of a gap between the wall and the levee fill on the canal side of the wall (Figure 16). At the London Avenue Canal, an additional effect of the gaps was that water flowed down through the gaps into the underlying sand. High water pressures in the sand uplifted the marsh layer on the landside of the levee, resulting in concentrated flow and erosion, removing material and reducing support for the floodwall, which failed catastrophically.

Figure 16. Example of I-wall breach on London Avenue Outfall Canal (north breach) resulting from formation of a crack along the water side of the floodwall, introducing high pore pressures under the levee and causing uplift and failure

The I-wall failure mechanisms at the IHNC, 17th Street Canal, and London Avenue were investigated by field explorations, laboratory tests to measure soil properties, limit equilibrium analyses of stability, finite element analyses of seepage and soil-structure interaction, and centrifuge model tests. These numerical analyses and physical tests all showed that the formation of gaps behind the walls was a key element in the failure (Figure 17).

After the I-wall failure that resulted in the breach at the IHNC, the water level in the canal continued to rise (Figure 18). At 9:00 AM, the water reached elevation 14.2 ft, 1.7 ft above the tops of the levees and floodwalls. Water flowing over the walls when they were overtopped eroded trenches on the protected side of the walls as it cascaded onto the levee fill. Soil that was providing support for the walls was removed by this erosion, making the walls less stable, resulting in two additional floodwall breaches, one on the east side of the IHNC, south of the first breach, and one on the west side. A fourth IHNC breach occurred when an overtopped levee on the west side was eroded away when it was overtopped.

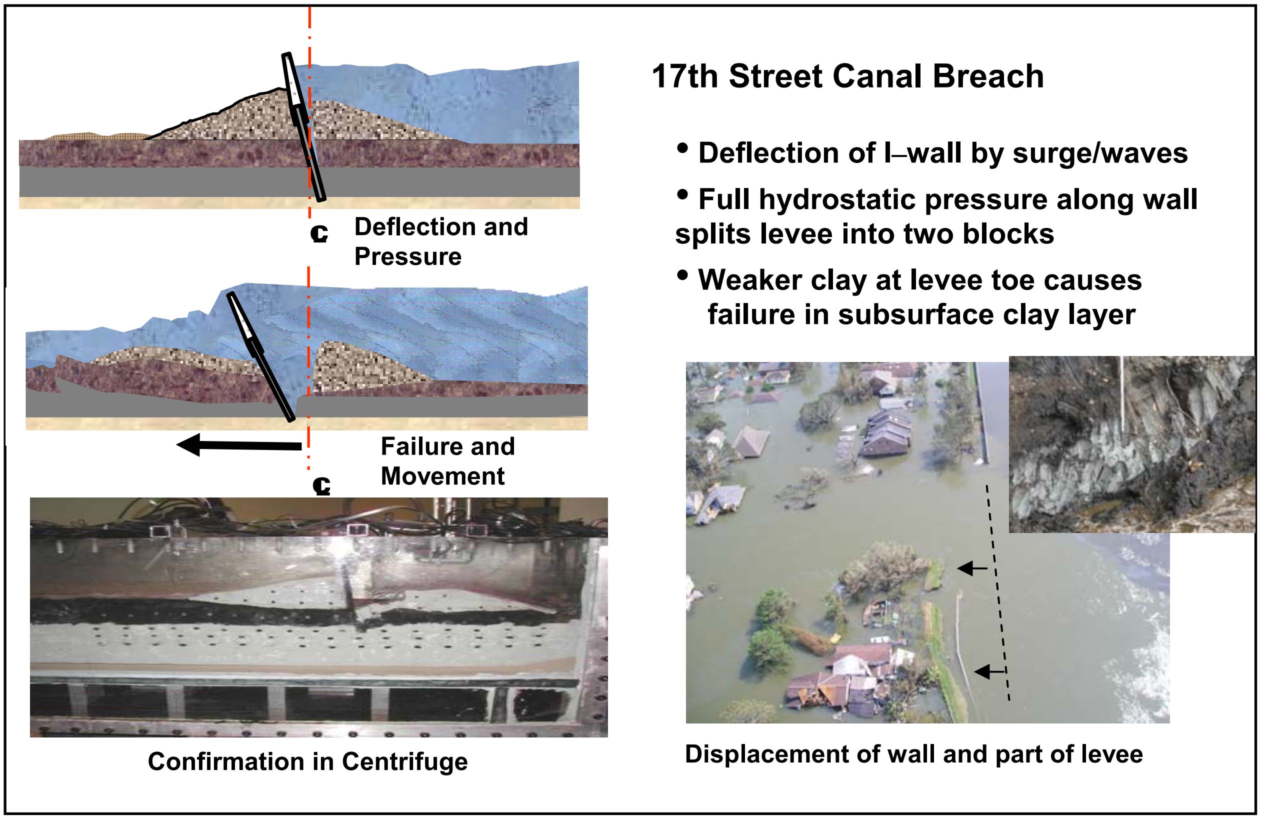

Figure 17. Depiction of failure mechanism for 17th Street and IHNC foundation failures. A crack forming along the front of the I-wall introduced high forces down the face of the sheetpile, resulting in lateral movement of the floodwall along a shear plane in the weak clay foundation

The flooding resulting from the overtopping and breaching was catastrophic. Figure 19 shows the extent and depth of flooding for the metropolitan area where almost 80 percent was inundated. Pumping stations were for the most part not operating due to prior evacuation of operators, loss of power, or loss of cooling water for the pumps. An evaluation of the pumping performance as a percentage of the total capacity is given in Figure 20. The pump stations in New Orleans were simply 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 reduced. Using temporary pumps and slowly bringing the permanent pumps on line after Katrina required 53 days to unwater the city.

Figure 18. Example of breach along IHNC (east side) from overtopping and scour (top) and scour behind adjacent section that did not fail (bottom)

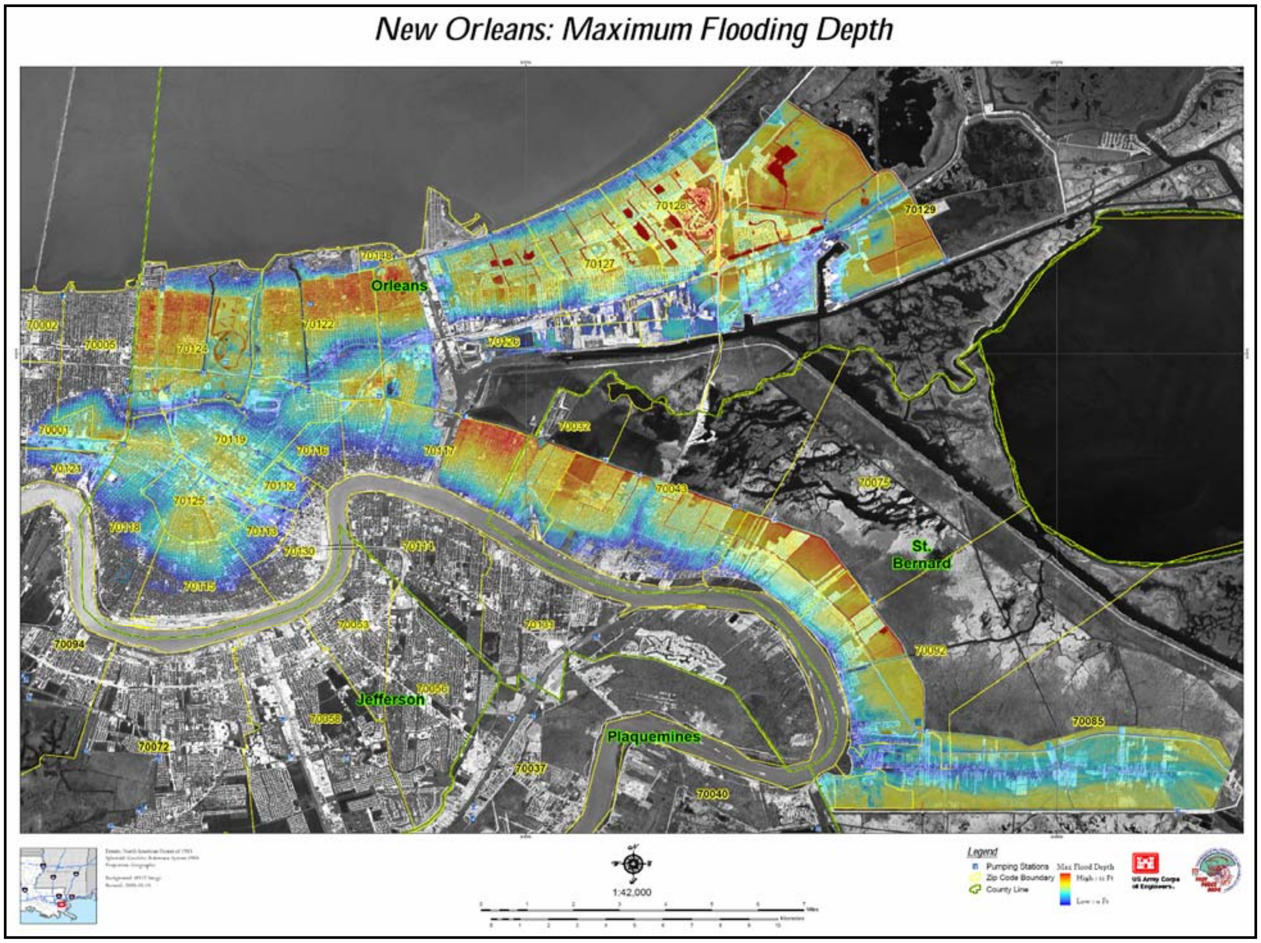

Figure 19. Map of maximum depths of flooding from Katrina

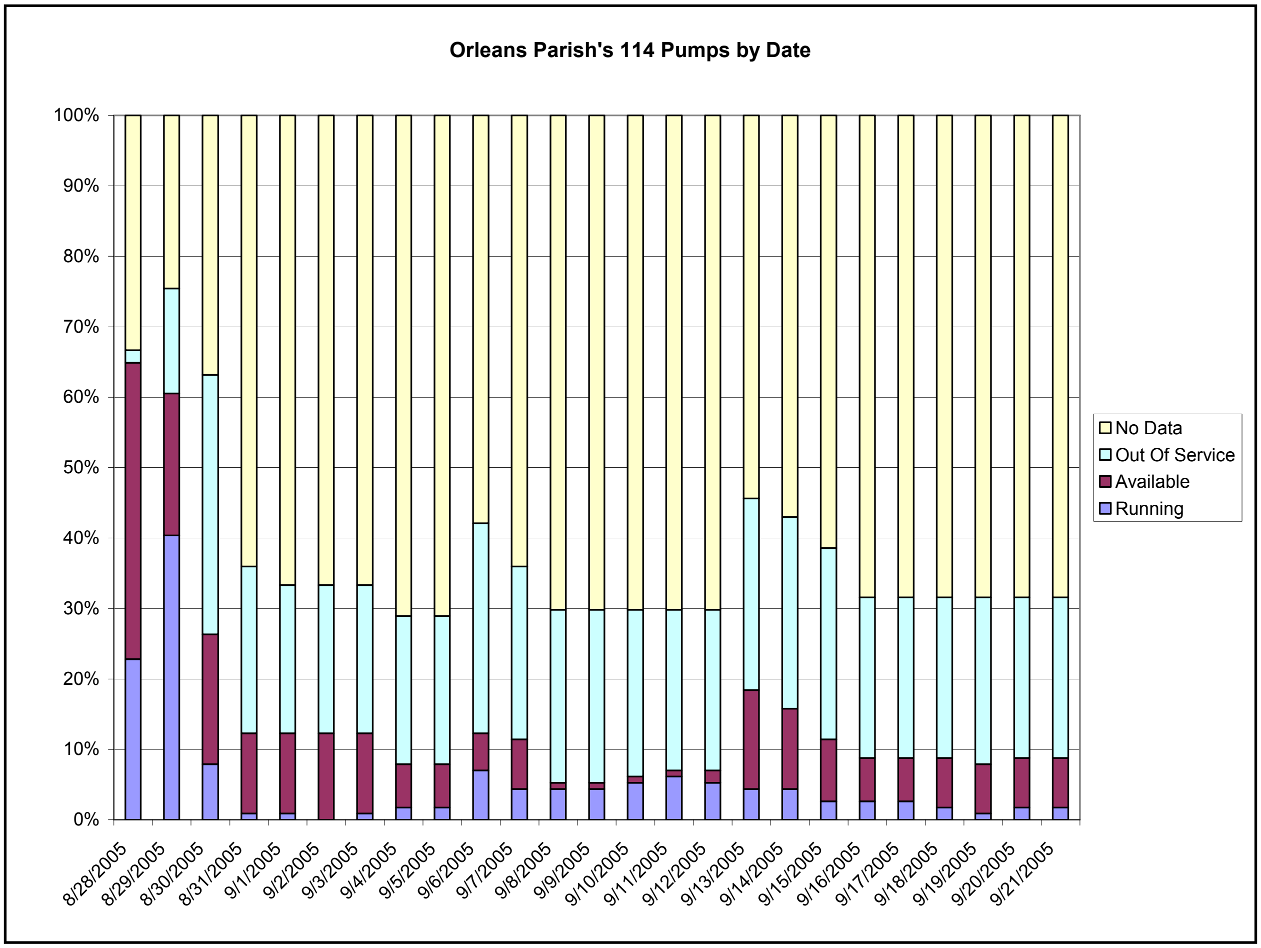

Figure 20. Example of pumping performance during Katrina

Scenarios run for the hypothetical situation of no levee or floodwall breaching, and assuming full pumping capacity, demonstrated that rainfall and overtopping would have caused extensive flooding, but that flooding in some areas, may be as little as one-third of that experienced during Katrina. Figure 21 is one example of that analysis for Orleans East.

The consequences of the flooding were enormous, dwarfing the losses from previous disasters. Figure 22 shows the distribution, by census block, of the percentage of the direct property losses (loss/value) that occurred in the metropolitan area. This graphic correlates primarily to elevation (depth of flooding) and concentration of assets. When coupled with the approximately $4.5 to $5.6 billion in public infrastructure damages, the total direct property losses for New Orleans alone reach nearly $25 billion. In contrast, Figure 23 shows the hypothetical percentage loss for the scenario of having no breaching (just overtopping) and full pumping capacity. While this scenario is not realistic for the time of Katrina, when added to the relationship shown in Figure 20, it is a testimony to the value of having a resilient hurricane protection system.

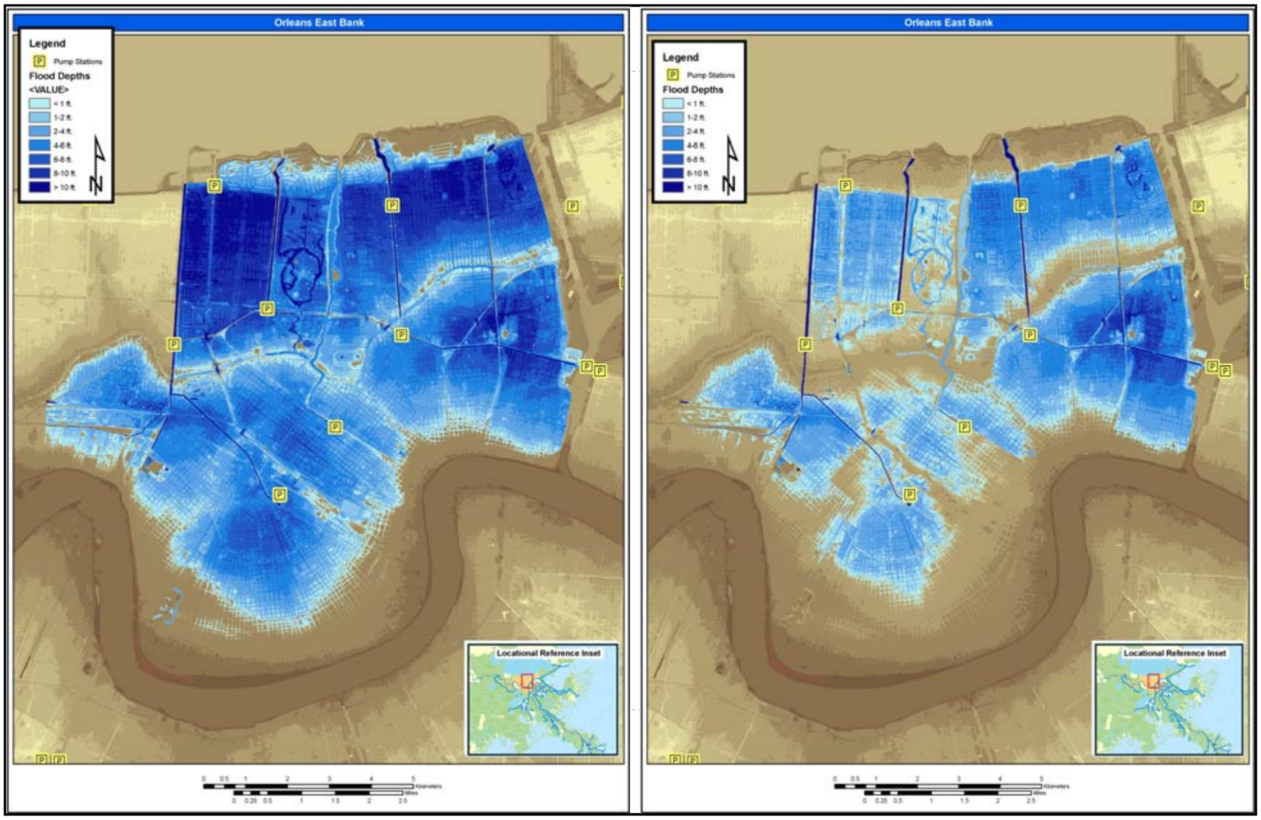

Figure 21. Comparison of flooding from Katrina (left) to hypothetical condition of no breaching and full pumping capacity (right) for Orleans East Bank

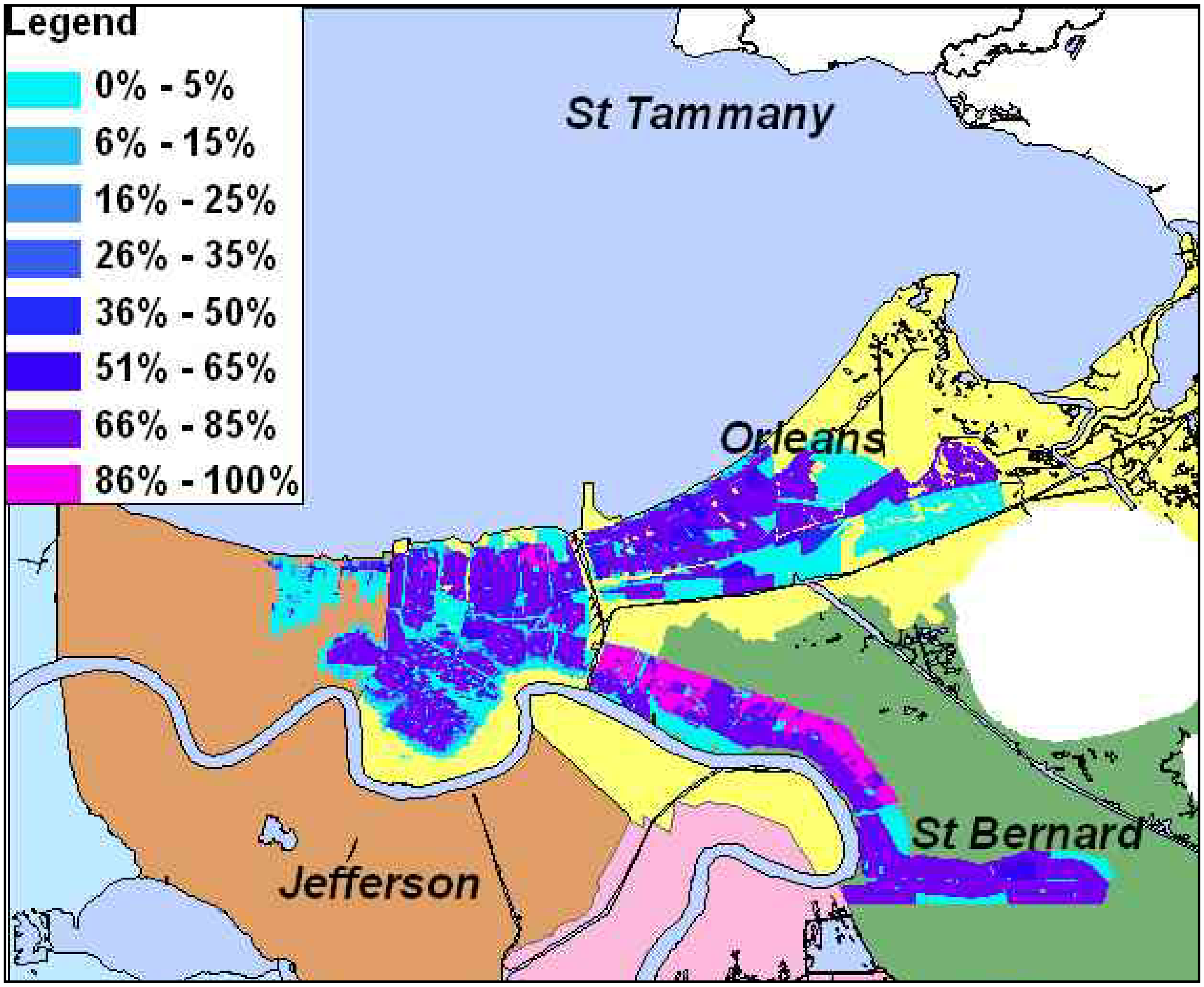

Figure 22. Distribution, by census block, of percent property damage (damage/value) from Katrina

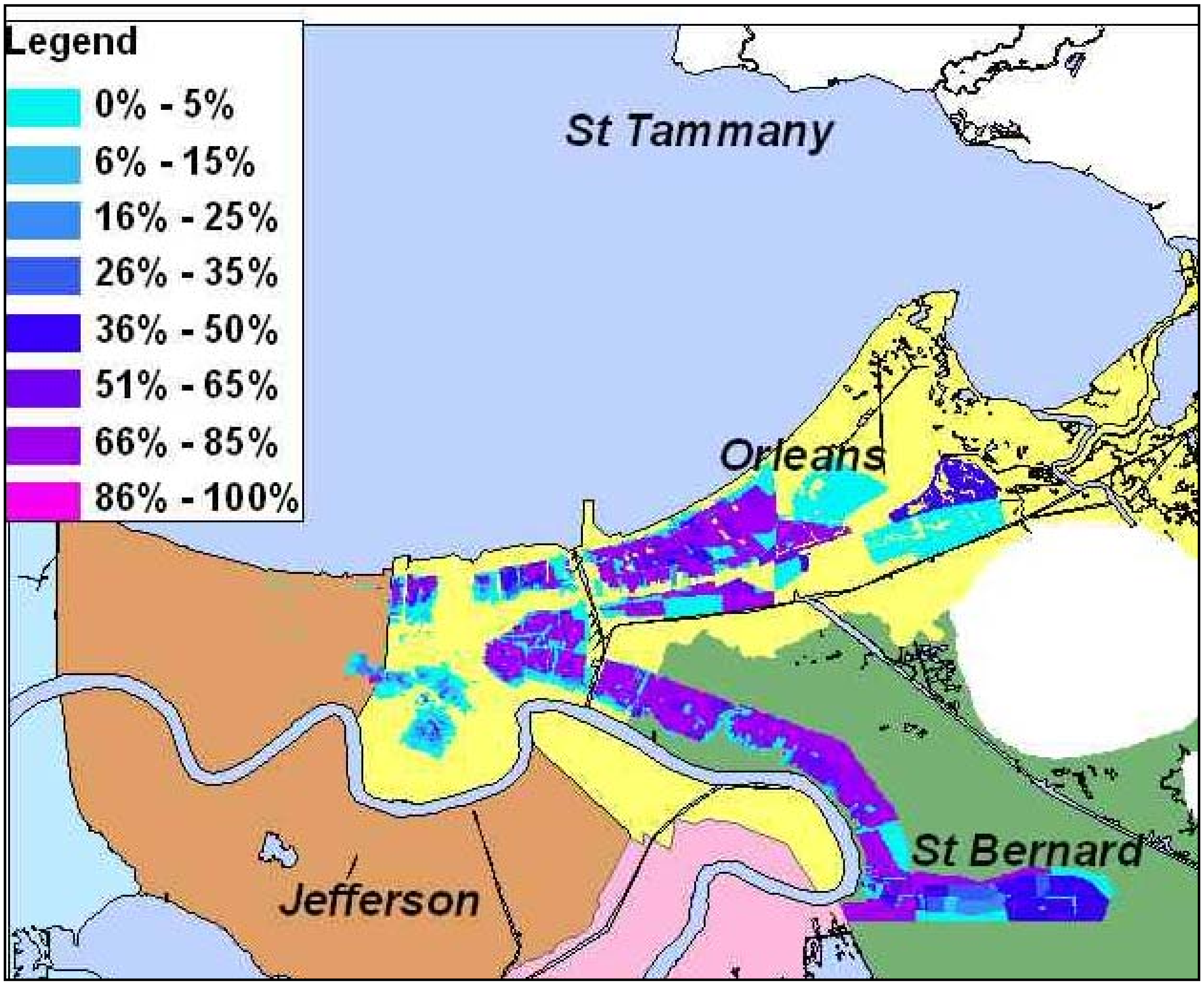

Figure 23. Hypothetical percent property damage (damage/value) for scenario of no breaching and full pumping capacity

The regional and long-term impacts are greater and have yet to be quantified. Loss of life was staggering with almost 1600 fatalities accounted for and another 400 missing and presumed dead. Loss of life was highly associated 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 in a disaster.

The flooding and resultant prolonged loss of services caused what has become 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 percent of the total. Commercial property losses were approximately 11 percent of the total while industrial losses were under 2 percent. 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 have been very slow to reopen.

Figure 24 shows an example of the pre-Katrina and post-Katrina (1 June 06) direct economic damage - elevation relationships developed for each subbasin. Similar relationships were developed for elevation and loss-of-life using Katrina data and the LifeSim model. Together these relationships provide a fundamental input to the risk and reliability analysis. The dramatic change in the curves from pre-Katrina to Post Katrina conditions represents the change in the value of the property from losses due to Katrina. Even if the probability of flooding remained the same, the risk (product of probability of flooding at a given level and level of consequences) for this subbasin would be decreased because of the reduced exposure for economic loss.

The risk prior to Katrina was significant, in part because New Orleans is mostly below sea level, in part because the hurricane protection system had not been completed, in part because it had not been tested, and in part because portions were just not up to the test. The gap component of the foundation failure mechanisms was not considered in the design of those structures and they had never experienced water levels above approximately 5 ft (compared to 8-10 ft in the outfall canals and over 14 ft in IHNC during Katrina). Levee sections created with hydraulic fill and capped with thin clay had never experienced design water levels, not to mention overtopping. Both components of risk were significant. The probability of a failure of floodwalls and some sections of levees were high, and there was a great potential for serious consequences because of the large population and extensive property being protected by the structures. The repairs since Katrina have been formidable and those sections of the system are no doubt the strongest. The temporary gates at the outfall canals will dramatically reduce the forces that the floodwalls along the canal experience. Replacing I-walls sections with stronger and higher T-wall sections along the IHNC will also significantly reduce risk, as will armor behind floodwall sections deemed vulnerable to overtopping and erosion. Rebuilding levee sections higher and with high quality clays will dramatically increase their resilience to overtopping. It is the other 40 percent that represent the greatest risk until additional measures can be taken to raise and strengthen them.

Given the ability to achieve an equal level of protection around the entire system, some areas will at least, in a relative sense, continue to harbor the greatest risk, those having elevations the most below sea level and those directly exposed to the full surge and wave environments that large storms can create. Given any overtopping, water will first inundate the lowest area. Coupled with rainfall, the performance (and therefore resilience) of the pumping stations will become the first line of defense. Given breaching, most likely where surge and wave environments can be most severe, the lowest areas again will flood first and flood the most. This risk assessment does not require the sophisticated model developed by the IPET, and it points out that there are rules of thumb that cannot be avoided. A risk model, however, gives planners and the public a common framework for quantifying their relative levels of vulnerability and understanding its source. That is a smart way to begin the process of reducing risk where it is most practical and will provide the most significant benefits.

There were numerous media reports of wide spread water contamination in and around New Orleans. Samples from bottom sediments in Lake Pontchartrain, and the marshes in St. Bernard as well as numerical modeling of surface water contaminant transport did not support these reports. Figure 25 shows the results of one of the modeling efforts, in this case to examine maximum surface water concentrations of arsenic (As) in Lake Pontchartrain. All of these investigations, which included other contaminants such as lead and coliform bacteria, showed that the floodwater contaminant impacts on the region were marginal and typically, did not exceed EPA standards. While there were localized contamination events, in general the New Orleans area did seem to have escaped wide spread pollutant contamination. The impact of salt water flooding of wetlands and marshes was significant and represents the most serious environmental damage sustained from Katrina.

Katrina is truly a disaster from which this nation must seek and apply lessons learned to prevent reoccurrence.

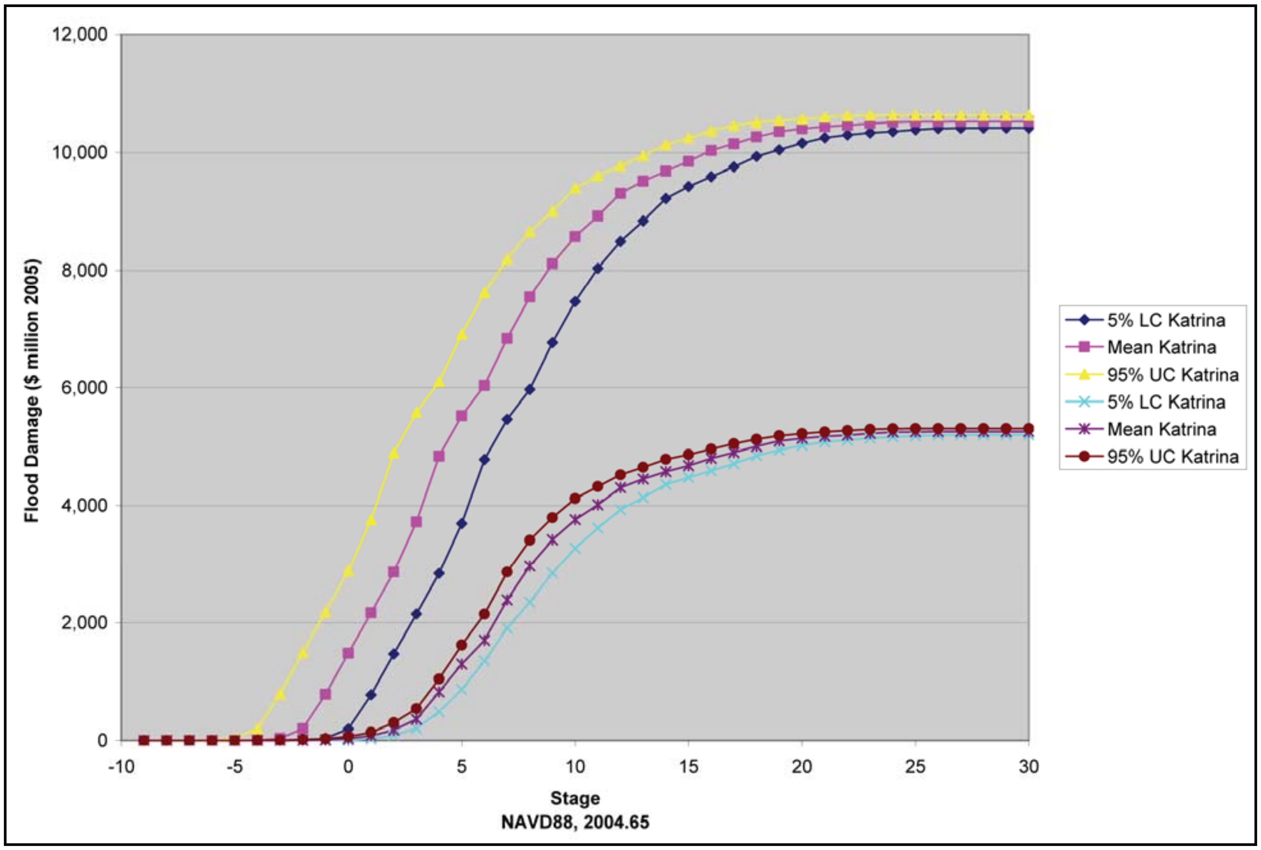

Figure 24. Comparison of flood damage – elevation relationships for pre- and post-Katrina scenarios for Orleans subbasin 5

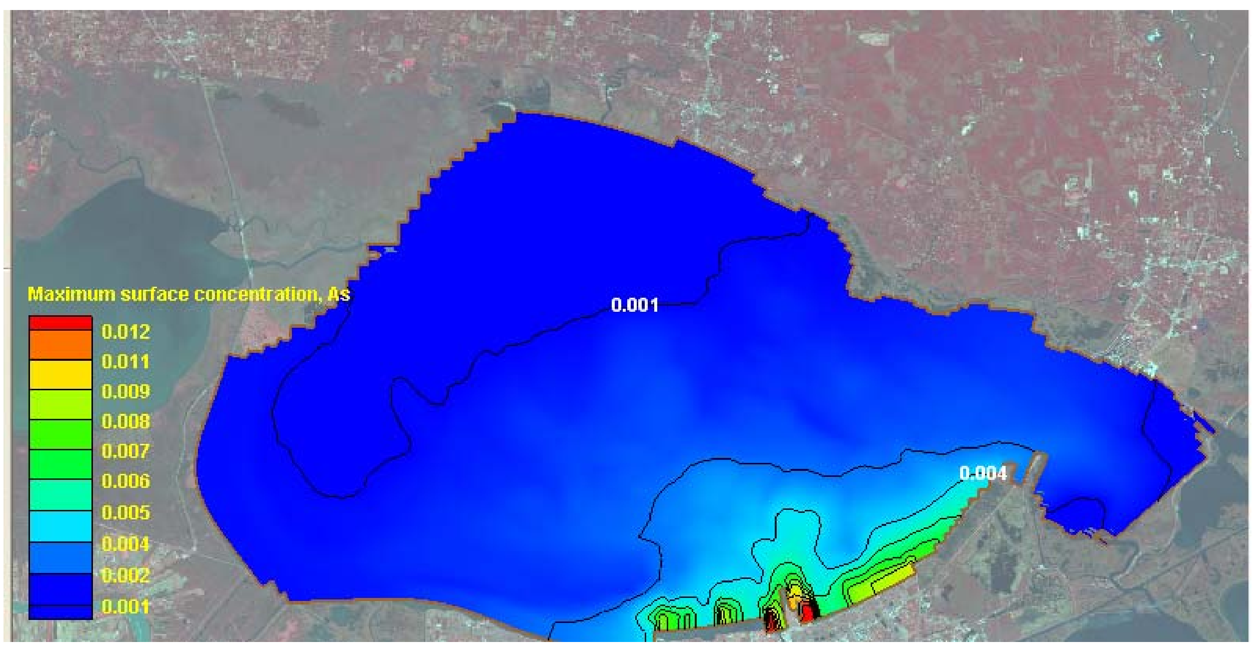

Figure 25. Maximum As water surface concentrations (mg/l total) in Lake Pontchartrain after Katrina

Interagency Performance Evaluation Task Force

IPET was established by the Chief of Engineers to determine the facts concerning the performance of the New Orleans Hurricane Protection System (HPS) in response to Hurricane Katrina. IPET has over 150 experts from 50 organizations conducting in-depth analyses that include understanding the surge and wave levels resulting from the storm; determining the forces experienced by the HPS; understanding the design, as-built, and as-maintained character of the HPS; determining the most likely causes and mechanisms for observed behavior (failure and success); characterizing the extent and consequences of flooding to include the influence of the pumping stations; and performing a risk and reliability assessment of the HPS. Appendix 1 provides the IPET principal leaders, their roles in IPET, and their affiliations and a list of the organizational affiliations of individuals serving on IPET teams. At the request of the Chief of Engineers, the American Society of Civil Engineers (ASCE) set up an External Review Panel to provide continuous review of the work of the IPET. The panel is comprised of experts from industry, academia, and government with a broad range of experience and expertise in each of the principal areas of analysis. At the request of the Secretary of Defense, the National Research Council established the Committee on New Orleans Regional Hurricane Protection Projects to provide strategic oversight of the IPET and to make recommendations concerning hurricane protection in New Orleans. Appendix 2 lists the members of the ASCE External Review Panel and their affiliations. Appendix 3 lists the members of the NRC Committee on New Orleans Regional Hurricane Protection Projects. Appendix 4 summarizes the IPET contributions to Task Force Guardian, the Corps organization responsible for the repair of the hurricane protection system.

…"to provide credible and objective scientific and engineering answers to fundamental questions about the performance of the hurricane protection and flood damage reduction system in the New Orleans metropolitan area."

LTG Carl A. Strock, Chief of Engineers, 10 Oct 2005

The IPET analysis is assisting the Corps and other responsible agencies in understanding why various components of the hurricane protection system performed as they did during Katrina, providing input to all of the ongoing efforts to reconstitute the hurricane protection system. This includes support to the three main efforts to fully achieve the current authorized levels of protection: 1) repair of the areas seriously damaged by Hurricane Katrina, 2) the design and construction efforts to restore the hurricane protection system to authorized elevations of protection, and 3) the design and construction for the completion of the previously authorized hurricane protection system (not yet completed because of lack of funds). The goal is to be able to use these lessons learned to reconstitute a more resilient and capable hurricane protection system than that which existed prior to Katrina. The extensive information repository, analytical tools, and analysis results also provide a significant new body of knowledge and analytical capability from which the Corps can begin evaluation of alternative approaches to providing higher levels of protection in the future. It is also hoped that the findings of the IPET efforts, coupled with the insights and interpretations of the ASCE External Review Panel and the NRC

Committee on New Orleans Regional Hurricane Protection Projects, will contribute to positive changes in engineering practice and water resources policy for the future.

During the conduct of the IPET studies, there has been continuous interaction with the Corps of Engineers entities in New Orleans responsible for the repair and reconstitution of hurricane protection in the region. These organizations, Task Force Hope, Task Force Guardian, and the New Orleans District, have representatives embedded in the IPET Teams, providing an effective two-way conduit for information and rapid transfer of results and lessons learned. It was imperative that the knowledge gained by the IPET and others be immediately made available to those responsible for repair and reconstruction.

IPET Objective

The objective of the IPET was to develop factual answers to the following questions:

- **Hurricane Protection System: What were the design criteria for the pre-Katrina hurricane protection system, and did the design, as-built construction, and maintained condition meet these criteria?**

- **Storm: What were the storm surges and waves used as the basis of design, and how do these compare to the storm surges and waves generated by Hurricane Katrina?**

- **Performance: How did the floodwalls, levees, pumping stations, and drainage canals, individually and acting as an integrated system, perform in response to Hurricane Katrina, and why?**

- **Consequences: What have been the societal-related consequences of the Katrina-related damage?**

- **Risk: Following the immediate repairs, what will be the quantifiable risk to New Orleans and vicinity from future hurricanes and tropical storms?**

A parallel objective was to share, as they were determined, the information, findings, and lessons learned from answering these questions with the personnel and organizations engaged in the repair and reconstitution of the hurricane protection system, and with the public. The goal was to inform decisions on the design and construction of repairs to the significantly damaged sections and the assessment of the condition and integrity of the undamaged sections prior to the next hurricane season. Secondary objectives were to provide information and analytical capabilities that would support the evaluation of alternative means to provide higher levels of protection in the future and to provide insights into the types of changes in engineering practice and policy that would facilitate more effective hurricane protection.

Prior Reports

IPET efforts are documented in three major reports, including this final report. All are available on the IPET public Web site, https://IPET.wes.army.mil . An uncommon element to this study is that the majority of the findings and lessons learned were transferred to those responsible for the repair and reconstitution of the hurricane protection system, as learned and prior to the publication of these reports. This was one of the most important objectives of the IPET, to positively impact the repair activities while ongoing and to provide capabilities needed to reconstitute long-term effective protection for the area.

Report 1: IPET Report 1, Performance Evaluation Plan and Interim Status, published as a draft on 10 January, 2006, documented the IPET scope of work and analysis methods that resulted from significant interaction with the individual experts and the collective body of the External Review Panel. ASCE provided their formal review of IPET Report 1 in a letter report to the Chief of Engineers on 20 February 2006, available on the ASCE Web site. The National Research Council Committee published their comments and review of the IPET activities and Report 1 in a letter report to the Assistant Secretary of the Army for Civil Works on 21 February 2006, available on the National Academies of Engineering Web site.

IPET Report 1 also provided a status report of the analysis in the various task comprising the IPET plan with a limited number of example products, mostly related to the initial storm surge and wave modeling. It included significant background information concerning the organization of the IPET activities, the participants and their affiliations, information sources and management, and the general approach for accomplishing the scopes of work.

Report 2: Report 2, Performance Evaluation and Interim Results, published as a draft on 10 March 2006, provided a synopsis of the analyses to date and presented significant interim results. A secondary objective was to provide at least a full prototype of the analysis that was ongoing for all of the IPET tasks to allow the ERP and NRC reviewers a greater opportunity to provide feedback and advice to enhance the ultimate impact and value of the IPET efforts.

Report 2 was structured around the five major questions that comprise the IPET mission. It presented some significant results of analysis that formed the basis for the findings in this report. The results ranged from the relatively complete products of some aspects of the performance evaluation to prototypes of products for other tasks. The geodetic vertical and water level datum and the storm surge and wave condition analyses are examples of areas where significant results were presented. In other areas a partial analysis was presented, for example the structural performance analysis of the 17th Street drainage canal breach, lacking only the numerical stability analysis component of the work. The information for other tasks, for example the risk and reliability analysis, represented prototypes for the final products under development. The intent for these areas was to document and describe how these products are being developed and what they will look like when published in the final report. Report 2 was provided to the ASCE External Review Panel on 9-10 March 2006 in Vicksburg, MS, and to the NRC Committee on New Orleans Regional Hurricane Protection Projects on 20 March 2006 in New Orleans, LA. The External Review Panel’s feedback to the Chief of Engineers on that meeting is available on the ASCE Web site.

The IPET met with the ERP for the forth time 3-5 May 2006 in New Orleans. The objective of the meeting was to provide detailed information and receive feedback on the analyses that were being completed for the final report. On 15 May 2006, the IPET met with the NRC Committee in New Orleans to provide a status report on the analyses and preparation of the draft final report. Insights gained from those meetings are included in this report. Final comments from both the ERP and NRC Committee, after their review of the draft final report, will be incorporated into this report prior to its final publication and release.

Draft Final Report

This report is the final report on the IPET performance evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System. It comprises nine volumes that document the work conducted by the IPET teams and the results of that work. The general content of each volume and how the results are being applied are described below:

Volume I: Executive Summary and Overview. Volume I provides an executive summary and overview of the IPET study and its principal findings and lessons learned. It is a big picture summary of the in-depth analysis and results presented in Volumes II to VIII.

Volume II: Geodetic Vertical and Water Level Datums. Because of the complex and variable subsidence in Southeast Louisiana, establishing an accurate vertical reference for measurements has been a constant challenge. By accelerating efforts already under way by the Corps of Engineers and the NOAA National Geodetic Survey (NGS), accurate elevations were established for the reference points within the region using modern global positioning system technology. The relationship of local mean sea level to the geodetic datum was also established to provide a complete reference system for all analysis, repair, and planning activities. Additional surveys were accomplished to accurately determine the elevation of all critical features and structures that comprise the hurricane protection system as well as perishable data such as high-water marks resulting from Katrina.

The elevations for the reference points for the geodetic vertical datum have been provided to the Corps of Engineers directly and to other agencies and the public through NOAA/NGS channels. All surveyed elevations for levees, floodwalls, pump stations, other structures, and high-water marks are being transitioned to the Corps and made available through the IPET Web site, https://IPET.wes.army.mil. Digital elevation data obtained by a variety of methods to include airborne LIDAR have been corrected to the geodetic datum and will be available through the IPET Web site. This information provided a common foundation for IPET analyses as well as the application of the results in the hurricane protection system repairs. By accurately defining the elevations of the current structures, these data provide a clear definition of the changes needed to achieve authorized protection elevations for the system as well as ultimately achieving 100-year or higher levels of protection. Guidance has been provided to update agency criteria and methods for managing the reference datums in areas of rapid and variable subsidence.

V**olume III: The Hurricane Protection System**. The hurricane protection system is comprised of three individual authorized projects. What is in place has been designed and constructed in steps over time, starting in 1965 and continuing today. This volume provides a detailed description of the hurricane protection system. It focuses on the character of the hurricane protection system starting with the definition of the hazard, defined by the Standard Project Hurricane (SPH), translation of the SPH into authorized levels of protection, the general methods and assumptions for the design of the floodwalls and levees to provide that protection, the as-built character following construction, and the maintained condition of the structures. It includes documentation of the geotechnical information available and used for the design and construction and provides references for the detailed information. To augment this information an annotated chronology of the significant decisions and communications that led to the constructed structures on the outfall canals is included. This provides significant insights as to what was built and the design intent. This is the first step in understanding and examining the performance of the entire hurricane protection system and providing a platform for the performance analysis of individual sites to better understand breaching.

The comprehensive description of the hurricane protection system has been a platform for the majority of the IPET analysis. It was essential to understanding the intent of the designers and the character of the built structures. It provided the fundamental information for the levee and floodwall performance analysis from geotechnical information on the subsurface conditions to the design assumptions and analyses used to develop the sheetpile depths, floodwall heights, and the levee geometry. The same information was a basic input to the characterization of the system for the risk assessment. The annotated chronology on the design and construction of the outfall canals was input to the Corps' companion forensic study examining why specific decisions were made in the evolution of those projects.

Volume IV: The Storm: Volume IV deals with characterization of Hurricane Katrina and the hydrodynamic environment it created. This involves two major components, a regional analysis of surge and waves generated by Katrina and high-resolution modeling of the surge and waves to better understand the time history of the static and dynamic forces that impacted the levees and floodwalls. The regional modeling provided a time history of the surge and wave environments for all locations around the hurricane protection system. This employed advanced computer codes using a very high resolution representation of the geospatial character of the nearshore environment and the hurricane protection system. The high resolution hydrodynamic modeling created a more detailed time history of water levels and forces in the confined spaces of the outfall canals, the IHNC, and the GIWW as well as the interaction of surge and waves with structures such as overtopping of levees along St. Bernard and Plaquemines Parishes. A time history of Katrina-generated forces, by location around the hurricane protection system, was essential to conducting a credible performance analysis, allowing the appropriate level of forces, based on the established timing of events to be used in the evaluation. The time line of events was developed by combining eyewitness interviews with a wide variety of physical information and evidence. The time line established when overtopping, breaching, and flooding occurred in the individual drainage basins and along the various reaches of the hurricane protection system. This was an essential input to the structural performance analysis, allowing accurate determination of the time history and character of the storm-generated forces to which structures were subjected at the time of overtopping or breaching. The wave, surge, and velocity information was provided directly to the Corps' Task Force Guardian for use in designing levee and floodwall repairs.

A special study was made to examine the impact of the MRGO channel on the storm surge levels in the IHNC. The ADCIRC model was run with the MRGO channel in its pre-Katrina condition and again assuming the channel did not exist. The results demonstrated that, for larger storms, the MRGO channel has little impact on the water levels in the IHNC.

Volume V: The Performance - Levees and Floodwalls. Volume V documents the structural performance analysis of the levees and floodwalls. The analysis addresses the floodwall breach sites on 17th Street and London Avenue Outfall Canals and the IHNC individually, describing the field investigations, computer modeling, and physical modeling used to determine the most likely failure mechanism. Sophisticated numerical models for stability and seepage, along with detailed field investigations, were used to determine the most likely failure mechanisms for each site. Centrifuge testing at both the Rensselaer Polytechnic Institute and the Engineer Research and Development Center was used to confirm these mechanisms and develop a complete picture of the processes. It also describes the analysis of Orleans Outfall Canal, which provided un-breached analogs for both the 17th Street and London Avenue sites. A broad analysis of the impact of overtopping and scour on the St. Bernard and Plaquemines levees is provided to understand the massive breaching that occurred in those parishes in terms of the types of materials used in the levees and the forces to which they were exposed.

The failure mechanisms determined for the I-wall breach sites, coupled with the knowledge gained by studying the Orleans non-breach analog sites, were used to develop criteria for investigating the remaining undamaged I-wall sections for performance integrity and to develop approaches to strengthen I-wall sections as necessary. Analysis for levee breaching was used to determine the primary causes of breaching and specify repair and rebuilding strategies that would be more robust. The knowledge gained is also being used to develop operating rules for managing water in the outfall canals after the temporary surge gates and pumps are installed and operating, as well as input to Corps Headquarters assessments of changes needed in engineering guidelines and design criteria.

Volume VI: The Performance - Interior Drainage and Pump Stations. Volume VI describes the second major component of the performance analysis of the physical system, interior drainage and pump stations. This volume describes the character of pump stations in each parish, documents their performance during and after Katrina, and provides performance information for each station. The performance curves, including those describing back flow, were critical inputs to the drainage models that were used to assess flooding. The development of interior drainage models is described along with their application to compute and map the extent of flooding from Katrina and to examine how different performance scenarios would have impacted flooding. The interior drainage modeling includes characterization of the impact of pump station performance and the relative impacts of breaching and overtopping (with no breaching) on flooding. The pumping and interior drainage information was a critical input to both the consequence and risk assessments.

Hypothetical scenarios were examined using the interior drainage and pumping modeling capability to explore a number of important questions for the future. These included potential differences in the extent of flooding if no breaching (levee or floodwall) occurred or if only the foundation failures occurred (no levee breaching), and the potential difference in flooding if the pumping stations could maintain full capacity during hurricanes. Together, these also provide an opportunity to examine the value of a totally resilient system, i.e., structures that can all survive overtopping and maintain full pumping capacity during a major hurricane.

Volume VII: Consequences. Volume VII describes the IPET efforts to define the losses that occurred because of Katrina and to consider the potential losses from future hurricanes. The consequences from Hurricane Katrina flooding have been characterized in economic, human health and safety, social and cultural, and environmental terms. The assessment of flood consequences has several purposes integral to understanding the dimensions of the Hurricane Katrina event as well as other possible hurricane and storm events. For example, consequences are one of the dimensions of risk necessary to understand the level of safety provided by the hurricane protection system. To achieve these objectives, a number of hypothetical scenarios were examined as well as the consequences of the Katrina event:

- Actual: Katrina with actual system performance—representing the actual flooding in greater New Orleans resulting from Hurricane Katrina.
- Hypothetical: Katrina with various levee and floodwall failure conditions—representing the estimated level of flooding in greater New Orleans that would have resulted from Hurricane Katrina had there been no failure of levees and floodwalls, foundation failure induced breaching only and considering different efficiency levels of interior pumping (Katrina pumping and full capacity pumping).
- Risk: Probabilistic risk scenarios modeled by the Risk and Reliability Assessment Team—representing residual hurricane-related flood risks in greater New Orleans as of August 2005 before the arrival of Hurricane Katrina, as well as flood risks as of June 2006 following repair of damages to the hurricane protection system caused by Hurricane Katrina.

The methods used and the specific consequences determined in terms of economic (direct and indirect), human safety and health, cultural and historical, and environmental losses are documented. Direct property damages represent monetary damages to residential, commercial, industrial, public buildings, vehicles, and infrastructure. Indirect economic consequence was focused on estimating local and regional economic impacts and examining possible changes in the structure of the regional economy from pre-Katrina levels into the future. Indirect economic consequences are represented in terms of possible repopulation of the area, capital stock formation, and employment levels. A limited scope economic forecast of population, employment, and local investment based on two "what if" simulations was developed as limiting control scenarios.

The types of human health and safety consequences considered varied by event scenario. For the actual Katrina scenario, the effects considered include recorded mortality as well as actual and potential morbidity, including both physical and mental health impacts. For the hypothetical Katrina scenario (without system failure), the assessment of human health effects focused only on potential mortality. The development of the loss of life – elevation relationships and direct economic damage – elevation relationships by sub-basin for the risk assessment is described, as well as developing similar relationships for the hypothetical scenarios to assist in the examination of potential consequences of future hurricane events.

The social and cultural consequences assessment considered social, cultural, and historical indicators as expressed in both quantitative and qualitative terms. These include indicators of populations, neighborhoods, communities, institutions and geographic points and locales, at local, regional, and national scales. For the actual Katrina scenario, these indicators were used to assess social and cultural changes from pre-Katrina levels. The environmental consequences assessment considered quantitative measures of contamination and loss of significant ecological resources. The specific ecological resources addressed include ecological support, fisheries, wildlife, pests, and special status species. For the actual and hypothetical Katrina scenarios, post-Katina ecological resource conditions were compared against pre-Katrina conditions for those resources.

The consequence information generated by the IPET was a direct input to the risk and reliability assessment and is being transferred to the Corps for application in the Louisiana Coastal Protection and Restoration Study. Consequence information for the lower sections of Plaquemines Parish is currently being assembled and will be provided in the final report scheduled for release in September 2006.

Volume VIII: Risk and Reliability. Volume VIII documents the risk and reliability methodology being conducted to provide a system-wide assessment of performance. It includes the risk methodology used, the characterization of the individual drainage subbasins and the features that impact hurricane protection, characterization of the expected performance (reliability) and uncertainty of the performance of individual features and reaches of the system, and the development of a comprehensive joint probability analysis of the hurricane hazard threat. System reliability is described by fragility curves that characterize the expected performance of individual reaches or structures as a function of storm water levels. The fragility curves were generated from a detailed evaluation of the subsurface conditions, the character of the structures, and understanding the relevant failure mechanisms (defined previously or from the IPET performance analysis). Approximately 2000 hypothetical storms were run through the ADCIRC model and a tailored wave estimation procedure to generate detailed information on the probability of different water (wave and surge) levels occurring at different locations around the hurricane protection system. This ensemble of storms represents the full range of storms that may hit New Orleans and provides a joint probability model for defining the hazard that each reach might experience in the future.

This work offers the opportunity to examine risk at the census block level or aggregated to subbasins, basins (parishes), or system-wide levels. It also allows examination of the impact of changes in the character of the protection for a given reach, providing a systems approach to examine how alternative protection measures can reduce risk. This can include relatively simple to very sophisticated measures. Simple measures might include armoring existing structures, elevating levees, and use of erosion-resistant materials, seepage berms, or relief wells. More sophisticated approaches could include replacing I-walls with T-walls and adding surge gates at the ends of the outfall canals. With limited modification, the analysis could include different types of approaches such as large surge barriers between Lake Pontchartrain and Lake Borgne.

Risk products are not presented in this draft report. The risk methodology is being validated and risk products will be subjected to a rigorous peer review and validation prior to their release. The risk assessment will contrast relative risk levels by subbasin prior to Katrina to those after repairs are complete (effectively 1 June 2006). The Risk and Reliability model and associated information will be transitioned to the Louisiana Comprehensive Protection and Restoration Study as a tool for evaluating alternative approaches for higher levels of protection.

Volume IX: General Appendices: Volume IX provides information considered important background for the overall IPET study and the analyses presented in the other volumes. It includes appendices on the Information Repository developed to support analyses, information on the Web site developed to provide a means to quickly share IPET analysis and results with the public, the IPET Project Management Plan, a summary of the contributions to Task Force Guardian, the official documents concerning IPET, the IPET Communications Plan, and the IPET management model.

Appendix 1
IPET Leadership, Affiliations, and Organizations

Task Force	Leader
Project Director	**Dr. Lewis E. Link** – University of Maryland
Technical Director	**Dr. John Jaeger** – U.S. Army Corps of Engineers, Huntington District
Project Manager	**Jeremy Stevenson** – U.S. Army Corps of Engineers, Huntington District

Team	Leaders
Data Collection and Management – Perishable Data, Systems Data, and Information Management	**Dr. Reed Mosher** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Geotechnical and Structures Laboratory **Denise Martin** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Information Technology Laboratory
Geodetic Vertical and Water Level Datum Assessment	**James K. Garster** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Topographic Engineering Center **David B. Zilkowski** – National Oceanic and Atmospheric Administration, National Geodetic Survey
Hurricane Surge and Wave Analysis	**Bruce Ebersole** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory **Dr. Joannes Westerink** – University of Notre Dame

Hydrodynamic Forces Analysis	**Dr. Donald Resio** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Coastal and Hydraulics Laboratory **Dr. Bob Dean** – University of Florida
Geotechnical Structure Performance Analysis	**Dr. Michael Sharp** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Geotechnical and Structures Laboratory **Dr. Scott Steedman** – Steedman and Associates, Ltd., United Kingdom
Floodwall and Levee Performance Analysis	**Dr. Reed Mosher** – U.S. Army Corps of Engineers, Engineer Research and Development Center, Geotechnical and Structures Laboratory **Dr. Michael Duncan** – Virginia Polytechnic Institute and State University
Pumping Station Performance Analysis	**Brian Moentenich** – U.S. Army Corps of Engineers, Portland District **Bob Howard** – South Florida Water Management District
Interior Drainage / Flooding Analysis	**Jeff Harris** – U.S. Army Corps of Engineers, Hydrologic Engineering Center, Hydrology and Hydraulics Technology Division **Steve Fitzgerald** – Harris County Flood Control District
Consequence Analysis	**Dr. Dave Moser** – U.S. Army Corps of Engineers, Institute for Water Resources **Dr. Patrick Canning** – U.S. Department of Agriculture, Economic Research Service
Risk and Reliability Analysis	**Jerry Foster** – Headquarters, U.S. Army Corps of Engineers **Bruce Muller** – U.S. Bureau of Reclamation

Organization

The IPET teams are comprised of individuals from a wide variety of organizations, bringing together a unique diversity and depth of knowledge and experience. These organizations are listed below.

Government Agencies

Federal Emergency Management Agency, Department of Homeland Security

Harris County, Texas, Flood Control District

Metropolitan Water Reclamation District of Greater Chicago

National Institute for Science & Technology

National Oceanographic & Atmospheric Administration, Atlantic Oceanographic and Meteorological Laboratory, Hurricane Research Division

National Oceanographic & Atmospheric Administration, Center for Operational Oceanographic Products and Services

National Oceanographic & Atmospheric Administration, National Geodetic Survey

South Florida Water Management District

United States Army Corps of Engineers

United States Bureau of Reclamation

United States Department of Agriculture, Economic Research Service

United States Geological Survey

Academia

Alfred University, New York

Georgia Institute of Technology

Johns Hopkins University

Louisiana State University

Massachusetts Institute of Technology, Department of Urban Studies & Planning

Michigan State University

Oklahoma State University

Pennsylvania State University

Rensselaer Polytechnic Institute

Stanford University

Texas A&M University

University of California

University of Delaware

University of Florida

University of Illinois

University of Maryland

University of Miami National Oceanographic & Atmospheric Administration Cooperative Institute for Marine and Atmospheric Studies

University of Missouri

University of New Orleans

University of North Carolina

University of Notre Dame

University of South Carolina

University of Texas

Utah State University

Virginia Polytechnic Institute & State University (Virginia Tech)

Private Industry

3001 Inc.

Abt Associates, Inc.

Ayres Associates

Beta Testing & Inspection, LLC

Burns, Cooley, Dennis

CH2M Hill

CTE/AECOM

Environ International Corporation, CA

Gannett-Fleming, Inc.

GeoComp Corporation

GeoDelft

Geomatrix Consultants, Inc.

Michael Baker Corporation

Oceanweather, Inc.

RAC Engineering

Science Applications International Corporation (SAIC) at NOAA/NCEP

SpecPro, Inc.

Steedman & Associates, Ltd.

Surfbreak Engineering

Taylor Engineering

URS Corporation

Victor Parr, consultant

Watershed Concepts

Appendix 2
American Society of Civil Engineers External Review Panel Members

Name	Organization
Christine F. Andersen	City of Long Beach California
Jurjen Battjes	Delft University of Technology
David E. Daniel	University of Texas at Dallas
Billy Edge	Texas A&M University
William Espey	Espey Consultants, Inc.
Robert B. Gilbert	University of Texas at Austin
Thomas L. Jackson	DMJM Harris
David Kennedy	California Department of Water Resources
Dennis S. Mileti	Colorado University (retired)
James K. Mitchell	Virginia Polytechnic Institute & State University (Virginia Tech)
Peter Nicholson	University of Hawaii
Clifford A. Pugh	U.S. Bureau of Reclamation
George Tamaro	Mueser Rutledge Consulting Engineers
Robert Traver	Villanova University
Lawrence H. Roth	American Society of Civil Engineers
John E. Durrant	American Society of Civil Engineers

Appendix 3
National Research Council Committee Members

Name	Organization
G. Wayne Clough	Georgia Institute of Technology
Rick A. Luettich	University of North Carolina
Frederic Raichlen	California Institute of Technology
Rafael L. Bras	Massachusetts Institute of Technology
Peter Marshall	Burns & Roe Services
Y. Peter Sheng	University of Florida
John T. Christian	Consulting Engineer
David H. Moreau	University of North Carolina
Robert H. Weisberg	University of South Florida
Jos Dijkman	Delft Hydraulics
Thomas D. O'Rourke	Cornell University
Andrew J. Whittle	Massachusetts Institute of Technology
Robin L. Dillon-Merrill	Georgetown University
Risa I. Palm	Louisiana State University
Delon Hampton	Delon Hampton & Associates
Kenneth W. Potter	University of Wisconsin
Jeffrey W. Jacobs	National Academy of Science

Appendix 4
Task Force Guardian Inputs

IPET Products Provided to Task Force Guardian and Task Force Hope

a. **Data Repository – 25 October 2005.** The IPET Data Repository was established as an entry point for collecting information pertaining to the New Orleans and Southeast Louisiana Hurricane Protection Projects that needs to be validated as factual. This repository supports both the IPET and TFH/TFG efforts by providing a database where information can be reviewed for accuracy and quality prior to posting the information on the IPET public website.

b. **Establishment of the IPET Public Website – 2 November 2005.** The IPET public website was established as a way to be fully transparent in effectively sharing factual information pertaining to the New Orleans and Southeast Louisiana Hurricane Protection Projects. The website provides a way to proactively communicate information that might otherwise require the public and TFG to process Freedom of Information Acts.

c. **Establishment of On-Line Team Workspace using Groove – 22 September 2005.** To enable IPET, ERP, and members of TFH/TFG with on-line workspaces to communicate and share information virtually, Groove software and technical support was provided by IPET. Through these virtual workspaces information can be effectively and efficiently shared. Groove is a primary tool used to bring the IPET, ERP, and TFH/TFG teams together in sharing knowledge and information required to accomplish their missions.

d. **Integration of the IPET Public Website and the TFH/TFG Electronic Bid Solicitation Websites – 15 November 2005.** As a way to more effectively enable public benefit from the historic and performance-related information on the IPET public website and the reconstruction plans and specifications on the TFH/TFG electronic bid solicitation website, electronic linkage was provided to facilitate integration of the two sites.

e. **"Summary of Field Observations Relevant to Flood Protection in New Orleans, LA" – 5 December 2005**. This IPET review provided Task Force Guardian with a simple statement of concurrence or nonconcurrence from the IPET floodwall and levee sub team and additional relevant discussion for each of the major findings in the ASCE/NSF report's chapter eight, "Summary of Observations and Findings." The additional discussion relates to the analysis being conducted by the IPET or others that would assist in applying the ASCE/NSF findings to the reconstruction of hurricane protection in New Orleans.

f. **"Preliminary Wave and Water Level Results for Hurricane Katrina" – 23 November 2005.** This IPET report to TFH/TFG included observations from the IPET surge and wave sub team from a field trip and overflight of New Orleans and Southeast Louisiana.

g. **"Summary of IPET Numerical Model of Hurricane Katrina Surge and Wave Plans, Approach and Methods" – 19 December 2005.** This PowerPoint presentation by the IPET surge and wave sub team provided TFH/TFG with an update on wave and water level results for Hurricane Katrina. Wave and water level results from fast-track simulations of upper Category 3 type storms on various storm tracks and a Standard Project Hurricane event were also provided.

h. **Review of Proposal to Float In and Sink a Barge to Close Canals by June 2006 – 28 December 2005.** The proposal included the use of existing large ship tunnel thrusters mounted on a barge with huge pumping capacities. Review determined that the closure plan does not have enough pumping capacity to match existing pumps during a hurricane.

i. **Technical Support to TFG on the Analysis and Design of the Reconstruction Plans and Specifications for the Breaches – Continuous Support as Needed.** Technical support continues to be provided to TFG on an as-needed basis. As a minimum, monthly face-to-face meetings take place in New Orleans. This support includes geotechnical and structural consultations. These discussions also include reviews of plans and specifications for reconstruction features such as T-walls, L-walls, I-walls, levees, and foundation investigations.

j. **Evaluation of Existing and As-Built Conditions at Canals – On-going.** This evaluation includes concrete and steel material properties for reinforcement and sheet piles on the I-walls, as-built length of sheet piles, surveys, and foundation material properties and boring logs.

k. **Life-cycle Documentation of the Hurricane Protection System – On-going.** This documentation includes a review of the design, construction, and operation and maintenance of the hurricane system.

l. **Verification of Current and Reconstructed Floodwall Elevations – November 2005.** Established a tidal gage in November 2005 at the 17th Street Canal to monitor current sea level relationships to the newest NAVD88 datum epoch (2004.65). Verified floodwall elevations on Lakefront outfall canals and IHNC relative to this latest tidal and vertical epoch.

m. **LIDAR Ground Truthing – On-going.** Currently performing ground-truthing surveys throughout the region to calibrate various LIDAR-based elevation models used by Task Force Guardian.

n. **Densification of Control Benchmarks – 31 December 2005.** IPET has established approximately 75 vertical benchmarks throughout the region. These control points are being used for Task Force Guardian construction activities.

o. **Establishment of GIS Team – 2 February 2006.** The "GIS Team" was established to maximize the effectiveness and efficiency of the GIS resources within IPET, Task Force Guardian, Task Force Hope, and the New Orleans District. The GIS Team consists of members from each of the four teams and provides a way to integrate efforts and share information pertaining to the HPS. The GIS Team will also provide for a way to assure a smooth transition of IPET generated GIS information to the New Orleans District upon disbanding of IPET once its performance evaluation is completed. Significant IPET data sets shared with TFG in January and February 2006 include the digital elevation models, vertical datum survey data, geotechnical data, and photographs.

p. **Insight into probable cause of breaching at 17th Street Canal – Continuous ending March 2006.** Information was shared with TFG on the probable cause of breaching at the 17th Street Canal. Recommendations were provided on considering the formation of a gap at the base of cantilever I-walls and shear strength variations between the centerline and inboard toe of levees used in combination with I-walls.

q. **Storm Surge and Wave analysis results for Katrina and historical storms – December 2005.** Information pertaining to modeled Katrina storm surge and wave heights and periods for various locations along the HPS was provided to TFG. In addition, modeled surge and wave results from other historical storms were also provided.

r. **Review comments on canal closure structures – December 2005 and January 2006.** IPET review comments for the outfall canal closure structures were provided to aid in development of high quality P&S for the closure structures.

s. **Provided comments in IPET Report 2 regarding comparison of Hurricane Katrina wave and period conditions with design values – March 2006.** Design wave conditions, particularly wave period, should be re-evaluated for the east-facing levees in east Orleans, St. Bernard and Plaquemines Parishes.

t. **Closure Structures Modeling – January – February 2006.** IPET members at MVN performed modeling analysis of the closure structures on 17th Street, Orleans and London Ave Canals.

u. **Closure Structures Interim Operations Plan – March 2006 – Ongoing.** IPET members review and comment on operations of the gates and pumps. This includes criteria for closing & opening, and coordination with local jurisdictions.

v. **MRGO White Paper – March 2006**. Input on analysis of MRGO effect on storm propagation into metropolitan New Orleans and vicinity.

w. **ITR on Heat Straightening Repairs at Empire Floodgate.** IPET team members visited the Empire Floodgate and reviewed the proposed repair plan approving of the corrective action plan and making further clarifying recommendations. IPET suggested requiring in the specs that the project supervisor be an experienced heat straightener possibly added to section 5 of the specs and that NDT be performed prior to and following the heat straightening. The initial NDT would benefit general initial assessment of the floodgate and provide a base line in the event you get an inexperienced contractor that does more harm then good. TFG will know if heat straightening caused cracking if you have a base line. TFG may want to consider the simultaneous application of V heat on both sides of the flange considering its thickness this could be added in section 3.5 of Avent's spec. IPET believes section 3.5.3 pertains to simultaneous vee heats on the same side of the flange.