



**US Army Corps
of Engineers®**

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

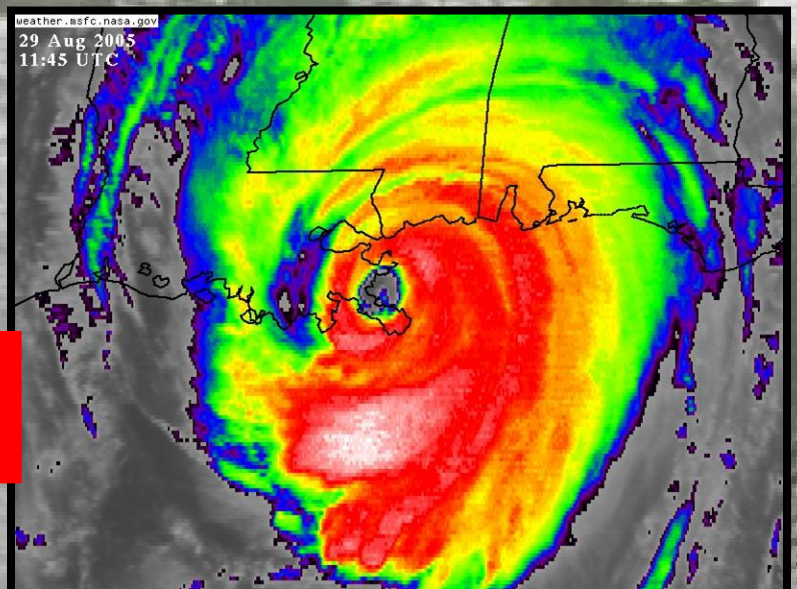
*Final Report of the Interagency Performance Evaluation
Task Force*

Volume 1 – Executive Summary and Overview

26 March 2007

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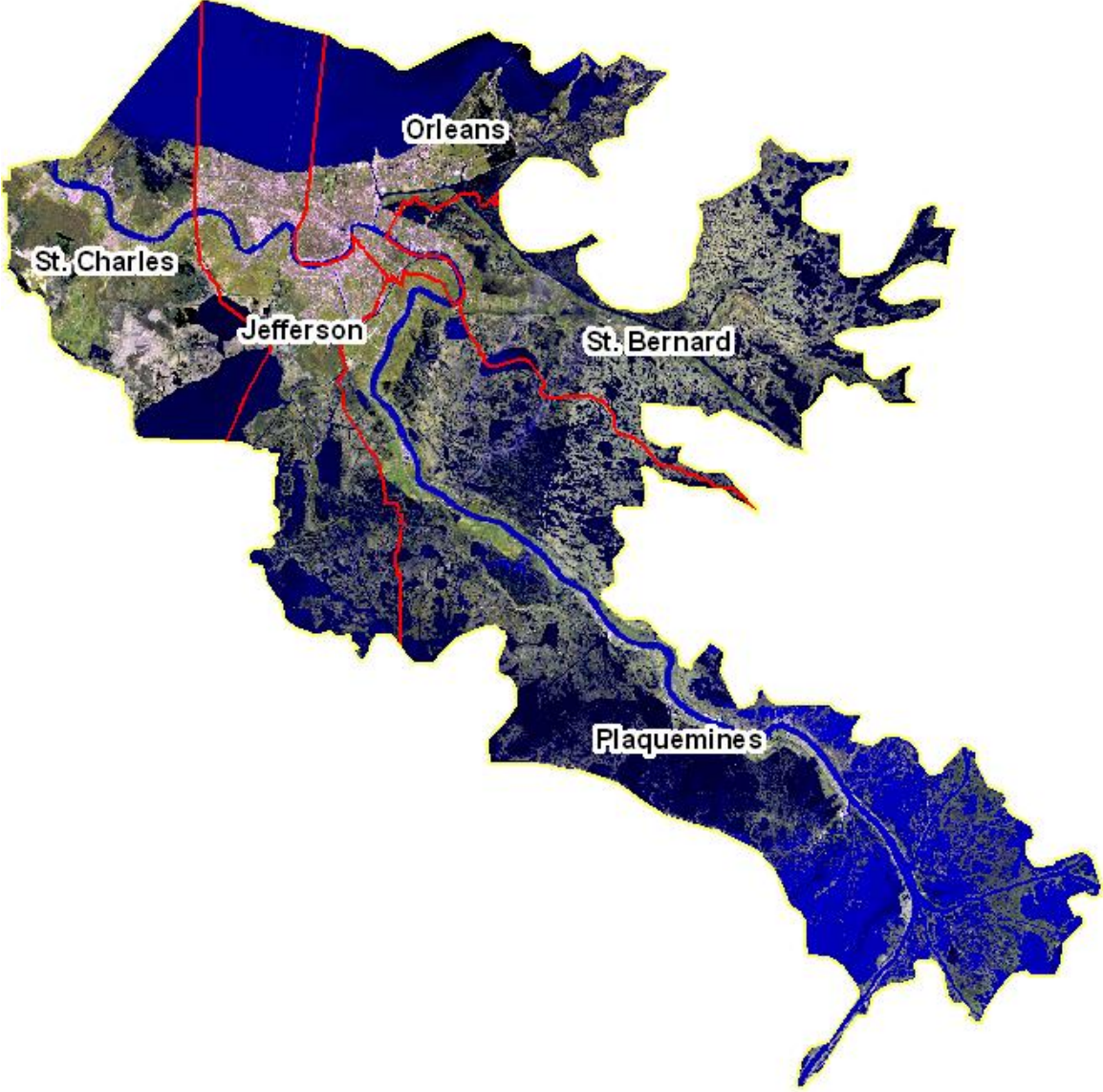


Volume I – Executive Summary and Overview
Volume II – Geodetic Vertical and Water Level Datums
Volume III – The Hurricane Protection System
Volume IV – The Storm
Volume V – The Performance – Levees and Floodwalls
Volume VI – The Performance – Interior Drainage and Pumping
Volume VII – The Consequences
Volume VIII – Engineering and Operational Risk and Reliability Analysis
Volume IX – General Appendices

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Volume I

Executive Summary and Overview



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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 (IPET), a distinguished group of government, academic, and private sector scientists and engineers who dedicated themselves to this task from shortly after Katrina struck through the publication of this report. IPET was created by the Chief of Engineers, U.S. Army Corps of Engineers, and the group's work was peer reviewed on a weekly basis by a distinguished external review panel of the American Society of Civil Engineers and independently reviewed by the National Research Council Committee on New Orleans Regional Hurricane Protection Projects. IPET 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 much of the IPET work are largely already in the ground, having been transferred and applied prior to the formal completion of this report. The bulk of the information and documents used or generated by the Task Force has been made available through a public web site, <https://IPET.wes.army.mil>, as available. At the time of the distribution of this report there are well over 4,300 documents on this site.

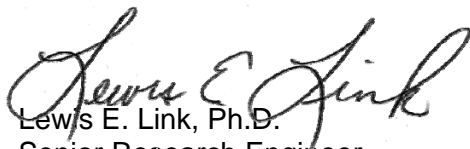
In spite of the large amount of work accomplished by the IPET and others, it is important to recognize that the body of knowledge that has been generated is not complete and much remains to be done to gain a comprehensive understanding of all aspects of hurricane risk reduction for the future. Much of this work was conducted within a highly constrained time frame. This drove investigators to apply tools and methods readily available and often with less than the optimum data. Time often precluded lengthy or comprehensive data acquisition, especially over the extensive area of the New Orleans Hurricane Protection System. Having made these points, it is also important to recognize that the analyses and results presented are the product of a highly capable team of experts and reflect their collective experience and knowledge. This work need not be repeated, rather it should serve as a substantial platform from which additional studies and evaluations are conducted.

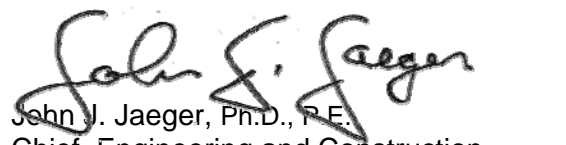
There are nine volumes in the final report, designed to provide a detailed documentation of the technical analyses conducted and their associated findings. They are organized around major technical tasks that together provided an in-depth system-wide assessment of the behavior of the hurricane protection system and lessons learned that have been incorporated into the immediate repairs and are integrated into the continuing efforts to improve the system and assess 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 IPET, the performance evaluation activities and IPET reports.

- **Volume II. Geodetic Vertical and Water Level Datums** – Update of geodetic and water level references for the region and determination of 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** – Documentation of 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** – Documentation and assessment of the behavior of individual damaged structures and development of criteria for evaluation of undamaged sections. Provision of input to repairs and ongoing design and planning efforts.
- **Volume VI. The Performance – Interior Drainage and Pumping** – Assessment of 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. Engineering and Operational Risk and Reliability Analysis** – 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. General Appendices** – Documentation of information resources and management, program management, and communications.

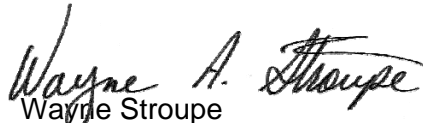
On behalf of the entire Interagency Performance Evaluation Task Force, the undersigned offer this report and the results therein as a contribution to the well-being of the people of New Orleans and Southeast Louisiana and the reconstitution of effective hurricane protection for their future.


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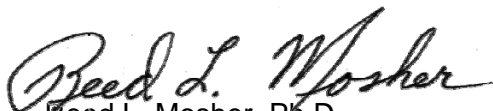

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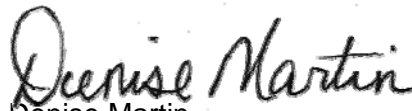
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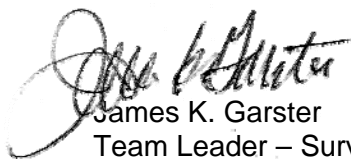
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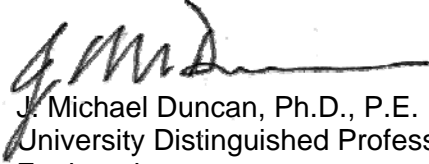
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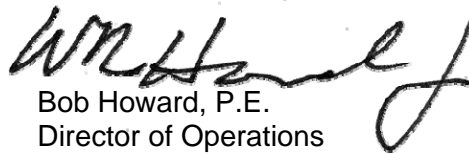
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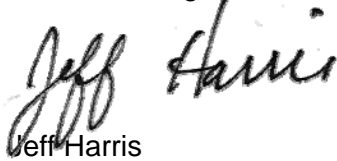
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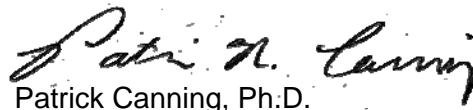
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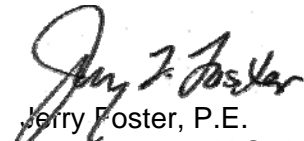
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Executive Summary

Introduction

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

- **The System:** What were the pre-Katrina characteristics of the hurricane protection system (HPS) components; how did they compare to the original design intent?
- **The Storm:** What was the surge and wave environment created by Katrina and the forces incident on the levees and floodwalls?
- **The Performance:** How did the levees and floodwalls perform, what insights can be gained for the effective repair of the system, and what is the residual capability of the undamaged portions? What was the performance of the interior drainage system and pump stations and their role in flooding and unwatering of the area?
- **The Consequences:** What were the societal-related consequences of the flooding from Katrina to include economic, life and safety, environmental, and historical and cultural losses?
- **The Risk:** What were the risk and reliability of the hurricane protection system prior to Katrina, and what will they be following the planned repairs and improvements (Dec. 2007)?

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

The nine volumes of the final report provide a detailed documentation of a broad, multi-disciplinary analysis of the hurricane protection system and its performance during Hurricane Katrina. The frequent professional interaction and review comments provided by the American

Society of Civil Engineers (ASCE) External Review Panel and the strategic oversight of the National Research Council (NRC) Committee on New Orleans Regional Hurricane Protection Projects have made substantial contributions to the conduct of the analysis and development of the results described in this report. This volume, Volume I, Executive Summary and Overview, provides an overview of the IPET and its efforts, a synopsis of the performance of the hurricane protection system during Katrina and a summary of the principal findings and lessons learned. All are described in more detail in Volumes II–IX. Since the hurricane protection system is only designed to manage flooding in the metropolitan New Orleans basin, wind-based consequences and any direct consequences exterior to the hurricane protection system are excluded from this report. In addition, the IPET did not examine organizational and jurisdictional issues that impacted the effectiveness of the physical hurricane protection system. These issues are being examined by a separate team in the Hurricane Performance Decision Chronology Study whose results will be reported separately.

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

Summary of Findings

The System: The system did not perform as a system. In some areas it was not completed, and in others, datum misinterpretation and subsidence reduced its intended protective elevation. The capacity for protection varied because of some structures that provided no reliable protection above their design elevations and others that had inadequate designs leaving them vulnerable at water elevations significantly below the design intent. The designs of the levee-floodwall structures along the outfall canals were particularly inadequate. A series of incremental decisions that went from the original “barrier” plan to the “parallel protection” structures ultimately constructed, systematically increased the inherent risk in the system without recognition or acknowledgment.

The Storm: Katrina created record surge and wave conditions along the east side of New Orleans and the coast of Mississippi. Peak water levels along the Plaquemines and St. Bernard levees and within the Inner Harbor Navigation Canal (IHNC) were significantly higher than the structures leading to massive overtopping and eventually breaching. Wave heights during Katrina were typically similar to those assumed for the design of the structures, except for Plaquemines Parish where they were higher than the design assumptions. Wave periods, however, were three times longer than the design assumptions, particularly along the east side of St. Bernard and Plaquemines Parishes. The longer period more energetic waves created much greater potential for runup and overtopping. Conditions within Lake Pontchartrain were roughly equal to the design criteria for the shoreline structures. The Mississippi River Gulf Outlet channel, presumed to be a major factor in propagating storm surge into the IHNC, was demonstrated to have little impact on storm water levels for large storms.

The Performance: With the exception of four foundation design failures, all of the major breaches were caused by overtopping and subsequent erosion. Reduced protective elevations increased the amount of overtopping, erosion and subsequent flooding, particularly in Orleans

East. Ironically, the structures that ultimately breached performed as designed, providing protection until overtopping occurred and then becoming vulnerable to catastrophic breaching. The levee-floodwall designs for the 17th Street and London Avenue Outfall Canals and IHNC were inadequate for the complex and challenging environment. In four cases the structures failed catastrophically prior to water reaching design elevations. A significant number of structures that were subjected to water levels beyond their design limits performed well. Typically, in the case of floodwalls, they represented more conservative design assumptions and, for levees, use of higher quality, less erodible materials.

The Consequences: Approximately 80 percent of New Orleans was flooded, in many areas with depth of flooding exceeding 15 ft. The majority, approximately two-thirds overall in areas such as Orleans East Bank and St Bernard, of the flooding and half of the economic losses can be attributed to water flowing through breaches in floodwalls and levees. There were at least 727 fatalities in the five parishes in and around New Orleans, and over 70 percent of the fatalities were people over age 70. The poor, elderly, and disabled, the groups least likely to be able to evacuate without assistance, were disproportionately impacted. Direct property losses exceeded \$20 billion, and 78 percent of those losses were in residential areas. There was an additional loss of over \$7 billion in public structures and utilities. The indirect consequences were equally disastrous. The breakdown in New Orleans' social structure, loss of cultural heritage, and dramatically altered physical, economic, political, social, and psychological character of the area are unprecedented in the United States. In themselves, these create a formidable barrier to recovery. Where water depths were small, recovery has been almost complete. In areas where water depths were greater, little recovery or reinvestment has taken place.

The Risk: The prototype risk assessment process can identify the areas most vulnerable to future flooding and with the highest residual risk. Given more consistent levels of protection that will exist in the 2007 time frame, in many areas, level of risk is closely associated with the property values and population densities in the subbasins and the elevation of the area (potential for deep flooding) The exception is in the areas bounded by the IHNC where the reliability of protection will be lower because of legacy structures (types and elevation) and continued threat of high surge and wave conditions. Final risk results will be published at the completion of the risk analysis.

Summary of Lessons Learned

The System: Planning and design methods need to be system-based, allowing a more in-depth analysis of how a combination of structures and measures will perform together. These methods need to be able to consider the performance of the system beyond the design criteria, including the life cycle value of resilience and redundancy in the design. Dynamic factors such as subsidence and changing hazard levels must be included. This requires an ability to develop and evaluate adaptive designs, protective concepts that allow planned augmentation to deal with expected changes as well as some ability to accommodate the unexpected. An accurate reference datum and monitoring of structure elevations, as well as the effective operation and maintenance of the hurricane protection system, are essential parts of this process. All assets that factor in the capability to provide protection, such as pump plants and closure structures, must be included in

the overall analyses, even if they are not a formal part of the protection system. With rapid changes in new knowledge and engineering practice, it is essential to continuously review and update technical guidance used in planning and design as well as providing an effective mechanism for the engineering community to adopt and mature new methods. The Standard Project Hurricane (SPH) methodology used to develop design criteria for the original system is outdated and should no longer be used. More flexible and robust probability-based methods are available that will provide better definition of the future hazard faced by protective structures.

The Storm: Sophisticated models that incorporate high-resolution spatial data and high-quality wind fields are essential to accurately characterize storm surge and waves. This is particularly true in an area such as New Orleans with complex shoreline comprised of both natural (marshes and ridges) and man-made barriers (levees and transportation corridors). These models need increased capabilities to accurately simulate the impact of barrier islands, marsh, and wetlands on surge and wave conditions. The interaction of the surge and wave conditions with structures such as levees and floodwalls requires special detailed modeling to accurately account for wave runup and overtopping, and to examine levee/wall response to dynamic loadings. Typically, very few measurements of waves and surge are made along the entire periphery of a HPS as part of a monitoring program. That was the case for this HPS. Large storms such as Katrina can cause failure of instrumentation intended to record the surge and wave environments created by the storm, and did so in this case. This creates a difficult problem for conducting analyses of a storm and its impacts. High-water marks were the only reference information reasonably available around the region for calibrating and validating surge modeling. Only a relatively small percentage of these marks (15 percent) were considered accurate enough for use, pointing to the need for more robust instrumentation that can survive storms as well as rigorous standards for evaluating the quality of high-water marks.

The Performance: Hurricane protection structures need to be designed as a part of a complete system-based approach to protection, providing balanced and uniform levels of protection from the perspectives of time, level of hazard, and reliability. Designs need to be conservative enough to accommodate unknowns. Designs need to consider dynamic wave loadings in situations where waves are present. The unanticipated failure mode defined in the IPET analysis for the outfall canal floodwalls is not the only potential failure mode for these structures not considered in the original designs. With the rapid expansion of knowledge and practice, it is necessary to frequently review the adequacy of existing infrastructure in the context of that new knowledge and have processes in place to respond expeditiously to any performance limitations that arise. Resilience should be factored in to all designs to prevent catastrophic failures and to protect the integrity of the hurricane protection system itself. The maintained condition of the levees is an important factor in their overall performance and should be monitored more rigorously and through evaluations that extend beyond visual inspections.

The Consequences: Even without the significant catastrophic breaching that occurred, the flooding and direct losses from Katrina would have been the worst in the history of the region. However, approximately half of the direct losses may have been averted if breaching had not occurred. This reduction in direct losses would likely have dramatically reduced the indirect consequences of the event. Together, this may have enabled a more rapid and systematic recovery. Resilience in the hurricane protection system would have provided that advantage.

Mapping the economic and human health and safety consequences of Katrina has created a powerful information base from which risk assessments and future planning priorities can be informed. Estimating the future distributions of population and property in the uncertain recovery and re-development environment proved very difficult. The scenario development accomplished to provide some insights into possible consequences of future hurricane events proved a feasible and valuable approach. Environmental losses were an essential component to the overall assessment of consequences, but they proved to be difficult to characterize beyond the short term, in part because of the already significant levels of contamination existing in the region. Not nearly enough information is available on the long-term impacts of saltwater intrusion and flooding on freshwater marshes, or the conditions and rates of recovery that can be expected.

The Risk: Risk assessment provides a new and more comprehensive method to understand the inherent vulnerability for areas protected by complex protection systems and subjected to uncertain natural hazards. It provides a direct view into the sources of vulnerability, providing a valuable tool for public officials at all levels to focus resources and attention on the most serious problems and to seek solutions that reduce risk through both strengthening the reliability of the physical structures and reducing exposure of people and property to losses. Given a relatively uniform level of reliability of the protection system, the relative risk values are largely related to elevation (below sea level) and the value of property or number of people who occupy those areas. The emergency response preparedness and efficiency of evacuation prior to a storm is a key component to reducing risk to life and human safety.

Overview

Interagency Performance Evaluation Task Force (IPET)

Establishment and Mission

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. The Task Force conducted in-depth analyses that defined the surge and wave levels resulting from the storm; determined the forces experienced by the HPS; characterized the design, as-built, and as-maintained character of the HPS; determined the most likely causes and mechanisms for observed behavior (failure and success); characterized the extent and consequences of flooding to include the influence of the pumping stations; and performed a risk and reliability assessment of the HPS.

“...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 assisted the Corps and other responsible agencies in understanding why various components of the HPS performed as they did during Katrina, and provided input to the ongoing efforts to reconstitute the HPS. This included: 1) repair of the areas seriously damaged by Hurricane Katrina, 2) evaluation and repair (as necessary) of areas not severely damaged, and 3) the planning and design for achieving 100-year certifiable (Federal Emergency Management Agency (FEMA) flood insurance) structures. The goal was to use these lessons learned to reconstitute a more resilient and capable HPS 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 to support evaluation of alternative approaches to providing higher levels of protection through the Louisiana Coastal Protection and Restoration Study (LaCPR). 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, had 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.

Objectives

The principal IPET objective was to provide answers to the following questions:

- **The Hurricane Protection System: What were the design criteria for the pre-Katrina HPS, and did the design, as-built construction, and maintained condition meet these criteria?**
- **The 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?**
- **The 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?**
- **The Consequences: What have been the societal-related consequences of the Katrina-related damage?**
- **The 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 HPS, and with the public.

Organization and Activities

Over 300 experts from more than 50 organizations have contributed to IPET. Those organizations included 25 universities, 23 private sector firms, and 10 government agencies. The government participants came from federal as well as local agencies such as the South Florida Water Management District and Harris County (TX) Flood Control District. This provided a broad array of experience and diverse perspectives to shape the analyses and interpret the results. There were 25 individuals from Task Force Guardian and the New Orleans District embedded in the IPET teams to provide direct two-way exchanges of information and ideas. This was essential to the rapid transfer of information and findings to the repair process.

The IPET was organized into ten technical teams. Each team had co-leaders with one from within the Corps of Engineers and one from an organization external to the Corps. This provided an extra dimension to the leadership, extending the talent and experience of each team and providing external ideas, resources, and oversight to their efforts. The team activities were coordinated by a Program Director and Technical Director, supported by a Program Manager

and Public Affairs Specialist. Legal and administrative support was provided through the Corps' Engineer Research and Development Center (ERDC) and the Huntington District. Appendix 1 provides the IPET principal leaders, their roles in IPET, their affiliations, and a list of the organizational affiliations of individuals serving on IPET teams.

In many ways the leadership and management model for IPET mimics that of the high-end strategic consulting firms that use a largely virtual business model. This model encourages diverse self-managed teams that cooperate under the framework of a total strategy for achieving project objectives. While each task had a specific scope of work, the key ingredient for the IPET leadership has been identifying and managing the interdependencies of the teams and their tasks to get to a final comprehensive performance evaluation. As the work of the teams progressed, their efforts have been progressively consolidated to enhance product compatibility and seamless integration. This was enabled by the project management function that, while virtual, provided the program/project architecture that glued the effort together, provided financial management and administrative support, and allowed the teams to focus on the technical analysis. A critical part of the project management activities was the development of a detailed management schedule and plan (see Volume IX) that inter-related all work efforts and provided a critical path for the entire effort. The key to accomplishing this extensive amount of work in a short time frame was the quality of the people involved in the teams and the continuous and open communications among them.

Another significant factor was the use of spiral development to evolve each major product. In this process, data, methods and analysis were developed and accomplished in a series of repeated cycles. Each time improvements were made based on such things as more complete information, validation of methods, increased sophistication of models and comparison to ground truth. This provided a significant opportunity for investigators to learn about the limits of the data and models being used and to focus efforts where needed. It also allowed teams to provide preliminary input to the analyses being conducted by other teams, providing early integration of activities and an ability to examine the compatibility of results.

Since the IPET was a virtual organization, multiple modes of communications were essential to success. A virtual office environment was set up using "Groove" software. This provided a collaborative environment for data, documents, and discussions. Individual workspaces were created for each team, the External Review Panel, Task Force Guardian, and other stakeholders requiring rapid access to IPET activities and information. IPET also used frequent phone conferences at the team level and across the entire organization, to maintain cognizance of the status of efforts and to discuss any issues that needed resolution. Representatives of the Corps offices engaged in the repair and rebuilding efforts, the Corps Headquarters, and occasionally members of congressional investigative committees, participated in these conferences. Phone conferences were also used to provide interim updates to the external review panels and committees. The IPET Web site (<https://IPET.wes.army.mil>) was the primary conduit to provide information to the public and other organizations interested in the ongoing analyses. This Web site became the primary avenue for providing to the public over 4,300 documents dealing with the design and construction of the hurricane protection system, as well as IPET communications and reports.

Having the exceptional R&D infrastructure of the ERDC available to the IPET was a major advantage and enabler for this work. Priority access to the Department of Defense Major Shared Resource Center's most capable supercomputers for hydrodynamic analysis dramatically accelerated the progress and enhanced the IPET efforts to model surges and waves. The ability to accomplish parallel numerical stability and seepage analyses at both the ERDC and at The Virginia Polytechnic Institute and State University accelerated the analysis and provided an invaluable check and balance on the results. Having priority access to the Army centrifuge at ERDC and the established ERDC ties to the Rennselaer Polytechnic Institute (RPI) centrifuge and European centrifuge experts at the GeoDelft enabled physical modeling for the breach sites to occur in an unprecedented time frame and also provided independent results for comparison. Physical hydraulic modeling of the 17th Street Canal provided a valuable complement to numerical modeling, offering details on wave and sloshing phenomena and the impact of debris on flow, unavailable from other sources. Availability of these and similar experimental assets such as drilling and soils testing capabilities and the support infrastructures associated with them (provided through ERDC and the New Orleans District and their contractors) allowed IPET analyses to progress at an unusually rapid pace. Most important was the available expertise that enabled these resources to be wisely used.

Review Process

At the request of the Chief of Engineers, the ASCE set up an External Review Panel (ERP) to provide continuous review of the work of the IPET. The panel was comprised of experts from industry, academia, and government with a broad range of experience and expertise in each of the principal areas of analysis. The ERP functioned as a real-time peer review body as well as an alter ego to the IPET teams. Formal meetings were held in November 2005, January 2006, March 2006, and May 2006. A final joint meeting was held in February, 2007 to review changes made to the IPET report in response to ERP recommendations. These meetings were comprehensive across-the-board reviews, including discussions of the work completed, the status of ongoing work, and the integration of the results from the different teams to generate the system-wide information required to meet the IPET objectives. During the intervening periods, individual members of the ERP maintained frequent communication with specific IPET teams to maintain cognizance of ongoing work and to provide short-term review and feedback on specific issues. The objective was to maintain a high level of credibility of the work and products while enabling IPET to continue working at a rapid pace to meet their objectives. This was especially important to providing validated information to Task Force Guardian for their work in repairing the damaged sections of the HPS. Note that the IPET draft Final Report and the completion of repairs were both scheduled for 1 June 2006. The ERP has issued letter reports to the Chief of Engineers after each major meeting with the IPET as well as providing a final report in November 2006. These reports are available on the ASCE Web page as well as the IPET Web page. Appendix 2 lists the members of the ASCE ERP.

At the request of the Secretary of Defense, the NRC 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. The NRC Committee provided a more strategic overview function. Formal public meetings were held by the

Committee in New Orleans in January, March, May, and July 2006, and in Washington, DC, in January 2007. A final meeting will be held to review the risk and reliability work as documented in Volume VIII upon delivery of the draft to the committee. IPET principals made formal presentations to the Committee at these meetings as well as engaging in technical discussions. During these meetings the NRC also received briefings from members of other teams engaged in analyses of the HPS during Katrina, experts in specific areas of interest, and the public. Communications between these meetings were dominantly written responses to questions or clarification of issues that were raised during the meetings. The NRC Committee has provided three formal interim reports to the Assistant Secretary of the Army on the progress of their review. They will generate a separate report on the Risk and Reliability Analysis in the February-March 2007 time frame and provide their final report during the summer of 2007. NRC Committee reports are available on the NRC Web page as well as the IPET Web page. Appendix 3 lists the members of the NRC Committee on New Orleans Regional Hurricane Protection Projects.

Prior Reports

IPET efforts are documented in four major reports, including two versions of the final report. The draft final report was released on 1 June 2006. It is superseded by this final report which contains considerable additional information and has been revised in format and presentation. 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 HPS as they were 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. Appendix 4 summarizes the IPET contributions to Task Force Guardian, the Corps organization responsible for repair of the HPS.

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 ERP. 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 NRC 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 Research Council Web site.

IPET Report 1 also provided a status report of the analysis in the various tasks 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 datums 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, e.g., 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, e.g., 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 ERP 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 ERP'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 fourth 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. The NRC and IPET met in July 2006 in New Orleans for a focused discussion on the risk assessment efforts. Insights gained from those meetings are included in this report.

Draft Final Report: A draft of the final report was released on 1 June 2006. The intent was to provide a reasonably comprehensive documentation of the IPET work and results prior to the formal reviews by the ASCE ERP and the NRC Committee. The draft final report was divided into the same nine volumes that comprise this final report. Volume VIII, Engineering and Operational Risk and Reliability Analysis, was not complete in that the risk assessment was only partially completed at that time. A preliminary description of the methods being used and the approaches taken to develop the risk information were described as well as projections of the type of products to be generated. Since that time there has been a major change in the approach taken to define the future hurricane hazard for New Orleans. The Corps of Engineers, FEMA, and the National Oceanic and Atmospheric Administration (NOAA) created a partnership to define a new, more technically rigorous methodology and to apply that methodology to generate a single federal hazard definition that would serve multiple uses. The new method adopted the wave and surge modeling approach used by the IPET and it adopted an abridged Joint Probability Concept which is different from the method originally proposed by IPET to make it more practical for operational applications. The intent was to use the hazard information generated to drive the IPET risk assessment, the Corps design of 100-year certifiable levees, and FEMA floodmap production. The risk assessment would also be a fundamental tool for use by the LaCPR to evaluate alternative approaches for achieving higher levels of protection. The new hazard definition methodology is described in Volume VIII of this report as a part of the documentation of the risk and reliability work.

Report Organization and Content

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. As of the date of this report release, the risk assessment and preparation of Volume VIII, which documents IPET's risk and reliability efforts and products, remain in progress. There will be an amended version of Volume I published after the completion of the risk assessment and the reviewed and finalized edition of Volume VIII. The general content of each volume and how the results are being applied are described below:

Volume I: Executive Summary and Overview. Volume I is 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 (GPS) technology. The relationship of local mean sea level (LMSL) 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 HPS 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 HPS 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.

Volume III: The Hurricane Protection System. The HPS 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 HPS. It focuses on the character of the HPS starting with the definition of the hazard, defined by the 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 HPS and providing a platform for the performance analysis of individual sites to better understand breaching.

Even though the pump stations and interior drainage facilities are not part of the official hurricane protection project, they are integrated physically and operationally during a hurricane event. Once rainfall occurs and seawater gets past the levees and floodwalls, the interior drainage and pump systems take over. A description of the drainage system and pump stations, and their condition and capacities are included in Volume III.

The comprehensive description of the HPS has been a platform for the majority of the IPET analyses. 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 analyses from geotechnical information on the subsurface conditions to the design assumptions and analyses used to develop the sheet-pile 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, the Hurricane Performance Decision Chronology 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, regional modeling and analysis of surge and waves generated by Katrina and local, high-resolution modeling and analysis 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 HPS. This employed advanced numerical models using a very high resolution representation of the geospatial character of the nearshore environment and the HPS. The high-resolution hydrodynamic modeling and analysis created a more detailed time-history of water levels and forces in the confined spaces of the outfall canals, the IHNC, and the Gulf Intracoastal Waterway (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 HPS, 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 timeline of events was developed by combining eyewitness interviews with a wide variety of physical information and evidence. The timeline established when overtopping, breaching, and flooding occurred in the individual drainage basins and along the various reaches of the HPS. 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 Mississippi River Gulf Outlet (MRGO) channel on the storm surge levels in the IHNC. The ADCIRC storm surge 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 RPI and ERDC 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 Pumping. 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 backflow, 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. The hypothetical condition of all structures being at authorized levels and no breaching was run to examine the potential flooding if the system had been completed as authorized.

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 HPS. 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:** Four hypothetical flooding scenarios are examined to explore consequences of alternative scenarios of flood control and hurricane protection system performance in greater New Orleans. These are summarized as follows:
 - Hypothetical Katrina Scenario 1 (Resilient Levees) – Levees and floodwalls crest elevations are at their pre-Katrina levels. Katrina overtops portions of the flood protection system, the levees and floodwalls maintain their integrity and do not breach, and interior pumping is as occurred during Katrina.
 - Hypothetical Katrina Scenario 2 (Resilient Levees and Pumps) – Levees and floodwalls crest elevations are at their pre-Katrina levels. Katrina overtops portions of the flood protection system, the levees and floodwalls maintain their integrity and do not breach, and interior pumping is at 100 percent availability.
 - Hypothetical Katrina Scenario 3 (Resilient Floodwalls) – Levees and floodwalls crest elevations are at their pre-Katrina levels. Katrina overtops portions of the flood protection system. Overtopped levees incur scour as in Katrina, but the floodwalls maintain their integrity and do not breach, and interior pumping is as occurred during Katrina.
 - Hypothetical Katrina Scenario 4 (Authorized System) – Levees and floodwalls are at authorized elevations and no breaching occurs. Overtopping can occur and pumps operate at 100 percent.

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 subbasin 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-Katrina 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 LaCPR.

Volume VIII: Engineering and Operational Risk and Reliability Analysis. Volume VIII documents the risk and reliability assessment for the New Orleans and Southeast Louisiana Hurricane Protection System. This was the IPET’s principal effort to accomplish a system-wide perspective of the past and near term capability of the HPS. This volume documents the methodology for defining the future hurricane hazard to New Orleans and vicinity, the methodology for characterizing and assessing the reliability (performance) of the HPS structures and related features against that hazard, the methods used for determining the likelihood of flooding in the various subbasins and protected areas, and the risk model itself. The risk model integrates all of these components with the consequence relationships described and presented in Volume VII to generate risk values in terms of both annualized expected loss of life and property losses. The hazard definition was accomplished through a partnership between the Corps of Engineers, FEMA, NOAA and IPET and adopted the rigorous surge and wave modeling capability assembled for the IPET work reported in Volume IV. This allowed development of a single body of knowledge on storm-generated water levels (surge, waves and wave setup) and frequency of occurrence for a large number of locations around the study area. It also provided a

single information resource for IPET risk assessment, FEMA flood mapping, Corps levee and floodwall design, and planning efforts to examine higher levels of protection through the LaCPR.

Over 150 historical and hypothetical storms were run through a quasi-coupled version of the ADCIRC and STWAVE models to define the storm water level - frequency of occurrence relationships for a wide variety of locations around the region. This ensemble of storms represents the full range of storms that can hit New Orleans and provides a joint probability model for defining the hazard (surge and wave environment) that each reach or structure might experience in the future. Because the nature of the structures comprising the HPS impacts the ultimate surge and wave levels, a number of the storms were modeled using three different geometries for the HPS. The first represented pre-Katrina conditions, the second represented the repaired HPS, and the third represented the projected 100-year certified structures planned for the future.

The reliability of the system is modeled by first characterizing the types and properties of the structures and features associated with the HPS. This includes gates, levees, floodwalls, pump stations, and bridges. The entire HPS is divided into reaches, sections considered to be reasonably uniform in properties and performance. In addition, specific structures are considered separately. The expected performance of each reach or specific structure is defined using fragility curves, relating the probability of failure to storm-generated water levels. The fragility curves consider failure by multiple mechanisms, such as potential for breaching before overtopping or as a direct result of overtopping. The fragility curves are based on the foundation conditions (soils) of the structures, character of the structure or feature (design, construction and maintenance), and the type of forces created by different water levels (storm surge + waves). Each fragility curve includes the uncertainties of different types of performance based on unknowns and possible variability in performance.

Combining the hazard with the reliability analysis provides estimates of the likelihood of area being flooded to different depths. As such, for each subbasin, one ends up with depth of flooding - frequency curves. When these are combined with the loss -depth of flooding curves generated in the consequence analyses (see Volume VII), it is possible to compute risk, for either loss of life or loss of property. It is important to note that the risk information not only provides a measure of the relative risk of living in different areas, but also the sources of the risk. High risk levels can be due to low and/or weak structures, low elevations in the protected area, or high densities of property or people in an area. Risk can be mitigated by strengthening and raising structures (minimizing exposure to flooding) or reducing the consequences of flooding (not placing people or property in the most vulnerable areas, and/or having a very efficient evacuation process).

The risk assessment contrasts relative risk levels by subbasin prior to Katrina to those after repairs and upgrades were complete. The risk and reliability model and associated information are being transitioned to the LaCPR as a tool for evaluating alternative approaches for higher levels of protection.

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 system-based 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.

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, the IPET Communications Plan, a summary of the contributions to Task Force Guardian, and the official documents concerning IPET.

Overall Uncertainty in IPET Analysis

In spite of the large amount of work accomplished by the IPET and others, it is important to recognize that the body of knowledge that has been generated is not complete and much remains to be done to gain a comprehensive understanding of all aspects of hurricane risk reduction for the future. Much of the IPET work was conducted within a highly constrained time frame. This drove investigators to apply tools and methods that were proven and familiar to the investigators and readily available. Time constraints often precluded lengthy or comprehensive data acquisition, especially over the extensive area of the New Orleans Hurricane Protection System. By their nature, performance evaluations generate inherent uncertainties that are incorporated in the ultimate results. It is important that these uncertainties be considered in the application of those results.

During the conduct of the IPET work considerable care was taken to evaluate data and data sources, consider the limits and capabilities of methods and processes used, and measure uncertainty when feasible. Data used were screened, validated, and managed through a corporate information management system. Significant sensitivity analyses were conducted when complex computer codes or models were applied to understand the relevance and limits of their output. In addition, a formal uncertainty analysis is a significant component of the risk and reliability assessment, tracking the levels of uncertainty in each component of the analysis process to include individual data sources and models dealing with the hazard, the hurricane protection system and its performance, and flooding and consequences of flooding. These are all essential to estimating uncertainty in the final risk and reliability products. Finally, the ASCE and NRC reviews of IPET work and results provided an independent perspective on uncertainties and their role in the quality of the findings and lessons learned. The following paragraphs highlight prominent areas of uncertainty associated with each major IPET mission area of investigation.

The System: The characterization of the system and its design was largely based on the documentation of the designers and the data they accumulated to effect the designs. This

information was augmented with field data acquired by a number of teams immediately after Katrina, as a component of the investigations conducted by the IPET, and during the extensive repairs by Task Force Guardian. These activities included significant excavation of damaged sites, floodwall concrete and steel testing at breached locations, new geotechnical data, and review of construction and inspection records. A major challenge was the knowledge of the elevations of the key structures. Re-establishing a more reliable and consistent reference to the updated geodetic vertical datum and local mean sea level was an essential first step. The magnitude and variability of subsidence in the New Orleans area make this an area of continuing uncertainty. Additional measurements to more stable reference marks outside the region and long-term collection of water level gage data would provide a more accurate representation of apparent subsidence (ground sinking and sea level rise) in the region. The LIDAR data used to characterize topography of the HPS itself and the interior areas, while calibrated with modern GPS technology and measurements, introduces some uncertainty.

It was literally impossible to treat the full extent of three-dimensional variability of the surface and subsurface characteristics of the structures. The characterization of the HPS structures, beyond specific breach sites studied in detail, was based on available records, the most recent observations by pre-Katrina inspection teams, and post-Katrina inspections conducted by both the IPET and Corps New Orleans District contractors. The density of subsurface information relative to the complexity of the geology in the region will always be a source of uncertainty with respect to the actual foundation conditions at any given point along the system. Local variability in conditions over a very large area such as this can be overlooked in this process.

The Storm: The surge and wave modeling conducted to understand the hydrodynamic environment created by Katrina was perhaps unparalleled. Very high resolution computational grids, the most accurate wind field spatial and temporal characterizations ever generated by NOAA, coupling of the interaction between surge and waves, and detailed modeling of the influence of the coastal and protective structures themselves on water levels resulted in a very sophisticated representation of the water levels and forces believed to have been generated by Katrina on the HPS. High resolution modeling was also accomplished to understand the wave and current environment within the confined channels such as the outfall canals and the IHNC, including physical modeling to examine the impact of debris on water flow and waves within the canals. This extensive effort was necessary because there was very little actual measured data for many of these factors.

All surge and wave models are driven by winds, but lack of surface wind measurements limited the assessment of wind accuracy near the peak of the storm. Accuracy of the wind drag formulation at extreme hurricane wind speeds is an additional source of uncertainty in water level calculations as well. Another major challenge in this area is the lack of measured water level data to calibrate the surge and wave models and to validate results. Essentially all gages external to the protection system were destroyed by the storm. Only one gage, at the Corps lock where the IHNC meets the Mississippi River, provided any significant water level data, and some of those data were erratic. High water marks were the only information source available over the region to compare to the computer predicted water levels. Yet high water marks along the exposed eastern side of St. Bernard and in Plaquemines were often of poor quality. Lack of

distributed gage data was a significant challenge and will continue to hamper future studies until survivable water level measurement systems are put in place. Finally, there were no direct measurements of the hydrodynamic forces on structures, impacting the ability to validate the high resolution hydrodynamic water modeling.

The Performance. The performance analysis was dependent on the characterization of the HPS structures, estimating the forces they were subjected to and the ability to model or calculate their possible behaviors. Since the structures varied in type and character with location, it was essential to define those differences. Modeling performance of the structures required a time history of forces, which in turn required a time history of the water levels and associated wave conditions. Much effort was expended to determine as accurately as possible when overtopping and breaching activities occurred. Interviews with many eye witnesses and a variety of other information sources were integrated to generate a most plausible time line for the major overtopping, breaching, and flooding events. This time line best fits all of the information available, but that information is by no means comprehensive for all locations. There were considerable conflicts in the testimony of the some of the eye witnesses interviewed.

Analysis of the floodwall behaviors required characterization of the subsurface conditions at each breach site, as well as in adjacent undamaged sections and at other locations where similar structures did not breach. Previously obtained soils information, most from the original design documents, were augmented by additional field data acquisition, but in a complex geologic condition such as New Orleans, there will always be a chance that local changes in conditions remain undetected. New technologies offer some improvements in this area and were applied whenever feasible. However, there was neither time nor resources available to conduct extensive new subsurface investigations beyond the breach sites.

Stability and seepage analyses require information on the geometry of subsurface layers and physical properties of the subsurface materials as well as those used in constructing the levees and floodwalls. IPET analysis relied on original design information, published technical studies of similar materials, as well as collection of new soils and materials information to establish property values for the materials at the sites. The extrapolation of these data to represent conditions at adjacent or other sites with presumed similar geology introduces uncertainty.

Analyses methods themselves can introduce uncertainty. The specific methods and the assumptions used can significantly influence results. For structural performance the assumptions concerning the shape of the failure plane and possible failure modes can influence the results of the analysis. IPET relied on the extensive experience and expertise of the investigators to use appropriate tools and make appropriate assumptions for the objectives of the study. Again, the ASCE and NRC review processes were extremely valuable in ensuring that the information and methods being used were appropriate.

Flooding/drainage analyses relied on proven hydraulic and hydrologic models supplemented with historical knowledge of the past performance of the system. These models require input of elevations of the sub-basins in the protected areas, descriptions of the drainage system and pumping capabilities, and characterization of the timing and dimensions of any breaches in the protection structures. The amount of rainfall, water flowing over structures or through breaches,

and the distribution of that water through the interior drainage system, is all included in the computation of extent and depth of flooding with time. The most significant uncertainties in this process are related to timing. This includes the time history of the breach formation, the time history of the water elevations that supplied the water that overtopped structures or flowed through the breaches, and the time history of pump station activities and the timing of rainfall in each sub-basin.

The Consequences: Consequences of flooding were characterized for both property and loss of life. The estimates of property damages are based on the type of property, the estimated value of the property, and estimates of the degree of damage/loss as a function of depth of flooding. The fundamental distribution and character of property values were derived from available government data bases that provided information to census block resolution. These data may not be current for all properties. Similarly, the value of properties was taken from tax and other associated data bases that have a time stamp and may not be current for all properties. The depth-damage relationships were derived from previous work accomplished by the Corps of Engineers and others and while representative of pre-Katrina conditions, may not accurately represent all individual properties. Depth-damage relationships for possible future scenarios were developed by making educated assumptions concerning the types of re-development that could occur and the expected values of those properties.

Loss of life information was developed using best available information by Parish and, if possible, by sub-basin. Since data of the location of individual fatalities was not available, it was not possible to provide distributed fatality information beyond political boundaries. While representative of the losses in each area, there are still questions concerning the actual total number of fatalities. Loss of life – flood depth relationships developed for use in the risk assessment are based on the LifeSim model which makes specific assumptions concerning evacuation, the ability of individuals by age to seek safety, and how these factors vary with different depths of flooding. Uncertainty was computed for both the property damage – depth of flooding relationships and the loss of life - depth of flooding relationships. There is significantly more uncertainty in the loss of life relationships than in the property loss relationships.

Across all of the consequence analyses, there was a significant effort spent on developing predictive relationships, but the ability to predict the relationship between environmental consequences and flooding is not fully developed and limits the ability to estimate long-term losses or impacts. Similarly, social and cultural scientists have no tools for predicting the impact of flooding different from what actually occurred. The discipline can document what occurred but cannot predict for different events. This is a significant source of uncertainty for both environmental and social sciences components of the IPET analyses.

The Risk: Risk assessment inherently characterizes the level of uncertainty in each step of the process. The hazard definition component involves defining the probability of experiencing surge and wave conditions for a range of potential hurricanes at various locations around the region. Primary sources of uncertainty in this step include the randomness of the hurricane parameters that model wind field time histories for hypothetical hurricanes, the ability of the surge and wave computer models to accurately translate wind fields into surge and wave

conditions, and the ability to assign appropriate probabilities to the specific events and the water conditions they generate.

The reliability component of risk assessment is based on a definition of the probable performance of individual structures or reaches (uniform sections) of a particular structure type for different water levels and conditions. These relationships, known as fragility curves, include a characterization of the uncertainty in that performance relationship. If all failure modes, or other aspects of performance, are not adequately represented, the resulting estimates of performance of the structures will introduce more uncertainty into the estimates of extent and depth of flooding that result from this analysis.

Uncertainty in the ability of the risk model to accurately predict the frequencies of flooding must also be estimated. The model must predict elevations and frequencies of flooding for hypothetical hurricanes for which there are no data to measure the accuracy of the predictions. Since the only historical experience available with sufficient data to test the risk model is Katrina, uncertainty in the risk model must be estimated conservatively.

The estimates of extent and depth of flooding are coupled with the last major component, the consequence analysis. Using the property and life relationships described earlier, the probability of experiencing flooding in a given area is combined with the likely economic or life losses for that location to generate information of the probable losses that would be experienced. This step is obviously dependent on the precision of the flooding estimates and the inherent variability in the loss relationships.

During the process of developing the risk assessment, the major information bases and methods being used have been examined for their sensitivity to quality of input data, the inherent uncertainty in model outputs, and the cumulative uncertainty in the final risk information. This uncertainty information will be published along with the risk products to document the relevance of the products and inform users.

Hurricane Katrina and Its Impact

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

overview of what happened during Katrina in the context of the five IPET mission questions and the analyses accomplished to answer those questions.

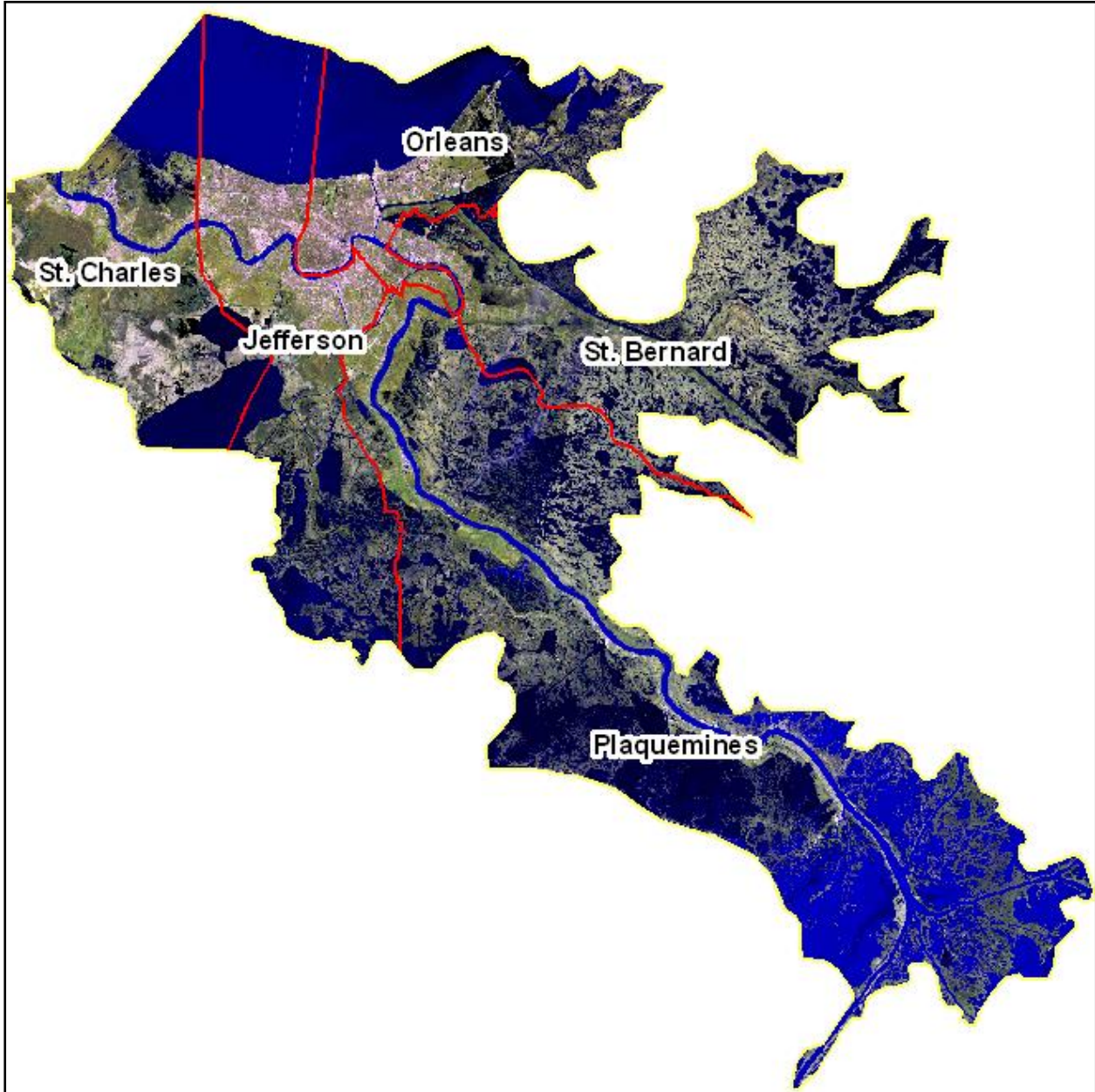


Figure 1. Principal area of analysis.

Historical Perspective

Geologic History and Setting: The following is a brief overview of the geologic setting in New Orleans and its influence on the HPS. A more detailed summary of the geologic history of the New Orleans region and the implications of the geologic conditions on the HPS is provided

in Appendix I-5. There is also significant discussion of geologic issues on the HPS in Volume III and extensive information on geology presented in Volume V.

The geologic history of the New Orleans area significantly influences the engineering properties of the foundation soils beneath the levees. Geologic and engineering data gathered from the different levee failures identify a spatially complex geomorphic landscape, caused by Holocene sea level rise, development of different Mississippi River delta lobes, and the distributary channels associated with delta development. Overlying the Pleistocene surface beneath the New Orleans area are predominantly fine-grained, shallow water depositional environments and related sediments associated with bay sound (or estuarine), nearshore-gulf, sandy beach, lacustrine, interdistributary, and paludal (marsh and swamp) environments. These environments define the New Orleans area history during the Holocene, and comprise the levee foundation for the different failure areas. A relict barrier beach ridge is present in the subsurface along the southern shore of Lake Pontchartrain. This relict beach blocked the filling of the lake with fluvial-deltaic sediments, impacted the supply and texture of sediment being deposited by advancing distributary channels, and influenced the engineering properties of these soils. Marsh and swamp soils beneath the failure area at the 17th Street Canal are much thicker than those beneath the London Avenue Canal because of the influence of the beach complex, and are thickest in the Inner Harbor Navigation Canal area.

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

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

Geographic History and Setting: Located in the low-lying Mississippi River delta in Louisiana, large portions of New Orleans lie near or below sea level, which has posed complex flood management problems since the city's founding in 1718. Historically, the greatest natural threat posed to residents and property in the New Orleans area has been from hurricane-induced storm surges, waves, and rainfall. Until the early twentieth century, construction was largely limited to the slightly higher ground along old natural river levees and bayous, since much of the rest of the land was low, swampy, and subject to frequent flooding. In 1899, the Sewerage and Water Board of New Orleans was created; it remains responsible for draining the city. The topography of New Orleans makes drainage a major challenge, with the same natural and

artificial levees designed to keep water out having the unintended effect of confining rainwater and sewage in the city. This led to perhaps one of the most sophisticated and comprehensive drainage systems in the world.

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

The Sewerage and Water Board today drains over 61,000 acres in New Orleans and neighboring Jefferson Parish of almost 13 billion cu ft (cubic feet) of water per year. The drainage system includes 90 miles of covered canals, 82 miles of open canals, and a multitude of pumping stations. However, pumping of groundwater from underneath the city has accelerated the subsidence that the area was already prone to because of its natural alluvial floodplain geology. The subsidence increases the flood risk, should the levees be breached or precipitation exceed pumping capacity, because the New Orleans bowl is becoming deeper as time and subsidence progress.

The geographic location of New Orleans makes the city particularly vulnerable to hurricanes. Fortunately, New Orleans has been impacted by only a few large storms. New Orleans was hit by major storms in the 1909 and 1915 Atlantic hurricane seasons. Much of the city flooded in September 1947 due to the Fort Lauderdale Hurricane. The next major threat came in the 1960s with Hurricanes Betsy and Camille.

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

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

The Lake Pontchartrain and Vicinity Hurricane Project was intended to protect areas around the lake (in Orleans, Jefferson, St. Bernard, and St. Charles Parishes) from flooding caused by a storm surge or rainfall associated with a hurricane that would be roughly the same as what is

today classified by the Saffir-Simpson Scale as a fast-moving Category 3 hurricane. The basis for this was the SPH developed for the Corps by the Weather Bureau (now the National Weather Service). The SPH is a steady-state storm based on an analysis of meteorological parameters of past large hurricanes. The assumption of steady-state precludes the consideration of some of the dynamic behaviors we now know characterize hurricanes such as decreasing in intensity and increasing in diameter as they approach shore. It also precludes consideration of the dramatic impact of large storms in generating surge and waves long before they reach landfall. For the initial definition of the SPH used in design of the New Orleans hurricane protection structures, hurricanes were considered that occurred during the period 1900 to 1956. Central Pressure Index (CPI) was the primary intensity criterion and the 1-percent recurrence CPI (100-year) was chosen for the initial SPH definition. When the additional consideration of the likelihood of a storm of that size hitting the area near New Orleans is added, it was estimated to be equivalent a 200- to 300-year recurrence event. The SPH was intended to represent the most severe meteorological conditions considered “reasonably characteristic” for the region. A maximum wind speed was also associated with the SPH; for Lake Pontchartrain and Vicinity, it was assumed to be 100 miles per hour.

Following Hurricane Betsy in 1965, the wind speed criterion was revised but all other characteristics remained the same. The 1965 version of the SPH was used for the design of both the Lake Pontchartrain and Vicinity and New Orleans to Venice Projects. In 1979, NOAA issued a report that significantly revised the SPH criteria, and this became the basis for the design of the West Bank and Vicinity Project. All activities with respect to the Lake Pontchartrain and Vicinity continued to use the original SPH criteria through the time of Hurricane Katrina.

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

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

A December 1977 court decision enjoined the Corps from constructing the barrier complexes and certain other parts of the project until a revised environmental impact statement was prepared and accepted. The Corps conducted a “Re-Evaluation Study,” published in 1984, in response to the court order and examined the feasibility of providing protection mostly by means

of raising and strengthening levees and floodwalls. The exact treatment of the outfall canals was not resolved. Based on this study, the Corps recommended shifting to the “high level plan” originally considered in the early 1960s. Follow-on efforts examined the use of butterfly surge gates and pump stations at the lake ends of the canals and the use of parallel protection levees and floodwalls along the length of the canals as the sole protection measure. The Energy and Water Development Act of 1992 mandated the use of parallel protection and set the stage for the construction of the levee and I-wall structures that were in place prior to Katrina. Note that the original authorization for protection occurred in 1965 time frame and the final resolution of how to provide protection for a large portion of the metropolitan area of New Orleans was not determined until 1992, over a quarter of a century later.

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

Some components of the system were not scheduled to be completed until 2015, primarily the West Bank and Vicinity Project. At no time has the entire New Orleans and Vicinity area had a reasonably uniform level of protection around its perimeter. At no time has any individual parish or basin had the full authorized protection planned for in 1965.

As of May 2005, the Lake Pontchartrain and Vicinity Project included about 125 miles of levees, major floodwalls, flood-proofed bridges, and a mitigation dike on the lake’s west shore. Progress on the project varied by area: 90 percent complete in Orleans Parish, 70 percent complete in Jefferson Parish, 90 percent complete in the Chalmette area, and 60 percent complete in St. Charles Parish. In 2002, a pre-feasibility study on whether to strengthen hurricane protection along the Louisiana coast was completed. A full feasibility study was estimated to take 5 years to complete. A major Emergency Response Exercise in July 2004 used the hypothetical Hurricane Pam to examine the ramifications of a storm much like Katrina. The results projected losses in excess of what happened in Katrina, including massive overtopping and breaching of levees.

The history of this HPS has been one of continuous incompleteness. This situation was a product of the overall water resources development process, the magnitude of the investments

needed to accomplish such projects, the piecemeal allocation of resources, the time and complex processes required to resolve differences in local and federal priorities, and the traditional step-by-step construction process for structures such as levees in subsidence-prone areas such as New Orleans. The affordability of protection appeared to be a major issue between local and federal authorities.

The System (for more information see Volumes II and III)

The HPS, 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 small sections of T-walls and a very small number of L-walls, basically similar to T-walls with a horizontal component on only one side at the base. Detailed maps showing the location of specific types of structures and their relationships to other features such as pump stations and closures are provided in Volume III and Volume VIII of this report. Figure 3 provides a schematic of the basic geometry of these structures. Figure 4 provides a general map of the New Orleans metropolitan area and the features of the HPS that were factors in the system performance during Katrina. Maps showing the detailed distribution of types of structures are provided in Appendix I-6.

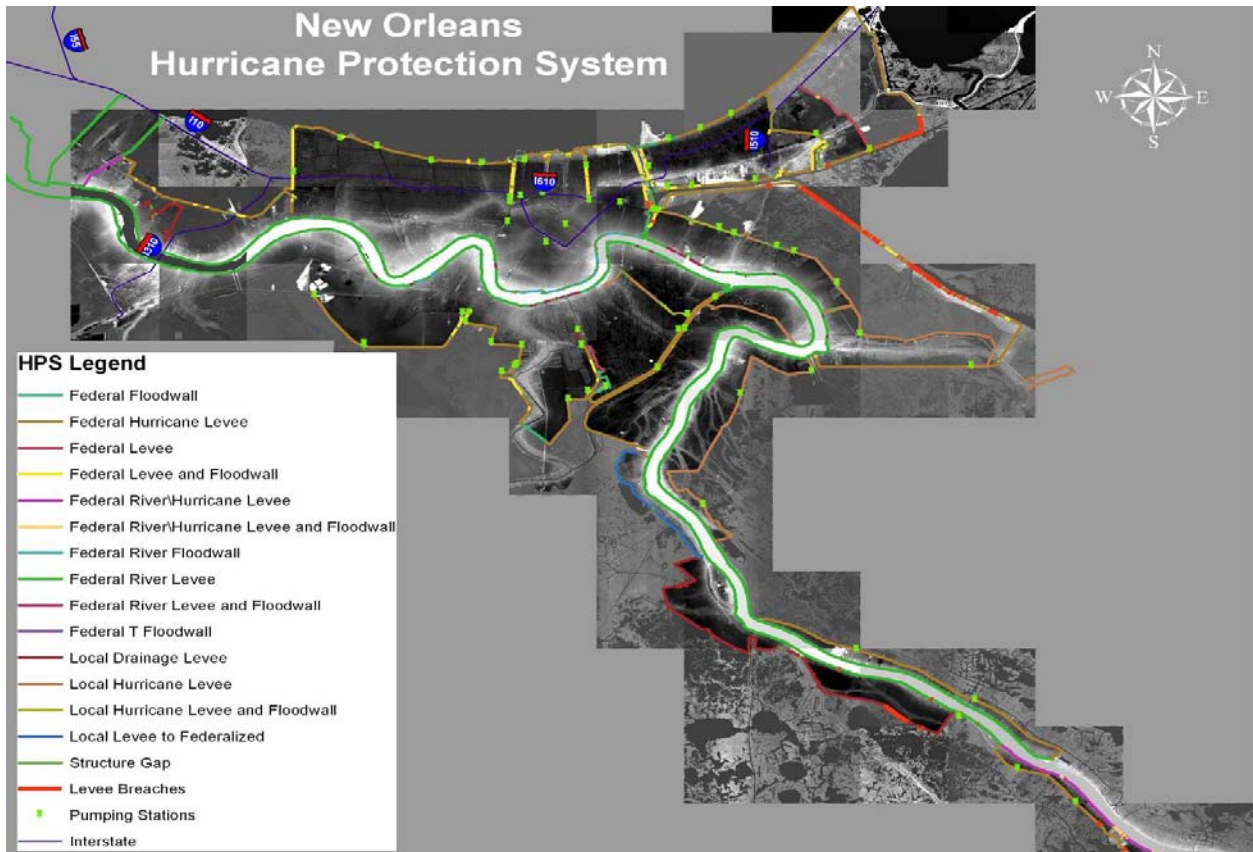


Figure 2. Outline of the New Orleans and Southeast Louisiana Hurricane Protection System.

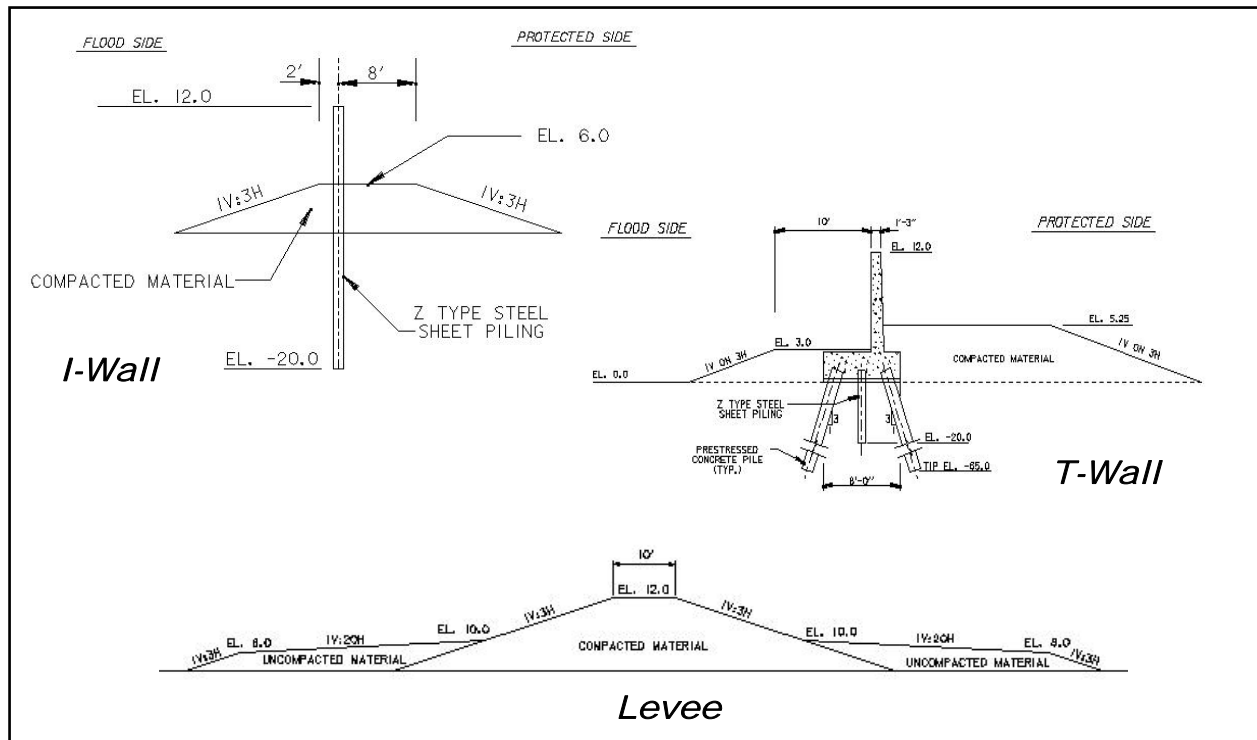


Figure 3. General schematic of major hurricane protection structures used in New Orleans and Vicinity.

The design criteria for these structures was based on the maximum water elevations expected from the SPH as previously described for each project. This amounted to, based on the 1900 to 1956 hurricane record, a 100-year level of severity storm that, considering the geometry of the Gulf, has a likelihood of 1:200 to 1:300 of hitting the area of New Orleans each year, hence a 200- to 300-year protection. The hurricane hazard of today, described in more detail in Volume VIII, is quite different and presents a much more severe challenge to the HPS. The dynamic aspects of hurricane behavior can not readily be factored into the SPH for New Orleans. In fact, the SPH concept is no longer considered state-of-the-art for defining the hazard and should not be used in future projects.

Another aspect of the HPS is that the designs constructed, with the exception of the few sections constructed with T-walls, did not include protection against overtopping. The structures were, in effect, designed to perform at water elevations up to overtopping, but not beyond. This is not atypical in flood protection measures, where cost justification is a primary decision factor. To gain protection from overtopping would have required such measures as armoring the back sides of levees and floodwalls or using more expensive T-walls in place of I-walls to prevent erosion. Some sections of levees were constructed with higher quality (from an erosion perspective) materials than others, basically clays hauled in versus lower quality soils dredged (the method termed hydraulic fill) from adjacent areas (as along the MRGO).

Along the outfall canals, I-walls were added to existing levees to gain higher protective elevations. Structures along the 17th Street and London Avenue Canals were designed with less conservative assumptions than those for the Orleans Canal. Soil strengths assumed for the clay layer underlying the 17th Street Canal were higher than warranted given the measurements

available. For all of the canals, the design analysis used acceptable but dated approaches for stability analysis and a factor of safety of 1.3. Failure modes examined were traditional for the time but did not explore other possibilities. The design for the Orleans Canal structures was more conservative than those for the 17th Street and London Avenue Canals. The levee section was wider and the freeboard of the exposed floodwall less. Orleans Canal had fewer real estate access restrictions, being adjacent to open public land. In the end, all of these differences played a large role in the ultimate performance of the structures during Katrina.

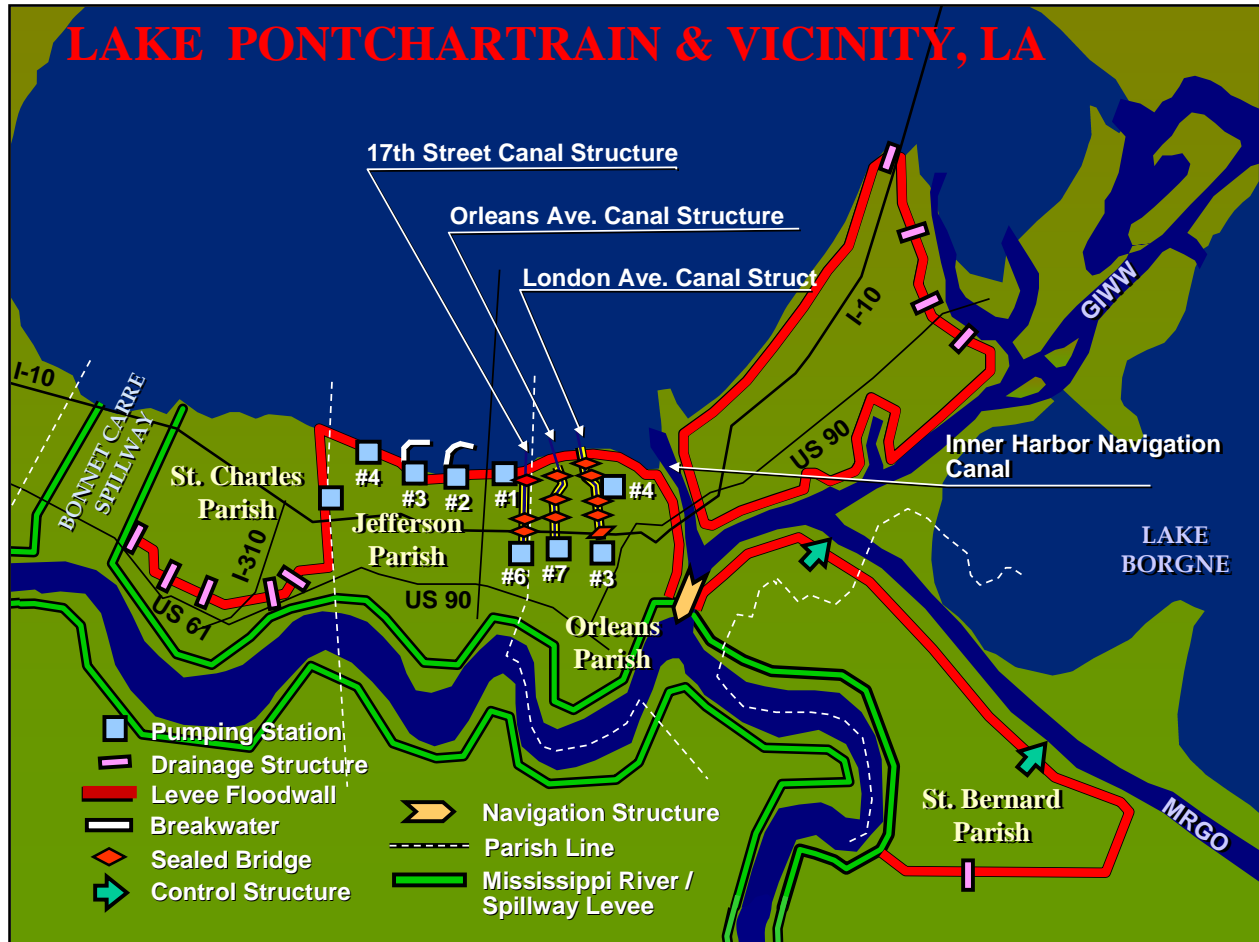


Figure 4. Map showing detailed geometry and features of the New Orleans metropolitan area.

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

The elevations of the current hurricane protection structures are significantly below the originally authorized heights in part from errors in initial constructed elevations, in part from rapid subsidence, and in part from sections where the authorized hurricane protection structures

are not yet in place. Figures 5 and 6 generally depict the degree to which structure elevations just prior to Katrina deviated from the authorized levels. Note that sections designated in red, being greater than 2 ft below the authorized level, can be from any one or some combination of the factors identified above. Substantial subsidence has occurred along the IHNC. The floodwalls along the outfall canals were constructed to elevations nearly 2 ft below the original intent because of errors in relating the local geodetic datum to the water level datum. Significant lengths of structures on the West Bank are incomplete as are small sections in metropolitan New Orleans such as the fronting protection at Pump Station No. 7 at the head of the Orleans Canal.

The repair process substantially changed the elevations of a number of sections of the HPS. Appendix I-7 provides maps comparing post-repair elevations of the HPS structures to authorized elevations. These maps are derived from the work of a number of contractors who conducted detailed examinations of the condition of the levee and floodwalls to determine the integrity of the system post-Katrina and identify any additional work needed to make the system ready for future hurricane seasons. The review processes were based on the criteria developed by the IPET analyses of sites that experienced breaching and those that did not.

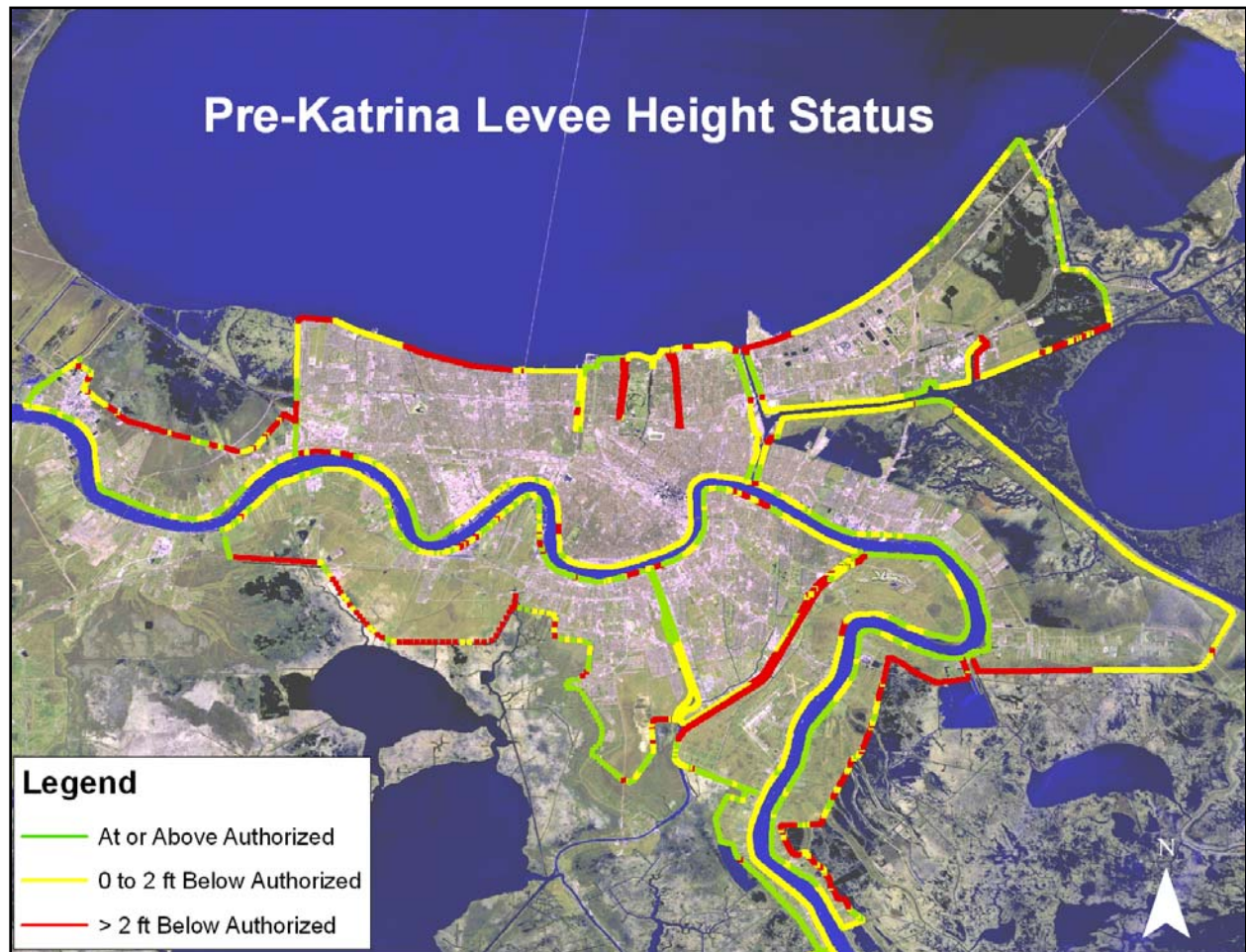


Figure 5. Map comparing pre-Katrina HPS structure elevations to authorized elevations, New Orleans metropolitan area and West Bank. Data derived from IPET risk assessment data base.

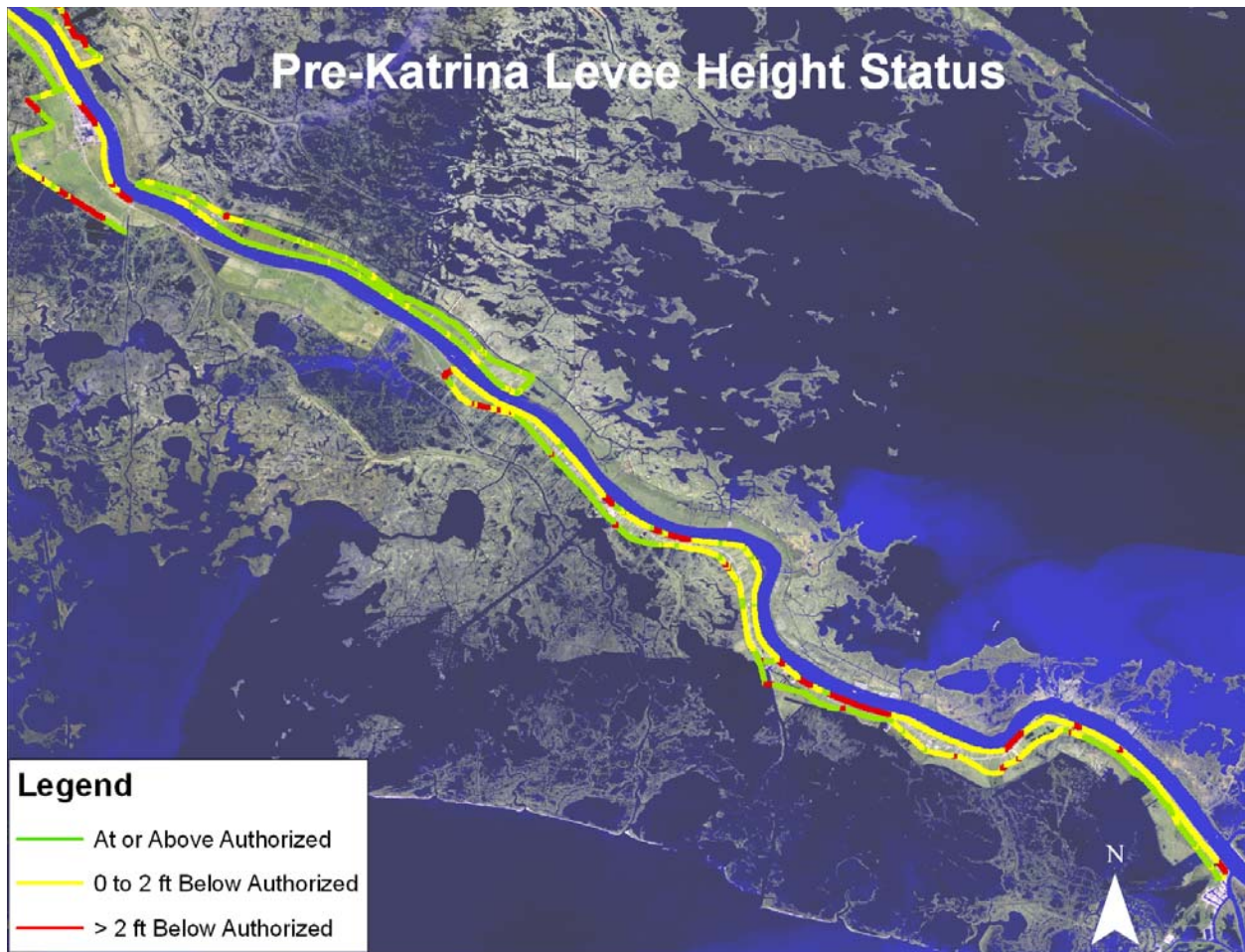


Figure 6. Map showing comparison of Pre-Katrina HPS structure elevations with authorized elevations for Plaquemines Parish. Data derived from IPET risk assessment data base.

The Storm (for more information see Volume IV)

The path followed by Hurricane Katrina, shown in Figure 7, caused severe surge and wave conditions on the east side of the HPS, from Lake Pontchartrain to southern Plaquemines Parish. Katrina struck early on the morning of 29 August 2005, after building up water levels to the east of New Orleans for several days. Katrina was a Category 5 storm with up to 139-knot (160-mph) sustained surface winds until it was approximately 170 miles from landfall. When it reached landfall at Buras, LA, around 0610 hr (6:10 a.m. Central Daylight Time, CDT) or 1110 Coordinated Universal Time, UTC), surface wind speeds were at about 100 knots (115 mph), but the long path through the Gulf, and its intensity and size, had built up record levels of surge and waves, larger than any previous storm to strike the area, or the North American continent.

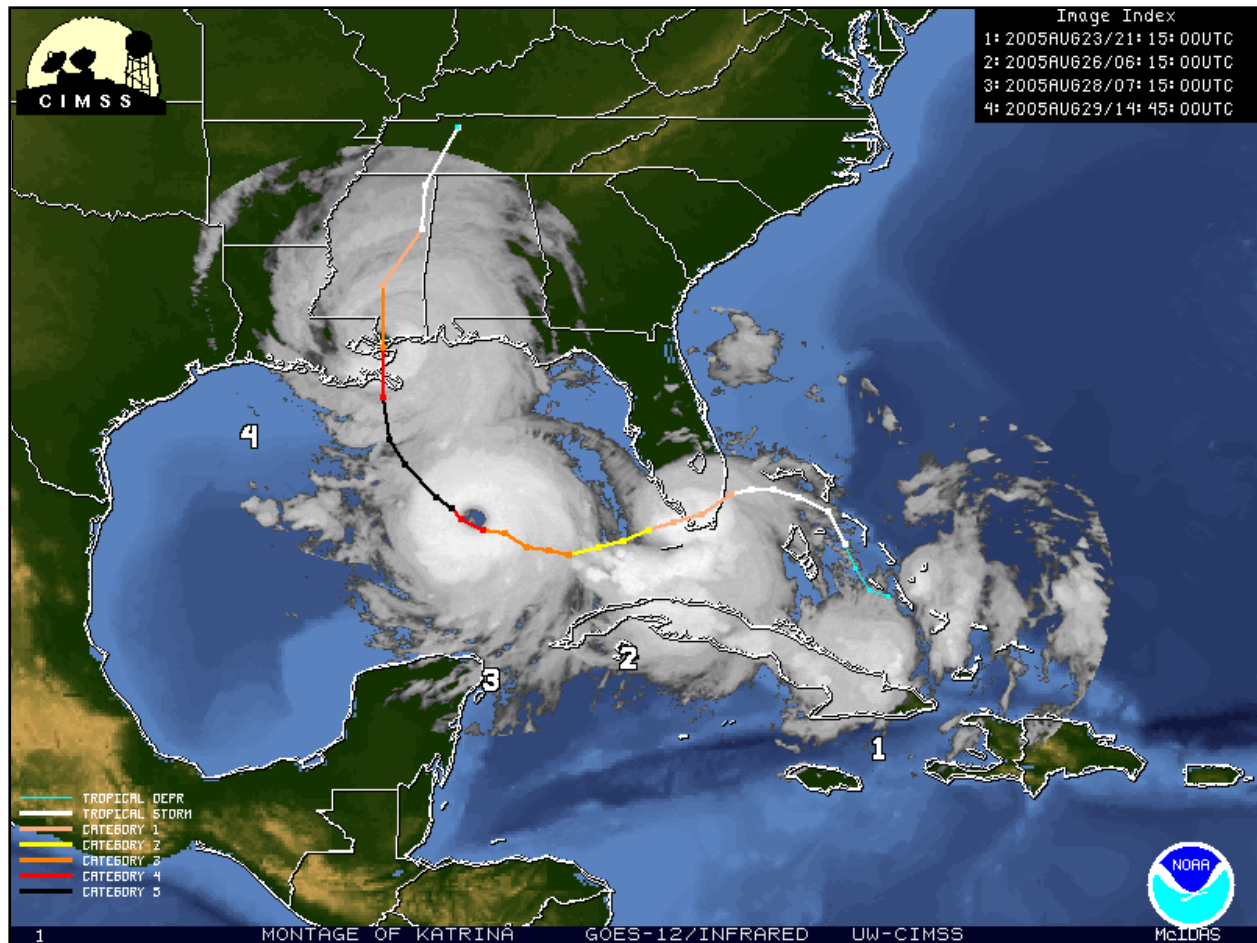


Figure 7. Hurricane Katrina path and intensity history. (intensity defined based on flight-level wind speeds, as opposed to surface winds).

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 levels and damage from hurricanes, it is not a particularly good predictor of the surge and wave generation potential for these storms. Surge and wave levels are particularly sensitive to the path the storm takes, the geometry of the coastline and the continental shelf, and the offshore character of the storm. Hurricane Katrina had much greater wave and storm surge generation potential than the SPH storms used to design the HPS.

Katrina swept through the New Orleans area rapidly, making a second landfall at Pearl River, MS, around 0945 hr (9:45 a.m. CDT (1445 UTC)) with surface wind speeds around 100 knots (115 mph). With it came record rainfall as shown in Figure 8. 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, depending on location, persisted for hours.

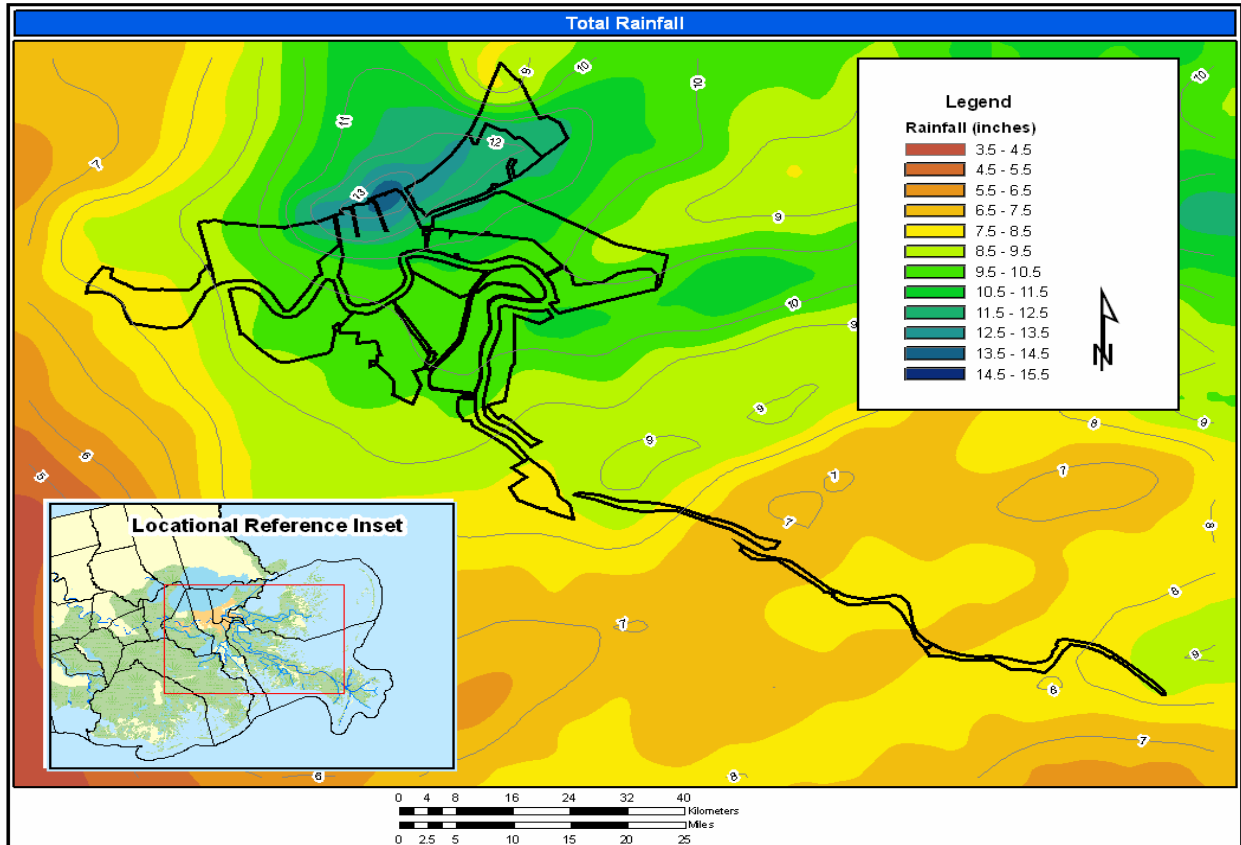


Figure 8. Hurricane Katrina rainfall totals.

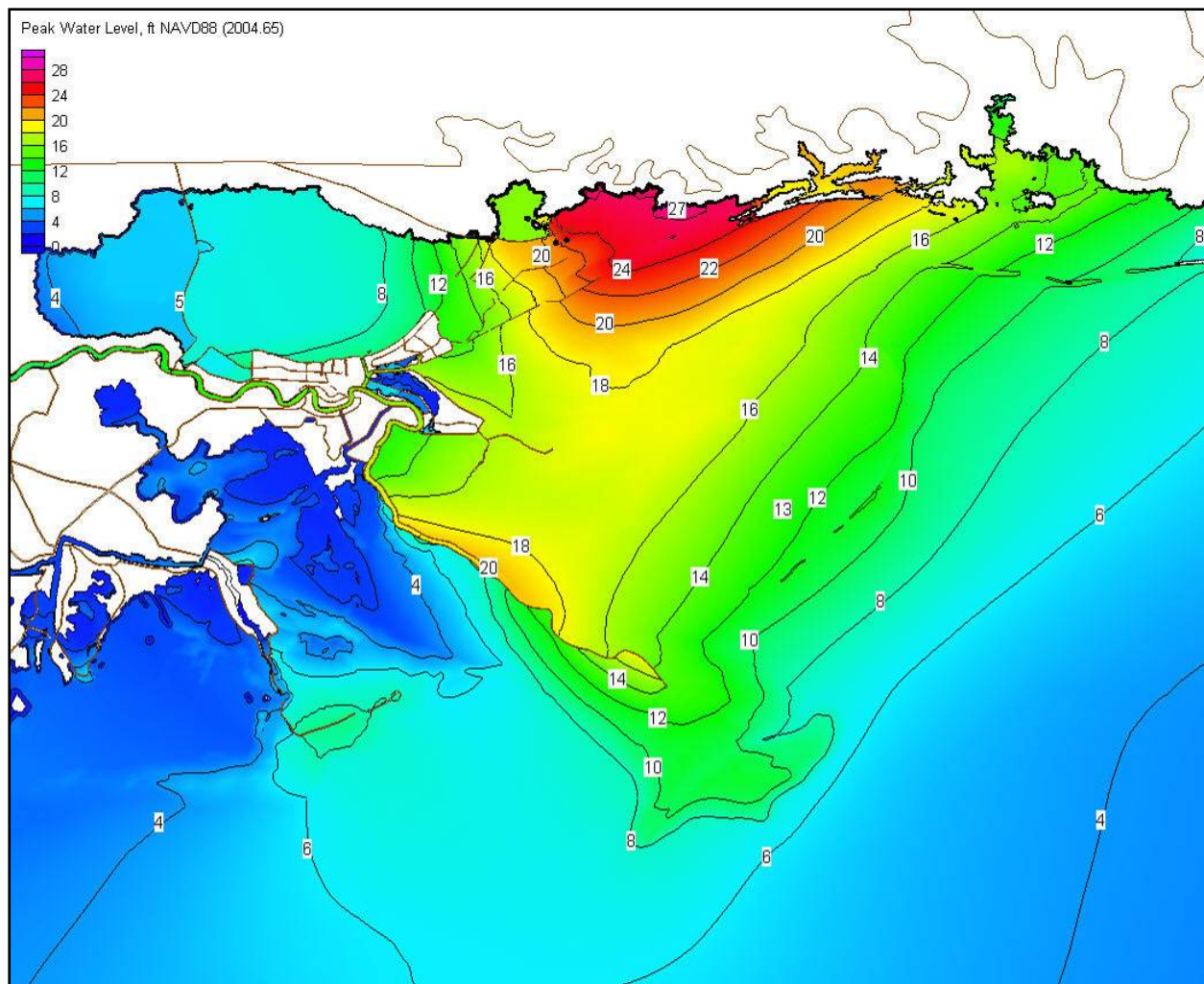


Figure 9. Maximum computed storm surge levels using the ADCIRC model, Mississippi to Louisiana region, water levels in feet NAVD88 (2004.65).

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 9 shows the maximum surge levels predicted for Katrina. The high water marks were used to confirm the accuracy of the model results, and in most cases they agree to within a foot or two. Surge levels ranged from about 10 to 12 ft along the south shore of Lake Pontchartrain to 20 ft along the Plaquemines Levees. Even enclosed areas such as the IHNC experienced water levels above 14 ft, not including waves.

Winds from Katrina generated a record-wave environment. Again, the lack of measurements caused 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 10 to 13. They demonstrate that the Katrina-generated wave environment was severe. The most significant finding was that the waves along the GIWW, St. Bernard, MRGO, and Plaquemines Levees were ocean-generated waves, with wave period in the 15 to 16-second range, much more capable of overtopping structures than the design-assumed wind waves with periods of 5 to 6 seconds.

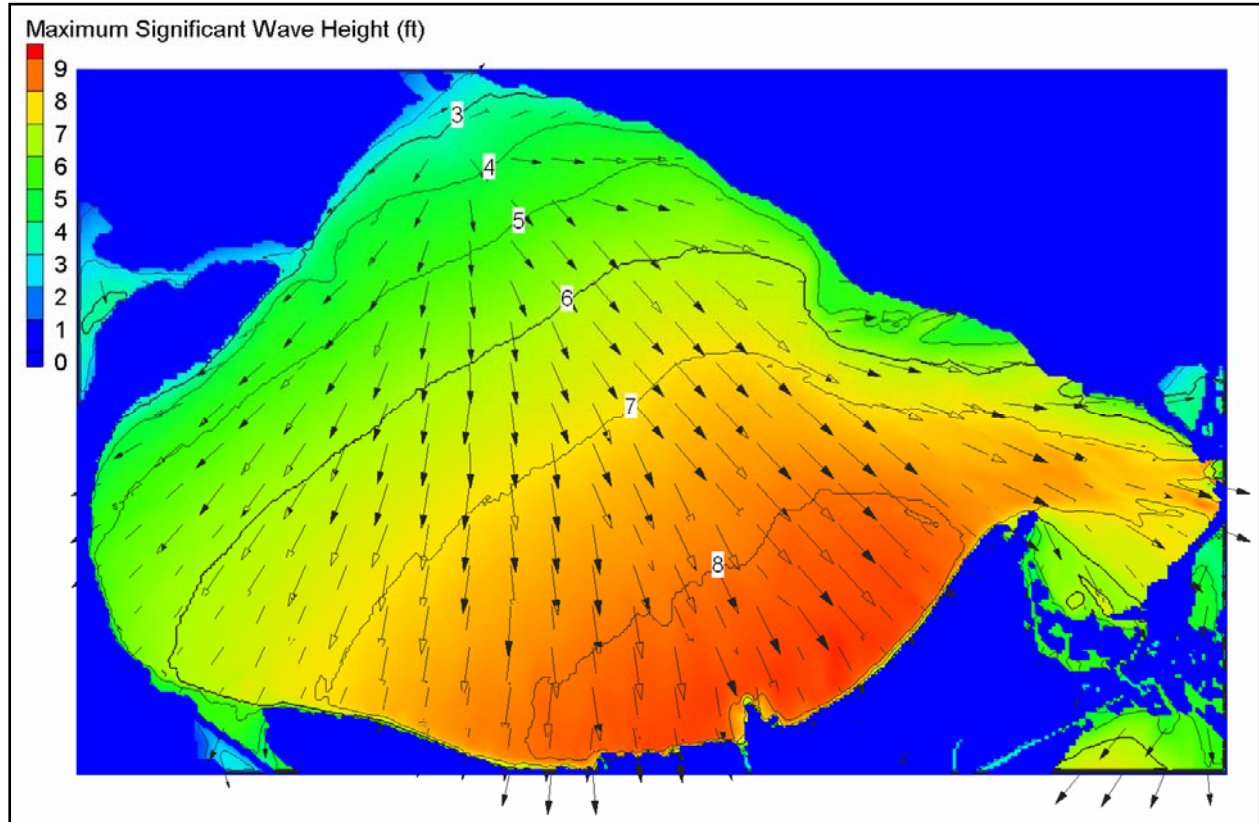


Figure 10. Lake Pontchartrain maximum modeled significant wave height and corresponding mean direction (wave heights in feet).

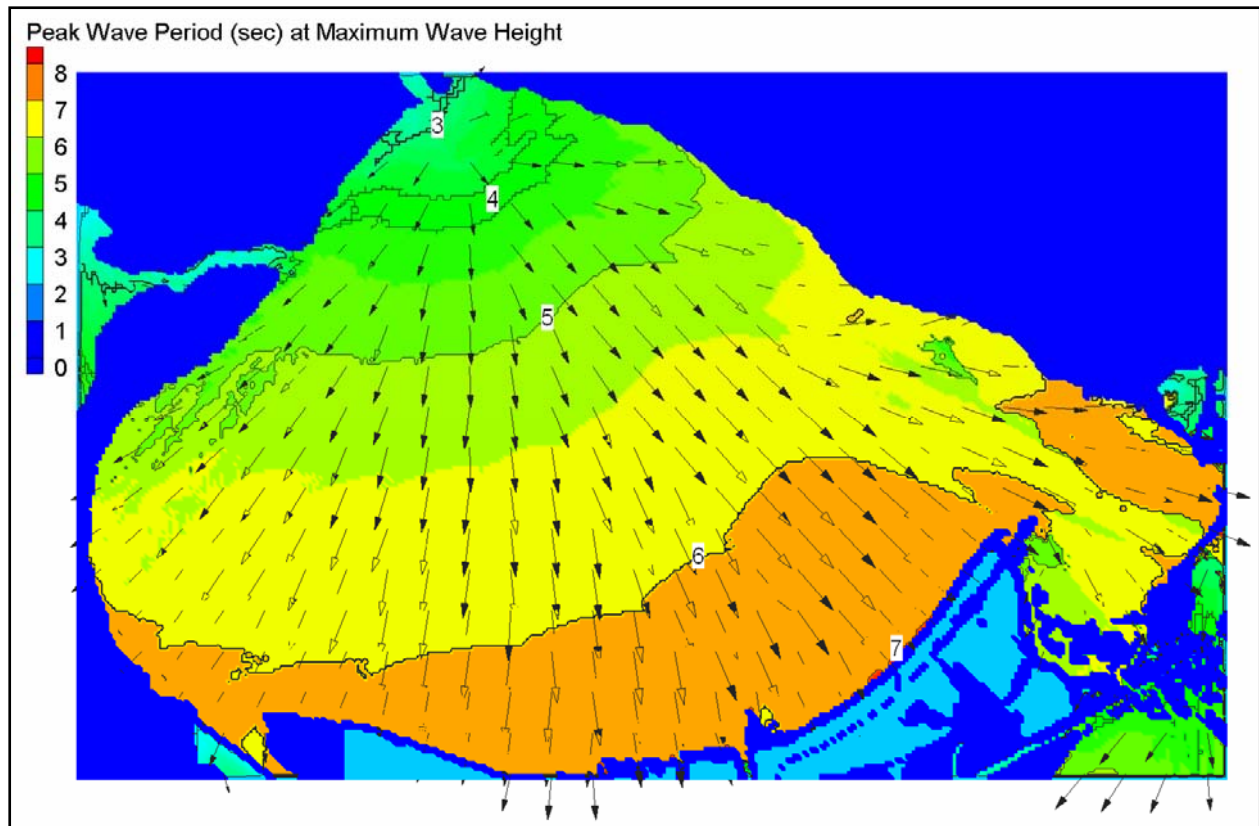


Figure 11. Lake Pontchartrain modeled peak wave period corresponding to the maximum wave height (periods in seconds).

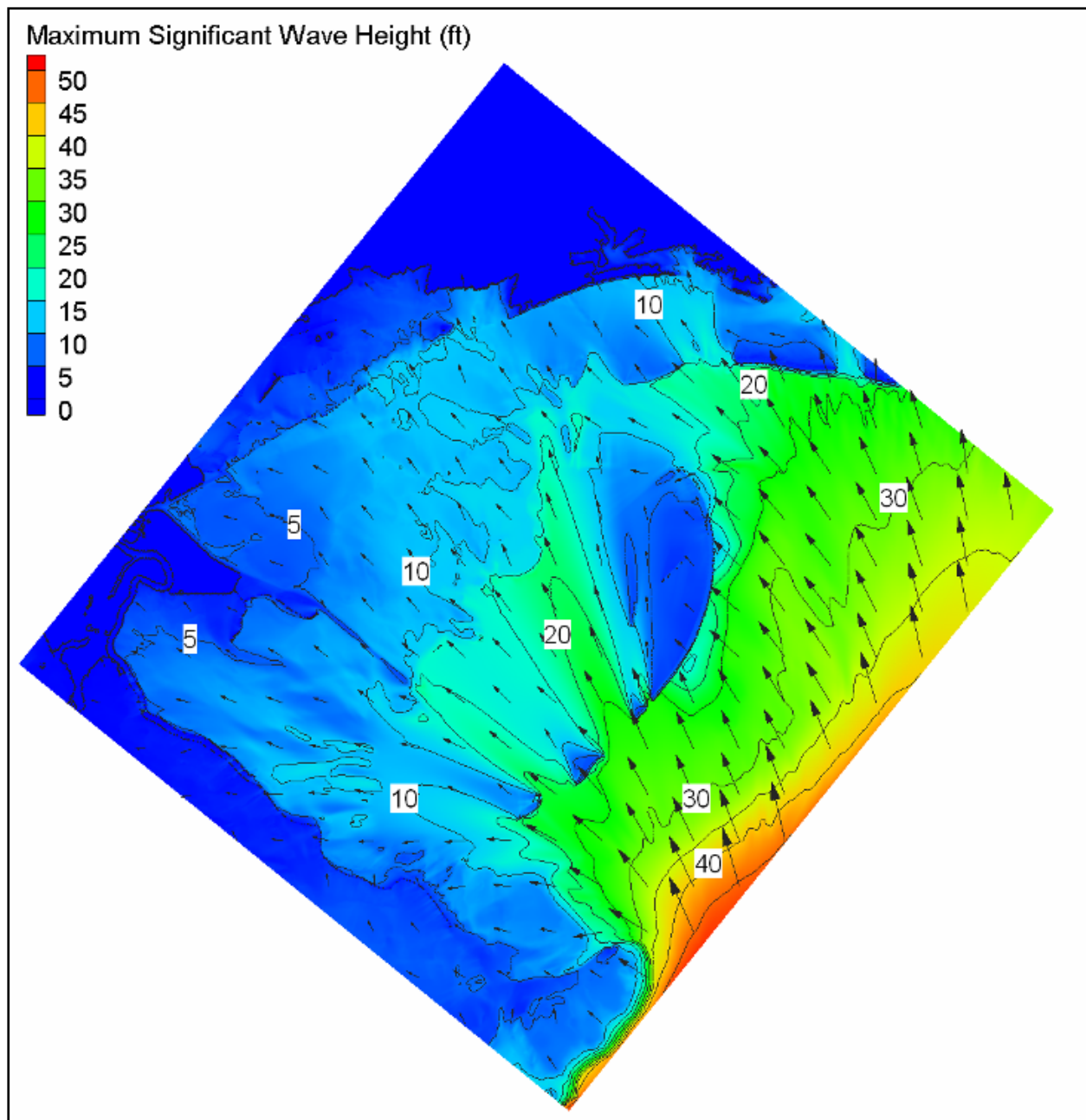


Figure 12. Southeast Louisiana maximum modeled wave height and corresponding mean direction (wave heights in feet).

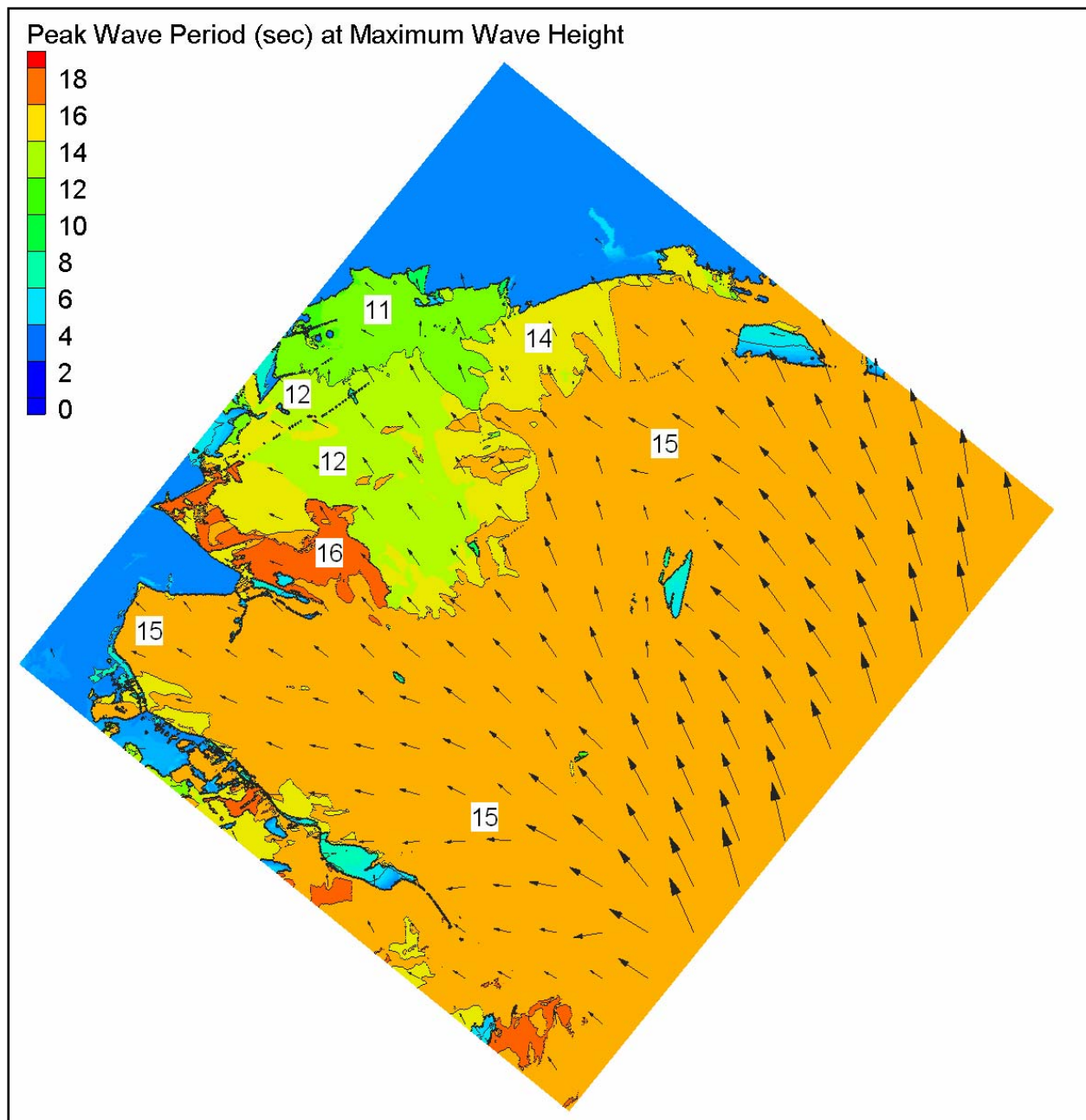


Figure 13. Southeast Louisiana modeled peak wave period corresponding to the maximum wave height (periods in seconds).

It is instructive to examine the surge and wave environment created by Katrina with respect to that assumed from the SPH from which the existing structures were designed. Figure 14 presents a simple comparison of the surge generated by Katrina with that used for the HPS design. Much more detailed information is available in Volume V of this report. Note that the surge in Lake Pontchartrain was roughly the same as the design levels assumed for the HPS. On the east side of New Orleans, Katrina generated surges were significantly greater than the design criteria, ranging from 17 to 20 ft compared to the 12 to 14 ft assumed in the design.



Figure 14. Comparison of general surge levels assumed in the SPH design (D) and estimated from Katrina (K). See Volume IV for more detailed information.

Figure 15 compares the wave conditions assumed for the SPH design and those estimated from Katrina. With the exception of Plaquemines Parish, Katrina generated wave heights were not much different from the design assumptions. In Plaquemines Parish, Katrina did generate significantly higher waves. Wave periods were a different story. In Pontchartrain, the period of Katrina-generated waves was similar to the design assumptions, in the 6- to 7-second range. Along the St. Bernard and Plaquemines Levees, however, Katrina generated 14- to 16-second period waves, approximately three times the design wave periods. This is very significant in that the longer period waves were largely generated in the Gulf and propagated in to shore and have much greater potential for runup and overtopping of HPS structures.



Figure 15. General comparison of wave height and period assumed in HPS design (D) and estimated from Katrina (K). See Volume IV for more detailed information.

The Performance (for more information see Volumes V and VI)

Figure 16 shows the locations of the most severe damage to the HPS. Over 220 miles of the protective structures were damaged by Katrina-generated surge and waves, as well as 34 of 71 pumping stations. Approximately 41 miles of structures were judged to be severely damaged. Initially there were a total of 50 major breaches identified, 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. Transitions between types of flood protection structures were also vulnerable, especially where the transition included a significant change in elevation between the structures. Detailed maps of the distribution of the major breaches are provided in Appendix I-8 along with a table documenting their characteristics and including the repair actions taken for a majority of the major breaches. The maps and table in Appendix I-8 list only 29 breaches. The differential from the original 50 is caused by aggregation of some of the breaches that were adjacent or related to each other for the purposes of repair and rebuilding.

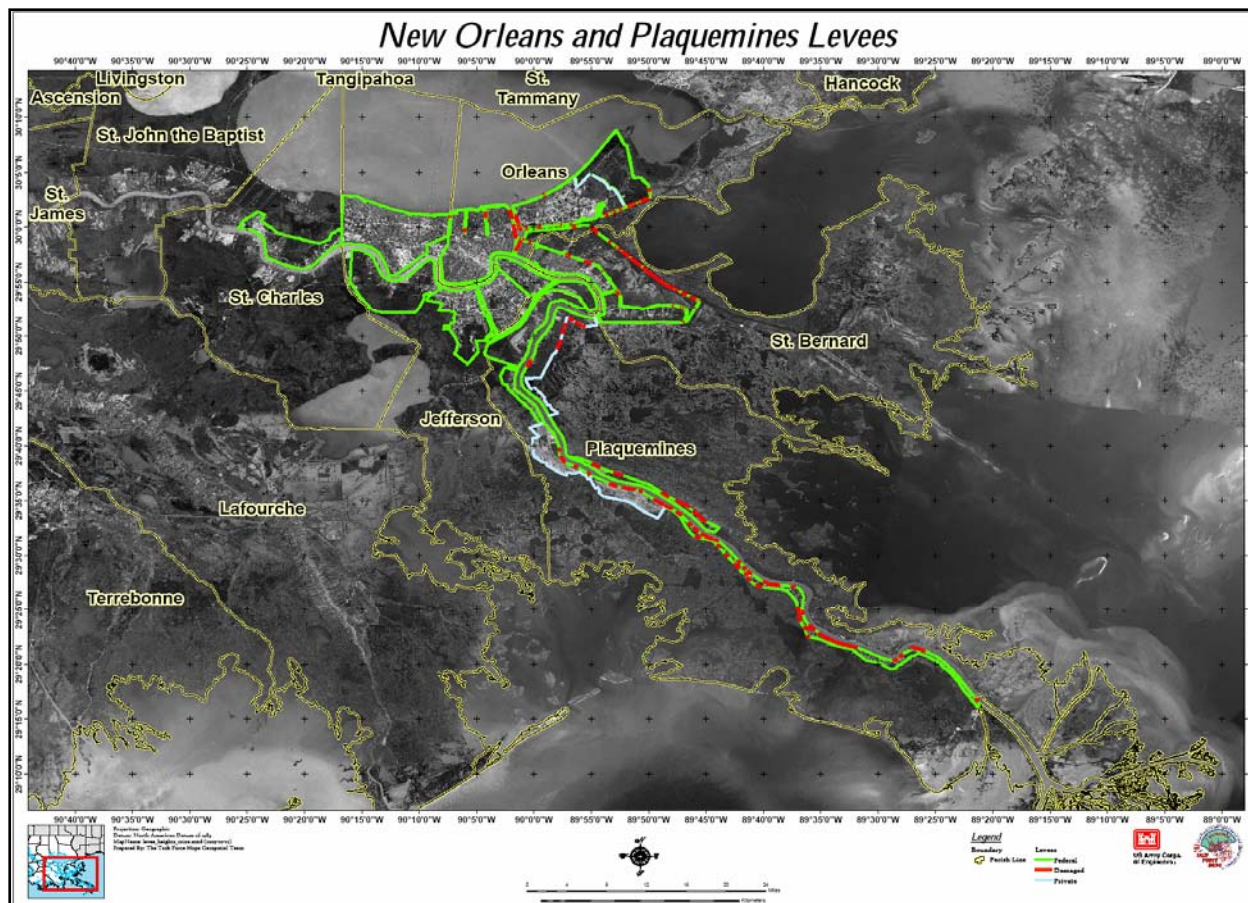


Figure 16. Locations (in red) of severe damage to hurricane protection structures resulting from Katrina.

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 17) and MRGO (Figure 18) that were constructed with materials dredged from the adjacent channels using hydraulic fill. Even though the levees were capped with clay, they were no match for the energetic environment they experienced. The overtopping waves created very high 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 (4 to 6 ft/sec). 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 19 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 17. Example of levee along New Orleans East, GIWW, breaching from overtopping and scour of erodible materials.



Figure 18. Example of levee breach along MRGO from overtopping and scour of erodible materials.



Figure 19a. Character of levee materials, New Orleans East and northern St. Bernard. This slide is incomplete for St. Bernard and shows only the hydraulic fill section along the MRGO.

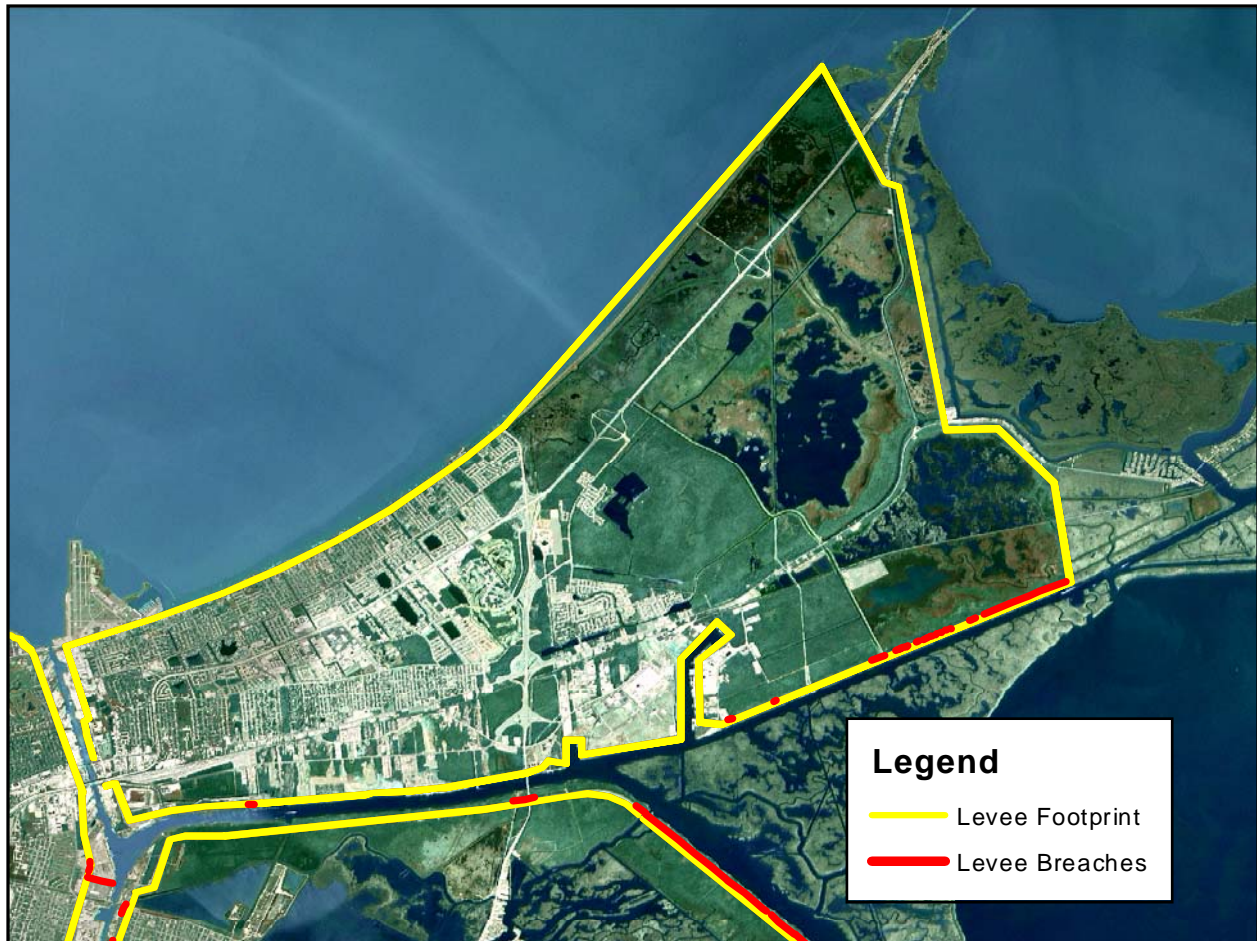


Figure 19b. Distribution of levee breaching, New Orleans East and northern St. Bernard.

Early in the morning, around 0500 hr, CDT, a section of I-wall along the Lower Ninth Ward breached. Underlain by the same marsh deposits and clay as the 17th Street Canal, the rising water and waves caused the wall to deflect enough to open a crack that created a direct avenue for high water pressures to reach the foundation. The weak clays underneath, now only reacting with the mass of soil on the protected side of the levee, could not withstand the force and displaced backward, a process that would repeat itself on the 17th Street Canal. The water levels in the IHNC were approximately 9.5 to 10.5 ft when the foundation failure occurred. At the 17th Street Canal, failure began with apparent displacement of a wall panel at about 0630 hr and ended with a full breach by 0900 hr. At about 0630 hr, the water level was estimated to have been 7 to 8 ft, and possibly 1 to 2 ft higher at the time of the catastrophic breach created by displacement of a levee section. No overtopping had occurred and the design water elevations had not been reached at either location, at the time of levee displacement. This process is depicted in Figure 20 and was confirmed by field investigations of the failure plane and site conditions, separate stability analyses conducted by Virginia Tech and ERDC, and physical testing by independent centrifuge tests at RPI and ERDC.

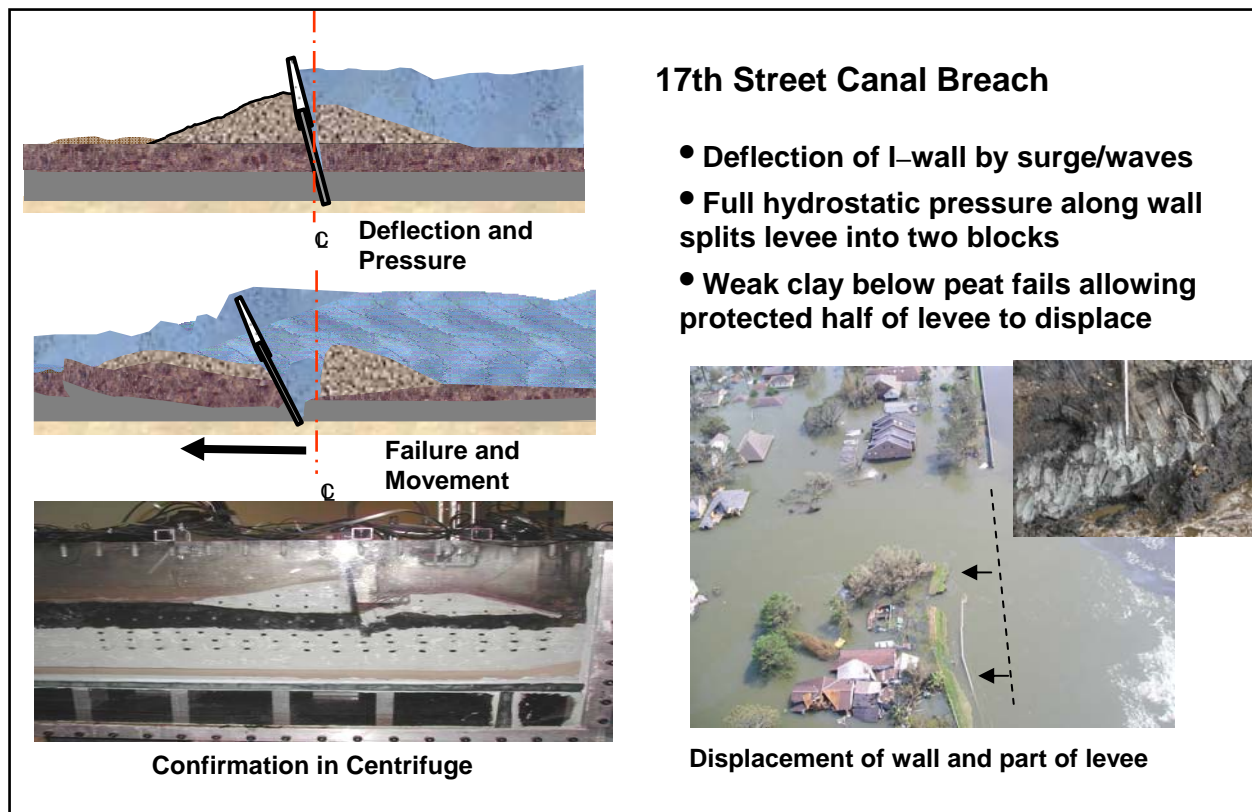


Figure 20. Depiction of failure mechanism for 17th Street and IHNC foundation failures. A crack forming along the front of the I-wall introduced high forces down the face of the sheet pile, resulting in lateral movement of the floodwall along a shear plane in the weak clay foundation.

At around 0700-0800 hours, not long after the 17th Street Canal breach started, the south breach on the London Avenue Canal was initiating. As in the case of the 17th Street Canal and IHNC failures, water elevations below the design levels caused a crack to form on the water side of the floodwall and allowed high pressures to be introduced directly into the foundation materials of the levee, this time relic beach sand. The porous sand quickly conveyed the pressure under the levee and caused significant uplift on the protected side. It also is likely that significant subsurface erosion occurred under the levee and caused a blowout on the protected side through which much sand and water flowed, decreasing the support for the levee and floodwall and causing a narrow failure. The north breach on the London Avenue Canal suffered a similar fate around the same time, 0700-0730 hr. This breach was much wider and involved less erosion, failure being caused by a loss of stability from the uplift. Water levels in the London Avenue Canal reached about 9 ft, below the design levels and well below the height of the I-walls. Figure 21 depicts the breaching mechanisms for the London Avenue breach sites. This finding was arrived at through detailed field investigations, independent seepage and stability analyses by Virginia Tech and ERDC teams and separate centrifuge modeling by RPI and ERDC.

Ironically, the Orleans Canal, geographically located between the 17th Street and London Avenue Canals, and having similar geological conditions, did not suffer failure, even though water levels there reached over 10 ft. The geology at the north end of the Orleans Canal is similar to 17th Street conditions (peat underlain by clay) and the south end is similar to London

Avenue subsurface conditions Peat underlain by relic beach sands). The design of the levees and I-walls for the Orleans Canal was more conservative than for the other canals with a broader and stronger levee section and less I-wall height above the levee crest. Soil strength assumptions were also more conservative than for the structures along the 17th Street Canal. This knowledge was an important component of the development of criteria for evaluating the integrity of the sections of the HPS that were not severely damaged. Combined with the knowledge of the failure modes for the I-walls and levees, a series of remedial actions were developed that could be used to at least temporarily strengthen sections of the HPS that were deemed least able to withstand a large storm. This led to a large scale examination of the HPS by the New Orleans District to identify areas needing remedial action prior to the 2006 hurricane season.

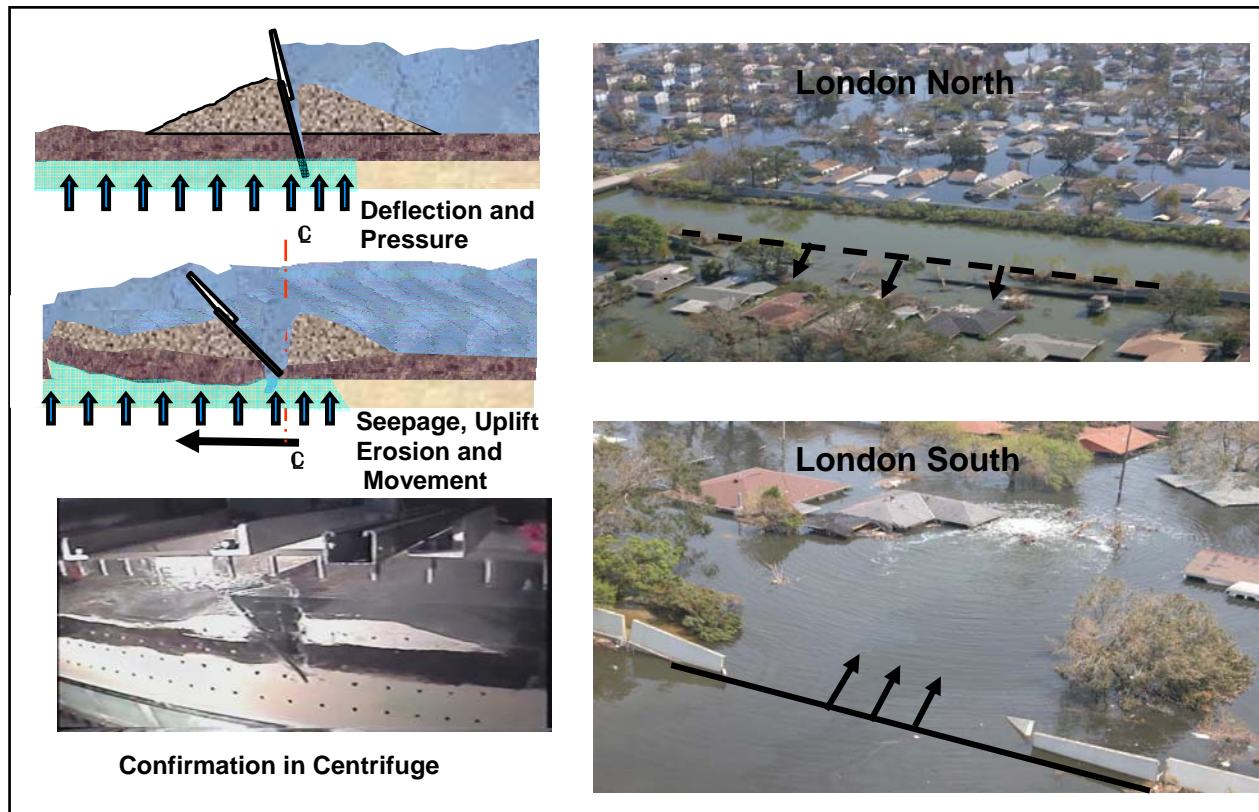


Figure 21. Depiction of London Avenue Canal north and south breaches caused by deflection of the I-wall and high uplift pressures introduced through the underlying porous sands, confirmed in centrifuge testing.

During mid-morning, the I-walls along the IHNC were overtopped and erosion behind the wall reduced their stability, causing three separate sections to fail. The top photograph in Figure 22 shows a section of I-wall along the IHNC collapsed after overtopping created a scour trench behind it and reduced its stability. The bottom photograph shows an adjacent section of I-wall where the scour trench formed but the wall did not fail. Water levels reached over 14 ft in the IHNC. There was also a levee failure along the west side of the IHNC that caused additional flooding into the Upper Ninth Ward. There were no T-wall failures with the exception of a small section in southern Plaquemines Parish.

The flooding resulting from the overtopping and breaching was catastrophic. Figure 23 shows the extent and depth of flooding for the New Orleans 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 clean cooling water for the pumps. An evaluation of the pumping performance as a percentage of the total capacity is given in Figure 24. 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 significantly reduced. Using temporary pumps and slowly bringing the permanent pumps on line after Katrina required 53 days to unwater the city.



Figure 22. Example of breach along IHNC (east side) from overtopping and scour (top) and scour behind adjacent section that did not fail (bottom).

New Orleans: Maximum Flooding Depth

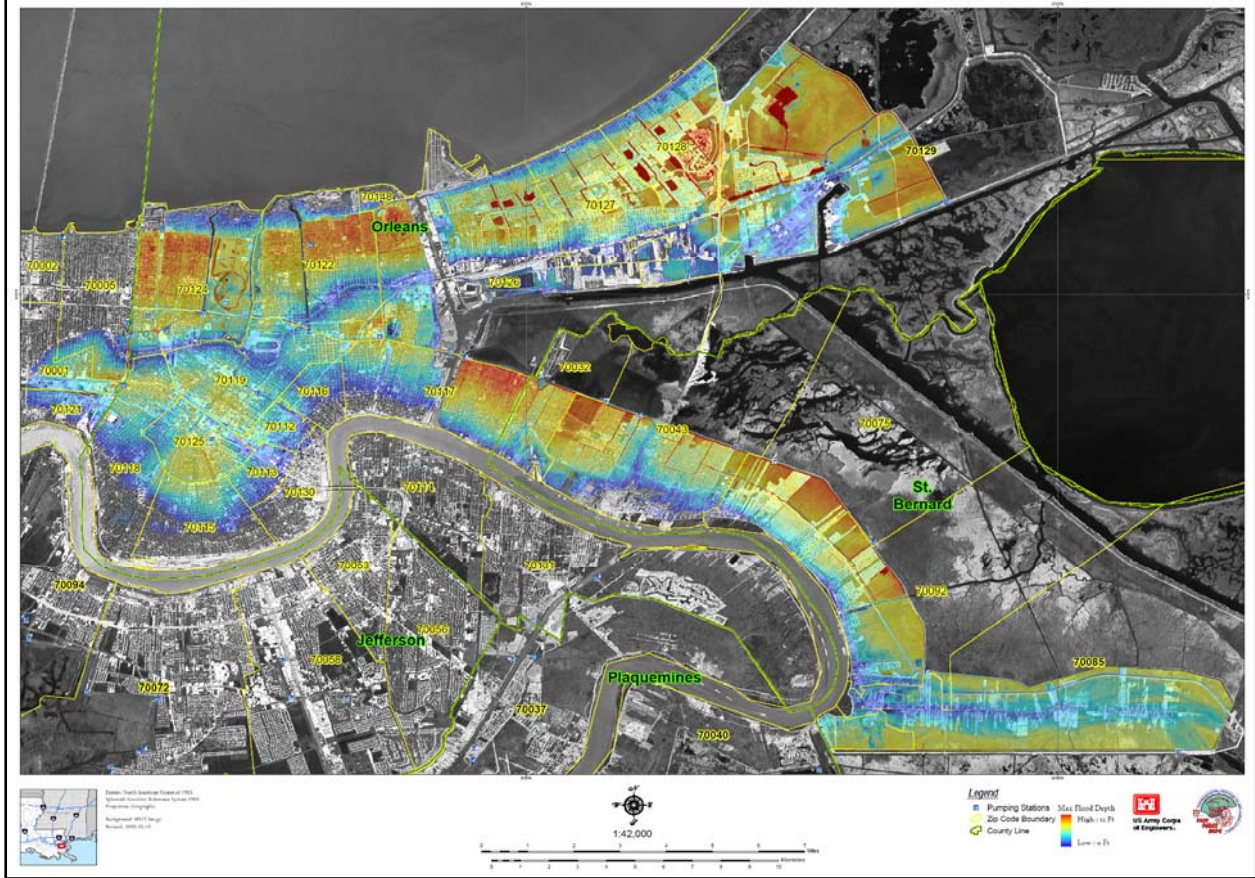


Figure 23. Map of maximum depths of flooding from Katrina. Greatest depths of flooding exceed 15 feet.

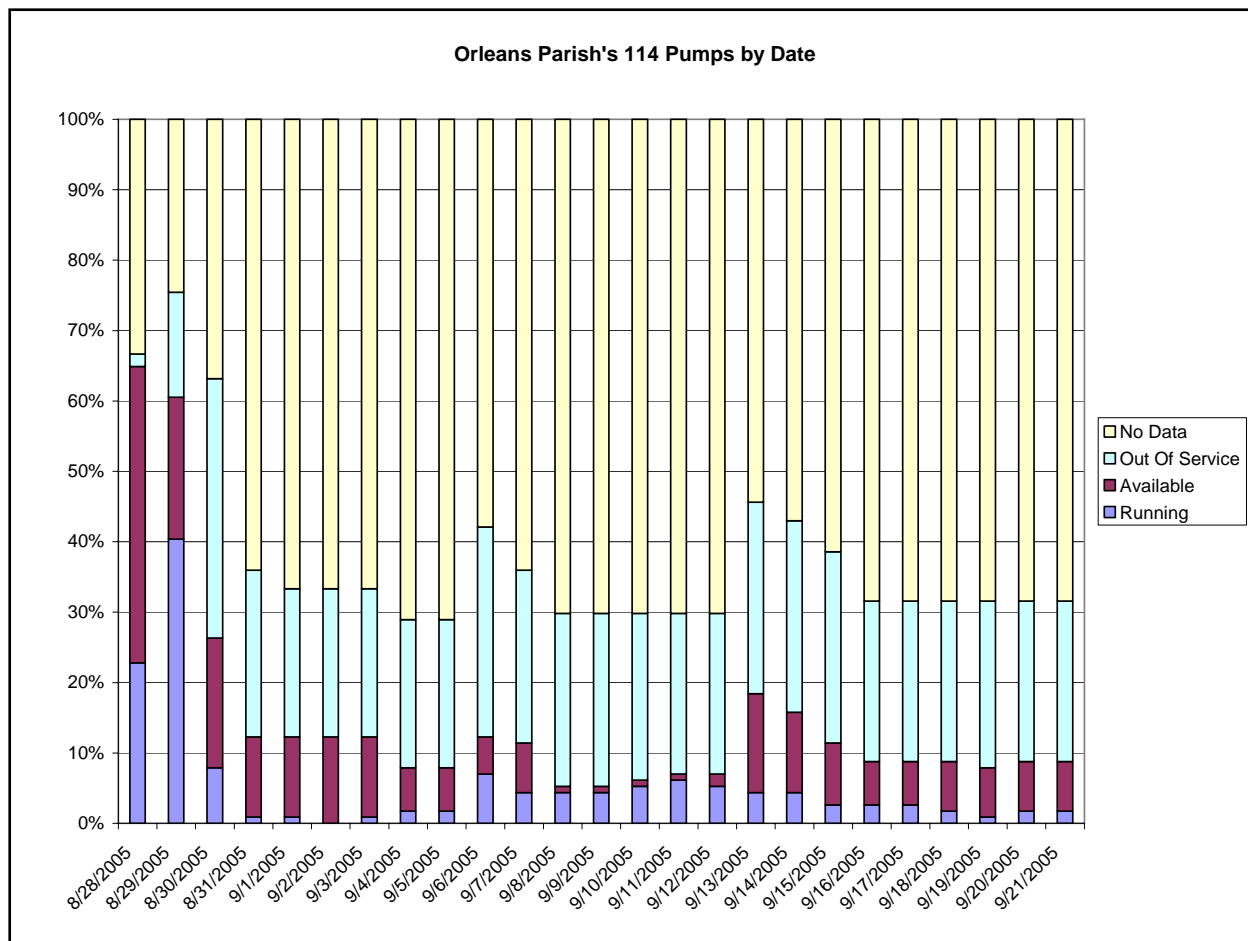


Figure 24. Example of pumping performance during Katrina.

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 have been as little as one-third of that experienced during Katrina with breaching and little pumping. Figure 25 is one example of that analysis for Orleans East. The total volume of flooding would have been approximately one-third of that experienced in Katrina if only overtopping and rainfall had contributed water to the protected area. Overtopping was extensive, but would have only occurred for a matter of hours. Breaching allowed water to enter the protected areas for days until the external water levels returned to lower levels and the breaches could be temporarily closed.

The Consequences (for more information see Volume VII)

The consequences of the flooding were enormous, dwarfing the losses from previous disasters. Figure 26 shows residential direct property losses. Approximately 78 percent of the direct property losses from flooding were experienced by residential property. This is in part due to their location in some of the lowest elevations of the city. Figure 27 shows the distribution, by census block, of the percentage of the direct property losses (loss/value) that occurred in the

New Orleans metropolitan area. This graphic correlates primarily to elevation (depth of flooding) and concentration of assets. When coupled with the approximately \$4.5 billion to \$5.6 billion in public infrastructure damages, the total direct property losses for New Orleans alone reach nearly \$25 billion. In contrast, Figure 28 shows the hypothetical percentage loss for the scenario of having no breaching (just overtopping) and full pumping capacity. While the pumping assumption of this scenario is not realistic for the time of Katrina, when added to the relationship shown in Figure 25, it is a testimony to the value of having a resilient HPS.

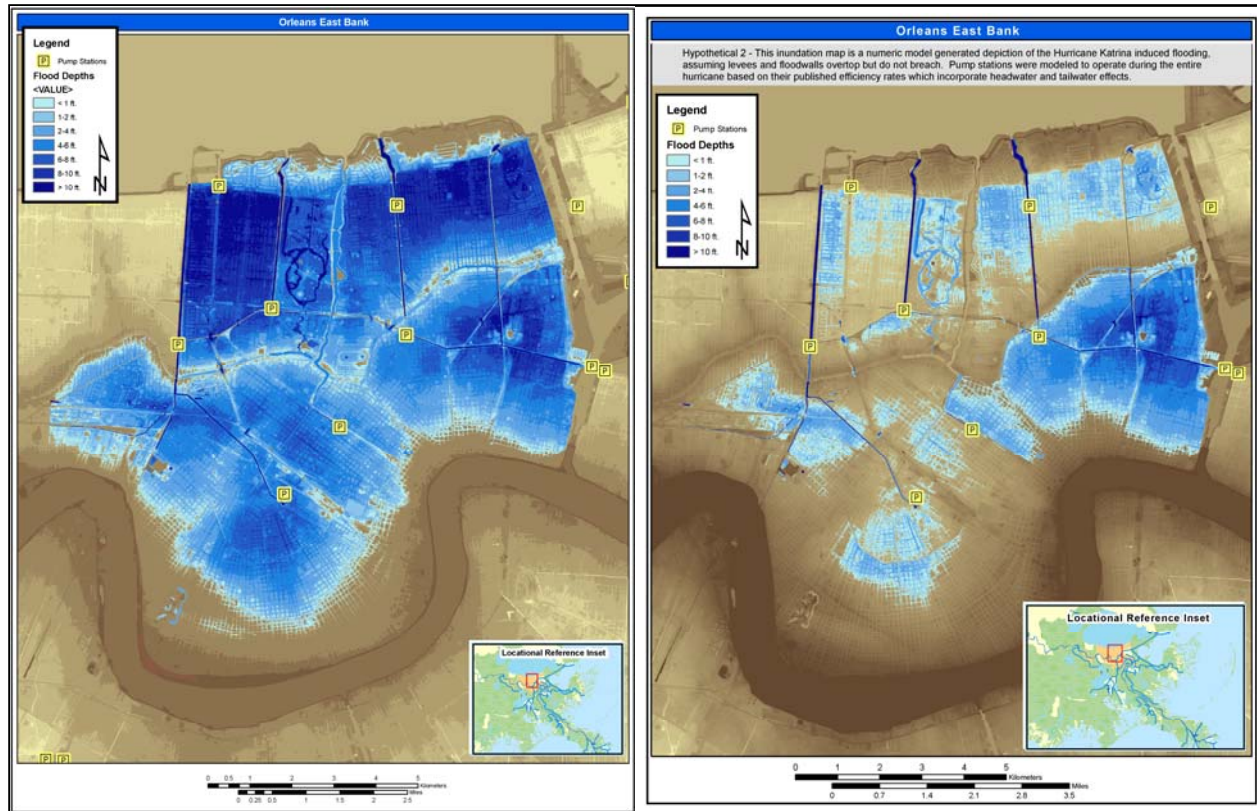


Figure 25. Comparison of flooding from Katrina (left) to hypothetical condition of no breaching and full pumping capacity (right) for Orleans East Bank.

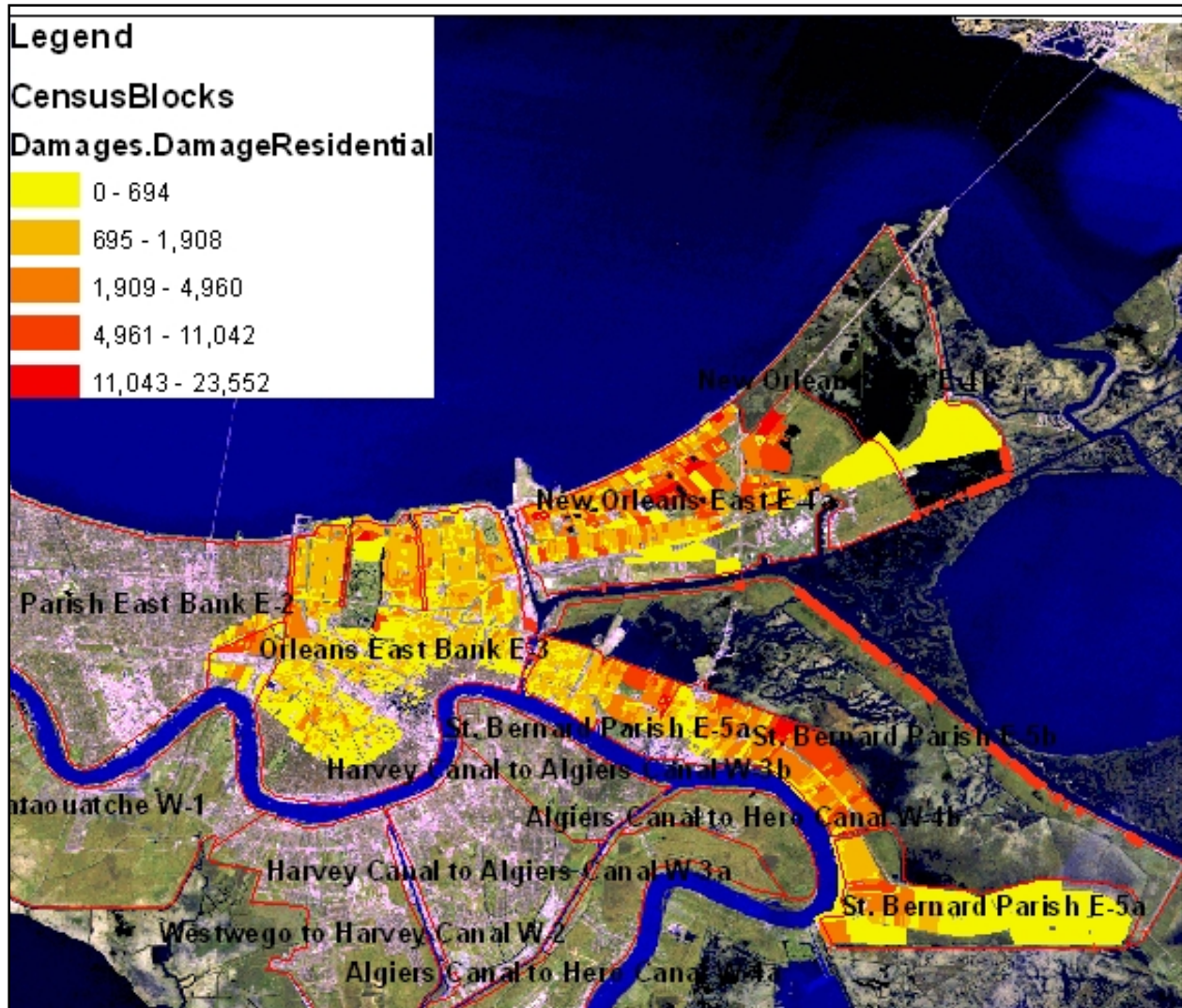


Figure 26. Distribution of Katrina-generated residential direct property damages by census block. Damages in thousands of dollars.

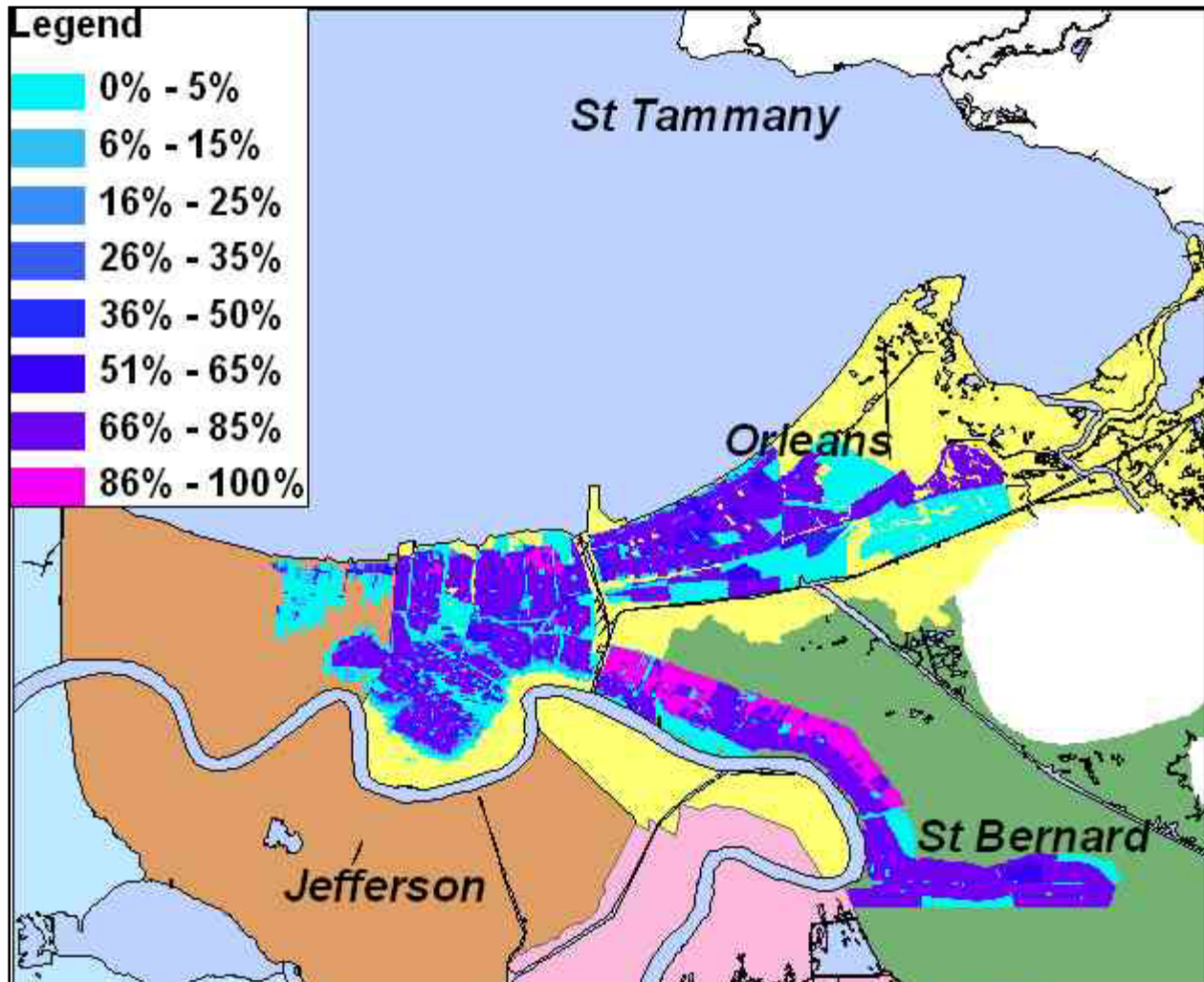


Figure 27. Distribution, by census block, of property damage (damage/value) from Katrina.

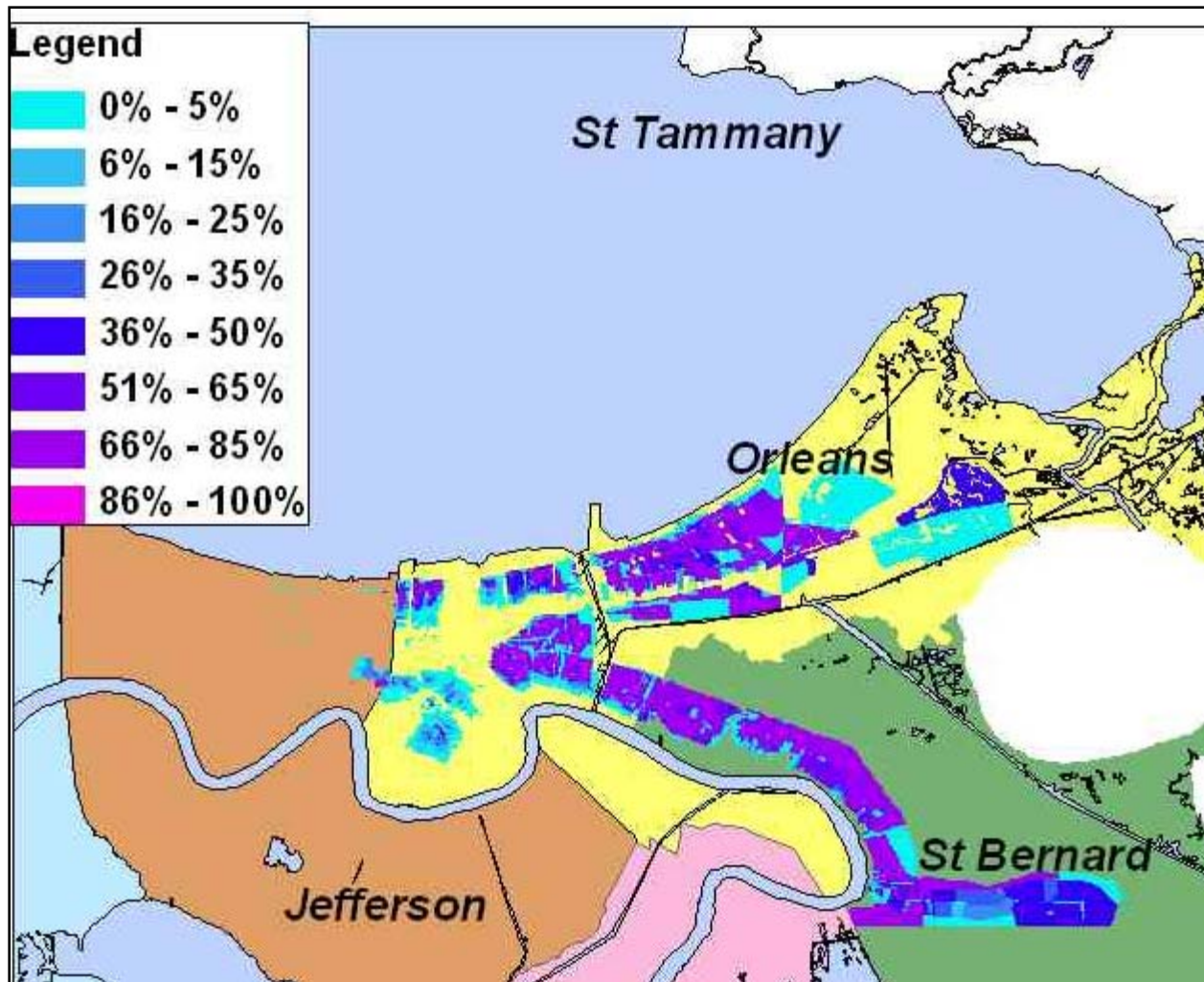


Figure 28. Hypothetical percent property damage (damage/value) for scenario of no breaching and full pumping capacity

Loss of life in the Gulf region was staggering, with almost 1,600 fatalities accounted for and another 400 missing and presumed dead. The New Orleans metropolitan area suffered over 727 storm-related deaths as of February 2006 analysis. Only 2 percent of the total fatalities in Louisiana were external to metropolitan New Orleans. The majority of deaths in Orleans Parish were caused by drowning and pre-existing medical conditions. The deaths in St. Bernard Parish were primarily attributed to drowning. Loss of life was highly correlated with evacuation. Of those who remained, the elderly were particularly vulnerable with three of every four persons who died being over 60 years old. In fact, the flooding in general was disproportionately cruel to the poor, the elderly, and the disabled, groups least likely to be able to care for themselves. Figure 29 summarizes the demographics of the fatalities.

A loss of life model, LIFESim, was adapted to estimate flood-related mortality associated with the New Orleans area. LIFESim, originally developed under the sponsorship of the Corps of Engineers, the Bureau of Reclamation, and the Australian National Committee on Large Dams, is a spatially distributed dynamic simulation model. It is used to estimate the exposure of the

population to various flooding conditions which is input to a Monte Carlo uncertainty model to estimate expected loss of life. The modeling, described in detail in Volume VII, was used to estimate loss of life for post-Katrina conditions.

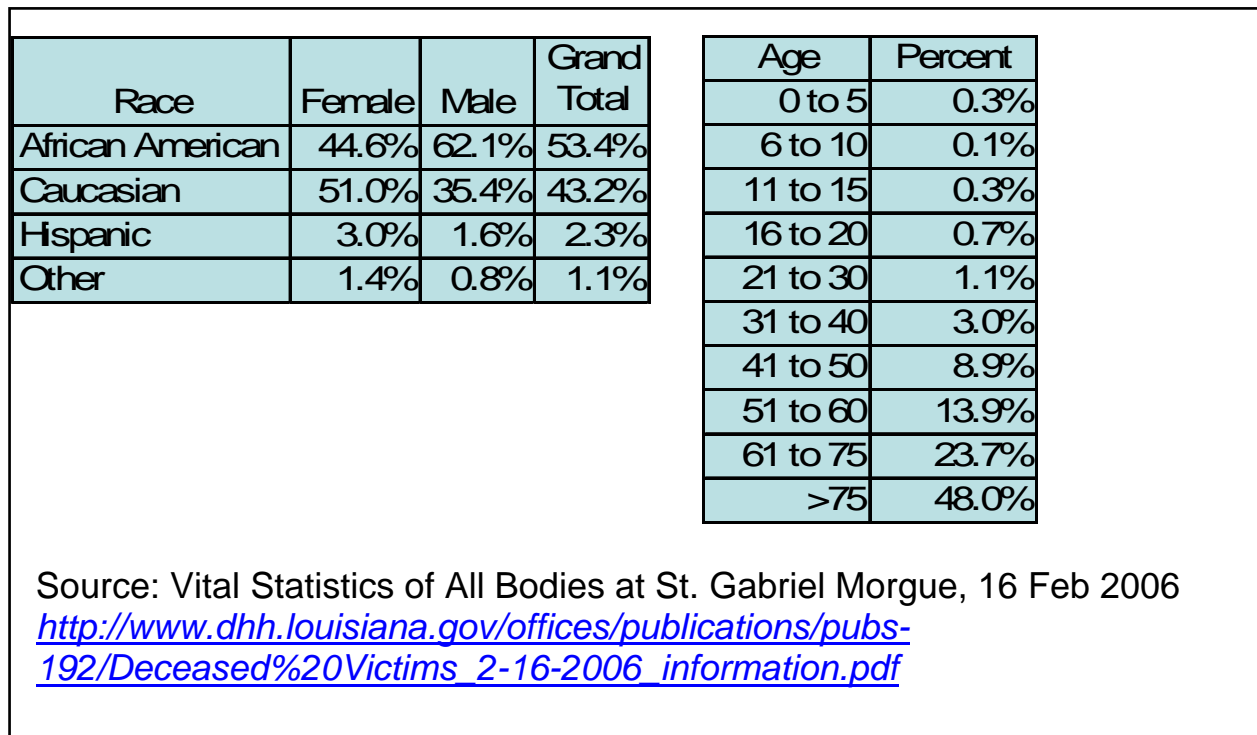


Figure 29. Summary of fatality data for New Orleans.

The flooding and resultant prolonged loss of services caused what became more of a migration than an evacuation, casting long shadows on the region’s ability to recover. Only 8 of 73 neighborhoods did not flood, while 34 were completely inundated. Residential property losses were a staggering 78 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 30 shows an example of the pre-Katrina and post-Katrina (1 June 2006) direct economic damage - elevation relationships developed for each subbasin. Similar relationships were developed for elevation and loss-of-life using Katrina data and for selected future scenarios using 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.

There were numerous media reports of widespread water contamination in and around New Orleans following Katrina. Samples from bottom sediments in Lake Pontchartrain and the Violet Marsh in St. Bernard Parish as well as numerical modeling of surface water contaminant transport did not support these reports. The three-dimensional hydrodynamic model CH3D and the three-dimensional water quality model CE-QUAL-ICM were used to model contaminant concentrations for a period of 90 days after Katrina. The RECOVERY model was used to simulate contaminant concentrations in the Violet Marsh area. Figure 31 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, benzo(a)pyrene, DDE, 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 seems to have escaped widespread pollutant contamination.

Along with the impact of waves, the impact of saltwater flooding of wetlands and marshes was significant and represents the most serious environmental damage sustained from Katrina. The U.S. Geological Survey estimated that approximately 118 square miles of wetland habitat was lost from the combined effects of Hurricanes Katrina and Rita. This is approximately four times the average annual loss of about 30 square miles measured since the 1930s. Hurricane Katrina caused extensive freshwater fish and oyster kills, especially along the north coast of Lake Pontchartrain, but had no identified direct impact on marine fish.

Katrina is truly a disaster from which this nation must seek and apply lessons learned to prevent reoccurrence. Part of the solution is understanding the distributed residual risk for the area. This requires a comprehensive risk and reliability analysis of the entire HPS.

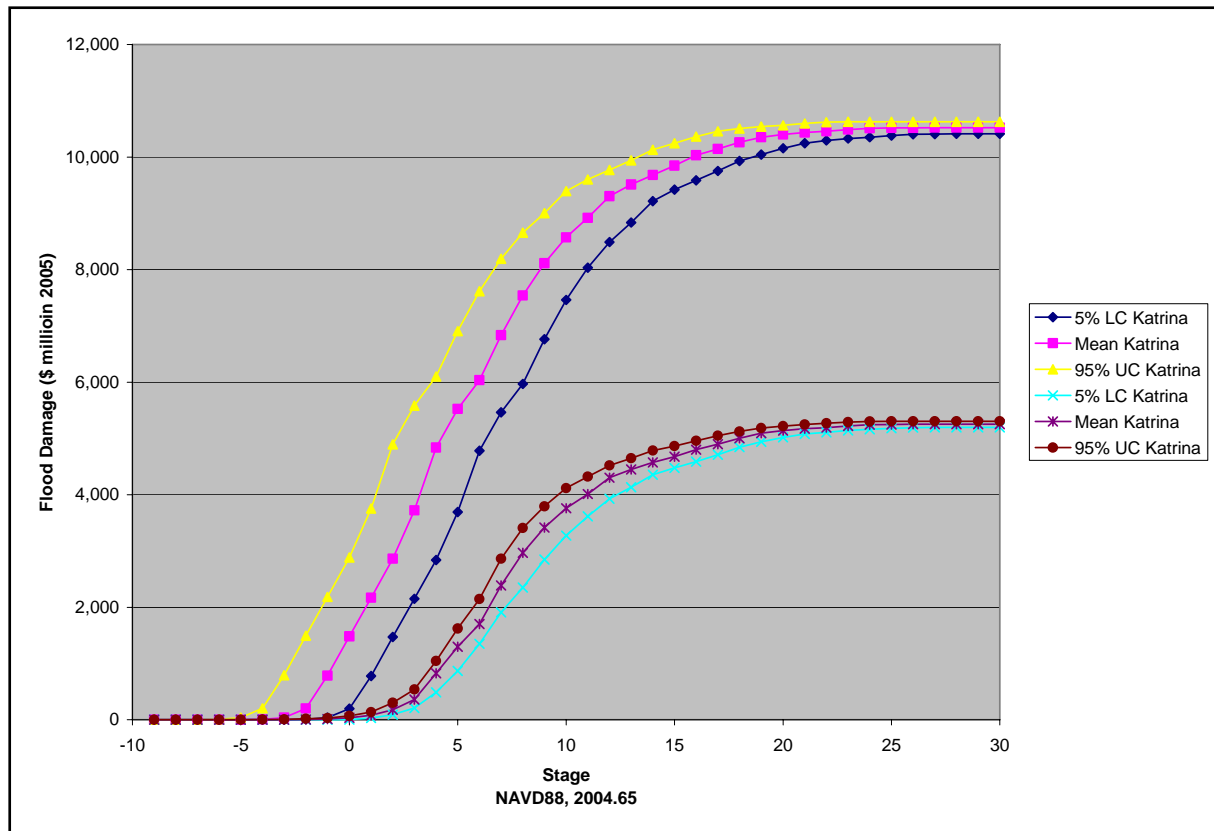


Figure 30. Comparison of flood damage – water level (in feet) relationships for pre- and post-Katrina scenarios for Orleans subbasin 5. LC and UC represent the lower and upper confidence limits of the data.

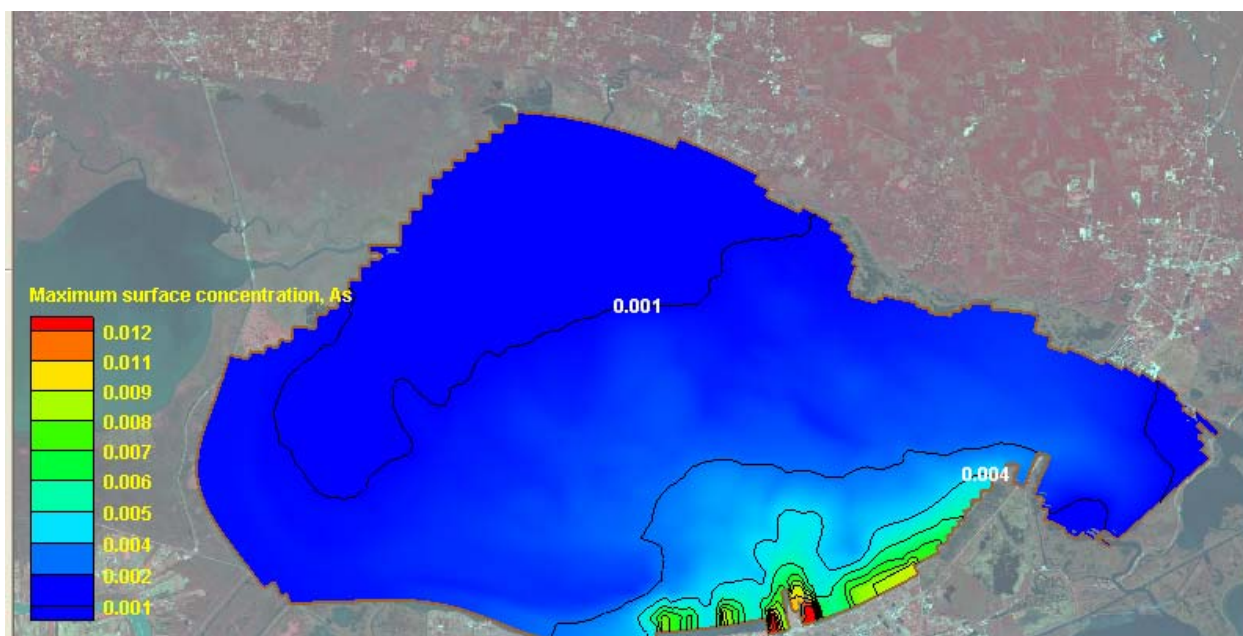


Figure 31. Maximum arsenic (As) water surface concentrations (milligrams per liter total) in Lake Pontchartrain after Katrina.

The Risk (for more information see Volume VIII)

The risk prior to Katrina was significant, in part because New Orleans is mostly below sea level, in part because the HPS 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 7 to 10 ft in the outfall canals and over 14 ft in IHNC during Katrina). Levee sections created with hydraulic fill and capped with a relatively thin clay layer had never experienced design water levels, not to mention severe overtopping. Both components of risk were significant. The probability of a failure of floodwalls and some sections of levees was 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-wall sections with stronger and higher T-wall sections along the IHNC will also significantly reduce risk, as will adding armor behind floodwall sections deemed vulnerable to overtopping and erosion. Rebuilding levee sections higher and with high quality clay soils will dramatically increase their resilience to overtopping. The areas with incomplete or legacy structures represent the greatest risk until additional measures can be taken to raise and strengthen them.

Given the difficulty in achieving and maintaining an equal level of protection around the entire system, some areas will continue to harbor the greatest risk — those having elevations the most below sea level, those with the highest subsidence rates and those directly exposed to the

full surge and wave environments that large storms can create. Given overtopping, water will first inundate the lowest areas. 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. The other major risk factor is consequences, the lives and property exposed to flooding and loss. As such, areas with the highest population densities are going to have higher risk than less populated areas, given similar levels of reliability.

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 reasonable way to begin the process of reducing risk where it is most practical and will provide the most significant benefits.

The IPET comprehensive risk assessment was ongoing at the time of the release of this volume. The information in this section will be amended to reflect the final risk analysis results upon finalization of that work and its review by the NRC Committee and ASCE ERP.

Principal Findings and Lessons Learned

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

Principal Findings

The System (see Volumes II and III)

Impact of Datum Misinterpretation: Spatial and temporal variations of 0.2 to 3 ft were found between the geodetic datum (land elevation reference) and local mean sea level (water level reference datum, LMSL). Some flood control structures in the region were authorized and designed relative to a water level datum (mean sea level), but constructed relative to the geodetic vertical datum incorrectly assumed to be equivalent to the water level datum. This resulted, in the case of the outfall canals, in structures built approximately 1 to 2 ft below the intended elevation. Updating of the reference elevation points for the region, although underway, was not completed. The use of out-of-date reference elevation points left decision makers without an accurate understanding of the actual elevations of the hurricane protection structures.

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

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

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

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

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

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

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

the Lake Pontchartrain and Vicinity Project for use on the outfall canals. The 1979 definition of the SPH was used for design of the West Bank and Vicinity protective structures.

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

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

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

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

The Storm (See Volume IV)

Katrina generated a storm surge and wave environment unparalleled in the history of New Orleans. Hurricane Katrina was a very large Category 3 storm when it passed the New Orleans area on the morning of August 29th. Twenty-four hours earlier this storm had been the largest Category 5 and most intense (in terms of central pressure) storm on record within the northern Gulf of Mexico. During Katrina, at a location due east of the Mississippi River delta and just offshore in deep water, NOAA Buoy 42040 recorded the highest significant wave height ever measured in the Gulf of Mexico (55 ft). That observation matched the largest significant wave height ever recorded by a sensor within NOAA's buoy network, in any ocean. The large size of Katrina throughout its history, combined with the extreme waves generated during its most intense phase, enabled this storm to produce the largest storm surges that have ever been observed within the Gulf of Mexico (up to 28 feet in Mississippi), as determined from analyses of historical records.

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

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

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

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

There was no evidence of significantly reduced surge levels and wave heights in areas adjacent to wetlands and marshes. Surge elevations and wave energy along the HPS were impacted mostly by the relative orientation of structures with respect to the direction of the wind

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

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

The Performance (see Volumes V and VI)

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

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

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

In the case of the sites underlain by clays, the formation of the gap to the base of the sheet piles introduced high loads along the depth of the wall which could not be resisted by the weak clays. At the IHNC site, the fact that the ground surface elevations beyond the levee toe were

significantly below those in the design cross sections contributed to the failure. Soil strength assumptions used in the design of the 17th Street structures were too optimistic. The formation of the gap and the associated hydrostatic pressures introduced at depth, along with effectively splitting the levee into two parts, resulted in a significant reduction in the factor of safety of the structure. This failure mechanism, in particular the gap formation to the bottom of the sheet piles, was not considered in the original design of these structures.

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

Transitions between types and levels of protection and between protection structures and other features created vulnerabilities to erosion and breaching and reduced the effectiveness of the protection. Some of the transitions are associated with changes in the organization responsible for the structures, some are due to incompleteness 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 HPS performed well. These tended to be sections with materials resistant to erosion and more conservative designs. The Orleans Canal levee-floodwalls are similar to those on the 17th Street and London Avenue Canals, yet they did not fail. The northern section of Orleans Canal is underlain by clays similar to the 17th Street breach site and the southern section is underlain by sand similar to the London Avenue breach sites. Investigations showed that the levees were more conservative in design, having broader base and less floodwall freeboard. In addition, more conservative soil strength values were assumed in their design.

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

Flooding from Katrina covered approximately 80 percent of the New Orleans metropolitan area. For Orleans East and St. Bernard Parishes, approximately two-thirds of the volume of flooding can be attributed to water flowing through breaches. The one-third due to overtopping and the very large amount of rainfall would itself have caused a significant level of interior flooding.

The three breaches in the outfall canals and I-wall/levee failures along the west side of the IHNC were responsible for approximately 70 percent of the flooding in Orleans East Bank. The remainder was due to the heavy rainfall (up to 14 in. in 24 hr) and overtopping.

Because of inoperability, pump stations played no significant role in the reduction in flooding during Katrina. Sixteen percent of the total pumping capacity was operating during

the storm, equivalent to approximately 18,000 cfs. The distribution of operating pumps across four parishes, however, reduced the impact of the pumping. Their inoperability, due to a combination of the necessary evacuation of operators, loss of power, loss of cooling water, and flooding, impacted the ability to unwater the city after the storm. Temporary pumps were useful after Katrina, but provided only a small fraction of the capacity needed. Reverse flow through some pumps added to the flooding in at least one parish. While methods are available to prevent reverse flow, they are dependent on human implementation and electrical power.

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

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

The Consequences (See Volume VII)

Loss of life was concentrated by age, with 70 percent of deaths being people over the age of 60. There were 727 fatalities in the five parishes examined. The poor were disproportionately affected. Loss of life also correlated to elevation, in terms of depth of flooding, especially with regard to the poor, elderly, and disabled, the groups least likely to be able to evacuate without assistance.

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

Approximately half of the direct economic 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. Losses and, in many respects, recovery can also be directly correlated to depth of flooding and thus to elevation. In some areas flooded by Katrina, where water depths were small, recovery has been almost complete. In areas where water depths were greater, little recovery or reinvestment has taken place.

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

The available information indicates that if environmental harm has come from the Katrina flooding of greater New Orleans, it was associated with past regional land and water development. Like many other cities, the soils and sediments of land and waters in New Orleans and other delta urban areas are contaminated with metals and organics at concentrations that often exceed health standards in areas of most dense development. The flooding of greater New Orleans removed some contamination from greater New Orleans and transported it to Lake Pontchartrain and Violet Marsh with pumped floodwater where it added a small increment to estuarine sediments. The IPET analysis did not look at local redistribution of contaminants within individual drainage basins. Katrina and Rita resulted in the loss of approximately 300 square kilometers of wetlands and marshes, all independent of the performance of the levees and floodwalls. Loss of wetlands regionally appears to fit a pattern of loss associated with past regional development as well. Overall, any sustained environmental loss from flooding and flood management is indicated to be very small in the context of long-term impacts from development in the region.

The Risk (See Volume VIII)

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

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

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

It is critical to estimate the inherent uncertainty in the individual components of the risk assessment and in the final risk products. Risk assessment combines a variety of data types and incorporates numerous models. Each of these has an inherent degree of uncertainty, in their values, in the ability of the models to replicate the processes they represent, and in the end products themselves. The level of uncertainty must be estimated and incorporated in an overall uncertainty analysis to understand the variance associated with the risk assessment results. This provides some measure of the confidence one can have in using the risk data.

Principal Lessons Learned

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

The System (see Volumes II and III)

Correct elevations and reference datum are essential. All hurricane and flood control protection structures should be designed, constructed, and maintained relative to an up-to-date local sea level reference datum. Areas experiencing variable subsidence, such as New Orleans, are likely to have systematic datum and elevation accuracy issues that need frequent attention. It is important to have appropriate monitoring stations (for tide and subsidence) in place and associated up-to-date guidelines for the application of this information to existing and new projects. In subsidence-prone areas, designs should consider multiple elevation increases over the life cycle of the structure.

Systems planning and design methods are needed. Planning and design methodologies need to allow for examination of system-wide performance. It is obvious from the IPET analysis that the piecemeal development of the New Orleans Hurricane Protection System provided a system in name only. This is especially true of the sections that have not been completed, transitions between types of protection that differ in capability (thereby representing weak points), and differences in the relative levels of reliability that created areas with greater likelihood of failure. The system-based approach should have a time dimension to allow consideration of the potential changes in requirements or conditions over the life of the project and to examine approaches to build in adaptive features and capabilities. Subsidence, changing population demographics, and the changing patterns of hurricane intensity and frequency are obvious examples of the time-dependent challenges hurricane protection systems face. All components that contribute to the performance of the overall system must be treated as an integral part of the system. Pump stations are one example in New Orleans. For any given drainage basin, the protection is only as robust as the weakest component of the system protecting that area and how effectively the various components that are interdependent operate together.

Frequent update to guidance and review of projects is critical. Design methods and designs need frequent review to determine whether they represent best practice and knowledge. Designs in coastal flood damage reduction projects need to include the concepts of resilience, adaptation, and redundancy to accommodate unanticipated conditions or structural behaviors. Design should be based on a system-wide understanding of the processes affecting the system and the interaction and interdependencies of the system components. This is especially true for the characterization of the hazard where modern probabilistic methods should be used.

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

The Storm (see Volume IV)

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

Sophisticated modeling using physics-based codes with high spatial resolution and accurate windfield input is necessary to depict the variable hydrodynamic environments created by large storms. Similarly, the traditional methods of assessing the frequency of occurrence of hurricanes, dependent primarily on historical data, are too simplistic to capture important characteristics of the hurricane hazard such as time- and space-dependent storm

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

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

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

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

The Performance (See Volume V and VI)

Designs need to better consider unknowns. The design approaches taken for the outfall canals were not conservative enough to deal with the unknowns, in this case the excessive floodwall deflection not considered in the design. Floodwall design methods need to consider a broader spectrum of possible behaviors, and resilience to overtopping should be considered as a fundamental performance characteristic. Research is needed to understand the full performance limits of structures and to discover new approaches for creating adaptive designs. The unanticipated failure mode defined for the I-walls from this analysis does not represent the only possible failure mode for these structures. Numerous other modes were considered in their design, and other yet undefined modes are likely to occur at some point in the future. Designers need to consider a broad range of failure modes, including some approaches beyond traditional or standard practice.

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

Planning methods should facilitate examination of system-wide performance. In addition, hurricane protection systems should be deliberately designed and built as integrated systems to enhance reliability and provide consistency in levels of protection. Components such as the interior drainage and pumping need to be an integral part of the system because of the important role they can play in limiting the amount and duration of flooding. Resilience in pumping capacity is especially important.

Resilience to catastrophic breaching can provide huge benefits in reduced loss of life and property. It is clear that a resilient HPS can provide enormous advantages. Resilience, in this case, refers to the ability to withstand, without catastrophic failure, forces and conditions beyond those intended or assumed in the design. For our purposes, resilience refers to the ability to withstand higher than designed water levels and overtopping without breaching. As demonstrated in this analysis of Katrina, approximately two-thirds of flooding and half of the losses were the result of breaching, i.e., the significant loss of protective elevation in structures. While overtopping alone from Katrina would have created dramatic flooding and losses, the difference is staggering in many regards. Reductions in losses of life, property, and infrastructure; associated reductions in the displacement of individuals, families, and the workforce, coupled with reduced disruption to businesses and social and cultural networks and institutions, would have a dramatic impact on the ability of a community and region to recover. Added to this is the savings of the time and funding needed to rebuild the protection system itself, which would accelerate the pace of recovery. Resilience is not a national priority in the development of hurricane protection systems, and resilience was not an element in the New Orleans HPS design.

The Consequences (See Volume VII)

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

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

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

The Risk (See Volume VIII)

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

Risk supports system-wide planning. A 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 system-based, requiring that the entire system be described in consistent terms and explicitly including uncertainty. Component performance is related to system performance as well as the consequences of that performance.

Risk expands the criteria for decision making. The risk-based approach is well suited for consideration of a variety of measures of merit. Factors such as loss of life, environmental losses, and cultural consequences can be included in decision making without reducing everything to one measure such as dollars. As applied for the IPET assessment, it allows aggregation and de-

aggregation of information to address issues at different scales, providing a useful tool for collaborative planning between responsible agencies at different levels. It also allows for a more comprehensive consideration of hazards. Instead of a single definition derived from limited historical data, a joint probability approach can consider events that reflect historical information as well as a variety of possible events, providing a more robust basis for considering the spectrum of hurricanes that may occur. Most importantly, risk and reliability allows decision makers to understand the relative levels of vulnerability that specific areas face, the nature of the consequences (e.g., loss of life, economic loss, or environmental loss), and to understand the source of the vulnerability. As such, it is an excellent tool for understanding the effectiveness of alternative approaches to reduce risk, which can be managed by changing the performance of the protection system or changing the nature or degree of related consequences.

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

Knowledge and Expertise

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

these puzzle parts get pieced together to create knowledge for designers and how do designers and reviewers get access to this information? How does the research or testing community become aware of applications, perhaps different from their original purpose, for their new knowledge?

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

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

Other Studies

There were a number of other studies conducted within the time frame of the IPET activities. Perhaps the most publicly recognized of these are the efforts of the Independent Levee Investigative Team led by the University of California at Berkeley (UCB) and Team Louisiana led by the Louisiana State University (LSU). It was important to have multiple teams examining the post Katrina situation in New Orleans. Given the very short time frame for effecting repairs and the huge task of rebuilding both the hurricane flood risk reduction system and New Orleans, multiple perspectives and analyses were a significant benefit.

These efforts differed dramatically in their scope, resources and levels of effort. The IPET was comprised of over 150 experts and another 150 support personnel with resources exceeding

\$22 M and direct access to the unique experimental facilities of the Engineer R&D Center as well as those of the 8 major government agencies, 23 private sector firms and 25 universities that composed the task force. In addition, the IPET efforts have been continuously peer reviewed by the ASCE External Review Panel and strategically reviewed by the NRC Committee on New Orleans Regional Hurricane Protection Projects. Team Louisiana and the UCB Teams were much smaller in all dimensions and did not have the benefit of real time or strategic peer review. While the IPET effort was highly focused on in-depth analyses of the engineering and system wide performance issues, the UCB effort was divided between work on the engineering aspects and some on the organizational and human factors. Team Louisiana also examined a broad spectrum of topics but in less detail. To date there has not been a formal report published by Team Louisiana, however, some of their information was incorporated into the UCB report.

Following release of the IPET Draft Final Report on 1 June, 2006, review comments were provided by the ASCE External Review Panel and the NRC Committee on New Orleans Regional Hurricane Protection Projects. In an endeavor to respond to their feedback and to ensure that the IPET Final Report contained the best information possible, IPET teams reviewed in some detail the work of the other studies. The objective was to incorporate as appropriate any information that would enhance the value of final IPET findings, lessons learned and analytical processes documented in the report. It was also important to provide feedback to engineers and organizations engaged in planning, design and construction of flood risk reduction structures in New Orleans and elsewhere. There were a number of issues that have been published by the media as well as the study reports that deserve some specific mention here. Specific findings and more detailed evaluation of analyses and data are provided in the other IPET report Volumes, particularly in Volume V.

There were two areas that constitute the major differences in the findings of the three efforts. The first deals with the failure modes of the floodwalls. While there was agreement by all that excessive deflection of the floodwall structures was a major component of the failure mode for the I-walls along the outfall canals, the study teams hypothesized somewhat different failure modes for the 17th Street breach site and for one site on the Inner Harbor Navigation Canal. This is significant for the future planning and design of these structures as well as understanding appropriate remedial measures to strengthen existing structures. For the 17th Street site, both approaches consider weak subsurface soils as the other major culprit in the failure mode. They differ in which subsurface layer was the failure plane. IPET analysis, based on numerical modeling by two independent teams, physical modeling by two independent centrifuge teams and site geotechnical investigations that included excavating the actual failure plane with a backhoe, placed the failure plane in the weak clay layer underlying the persistent layer of peat in the region. The UCB Team, based on small diameter Shelby tube soil samples and limited numerical analyses, hypothesized a thin slippery layer within the peat layer (overlying the weak clay) as the slip plane. IPET has not been able to detect a widespread thin (inch or less in thickness) layer within the peat layer, in spite of having physically harvested large volumes of peat for use in centrifuge testing and acquisition of significant additional subsurface soils data.

IPET has proposed that the failure mode for the northern (IHNC) breach (near Florida Avenue) on the east side of the IHNC near the Lower Ninth Ward, was similar to that experienced at the 17th Street breach, deflection of the wall and failure within the underlying

weak clay layer, with additional influence of the local topography. The elevation of the land on the protected side of the floodwall was significantly less than shown in the original design documents which would have decreased the ability of the levee to withstand the high forces it experienced. The UCB analysis focused on seepage as an issue at this site. Since the geology of the site is similar to that at the 17th Street breach, with weak clay under the pervasive peat layer, it is difficult to find evidence of major seepage through the clay or the peat. UCB assumptions for permeability of the peat were far higher than any measured for the actual materials or published values for similar materials. While these values of permeability would indicate seepage, IPET has found no justification for these assumptions and no physical evidence of seepage being a systemic performance issue at this site.

The second area of significant difference dealt with the performance of the levees, specifically along the Mississippi River Gulf Outlet (MRGO). The UCB report and numerous media accounts attribute to these teams, hypothesized that these levees “crumbled” prior to water levels reaching the crest of the levees. There was also stipulation of wave action causing high pore pressures within the levee materials leading to deterioration by slumping and seepage induced erosion. An analytical basis for these hypotheses has not been presented to date.

It is true that the relatively permeable and erodible materials of the levees constructed by hydraulic fill did contribute to their ultimate breaching. However, analysis and field observations demonstrate that the UCB/LSU hypothesis was not the systemic process leading to breaching. IPET analysis of this phenomena included regional analysis of the surge and wave hydrographs along the levee sections, detailed modeling of wave action and currents in proximity to the levees and analysis of erosion process for the materials comprising the levees.. The IPET analysis and physical evidence at the sites show that the systemic issue for levee performance was overtopping and the subsequent erosion from waves and ultimately surge. Where waves were incident perpendicular to the levees, the overtopping waves created velocities on the protected side of the levees up to three times those experienced on the front (water) exposed sides. This created a potential for erosion 27 times more severe on the crest and protected sides of the levees. In addition, claims of wave action increasing pore pressures within the relatively permeable materials of the interior of the levees leading to seepage induced erosion do not stand the ‘test of time’. The permeability of the materials was not sufficient to allow this process to take place in the time frame of the exposure to high waves and surge.

For levee sections that experienced waves traveling more aligned with their orientation, velocities on the protected sides were significantly lower and significantly less erosion occurred.

There are meaningful lessons learned in the above examples. In an environment as complex and heterogeneous as this, there are many possible failure modes. It is critical to consider them all in any analysis, planning or design activity. To do so requires detailed and comprehensive information and analyses with cross checks from independent sources, not always feasible when resources and time are limited. It is particularly important to determine if an anomaly observed locally is just that or a component of a widespread characteristic that represents a systemic performance issue.

Another major lesson learned is that it is not likely that all possible failure modes have been identified or observed for structures in complex geological environments such as in New Orleans. The engineering community should continuously seek additional insights on potential performance for wide ranges of conditions and incorporate as often as possible potential non-traditional behavior modes in their analyses.

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, Texas, 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 composed 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 and Technology

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

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

National Oceanic and 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 and 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 Oceanic and 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 and 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	University of Colorado (retired)
James K. Mitchell	Virginia Polytechnic Institute and 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 Research Council

Appendix 4

Task Force Guardian Input

IPET Products Provided to Task Force Guardian (TFG) and Task Force Hope (TFH)

- 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 Act requests.
- 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 – Completed June 2006.** Technical support was provided to TFG on an as-needed basis. As a minimum, monthly face-to-face meetings took place in New Orleans. This support included geotechnical and structural consultations. These discussions also included 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 – Completed June 2006.** This evaluation included 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 – Completed October 2006.** This documentation included 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 gauge 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 – Completed November 2006.** Ground-truthing surveys were performed 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 were 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 Plans and Specifications 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 reevaluated for the east-facing levees in East Orleans, St. Bernard, and Plaquemines Parishes.
- t. **Closure Structures Modeling – January – February 2006.** IPET members at the New Orleans District performed modeling analysis of the closure structures on 17th Street, Orleans, and London Avenue Canals.
- u. **Closure Structures Interim Operations Plan – March 2006 – Completed November 2006.** IPET members reviewed and commented on operations of the gates and pumps. This included criteria for closing and 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 specifications that the project supervisor be an experienced heat straightener possibly

added to section 5 of the specifications 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 baseline in the event you get an inexperienced contractor that does more harm than good. TFG will know if heat straightening caused cracking if you have a baseline. 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 specifications. IPET believes section 3.5.3 pertains to simultaneous V-heats on the same side of the flange.

Appendix 5

Regional Geology and History

Introduction

A review of the geology and geologic history of coastal Louisiana is presented to establish the general framework for the soils and stratigraphy beneath the New Orleans levee failures. Geologic processes active during the past 5,000 years directly relate to the development of the land mass upon which the New Orleans area is situated, and the resulting stratigraphy beneath the levee failures at the 17th Street, London Avenue, and Inner Harbor Navigation Canals. Failures of six I-wall reaches and one earthen levee occurred at these three canals. These canals were responsible for the extensive flooding in the New Orleans metropolitan area following Hurricane Katrina. Levees in the IHNC area were mainly overtopped by storm surge during Hurricane Katrina, while levees at the 17th Street and London Avenue Canals were not overtopped, but failed at water levels below their design height. Geologists working in support of USACE flood control projects in the Lower Mississippi Valley (LMV) have typically classified the geology beneath structures and levees according to specific depositional environments. These lithostratigraphic units are associated with diagnostic fluvial and deltaic processes, and they are classified according to soil texture, sedimentary structures, organic content, fossils, and associated engineering properties. USACE geologists has been involved with studies of the New Orleans area geology since the 1940s and have applied an engineering geology classification to the underlying stratigraphy (Fisk 1944; Schultz and Kolb 1954; Kolb and Van Lopik 1958, 1965; Kolb 1962; Montgomery 1974; Kolb, Smith, and Silva 1975; Britsch and Dunbar 1990; Saucier 1994; Dunbar et al. 1994, 1995; Dunbar, Torrey, and Wakeley 1999).

Physiography and Setting

The city of New Orleans is situated in Jefferson and Orleans Parishes along the eastern edge of the Mississippi River's deltaic plain. Broad natural levees associated with the Mississippi River, Bayou des Familles, and Bayou Metairie are the most prominent physiographic features in the area (Figure 5-1). Surface elevations are generally near sea level and range from approximately 15 ft above sea level along the crests of the Mississippi River levees to below sea level over much of the area north of the river. Increased urban reclamation of low-lying areas occurred after World War II by draining the cypress swamps that were present north of the city to meet the demands for expansion and population growth. A map of the greater New Orleans area from 1849 is presented in Figure 5-2, showing the extensive swamps and major physiographic features north of the river, before the advent of the twentieth century urbanization. Continuous pumping of surface and ground water drainage to support residential development has contributed to the desiccation of these swamp and marsh soils, and has lowered the ground surface to below sea level for a significant portion of the city. Levees that encircle the city and

continuous pumping of surface water are required to keep the sea from reclaiming the “Crescent City.” Sea level rise of approximately of 1 to 3 ft during the next century due to global warming will provide even greater challenges to local, state, and federal officials and engineers tasked with protecting this historic American city, and other cities along our nation’s coasts.

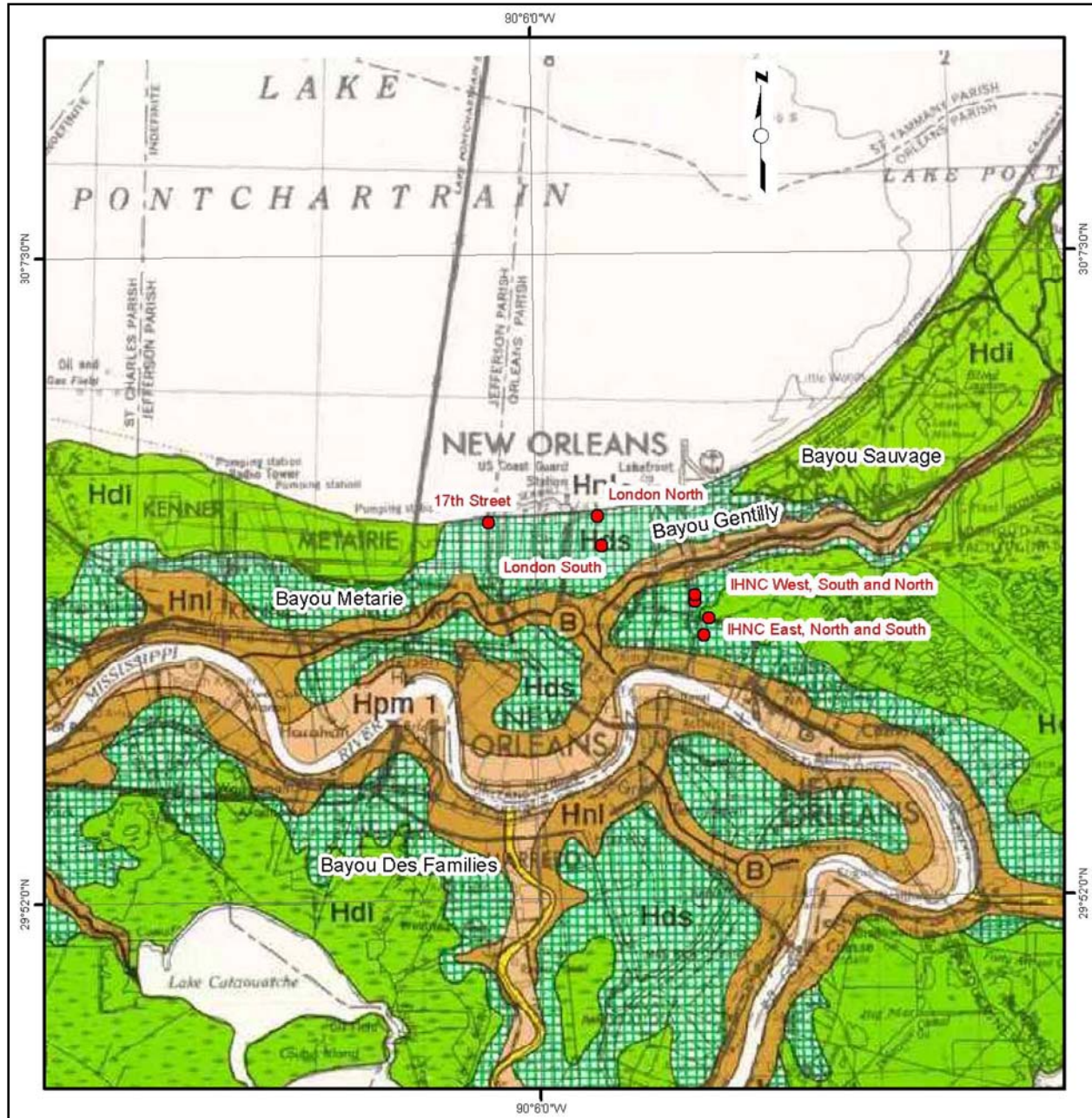


Figure 5-1. General map of the New Orleans area geology showing the limits of the different surface depositional environments (Saucier 1994). Map symbols are as follows: H = Holocene, d = deltaic, i = interdistributary, s = inland swamp, nl = natural levee, pm1 = point bar (most recent meander belt), B = St. Bernard distributary channel. Bayous Metarie, Gentilly, and Des Families are abandoned St. Bernard distributaries.

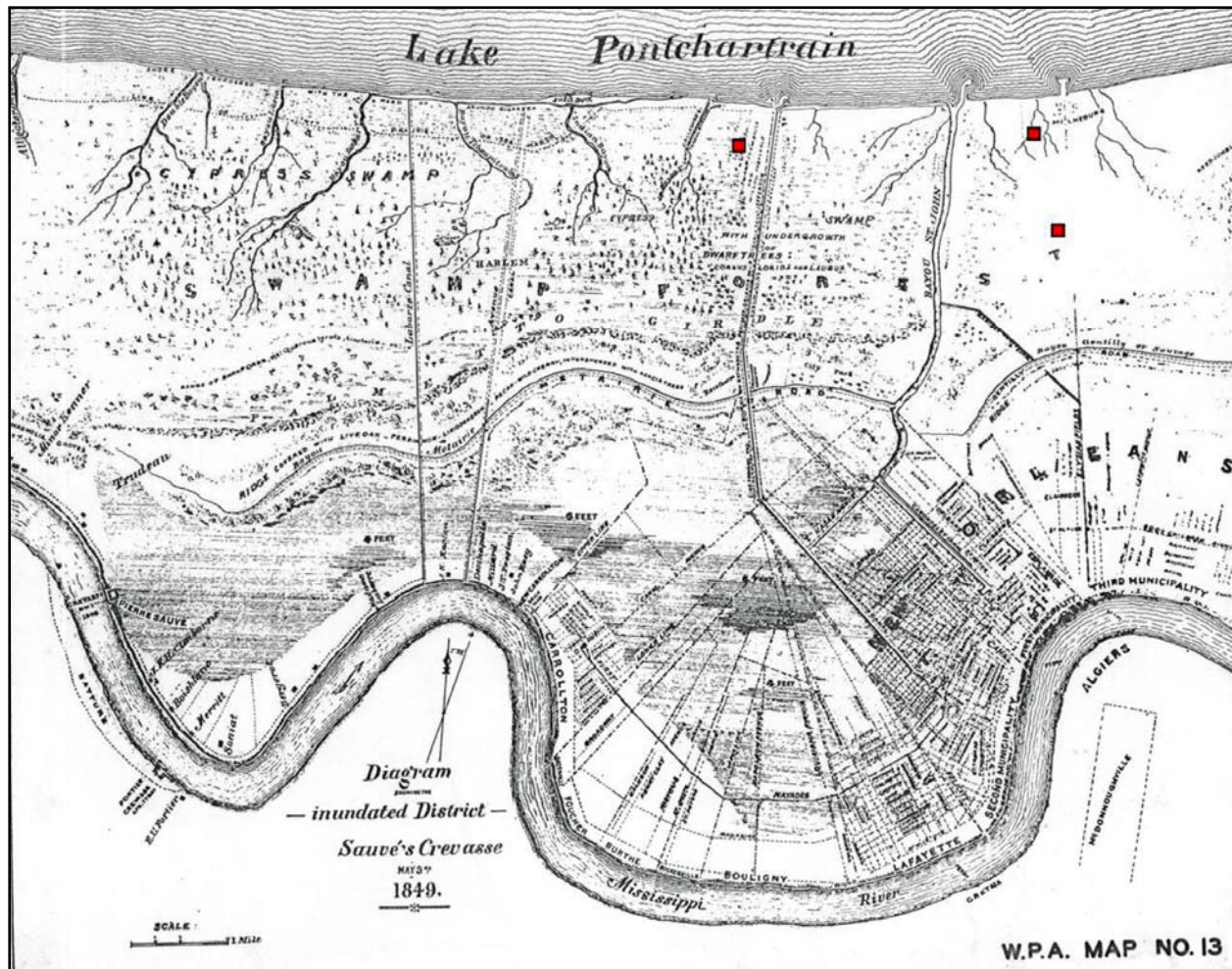


Figure 5-2. New Orleans area map from 1849 showing the locations of the Bayous Metairie and Gentilly distributary channel, the cypress swamps north of the city, and locations of 17th Street, London North, and South Canal breaches (marked by red squares, beginning from left to right and going clockwise). Bayous Metairie and Gentilly merge into the Bayou Sauvage distributary channel east of the New Orleans area. From Work Projects Administration (1937).

Geologic History

A geologic history has been developed for the Mississippi River’s deltaic plain based upon thousands of engineering borings drilled during the past 50 years, thousands of radiocarbon age dates determined from organic deltaic sediments, and numerous geologic studies conducted in this region (Kolb and Van Lopik 1958a, 1958b, 1965; Kolb 1962; Kolb, Smith, and Silva 1975; Kolb and Saucier 1982; Frazier 1967; Saucier 1963, 1994; May et al. 1984; Britsch and Dunbar 1990; Dunbar et al. 1994, 1995). More than 10,000 borings have been drilled in the greater New Orleans area during the past 50 years in support of foundations for the many engineered structures. Boring data identifies a complex geology that is related to the different course shifts by the Mississippi River and formation of its deltas during Holocene time (Figure 5-3). Continental glaciers covered much of North America 15,000 years before the present, with sea

level approximately 350 ft below the present level and the Gulf shoreline significantly farther seaward than its present location (Kolb, Smith, and Silva 1975). The ancestral Mississippi River and its tributaries were entrenched into the underlying Pleistocene surface below Baton Rouge, and they had developed a broad drainage basin, approximately 25 miles wide, with the axis of this entrenchment in the vicinity of Houma, approximately 45 miles southwest of New Orleans. Global warming and glacial melting caused eustatic sea-level rise, which stabilized between 4,000 to 6,000 years ago, and was 10 to 15 ft lower than the present level (Figure 5-4).

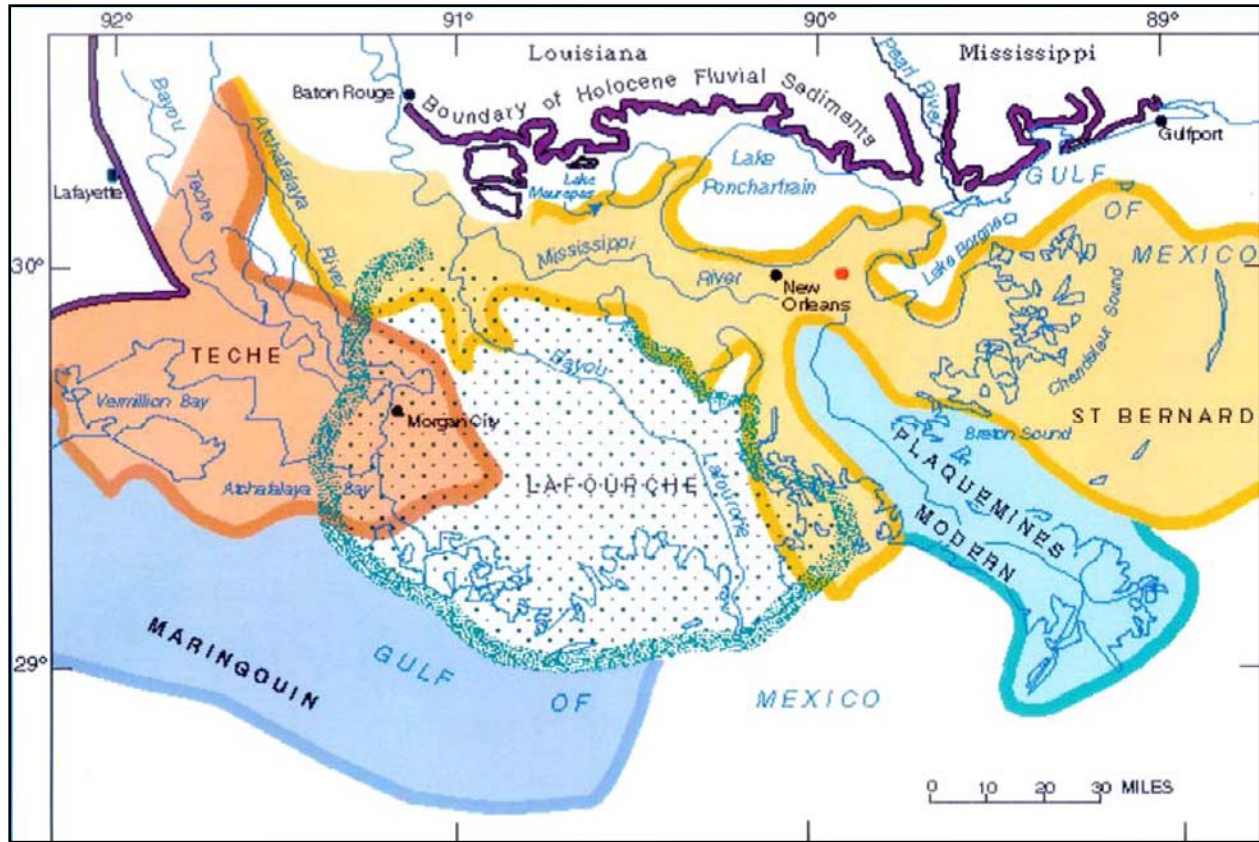


Figure 5-3a. Holocene deltas of the Mississippi River (after Fraizer (1967)).

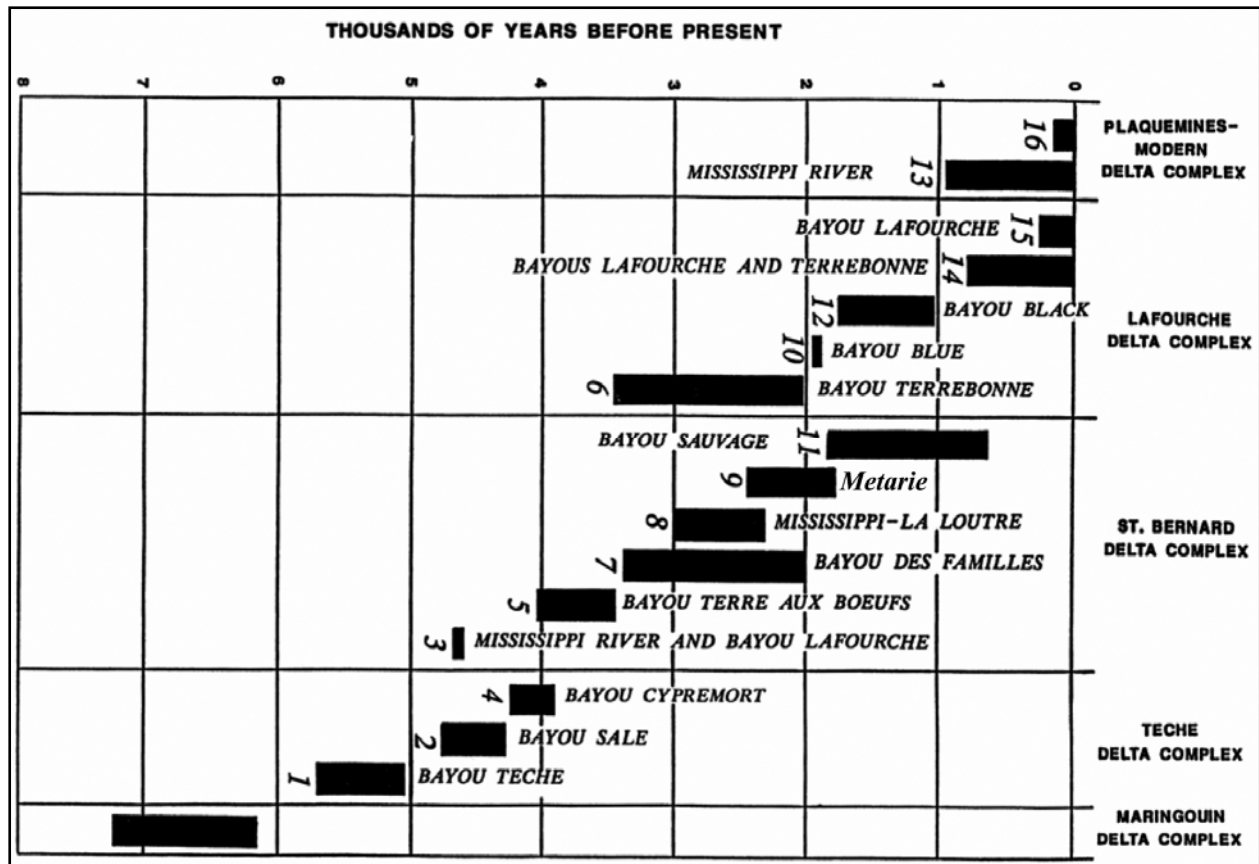


Figure 5-3b. Chronology of major Holocene distributary channels (after Fraizer (1967)).

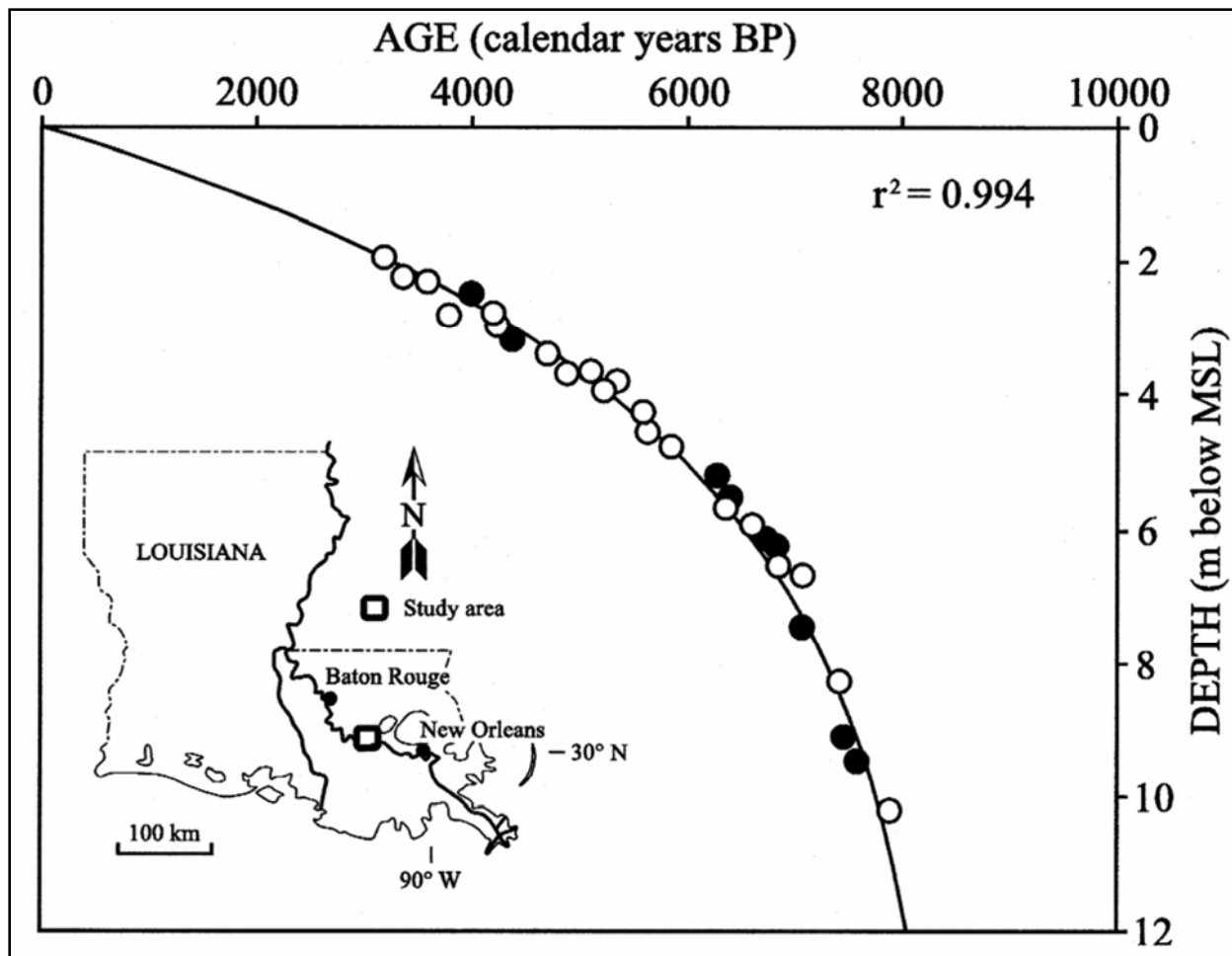


Figure 5-4. Holocene sea level curve for the eastern Mississippi River deltaic plain based on carbon-14 dating of basal peats at the transgressive Holocene and Pleistocene contact (Tornqvist et al. 2004).

Holocene sea level rise drowned the drainage valley and tributary network of the ancestral Mississippi River and caused massive deposition of fluvial sediment within this broad alluvial valley. Creation of the present-day deltaic plain began with the sea level near its present stand. Coastal Louisiana is the product of numerous, but generally short-lived, delta systems that have built seaward by deposition of fluvial transported sediment. These deltas have been subsequently reworked and modified by coastal transgressive processes. Five major deltaic systems have built seaward during the past 7,000 years as shown in Figure 5-3 (after Frazier 1967).

Each delta system contains a network of several major distributary channels and numerous smaller channels that terminate at the sea's edge where they discharge transported sediment to the sea. Collectively, this network of seaward prograding and bifurcating distributary channels forms a short-lived delta lobe complex. Relative ages of these deltas and the major distributary channels (Figure 5-3b) are well established by radiocarbon dating of the sediments in these systems (Kolb and Van Lopik 1958a; Fisk 1960; McFarlan 1961; Frazier 1967; Smith, Dunbar, and Britsch 1984). The first major advance of a delta into the New Orleans area occurred by the St. Bernard system approximately 3,500 to 4,000 years ago via several major distributary

channels (see Figures 5-1 and 5-3b). The land in the New Orleans area was established by this delta system. Partial Mississippi River flow continued to pass through the New Orleans reach following abandonment of this delta for the Lafourche delta complex south of Donaldsonville. After abandonment of the Lafourche system, approximately 500 years before present, Mississippi River flow returned to the present course. Historic construction of levees has prevented the river from seeking a different and shorter route to the Gulf. Active deltaic growth is occurring at the mouth of the Mississippi River and at the mouth of the Atchafalaya River.

Geologic Structure and Faulting

Holocene sediments underlying New Orleans are part of the seaward thickening wedge of Quaternary sediments that dip gently to the south and fill the Gulf of Mexico basin. Geologic structures within this sedimentary prism are piercement salt domes and growth faults. No salt domes are present beneath the greater New Orleans area. Faulting has been identified in the subsurface throughout the deltaic plain and in the Pleistocene deposits exposed at the surface north of Lake Pontchartrain (Wallace 1966, Snead and McCulloh 1984, Gagliano 2005, Dokka 2006). These faults are generally not considered tectonically active (i.e., U.S. Army Corps of Engineers (USACE) usage that implies Holocene movement and capable of producing large magnitude earthquakes that affect engineered structures). Instead, they are related to sedimentary loading, compaction, and consolidation of sediments in the Gulf of Mexico basin. Detailed study of the Pleistocene deposits by Kolb, Smith, and Silva (1975) did not identify faulting in the New Orleans area. Their study identified only one nearby fault in Lake Pontchartrain. Recognition of this fault was based on closely spaced borings and geophysical data. Subsequent geologic mapping of the eastern deltaic plain by Dunbar et al. (1994, 1995) did not identify any Holocene faults based solely on boring and engineering data. Surface faults occurring in Holocene sediments by movement in the underlying Pleistocene deposits are difficult to detect because unconsolidated sediments tend to warp rather than shear. Better resolution of Holocene and Pleistocene stratigraphy using seismic data, combined with closely spaced borings, and a dense network of elevation benchmarks are needed to determine whether Holocene movement in deltaic sediments are associated with the underlying Pleistocene fault structure.

Geologists in the New Orleans District generally evaluate the presence of faulting in studies of the subsurface stratigraphy during boring programs to determine the geotechnical properties of the foundation for the proposed structures. Additionally, radiometric dating of organic sediments is routinely conducted as part of the site investigations to determine geologic based subsidence histories for the area under study. Fault movements are generally factored into the subsidence history for the structure. Evidence of faulting would be reflected by subsidence, especially if the rates are abnormally high. Furthermore, land loss and engineering geology mapping studies by the New Orleans District have been evaluated for the presence of faults, as linear trends in land loss may define their presence (Dunbar, Britsch, and Kemp 1992; Britsch and Dunbar 1993, 2005). In the New Orleans area, no evidence of faulting was identified at the canal levee failures from the boring and stratigraphic evidence gathered and evaluated by the IPET team during focused studies at these areas. Stratigraphic evidence obtained and evaluated from these sites indicates other mechanisms are responsible for the different canal failures.

Holocene Environments of Deposition

The geology in the LMV and the New Orleans area has traditionally been defined by USACE geologists according to depositional environments. Surface environments include natural levee, point bar, inland swamp, fresh marsh, and abandoned distributary channels (see Figure 5-1). Distributary channels are associated with two major St. Bernard distributary systems, the Bayou des Familles-Barataria and the Bayou Metairie-Sauvage system (Figure 5-3b). The Bayou des Familles-Barataria extends due south from the Mississippi River and was active approximately 2,000 to 3,400 years before present (Figure 5-1), while the Bayou Metairie-Sauvage-Gentilly course is located north of the Mississippi River and was active about 2,500 to 700 years before the present (Frazier 1967, Saucier 1963). These distributary systems filled the shallow water in the New Orleans area with fluvial-deltaic sediments. Overbank deposition from these active distributary channels has formed well developed natural levees that transition to inland swamps and low-lying marsh environments. Sediments within these different environments generally become finer-grained with increasing distance from the distributary channels and have a corresponding increase in organic content.

USACE foundation and regional geologic studies show the Holocene fill ranges from 70 to 80 ft in thickness across much of the New Orleans area and is composed of stacked depositional environments, related to shifting delta systems and their seaward advancement and growth. Where the Mississippi River has scoured in the bends of the river, the Holocene fill exceeds greater than 150 ft in thickness (Dunbar, Torrey, and Wakeley 1999; Saucier 1994). Major deltaic environments overlying the Pleistocene surface in the vicinity of the canal failures include nearshore gulf, bay sound-estuarine, intradelta, relict beach, lacustrine, and interdistributary environments (Dunbar et al. 1994, 1995). Regional geologic maps and cross sections from the Louisiana Coastal Plain and the greater New Orleans area are presented on a USACE geology website of the LMV and show the vertical and horizontal limits of these different environments of deposition in the subsurface (see Corps geology website for the LMV to obtain maps and cross sections at lmvmapping.ercd.usace.army.mil). Similarly, cross sections were developed from the boring information at the different failure sites where they define the vertical and horizontal limits of these environments in the subsurface, presented in discussions about each breach site in Volume V of the IPET report.

Correlations between depositional environments and the engineering properties of the soils that form these lithostratigraphic units are summarized in Table 5-1 (Kolb and Van Lopik 1965). A detailed discussion and presentation of the physical and engineering properties characteristic of these different depositional environments is beyond the scope of this study. A comprehensive description of these environments is provided in several USACE studies (Kolb and Van Lopik 1958a, 1959b, 1965; Kolb 1962; Montgomery 1974; Kolb, Smith, and Silva 1975; Saucier 1994), which are presented at the above LMV geology website.

Table 5-1a. Selected engineering properties of deltaic depositional environments, soil texture (Kolb 1962 and Kolb and Van Lopik 1965).

DEPOSITIONAL TYPES	LITHOLOGY PERCENT				REMARKS
	0	25	50	75	
NATURAL LEVEES					Disposed in narrow bands flanking the Mississippi River and its abandoned courses and distributaries. Elevation varies from 25 feet near Baton Rouge to sea level.
POINT BAR					Usually found flanking the more prominent bends of present and abandoned courses. Thickness in excess of 100 feet.
PRODELTA CLAYS					Fat clay in offshore areas and at depth beneath deltaic plain. Thickness ranges between 50 and 400 feet.
INTRADelta					Coarse portion of subaqueous delta. Intricately interfingered deposits. Disposed in broad wedges about abandoned courses and major distributaries.
INTERDISTRIBUTARY					Forms clay wedges between major distributaries. Minor amounts of silts and fine sands typically occur in very thin but distinct layers between clay strata.
ABANDONED DISTRIBUTARY					Form belts of clayey sediments from a few feet to more than 1000 feet in width and from less than 10 to more than 50 feet in depth.
ABANDONED COURSE					Form belts of fairly coarse sediment in abandoned Mississippi River courses. Lower portion filled with sands, upper portion with silts and clays. Coarsest fill near point of diversion.
SWAMP					Tree-covered organic deposits flanking the inner borders of the marsh and subject to fresh-water inundation. Deposits 3 to 10 feet thick.
MARSH					Forms 90 percent of land surface in the deltaic plain. Ranges from watery organic oozes to fairly firm organic silts and clays. Average thickness 15 feet.
ABANDONED TIDAL CHANNELS					Found principally in peripheral marsh areas. Average depths on the order of 25 feet. Widths average 200 feet. Filling varies from peat to organic clay.
SAND BEACH					Border the open gulf except in areas of active deltaic advance. May be a mile or more wide and more than 10 miles long. Sand may pile as high as 30 feet and subside to depths 30 feet below gulf level.
SHELL BEACH					Border landward shores of protected bays and sounds and marshland lakes. Vary from 25 to 200 feet in width and from 2 to 6 feet in height. Lengths usually less than a mile.
LACUSTRINE					Deposits vary in thickness from 2 to 25 feet. Stratification in clayey lacustrine deposits is poorly developed or lacking.
REEF					Active reefs found principally in bay-sound areas. Buried reefs 5 to 10 feet thick a common occurrence within deltaic plain. Reach dimensions of 1/2-mile wide and 10-miles long.
BAY-SOUND					Relatively coarse sediments on bottoms of bays and sounds. Thickness between 3 and 20 feet.
NEARSHORE GULF					Found at the borders of the open ocean seaward of the barrier beaches. Thickness normally increases with distance from shore.
SUBSTRATUM					Massive sand and gravel deposits filling entrenched valley and grading laterally into nearshore gulf deposits. Material becomes coarser with depth.
PLEISTOCENE					Ancient former deltaic plain of Mississippi River. Consists of environments of deposition and associated lithology similar to those found in Recent deltaic plain. Depth of this ancient, eroded surface increases in a southerly and westerly direction in southeastern Louisiana.

LEGEND					
	GRAVEL (>2.0 MM)		SAND (2.0-0.05 MM)		SILT (0.05-0.005 MM)
	CLAY (<0.005 MM)		ORGANIC MATERIAL		SHELL

Table 5-1b. Selected engineering properties of deltaic depositional environments (Kolb 1962 and Kolb and Van Lopik 1965).

DEPOSITIONAL TYPES	NATURAL WATER CONTENT PERCENT DRY WEIGHT	UNIT WEIGHT LB/CU FT	SHEAR STRENGTH ⁽¹⁾	
			COHESIVE STRENGTH LB/SQ FT	
	0 50 100 150 200 60	80 100 120 140	0 200 400 600 800	
NATURAL LEVEES			VALUES RANGE TO APPROXIMATELY 2600 CHARACTERISTIC RANGE 800-1200	
POINT BAR	FINE FRACTION ONLY	INSUFFICIENT DATA	INSUFFICIENT DATA	
PRODELTA CLAYS				
INTRA-DELTA		INSUFFICIENT DATA	INSUFFICIENT DATA	
INTERDIS-TRIBUTARY				
ABANDONED DIS-TRIBUTARY	INSUFFICIENT DATA	INSUFFICIENT DATA	INSUFFICIENT DATA	
ABANDONED COURSE	INSUFFICIENT DATA	INSUFFICIENT DATA	INSUFFICIENT DATA	
SWAMP			INSUFFICIENT DATA	
MARSH	VALUES RANGE TO APPROXIMATELY 800	INSUFFICIENT DATA	VERY LOW	
ABANDONED TIDAL CHANNELS	INSUFFICIENT DATA	INSUFFICIENT DATA	VERY LOW	
SAND BEACH	SATURATED	INSUFFICIENT DATA	0	
SHELL BEACH	SATURATED	INSUFFICIENT DATA	0	
LACUSTRINE				
REEF	SATURATED	INSUFFICIENT DATA	0	
BAY-SOUND				
NEARSHORE GULF	SATURATED	INSUFFICIENT DATA	0	
SUBSTRATUM	SATURATED	INSUFFICIENT DATA	0	
PLEIS-TOCENE			VALUES RANGE TO APPROXIMATELY 3500 CHARACTERISTIC RANGE 900-1700	

(1) SHEARING STRENGTH OF CLAYS BASED ON UNCONFINED COMPRESSION TESTS.

TYPICAL RANGE OF VALUES INDICATED BY LENGTH OF BAR. BAR WIDTH INDICATES RELATIVE DISTRIBUTION OF VALUES.

Classification of the subsurface stratigraphy beneath the failure sites by the IPET investigation team was made according to depositional environments from the available boring data. Geologic cross sections at each failure area were prepared from the available boring data to support the engineering analyses of the failure mechanisms. Interpretation of the underlying stratigraphy is based on the Corps classification of depositional environments gained from more than 50 years of corporate experience in geologic mapping and evaluation of fluvial deltaic deposits in the coastal plain in support of foundation studies for various flood control projects (Fisk 1944; Schultz and Kolb 1954; Kolb and Van Lopik 1958a, 1958b, 1965; Kolb, Smith, and Silva 1975; Saucier and Kolb 1982; Saucier 1994). Engineering properties of fluvial-deltaic soils are uniquely related to their origin, their age, local current and wave conditions, sedimentary structures, and the subsequent geomorphic processes and man-made changes that have occurred after their deposition. The greatest contrast in engineering properties occurs between the high and low energy depositional environments and sediment age, namely whether the sediments are Holocene or Pleistocene.

A prominent buried beach ridge lies between Lake Pontchartrain and the Mississippi River that has directly influenced levee foundation properties and contributed to the subsequent failures at the 17th Street and London Canals (Figure 5-5). A relatively stable, but lower (10 to 15 ft lower than present) sea level 4,000 to 5,000 years ago permitted sediments from the Pearl River east of New Orleans area to be concentrated by longshore drift, forming a prominent sandy spit or barrier beach complex known as the Pine Island Beach (Saucier 1963, 1994). The levee breach at the 17th Street Canal was located on the protected or back barrier side of this beach system, while both of the London Avenue Canal levee breaches were located on the main axis, where the maximum sand thickness occurs. Consequently, soft soils at the 17th Street break are much thicker and finer-grained than those beneath the London Canal. Foundation soils at the 17th Street Canal levee are dominated by clay while those at the London Canal are composed mainly of sand. Levee failures in the IHNC area are located on the seaward side of the beach complex and south of the Bayou Metairie-Sauvage distributary system. The Pine Island Beach trend prevented this distributary system from completely filling Lake Pontchartrain with sediment. Because of the high sediment rates and close proximity to the Bayou Metairie-Sauvage distributary and the present course of Mississippi River, the IHNC area has thick deposits of fine-grained soils consisting of natural levee and inland swamp.

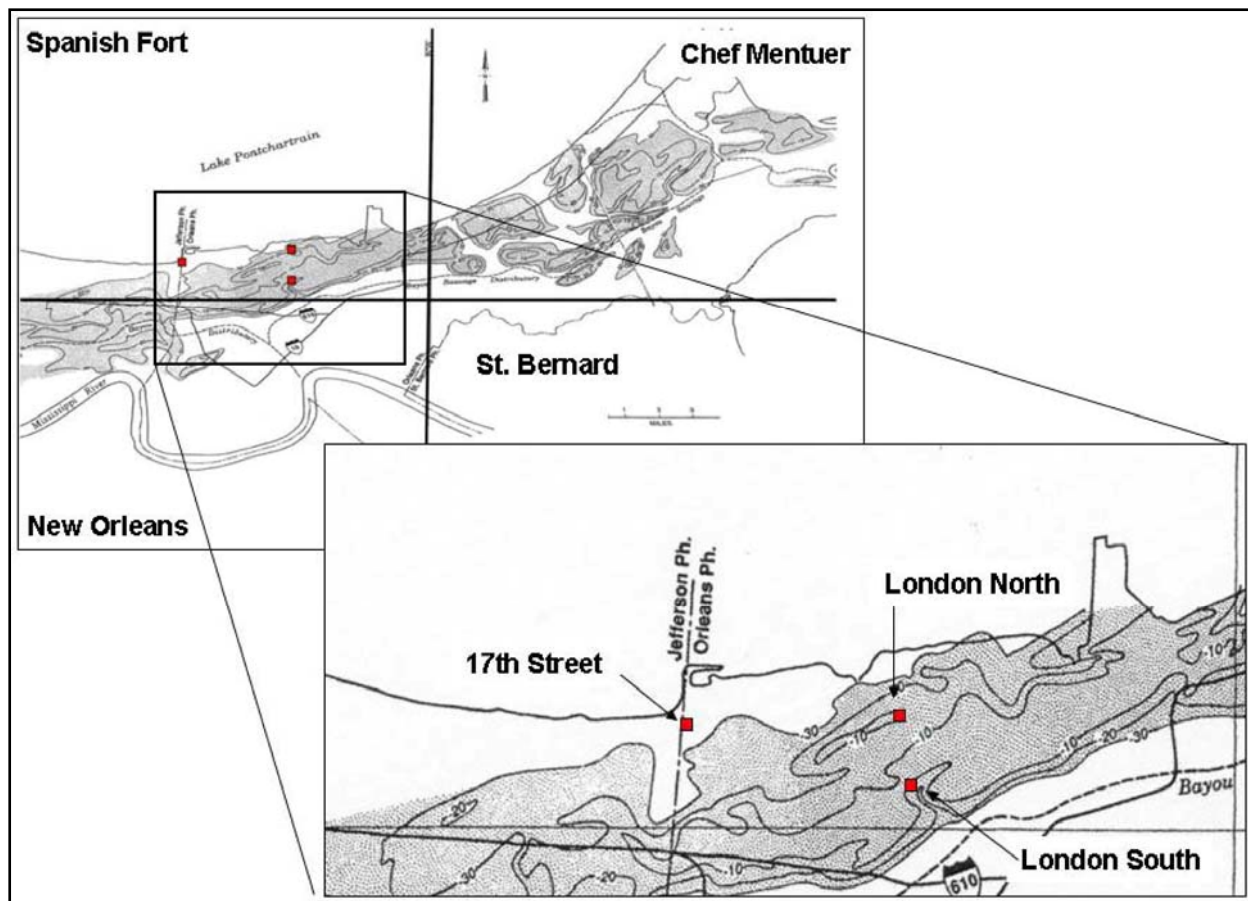


Figure 5-5. Contour map of the buried Pine Island Beach with elevations in ft MSL (Saucier (1994)).

Subsidence and settlement

Loss of wetlands in coastal Louisiana is among the most severe in the United States. Historic rates have been as high as 42 square miles per year during the mid 1960s. During the period between 1983 and 1990, loss rates were at about 25 square miles per year (Britsch and Dunbar 1993, 2005). Because of Hurricanes Katrina and Rita, rates are in excess of 200 square miles per year (*Times-Picayune* 11 October 2006). Lost wetlands in the Mississippi River deltaic plain are related to a combination of factors, including erosion by wave and storm surges, global sea level rise, regional subsidence from sedimentary loading of the Gulf of Mexico basin, local subsidence due to compaction and consolidation of the Holocene deltaic sediments, oil and groundwater extraction, movement along Quaternary faults, movement of the underlying Jurassic salt layer, movement of salt domes, and impacts caused by man's activities.

Man's activities have included construction of levees, the building of flood control and diversion structures, dredging of navigation and petroleum canals, and the dewatering and pumping of low-lying coastal plain areas to support agricultural and urban development. Subsidence in the Louisiana coastal zone and the New Orleans area involves both sea level rise and the general lowering of the land surface because of the different natural and man-made

mechanisms listed above. Further contributing to the wetland loss has been the confinement of the Mississippi River to a fixed course by levee construction and bank stabilization, which has prevented fluvial transported sediments from reaching the distal parts of its former floodplain during the annual flooding, and the creation of new land areas by crevassing, channel avulsion, and formation of new deltas. In the New Orleans area, subsidence has been severe, due in large part to historic dewatering of swamp and marsh soils, and because of the lack of new sediment from reaching low-lying areas on the floodplain from levee confinement. Active land building by fluvial-deltaic processes in coastal Louisiana has been restricted to the Mississippi and Atchafalaya River deltas.

Subsidence rates in the Louisiana Coastal Plain and the New Orleans area have been the focus of several recent studies (Dixon et al. 2006; Meckel, ten Brink, and Williams 2006; Miller and Douglas 2004; Shinkle and Dokka 2004; Burkett, Zilkoski, and Hart 2003; Penland et al. 1989). Subsidence rates reported for the New Orleans area are variable (Figure 5-6). Subsidence rates are generally higher in the low-lying areas near the lake front as compared to the natural levees flanking the active channel and its distributaries. Generally, the low-lying swamp areas (Figure 5-2) are more compressible due to their fine-grained texture and higher water contents, as compared to the natural levees soils with lower water contents and coarser-grained textures. Current, short-term estimates of subsidence in the New Orleans area average about 5 mm/yr (Dixon et al. 2006; Burkett, Zilkowki, and Hart 2003). Geological estimates of long-term subsidence in the New Orleans area based on carbon-14 dating of buried peats and organic sediments, and they indicate the general background rate is about 0.5 to 1 ft per century, or about 1.5 to 3 mm/yr (from unpublished USACE C-14 data and Kolb and Van Lopik (1958), respectively). Short-term subsidence rates in the New Orleans area are nearly 3 to 4 times higher than the background rate determined from geologic time scales spanning several thousand years. The geologic background rate also incorporates sea level rise as a component, since peats are assumed to form at the land-water interface within coastal marsh settings, and thicken in response to deltaic sedimentation and continued marsh growth under a rising sea level.

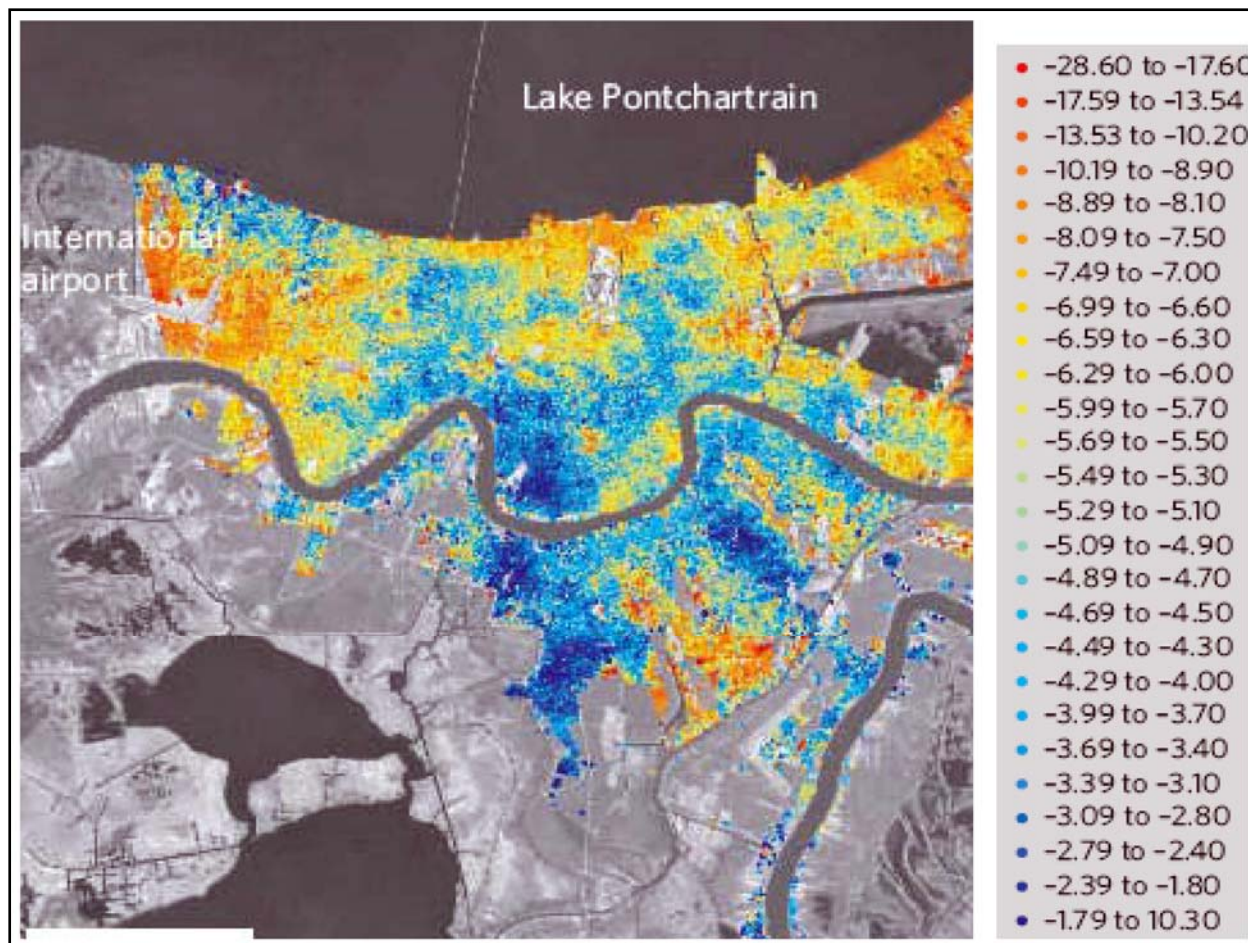


Figure 5-6. New Orleans area subsidence rates in mm/yr, based on 33 Radarsat satellite scenes from 2002 and 2005 (Dixon et al. (2006)). Rates are generally highest near the Lake Pontchartrain shoreline. Lake front area contains dredge fill from early 1900s. This area also corresponds to the protected or back barrier side of the buried Pine Island beach complex (see Figure 5-5).

An underlying cause for the higher historic subsidence rates in the New Orleans area has been the construction of drainage canals during the twentieth century, and dewatering of the organic (swamp and marsh) soils shown in Figure 5-2 to accommodate the increased demands for land development and population growth. Lowering of groundwater levels by construction of drainage canals and pumping of surface drainage has caused a corresponding net reduction in soil volume, oxidation of the dewatered organic sediments, and an overall decline in surface elevation throughout the city. Data presented by Saucier and Kolb (1982) estimate total subsidence in the Kenner area of Eastern Jefferson Parish may be as much as 70 in. since dewatering began (Figure 5-7). Saucier and Kolb referred to this human induced subsidence as “settlements,” because of its underlying engineering origin. Added to the settlements from dewatering are the secondary effects of residential construction and loading of the ground surface by building foundations (Eustis Engineering Company 1984).

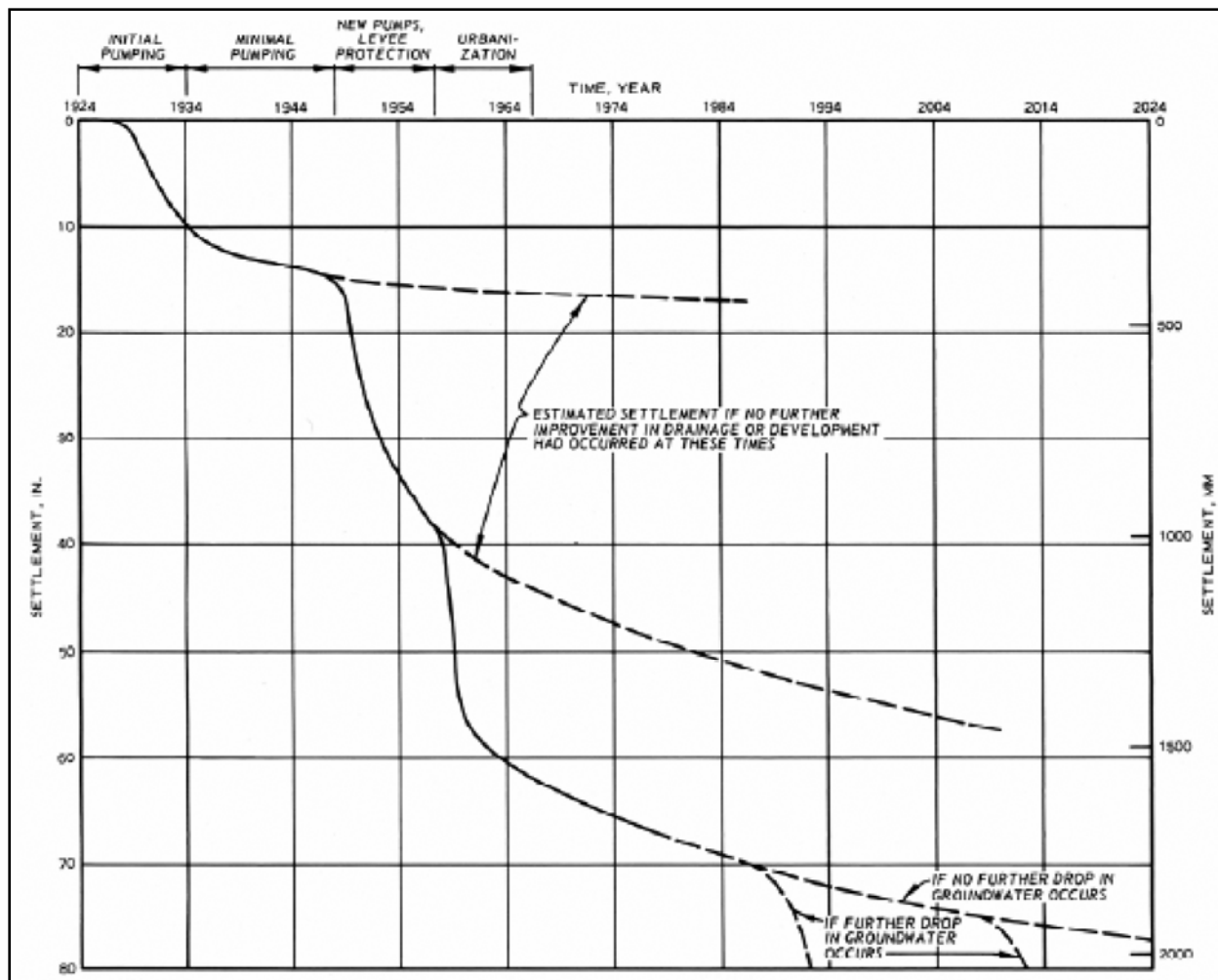


Figure 5-7. Estimated settlement history in the Kenner area due to dewatering of near surface organic sediments by drainage canals and pumping (from Kolb and Saucier (1982) using unpublished data by Traughber and Gore). Dewatering of organic sediments causes volume reduction in these sediments and results in oxidation, which lowers the ground surface.

Site specific, cumulative changes in surface elevation in Orleans Parish have been identified in a study by URS (2006). Comparison of historic 5-meter elevation data, relative to a constant datum between 1895 and 2002, indicates total subsidence and/or “settlement” in some parts of the city ranges from 8 to 10 ft (Figure 5-8). Positive land gain in Figure 5-8 corresponds to early 1900s dredge filling to create the New Orleans lake front. Highest values of elevation decline during the past 100 years are in areas underlain by thick marsh and swamp deposits. Furthermore, these areas are located on the back barrier side of the buried Pine Island beach, consisting of 70- to 80-ft-thick, unconsolidated Holocene deltaic sediments. Boring data and cross sections developed from this area identifies the underlying geology as consisting in descending order and increasing age as 8- to 12-ft thick sequence of 3,000 year or less paludal (marsh and swamp) deposits, 20- to 25-ft-thick lacustrine sediments, 10- to 20-ft-thick sand that is part of the Pine Island Beach complex, and 30- to 40-ft-thick fine-grained, bay sound deposits that overlie the stable Pleistocene surface (Schultz and Kolb 1954; Kolb and Van Lopik 1958a; Fisk 1960; Kolb, Smith, and Silva 1975; Dunbar et al. 1994, 1995; USACE 1988, 1989, 1990).

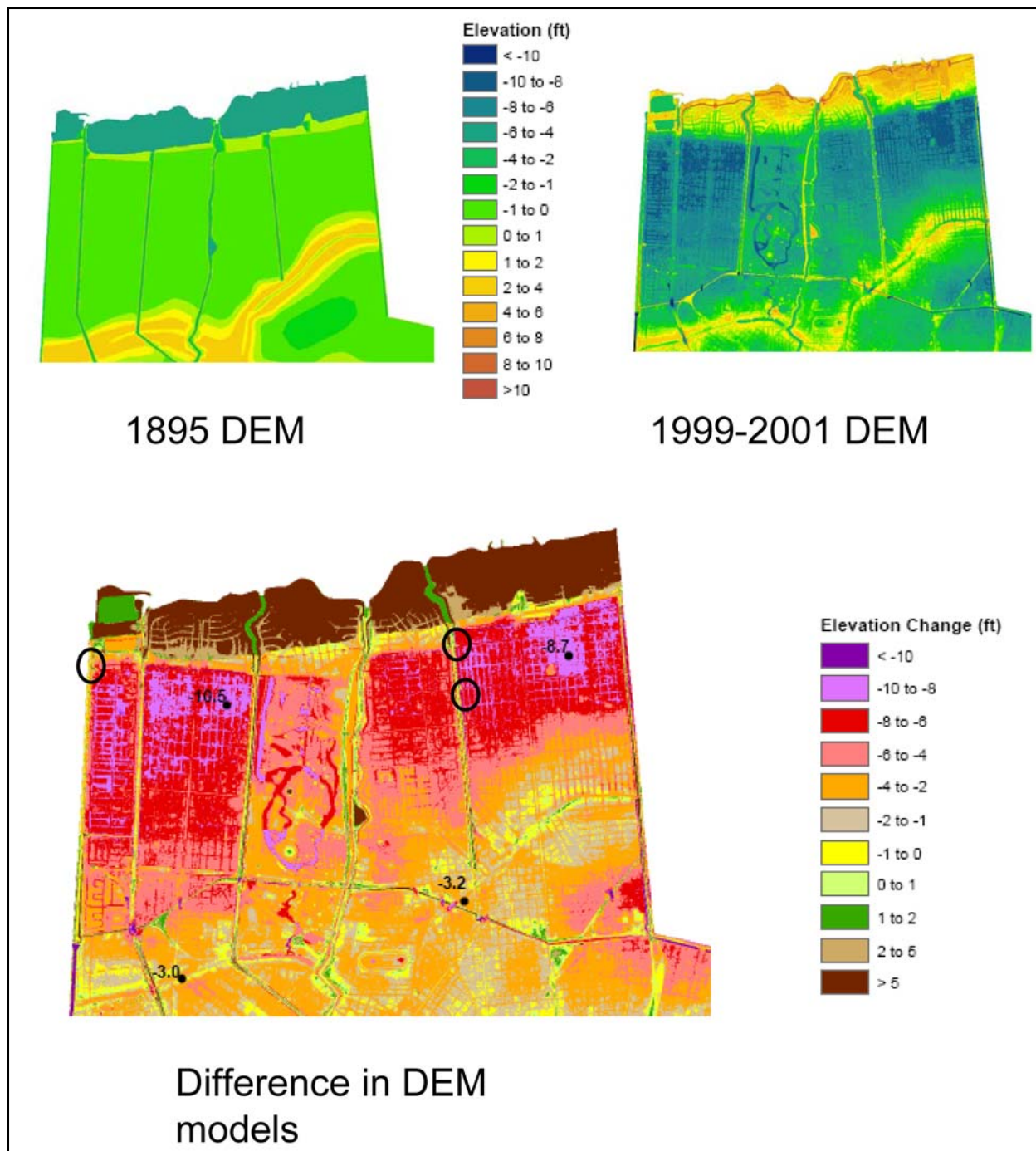


Figure 5-8. Changes in ground surface elevation between 1895 and 2001 (URS (2006)). Comparison is based on 1895 historic topographic map and 1999-2001 digital elevation models (DEMs). Locations of failures are identified by open circles, from left to right are 17th Street Canal, London Canal North breach (top), and London.

Settlements beneath the drainage canals are considerably less than the adjoining residential areas in Figure 5-8. Historic settlements are probably less severe because of construction related compaction of the foundation by the added weight of the levee during its initial dredging during the late 1800s and early 1900s and continued maintenance of levee height since. Figure 5-7

suggests that settlements are most severe after the initial dewatering process occurs, and then stabilizes at a constant background rate. Present day surface elevations near the landside toe of the levee breaches are generally between -5 and -6 ft NAVD88. Considering that the original swamp surface was probably 1 to 2 ft above sea level before urbanization began (Figure 5-2), large settlements of more than 70 in. are the norm, rather than the exception during historic time in the New Orleans area. Both short-term (man-made) and long-term (geologic) mechanisms are involved in the subsidence problem beneath the city.

Another historic perspective of New Orleans subsidence rates is provided by elevation measurements from the ALCO1931 benchmark during a 53-year record of measurements (Figure 5-9). This benchmark is located on the west side of the Hammond Highway Bridge, near the Coast Guard Station, and near where the 17th Street Canal breach occurred. An elevation difference of -2.095 ft relative to NAVD88(2004.65) or -2.345 ft relative to MSL in 2005 was reported for this benchmark for the 53-year period of record. The net difference in elevation includes changes in the survey datum (or spheroid model of the earth used) and a component of subsidence. By subtracting the difference in survey datum from the overall value, the resultant value corresponds to historic subsidence changes at this location during the period of record, and generally 40 to 50 years after canal construction and dewatering have occurred. At the ALCO1931 location, it has been estimated that the datum changes account for about 0.19 ft or 2.28 in. of the total measured difference (J.K. Garster, personal communication). Subtracting the datum component from the total difference yields a subsidence component of -1.905 ft (580.6 mm) relative to NAVD88 (2004.65) and -2.155 ft (656.8 mm) relative to the MSL datum. This net difference corresponds to an annual subsidence rate of 0.43 in./yr (10.95 mm/yr) relative to NAVD88 (2004.65), or 0.49-in./yr (12.4 mm/yr) relative to MSL (which incorporates sea level rise) for the 53-year period of record. These rates correspond to cumulative subsidence rates of between 3.59 and 4.07 ft (1.095 and 1.24 m) per century, and probably accurately reflect the latter stages of the subsidence curve in Figure 5-7 in areas that have undergone dewatering.

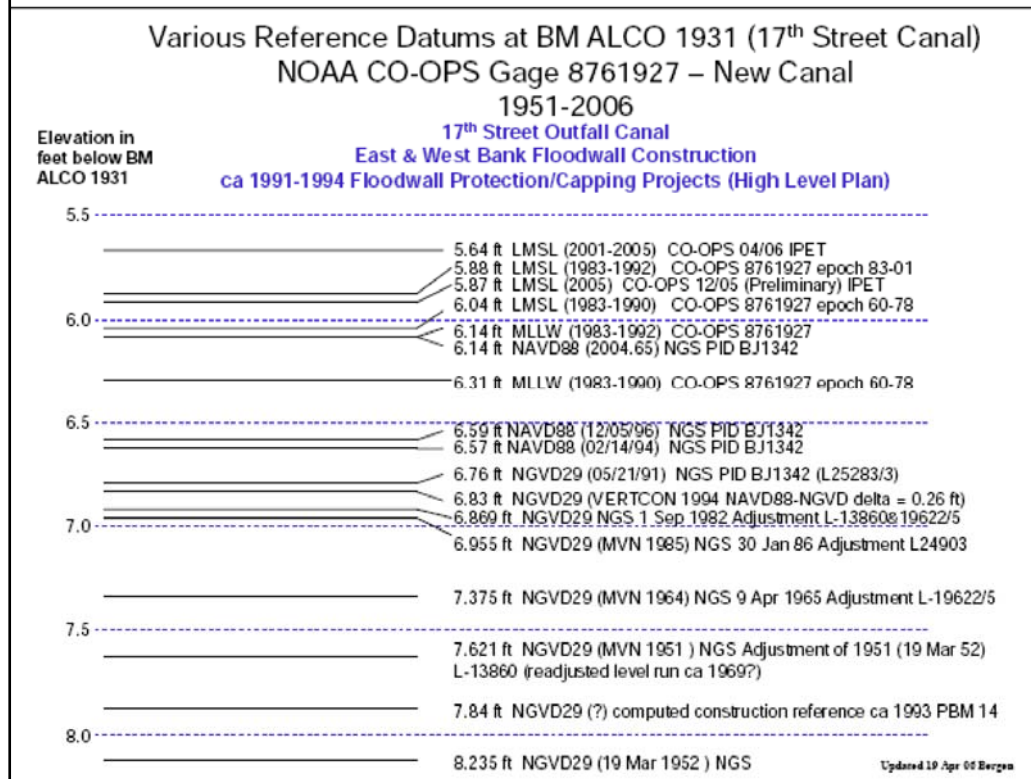
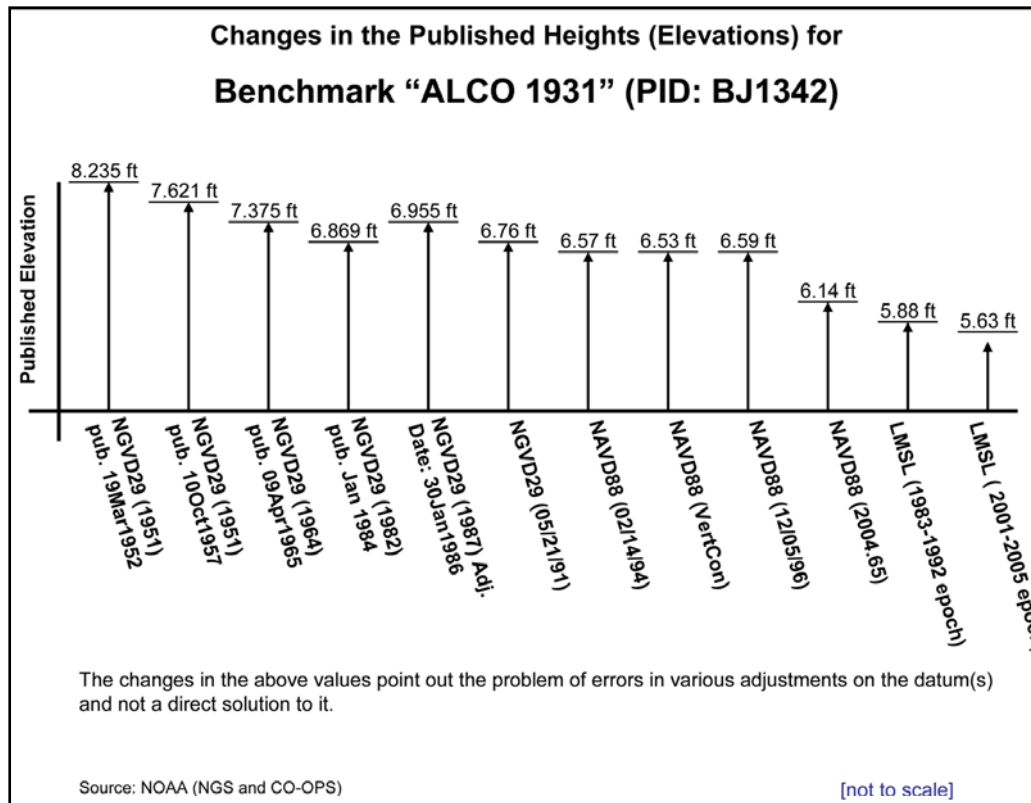


Figure 5-9. Changes in elevation reported for the ALCO benchmark, near the Hammond Highway Bridge at 17th Street Canal (from IPET, Chapter 2, Figures 69 and 33, respectively).

Subsidence rates identified by the various methods described above in Figures 5-6 through 5-9 are important for understanding the short- and long-term impacts to engineered structures, and designing effective solutions for flood protection in New Orleans. Hurricane protection of the drainage canal levees consisted of I-wall and T-wall construction during the early 1990s. Changes in elevation due to subsidence were generally not incorporated into the design of I-walls and T-walls for hurricane protection. Impacts to levee stability and subsequent levee performance from changes in elevation due to subsidence were nonexistent or negligible. In terms of levee performance, no differential settlements have been reported during the annual levee inspections, nor were they documented by the current IPET investigation. If significant subsidence had occurred, it may have caused deformation between I-wall panels, which may have compromised the integrity of the HPS, and resulted in poor performance. Short-term subsidence was not an issue factoring into the poor performance of the I-walls at the canal levee failures.

No structural impacts to levee performance are attributed to subsidence during Hurricane Katrina, except in terms of the level of protection afforded from the design flood height. Height of the flood protection was not at levels authorized by Congress because of poor understanding and effective resolution of the different benchmark datums that were incorporated into the engineering of the flood protection system. Congress authorized a level of protection that was not achieved because of faulty resolution of the datum and historic changes from subsidence.

With a forward look to the future for coastal Louisiana, the New Orleans District currently has no funding for a systematic, district-wide program for monitoring subsidence within man-made and natural settings. All of the subsidence rate calculations are long-term estimates, or short-term estimates from a few site specific benchmarks. In order to effectively address subsidence and its implications for flood protection, a district-wide program for monitoring subsidence using the latest technology must be implemented. Important to this program will be a dense network of benchmarks upon the levees and its structural components, as opposed to only highway benchmarks, that accurately measures the subsidence rates across the Louisiana Coastal Plain for effective solutions that mitigate subsidence, land loss, and flood protection.

Summary

Inland swamp and marsh soils form the foundations for the levees, and these soils require special attention for effective engineering of structures. Urban reclamation of low-lying areas has impacted the surface topography during historic time and has involved draining the cypress swamps that were present north of New Orleans to meet the demands for city expansion and population growth. Continuous pumping of surface and groundwater drainage are necessary to keep groundwater levels below residential development. This process has directly contributed to the desiccation of the underlying swamp and marsh soils, and lowered much of the ground surface below sea level over a significant portion of the city. Levees that encircle the city and continuous pumping into the drainage canals are now required to prevent flooding. A buried beach ridge, located between the south shore of Lake Pontchartrain and the Mississippi River, has directly affected levee foundation and engineering properties at the 17th Street and London Avenue Canals. The thicknesses of inland swamp and marsh deposits at the canals are controlled

by the presence of the buried relict beach and their proximity to prehistoric distributary channels, which created the land area beneath New Orleans. Swamp and marsh soils are thickest behind the beach ridge and the IHNC area, and are the thinnest over the axis of the beach ridge. Focused geologic studies of the levee breaches indicate weak lacustrine soils were responsible for the levee failure at the 17th Street Canal. High storm surges in the canals appear to have elevated pore pressures in the pervious beach sands that ultimately contributed to the levee failures at the London Avenue Canal. Further east in the IHNC area, the hurricane-generated storm surge overtopped and scoured the soil foundations behind the vast majority of I-walls that failed. Ultimately, the lessons that emerge from Hurricane Katrina are that the geology and associated hazards imposed by weak and pervious foundation soils must be clearly defined and better understood. Local differential subsidence was not a factor in the poor performance of the structures that breached due to foundation failures; however, lower than authorized elevations contributed to the overtopping and failure of both floodwalls and levees. A dense network of benchmarks is needed on Corps levees and structures to effectively characterize long-term subsidence trends.

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Appendix 6

Distribution of Hurricane Protection System Structures

The following maps depict the distribution and types of the structures composing the New Orleans and Vicinity Hurricane Protection System prior to Katrina. The reach and transition points described on these maps are identical to those being used for the IPET risk assessment reported in Volume VIII.

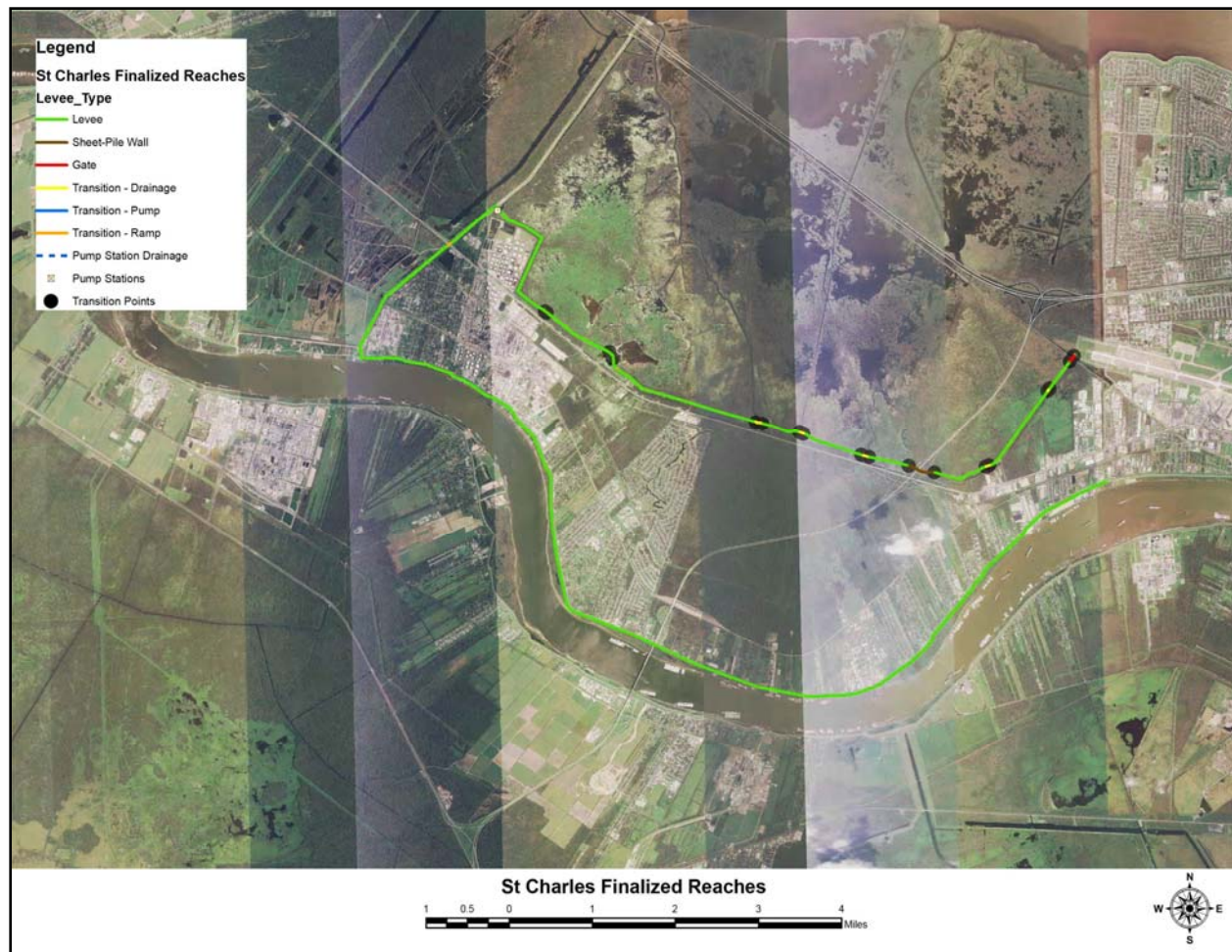


Figure 6-1. St. Charles.

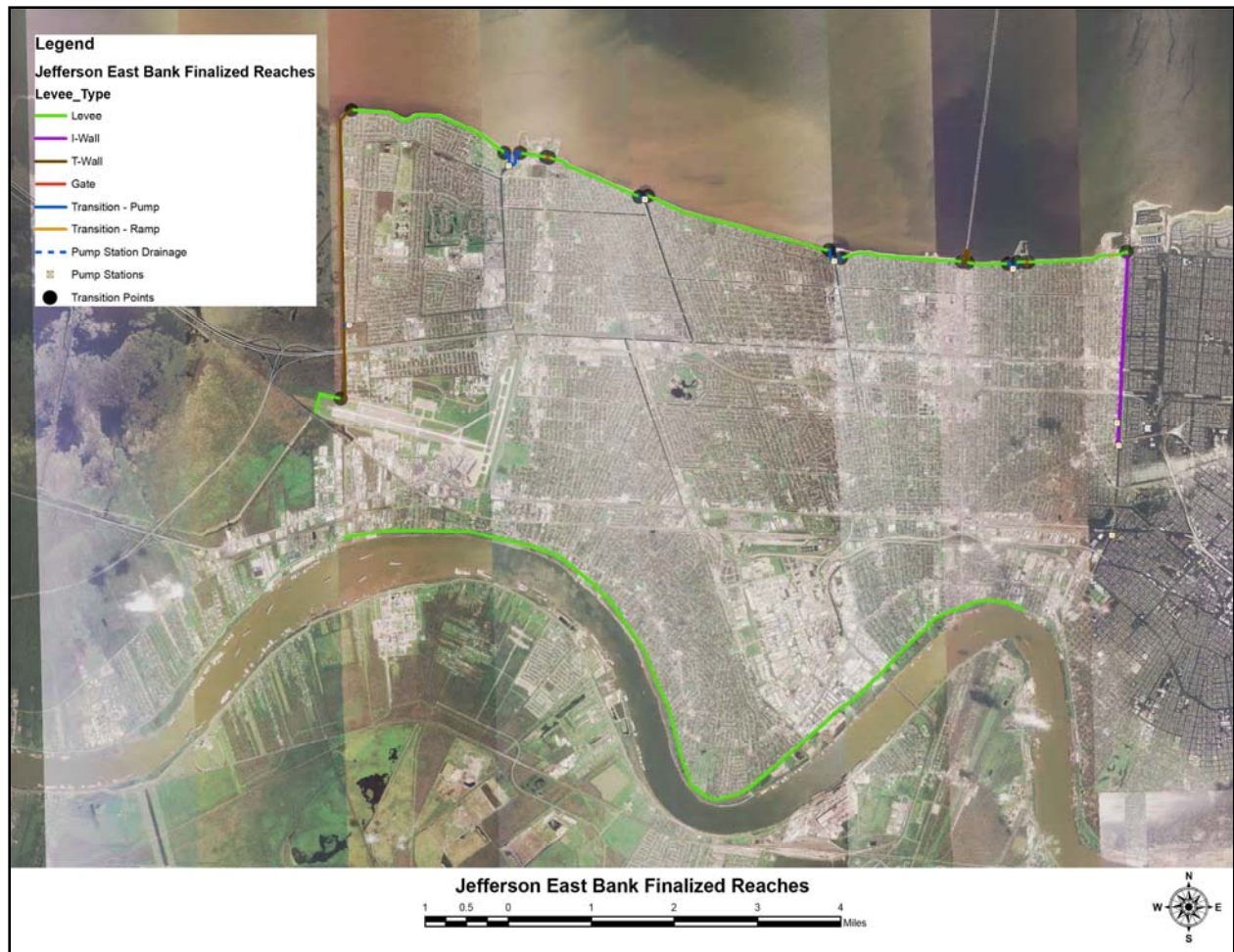


Figure 6-2. Jefferson East Bank.

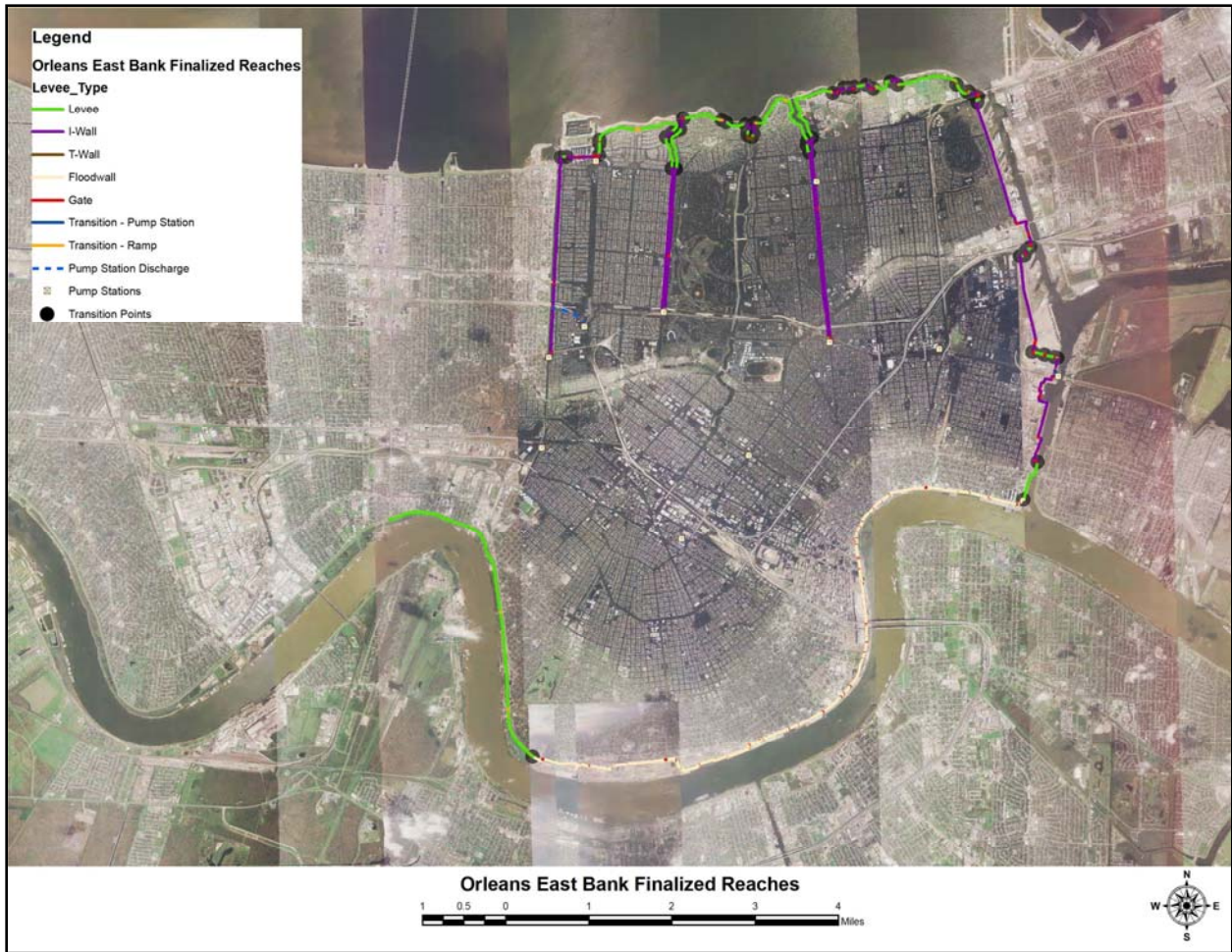


Figure 6-3. Orleans East Bank.



Figure 6-4. New Orleans East.

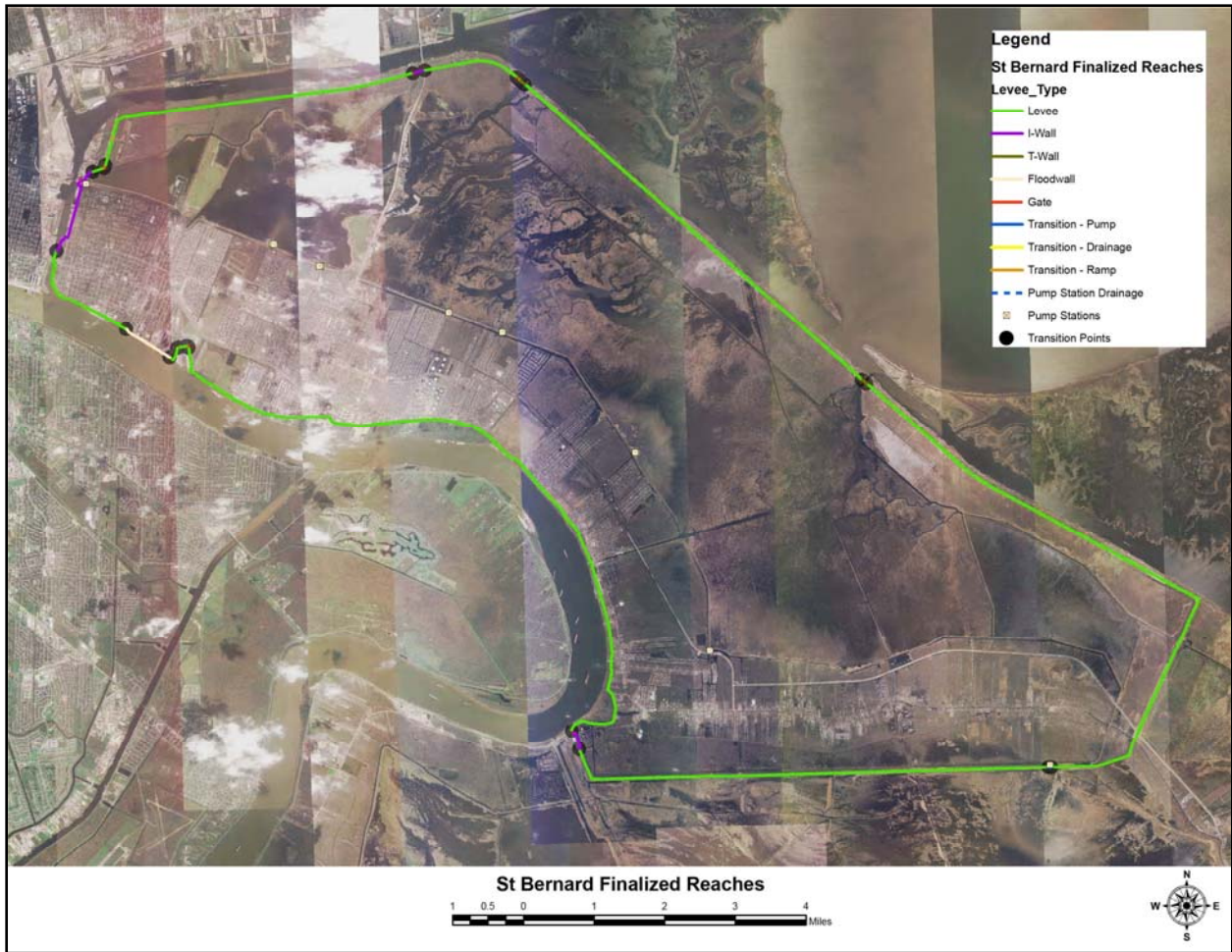


Figure 6-5. St. Bernard.

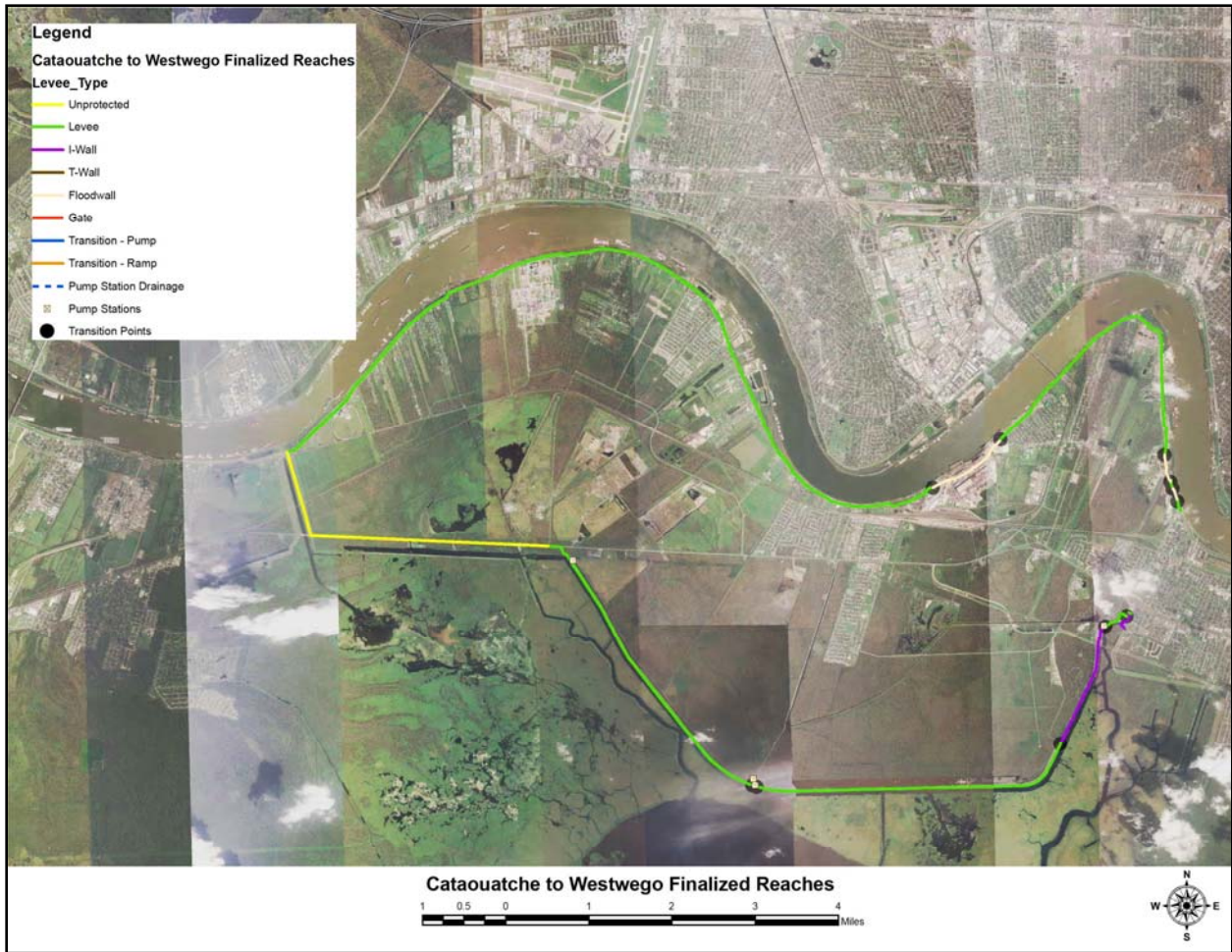


Figure 6-6. Westwego to Harvey Canal.

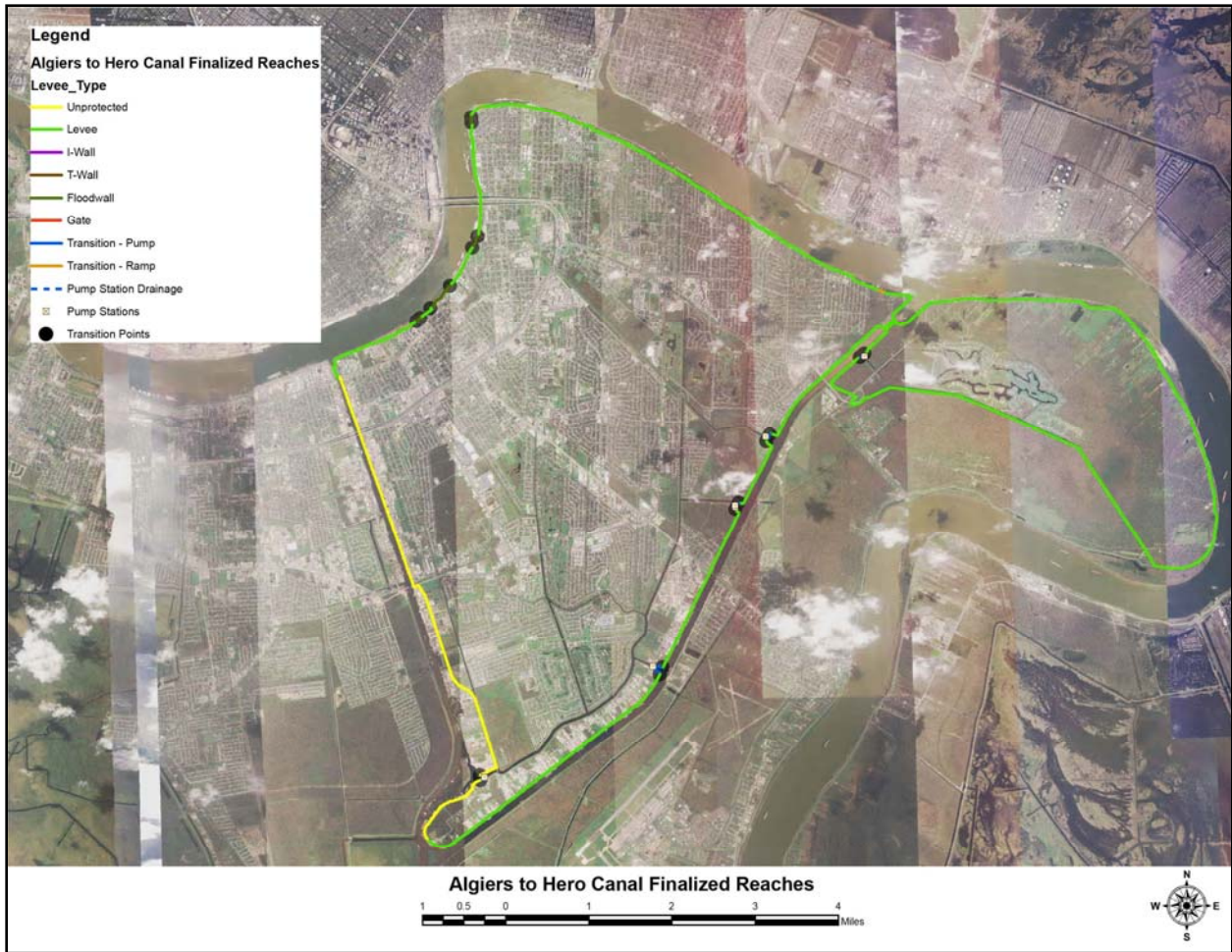


Figure 6-7. Algiers to Hero Canal.

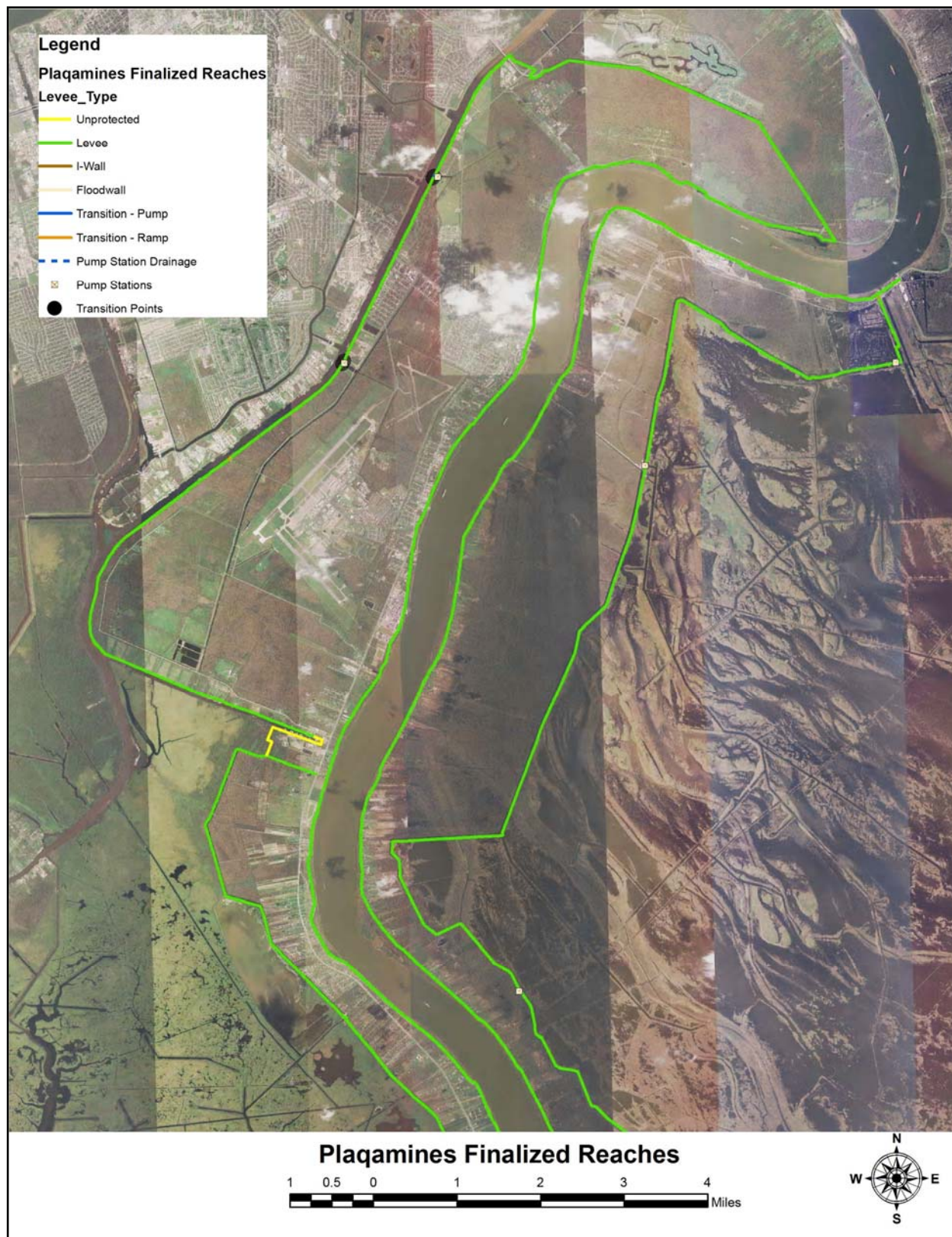


Figure 6-8. Plaquemines 1.

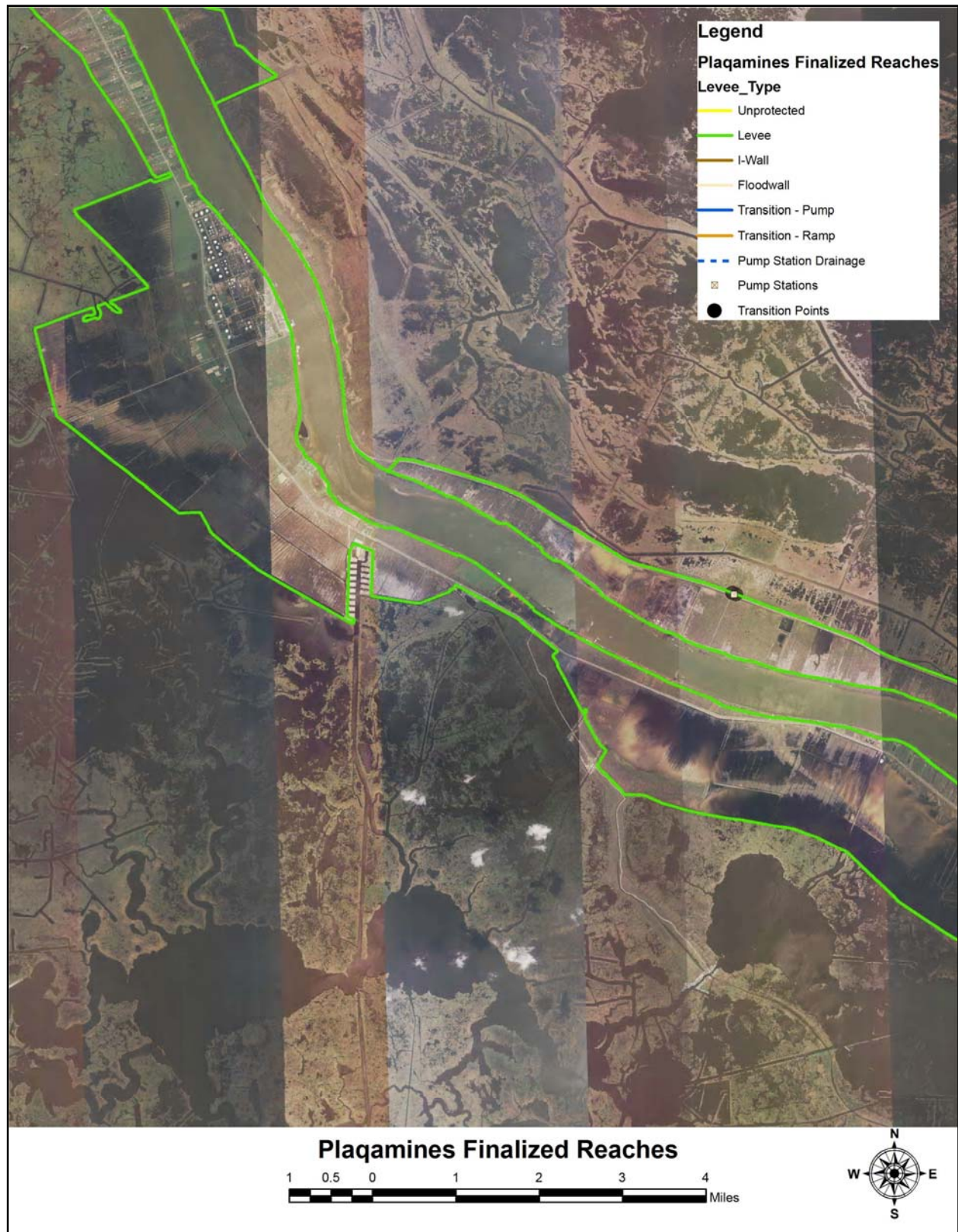


Figure 6-9. Plaquemines 2.

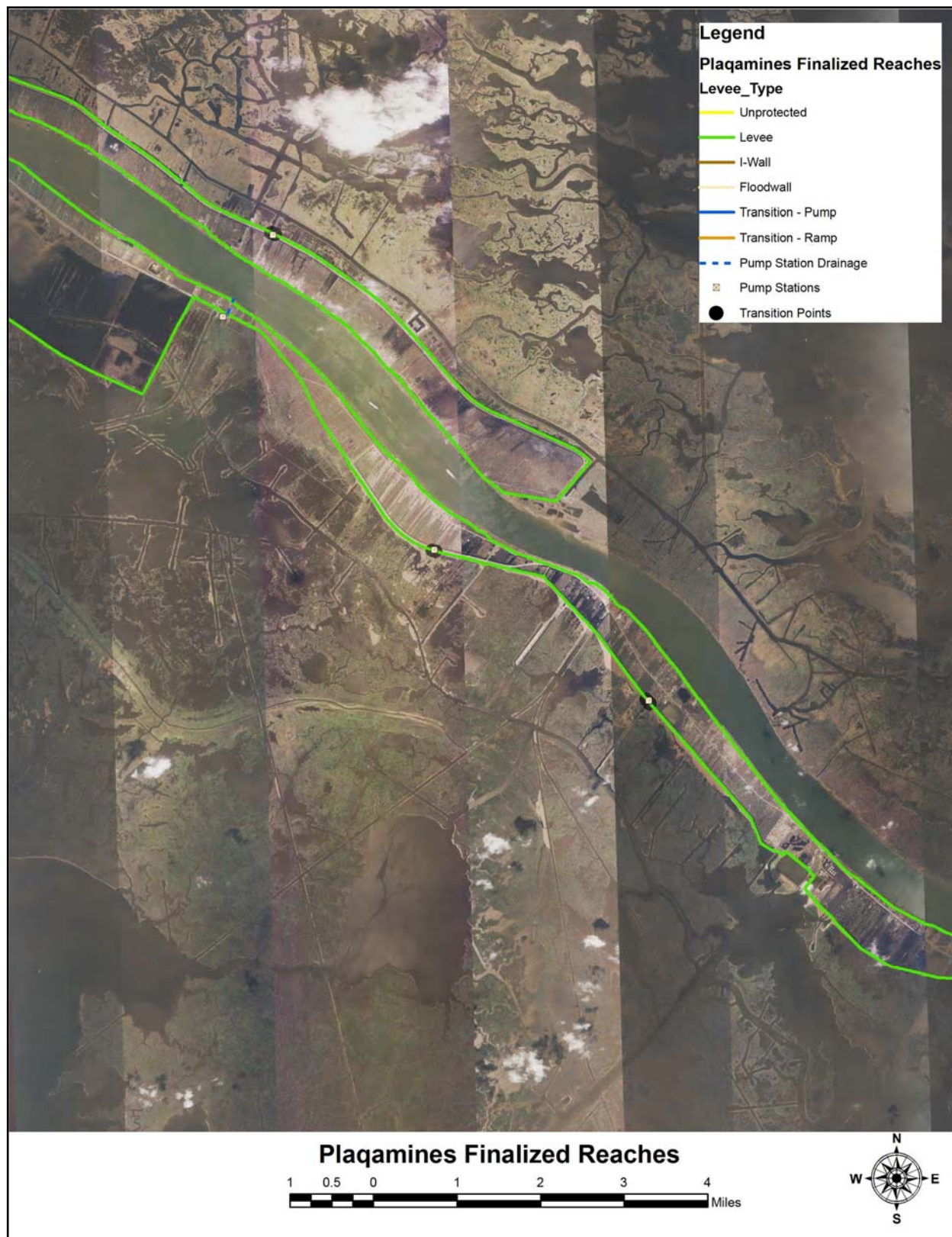


Figure 6-10. Plaquemines 3.

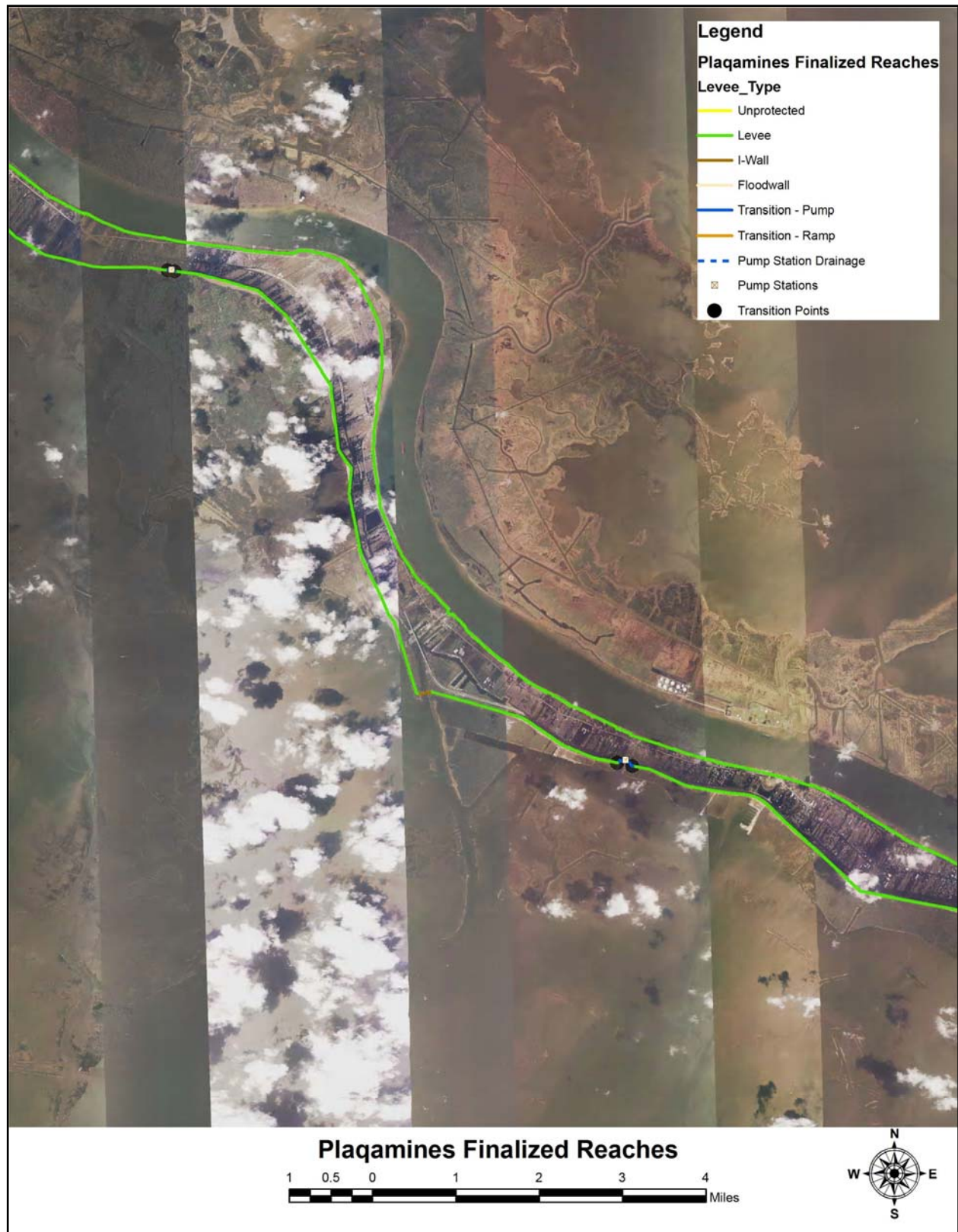


Figure 6-11. Plaquemines 4.



Figure 6-12. Plaquemines 5.

Appendix 7

Post-Katrina Hurricane Protection System Elevations Relative to Authorized Elevations

The maps below were adapted from information provided by the New Orleans District. They represent a component of a post-Katrina assessment of levee and floodwall conditions to determine actions necessary for strengthening the structures for future hurricane seasons. Criteria for the review and survey were provided by IPET based on analyses of sites that breached and comparable sites and structures that did not breach.

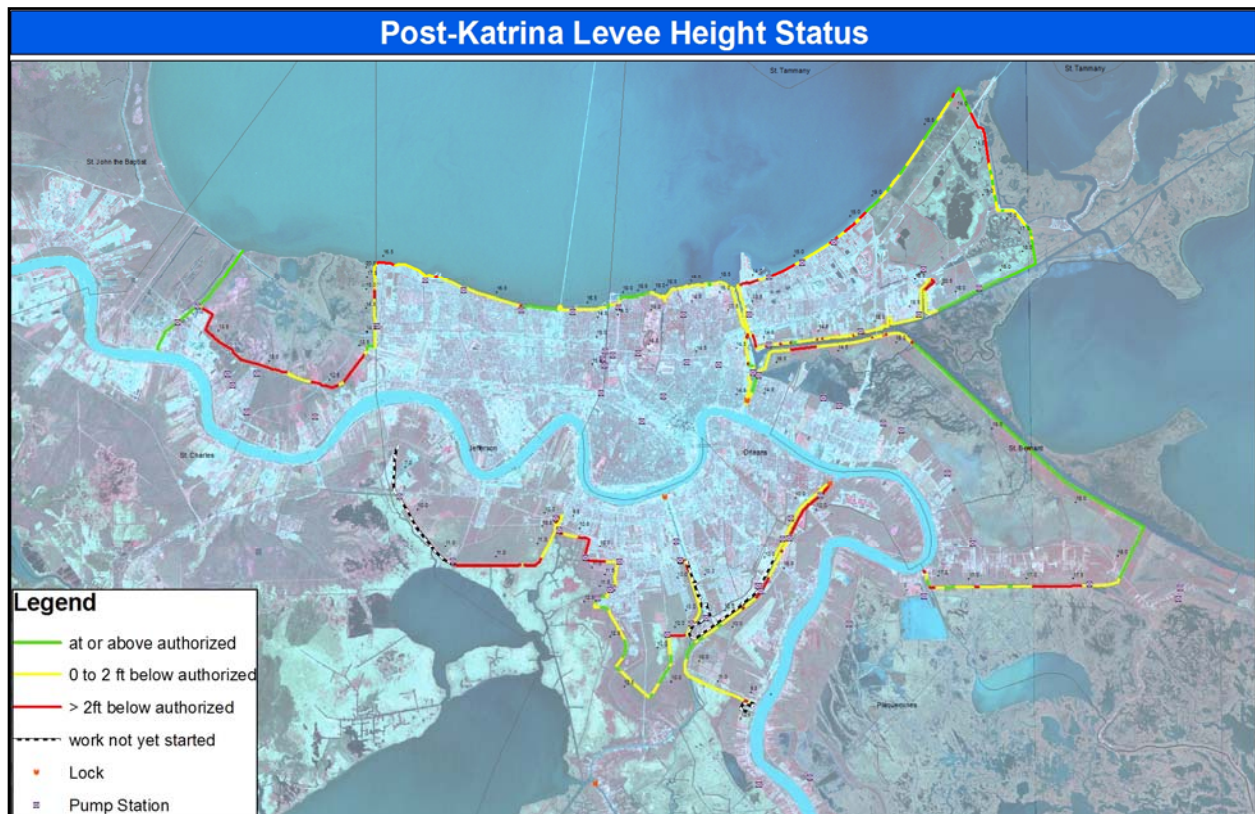


Figure 7-1. Comparison of repaired structure elevations (post-Katrina) to authorized elevations for northern portion of the hurricane protection system. (Source, New Orleans District.)

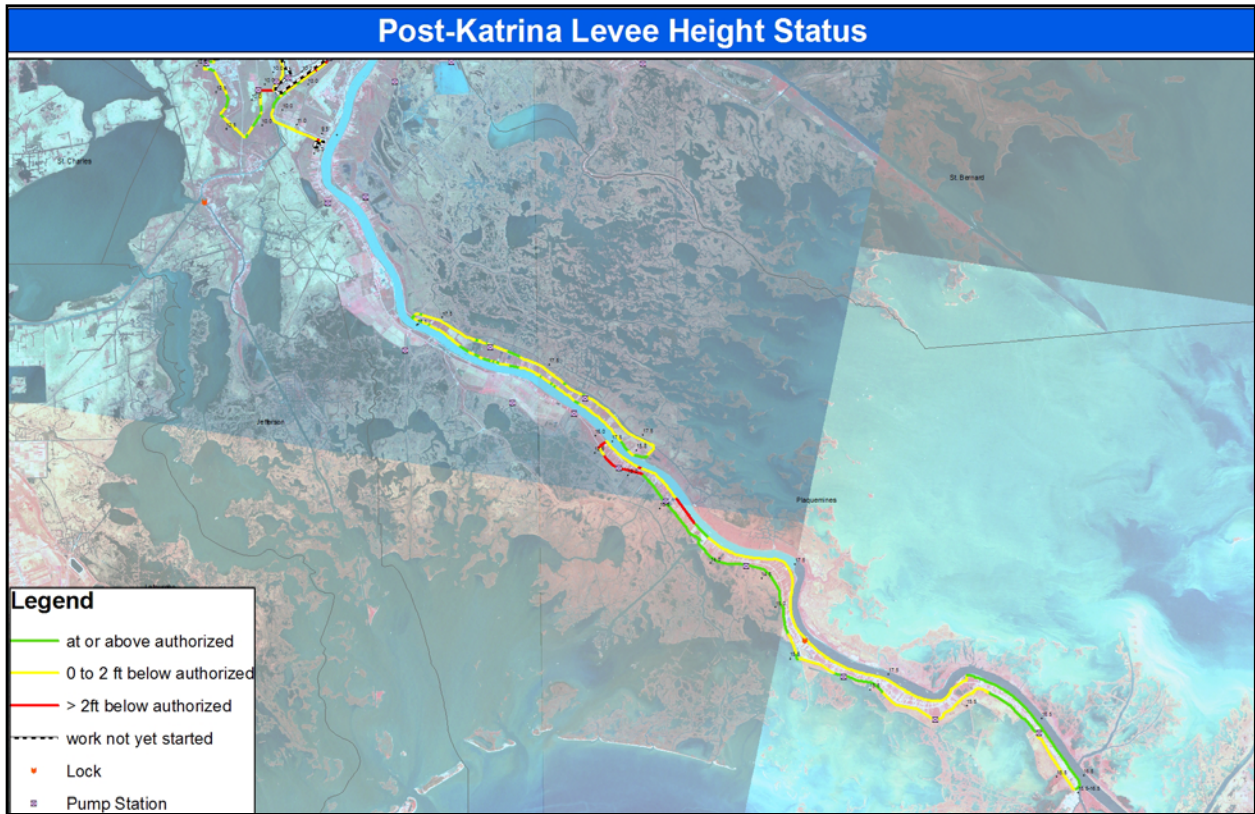


Figure 7-2. Comparison of repaired structure elevations (post-Katrina) to authorized elevations for the southern portions of the hurricane protection system. (Source, New Orleans District.)

Appendix 8

Maps and Associated Descriptions of Breach Sites

The maps below show the distribution of the major breach sites that resulted from Hurricane Katrina. Table 8-1 describes each major breach site and the general character of the repairs planned for the site and its vicinity. There are less than 50 sites depicted here since some of the original individual sites were combined for purposes of contracting for their repair.



Figure 8-1. Distribution of breaches, Orleans East Bank.



Figure 8-2. Distribution of breaches, New Orleans East.

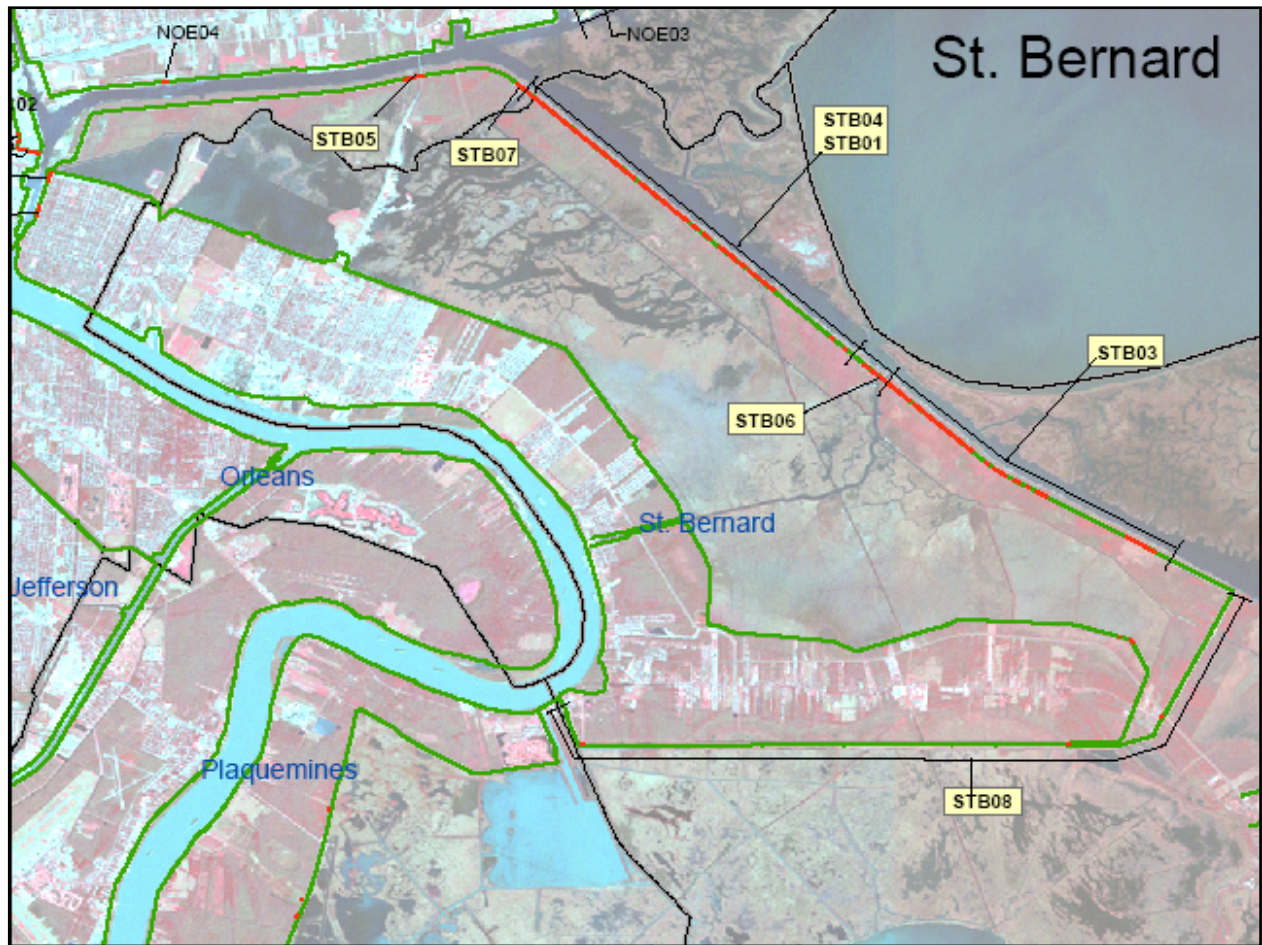


Figure 8-3. Distribution of breaches, St. Bernard.

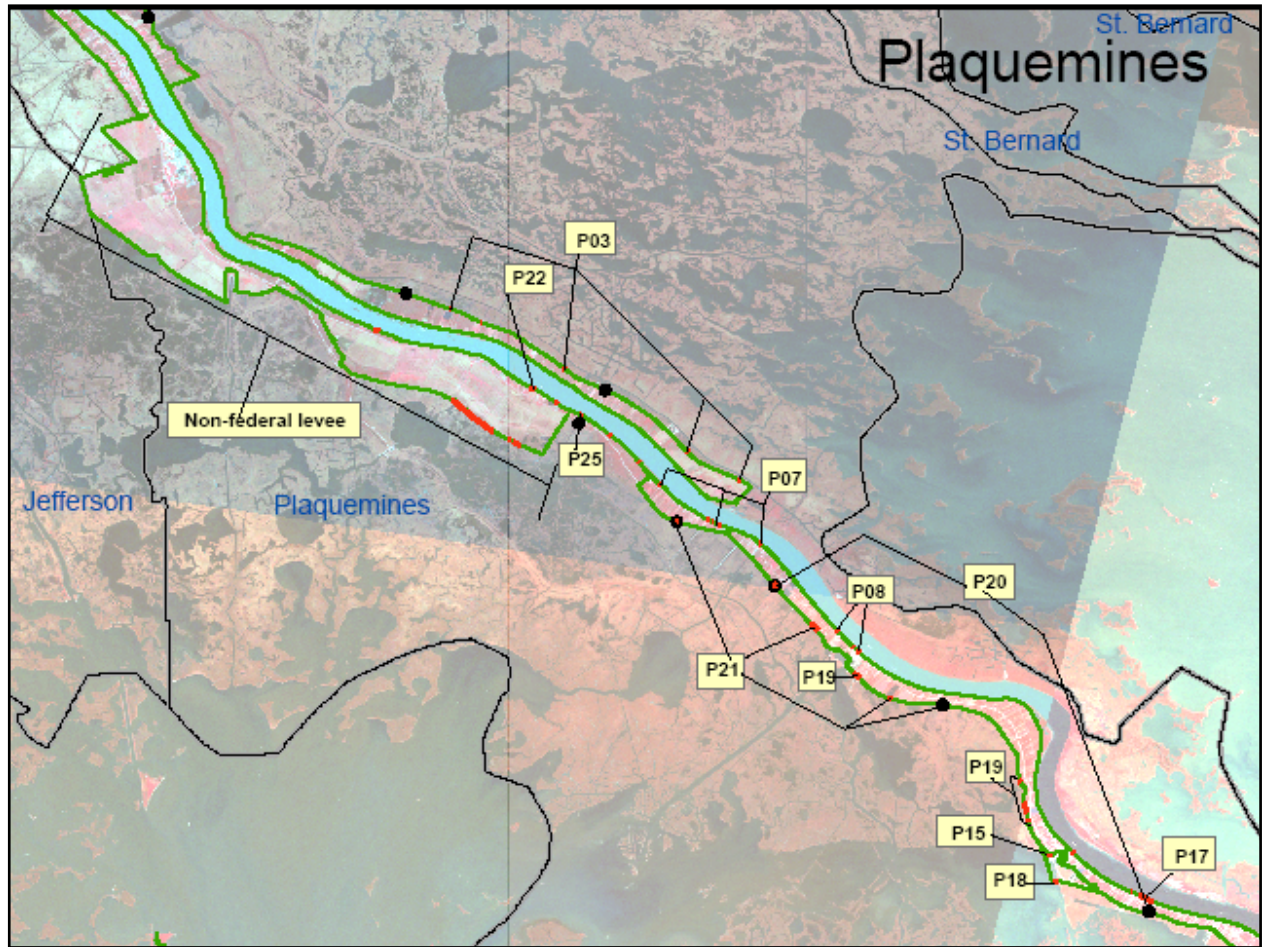


Figure 8-4. Distribution of breaches, Plaquemines.

**Table 8-1
Character of Breach Sites and General Repairs**

Breach/Project ID	Breach Location Description	Damage Description	Repair Description
IHNC01	East Side N. Claiborne Ave to Florida Ave	There are approximately 4,000 lineal ft of concrete I-wall flood barrier. Damages consisted of a breach of the floodwall immediately south of Florida Ave (250') and a breach approximately 100 yds north of Claiborne Ave (850') with the remaining portions of the floodwall having areas of severe scour and tilting of the I-wall.	Repair work includes replacement of the concrete I-wall with a concrete T-wall, supported on H-piles and sheet piling.
IHNC02	West Side France Rd ramp to Benefit St	This section consists of concrete I-wall. The damage in this area consisted of a breach of the floodwall at the container terminal along France Rd. There was also heavy scour of the floodwall.	Repair work consists of removing approximately 1,300 lineal ft of the damaged concrete I-wall and replacing it with new concrete L-wall, supported by steel H-piles and longer steel sheet piles.
IHNC05	West Side Vicinity France Rd ramp to IHNC	This section consists of approximately 1,600 ft of existing levee and concrete floodwall that was breached and experienced severe scour.	Repair work consists of replacement with a new concrete T-wall.
IHNC07	East Side, Lock to Claiborne	Approximately 1,400 lineal ft of concrete I-wall flood barrier was damaged by scour.	Repair work consists of scour repair.
NOE01	Back Levee, Michoud Levee to CSX RR	Approximately 4.3 miles of levee experienced severe scour.	Repair consists of rebuilding the existing levee back to its constructed grade with 680,000 cu yd of earthen material, seeding and fertilizing
NOE02	Pump Station No. 15	The existing steel sheet-pile wall was severely damaged and the levee experienced severe scour.	Repair work consists of removing the damaged steel sheet pile wall, installing a new concrete T-wall, filling in scour holes and bringing the damaged levee back up to pre-Katrina elevation.
NOE03	Air Products Site	The existing concrete I-wall and steel sheet-pile wall were severely damaged and the levee experienced severe scour.	Repair work consists of removing the damaged concrete I-wall and steel sheet-pile wall, filling in scour holes, installing a new concrete I-wall, and raising the damaged levee to pre-Katrina elevations, seeding and fertilizing.
NOE04	Citrus Back Levee Floodwall	The existing concrete I-wall was severely damaged and the levee experienced severe scour.	Repair work consists of removing the damaged concrete I-wall sections, filling in the scour holes, regrading the damaged levees, constructing a new concrete wall, and putting in an earthen stability berm on the landside of the wall, seeding and fertilizing.
NOE05	Floodgate at CSX Tracks	The existing concrete wall and railroad closure gate were severely damaged and the levee experienced severe scour.	Repair work consists of removing the existing concrete wall and railroad closure gate, filling the scoured areas, constructing a new closure gate and new concrete T-walls and I-walls, placement of rip rap, concrete slope paving and concrete roadway.

**Table 8-1
Character of Breach Sites and General Repairs**

Breach/Project ID	Breach Location Description	Damage Description	Repair Description
OEB02	17th St. Canal floodwall	Damage to this section consists of a 455-ft breach of the floodwall on the east side of the canal.	Repairs involved replacing 455 ft of reinforced concrete T-wall. The T-wall consists of a reinforced concrete base slab with a reinforced concrete wall extending up to elevation +14.0 ft.
OEB04	London Ave. Canal floodwall at Mirabeau Blvd	Damage to this section consists of a 425-ft breach of the floodwall on the east side of the canal.	Repairs involved replacing 425 ft of reinforced concrete T-wall.
OEB06	London Ave. Canal floodwall at Robert E. Lee	Damage to this section consists of a 720-ft breach of the floodwall on the west side of the canal.	Repairs involved replacing 720 ft of reinforced concrete T-wall.
STB04	MRGO between Bayou Bienvenue and Bayou Dupre Control Structure	Damage to this section consists of a 6.2-mile reach of levee that lost approximately 12 ft of levee elevation. Additionally, a total of 4,300 ft of sheet-pile floodwall was badly damaged.	Repairs include restoring the entire levee reach to the design grade elevation, which requires the placement of an estimated 1,040,000 cubic yards of fill material. Replace sheet-pile walls with 30' sheets.
STB03	MRGO East of Bayou Dupre	Approximately 12 ft of levee elevation was lost in an 8,000 ft section of levee immediately southeast of Bayou Dupre. Approximately 8 ft of levee elevation was lost in a 2,500-ft section of levee southeast of Bayou Dupre. Approximately 700 ft of sheet-pile floodwall was damaged.	The entire levee reach will be restored to the design grade elevation, requiring the placement of an estimated 1,120,000 cubic yards of fill material. The damaged sheet pile floodwall will be replaced.
STB05	Paris Road floodgate	Damage to the closure structure included scour of the structural backfill resulting from overtopping of the closure panels and the impact from a loose barge.	Repair involves filling structural and structural backfill scour adjacent to floodwalls and four closure structures.
STB06	Bayou Dupre Control Structure	Adjacent section of the floodwall failed and the fill around other sections of floodwalls was eroded away due to overtopping. Mechanical and electrical systems were also damaged.	Repair involves repair of floodwall and structural backfill of the control structure, including a significant scour hole to be filled with 17,500 cubic yards of granular backfill and protected with grouted riprap.
STB07	Bayou Bienvenue Control Structure	Damage resulted from a loose barge hitting an adjacent floodwall and the fill around the floodwall eroding due to overtopping. Mechanical and electrical systems were also damaged.	Repair involves repair of floodwall and structural backfill of the control structure, including a significant scour hole to be filled with 28,600 cubic yards of granular backfill and protected with grouted riprap.
STB08	MRGO to Caernarvon Levee	Damage included scour on the backside of the about 10.8 miles of levee.	Repair involves filling the scour areas.
P03	NOV East Bank, Reach C	Damage consisted of approximately 2.6 miles of crown erosion and <500 ft of riverside and landside slope erosion was identified. The back levee sustained a complete breach with associated scour hole. A ground survey shows that the breach was 190 ft wide at the levee centerline and the scour hole extends to -21 NGVD.	Repair involves the entire 16-mile east bank back levees, including clearing and grubbing, excavation, placing semi-compacted fill and armor stone, fertilized, seeding and other incidental work.

**Table 8-1
Character of Breach Sites and General Repairs**

Breach/Project ID	Breach Location Description	Damage Description	Repair Description
P07	MRL Levee, City Price to Port Sulphur	Damage consisted of 0.6 mile of riverside paving block damage and 3.1 miles of minor landside slope erosion.	Repair involves hauling, placing and compacting fill and crushed limestone, fertilizing and seeding.
P08	MRL Levee, Port Sulphur to Fort Jackson	Damage consisted of paving block damage, crown erosion, landside slope erosion, riverside slope erosion, and erosion at the ends of and behind sheet pile and concrete capped hurricane protection walls (2.8 miles).	Slope and crown scour will be repaired.
P15	NOV Empire Flood Gate	The back levee sustained ruinous damage to sheetpile walls in the vicinity of the Empire lock and canal, and to the levee crown on either side of the sheet pile. The Empire flood gate was stuck in the open position during Hurricane Katrina.	Mechanical, electrical, and structural repairs will be made to the Empire Flood Gate.
P17	NOV Enlarged Levees, Buras Area	Hurricane protection floodwalls were damaged	Damaged floodwalls will be replaced.
P18	NOV Back Levee Repair, Reach B-1	Damage consisted of crown and slope scour along an 11-mile reach from Empire to Fort Jackson. Severe damage occurred at places where hard points intersected - at wing walls for Sunrise and Hayes pumping stations, and at a pipeline crossing.	Slope and crown scour will be repaired.
P19	NOV Levee, Above City Price and Reach A	Damage involved crown and slope scour as well as levee breaches at two locations near Nairn. One breach occurred where a pipeline passed thru the embankment, while the other breach occurred where a deep canal lay just inside the levee toe.	Slope and crown scour will be repaired.
P20	NOV West Bank Back Levee Floodwall	Damage involved a levee breach near Hayes Pump station and a breach at the Sunrise Pumping Station. The breach at the Sunrise pumping station destroyed about 200-ft of structural T-wall. The breach was 180 ft wide, 500 ft long and included a 25-30-ft deep scour hole.	T-walls will be replaced and additional sheet-pile wing walls will be constructed at the Hayes Pumping Station.
P21	West Bank Back Levee Repairs	Floodwalls (sheet pile I-walls) were damaged at Freeport, Home Place Marina, Gainard Woods Pump Station, and Diamond Pump Station. The Diamond Pump Station sustained erosion at the ends of the concrete transition wall.	Floodwalls will be repaired
P22	Woodland Emergency Repair	Damage involves a levee breach at Woodland on the west bank of the Miss. River.	The levee will be repaired.
P25	West Pointe a la Hache Siphon Repair	Damage involves a levee breach.	The damaged levee section will be reconstructed, sheet pile cutoff walls will be extended upstream and downstream of the siphon, and the slope pavement on both sides of the crown of the levee will be replaced.