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 I – Executive Summary and Overview

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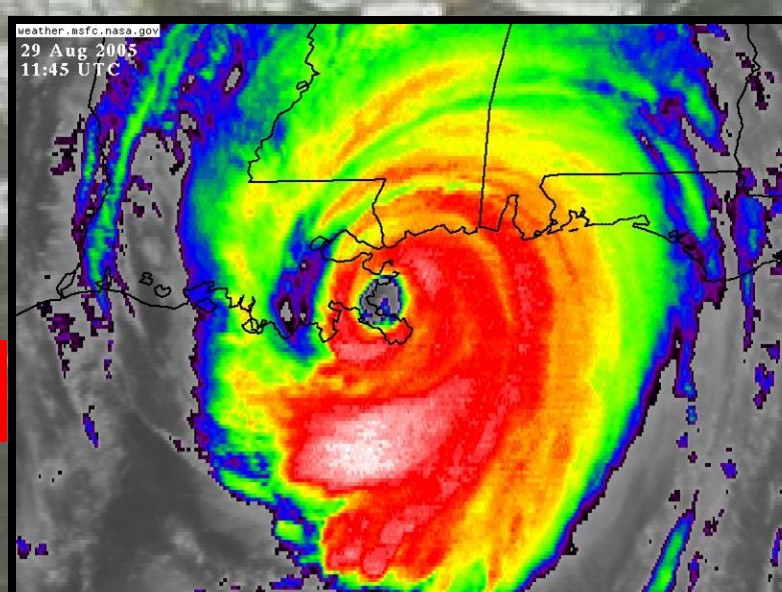

FINAL

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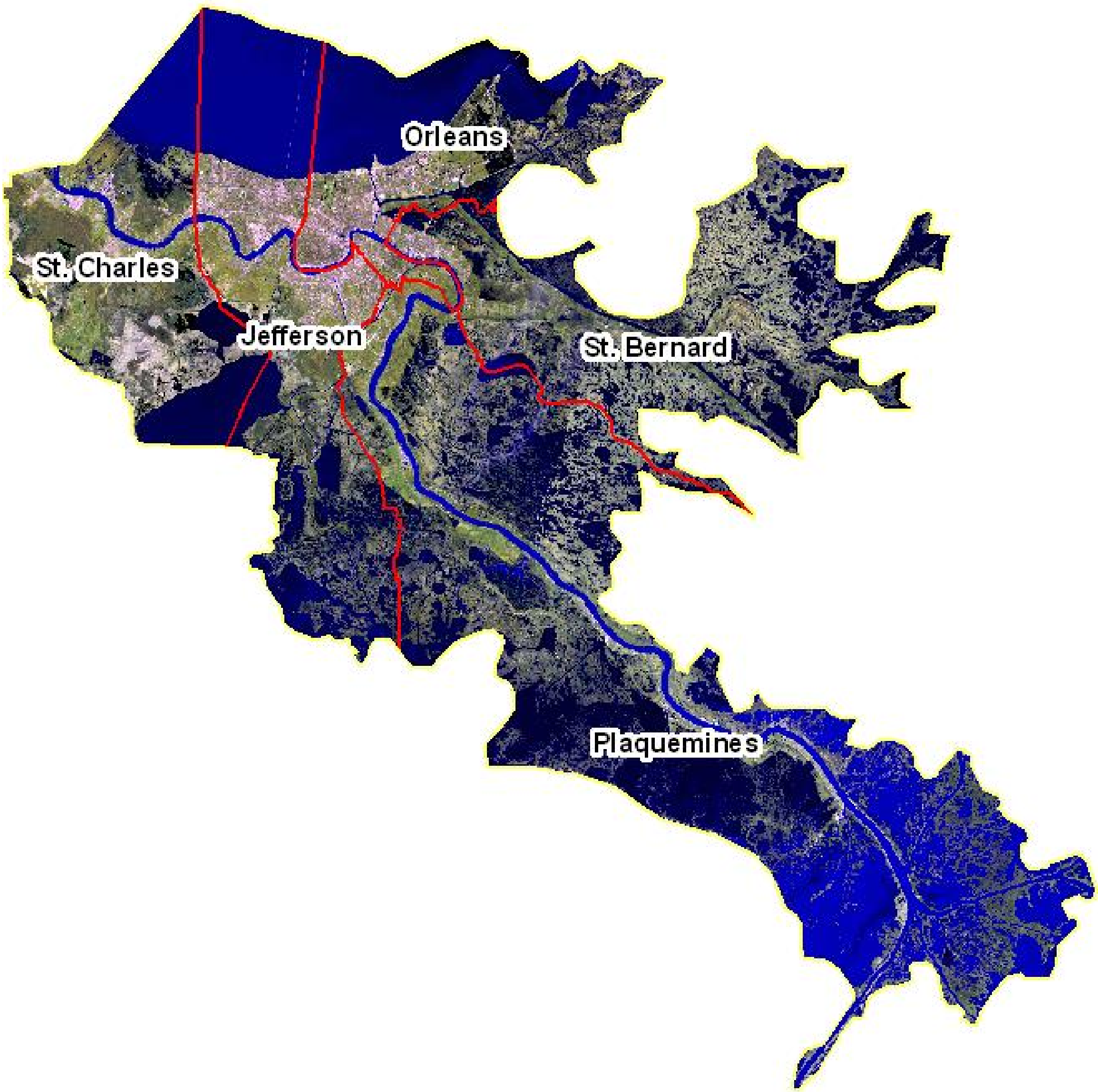
Volume I
Executive Summary and Overview



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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 continuous basis by a distinguished External Review Panel (ERP) 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 to acquire 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 development of effective hurricane risk reduction and management capabilities for their future.

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Executive Summary

Introduction

This report, *Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System*, is the final report of a series concerning the in-depth analysis of the New Orleans and Southeast Louisiana Hurricane Protection System (HPS) 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 HPS 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 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 (including economic, life and safety, environmental, and historical and cultural losses)?

- The Risk: What were the risk and reliability of the HPS prior to Katrina, and what will they be following the planned repairs and improvements (June 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 HPS 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) provides analytical methods and a body of knowledge to assist in planning and designing more effective risk reduction and management measures in the future. The IPET analytical tools and information bases are being transitioned to the Corps of Engineers and other agencies to assist in developing more effective approaches for reducing risk from extreme events.

The nine volumes of the final report provide a detailed documentation of a broad, multi-disciplinary analysis of the HPS 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 (ERP) 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 IPET and its efforts, a synopsis of the performance of the HPS during Katrina, an overview of the risk and reliability assessment and a summary of the principal findings and lessons learned. All are described in more detail in Volumes II–IX. Since the HPS is only designed to manage flooding in the metropolitan New Orleans basin, wind-based consequences and any direct consequences exterior to the HPS are excluded from this report. In addition, IPET did not examine organizational and jurisdictional issues that impacted the effectiveness of the physical hurricane protection system. These issues were examined by a separate team and are reported in "Decision Making Chronology for the Lake Pontchartrain and Vicinity Hurricane Protection Project" authored by Douglas Woolley and Leonard Shabman and published in March of 2008. This report is available on the U.S. Army Corps of Engineers Web page (*http://www.IWR.USACE.army.mil/inside/products/pub/hpdc/hpdc.cfm*).

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 initial 1960s-based design criteria, the Standard Project Hurricane, was redefined during the design and construction phase, but the system component designs were not altered to address those changes. 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 many pump stations around New Orleans were also not an integral part of hurricane protection, focused mainly on removing rain and ground water from the protected areas. The designs of the levee-floodwall structures along the outfall canals were particularly inadequate. A series of incremental decisions, extending 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 (MRGO) 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: Hurricane Katrina resulted in 50 major breaches With the exception of four levee-flood wall foundation design failures, all of the major breaches (a total of 46) were caused by overtopping and subsequent erosion. Protective elevations that were below those required by the design caused an increase in 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 lack of resilience to overtopping significantly increased flooding and resultant losses. The levee-floodwall designs for the 17th Street and London Avenue Outfall Canals and the IHNC were inadequate. 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 pump stations were largely inoperable during Katrina due to lack of resilience in their power supplies and safe havens for operators.

The Consequences: Approximately 80% 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. As of December 2005, the National Hurricane Center reported that there were approximately 1300 fatalities in Louisiana directly related to the forces of Katrina, a significant majority within New Orleans. Over 70% 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% 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, significantly less recovery or reinvestment has taken place.

The Risk: The prototype risk assessment for New Orleans identified the areas most vulnerable to future flooding and with the highest residual risk. **Residual risk is the vulnerability that remains after all risk reduction measures are considered.** As illustrated in Figure 1, the risk reduction can be achieved by a wide variety of measures, some structural and others non-structural. Figure 1 also indicates that regardless of how much you do, there will always be some residual risk remaining. It is most important to quantify and communicate the residual risk. The risk analysis process also was demonstrated to be an effective system-wide tool to examine the value and impact of changes in the protective measures or alternatives for managing risk.

Figure 1. Illustration of residual risk and risk reduction measures. Source: U.S. Army Corps of Engineers.

Given the improvements in the HPS accomplished by June 2007, the residual vulnerability to flooding was reduced significantly in a few areas and moderately in others. Large areas of New Orleans and Southeast Louisiana remain very vulnerable to flooding from large hurricanes. The areas gaining the most benefit were those whose primary source of vulnerability was the outfall canals. The relative levels of risk for loss of life and property remain closely associated with the property values and population densities in the sub-basins and the land elevation (potential for deep flooding). The areas in proximity to the IHNC, where reinforced 2007 HPS structures have a reduced likelihood to catastrophically breach, remain very vulnerable to flooding by overtopping. Similarly, the West Bank (region of New Orleans to the west and south of the Mississippi River), where significant reaches existed in 2007 without completed HPS structures, remains highly vulnerable to flooding.

Risk remains significant for the 2% or the 50-year return period flood; however, it is primarily due to rainfall, not hurricane surge and wave conditions. Pumping can have a substantial impact at this level to reduce flood depths in most areas; however, the impact of pumping is highly dependent on the efficiency of the drainage system and the operational reliability of the pumping stations. While the IPET analysis includes the contribution of rainfall associated with hurricanes to the overall volume of floodwaters, it does not account for non-hurricane rainfall events which may generate greater volumes of rain water than many hurricanes.

Given the status of the HPS in 2007, all of New Orleans and Southeast Louisiana remains highly vulnerable to catastrophic flooding for flood events that are in the neighborhood of 0.2% or the 500-year return period. The general risk in New Orleans can be placed in context using the classical risk chart in Figure 2. This graphic plots frequency of occurrence against number of fatalities. The blue line represents international guidelines for existing dams. The red line represents residual risk in New Orleans prior to Katrina and the green lines represent residual risk in 2007. The bottom line is that while improving, residual risk is still very high and much work needs to be done to improve the situation. This chart should not be interpreted as a recommendation for applying to levees the risk guidelines for dams. There presently are no guidelines for levees.

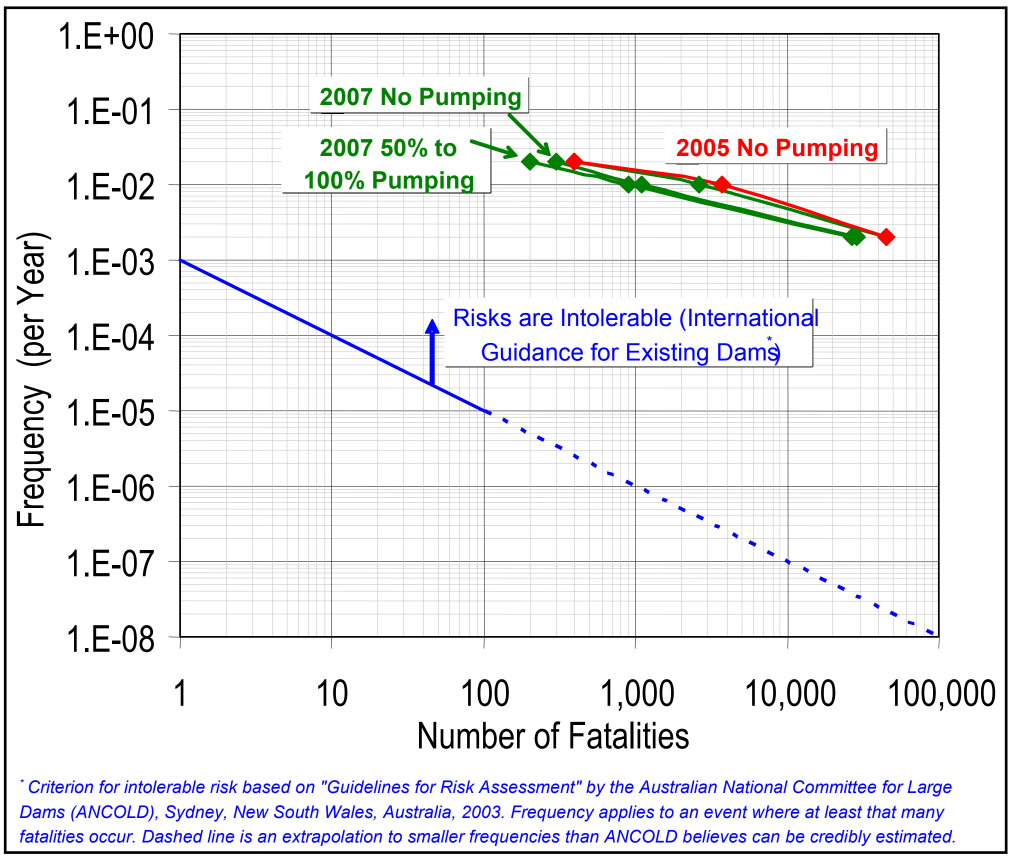

Figure 2. Frequency-Fatality relationship for New Orleans based on IPET estimates of expected loss of life. (Source: ASCE External Review Panel)

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. They should also allow examination of what is considered a system at one scale as a component of a larger, regional system. 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 HPS, 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. With rapid changes in 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; Katrina 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%) 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 HPS 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, at least half of the direct losses may have been averted if catastrophic breaching had not occurred. This reduction in direct losses would likely have dramatically reduced the indirect consequences of the event as well. Together, this may have enabled a more rapid and systematic recovery. Resilience in the HPS would have provided that advantage. It is also clear that emergency response planning must focus more attention on providing necessary assistance to those unable to self-evacuate.

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 redevelopment 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 of 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 physical structures and reducing exposure of people and property to losses by non-structural means. 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. This is especially important for those who need assistance to evacuate.

Communicating risk is a difficult task that can only be achieved though a spectrum of coordinated efforts. Key among these efforts is having relatively simple graphical representations of the vulnerability to flooding and risk. Also essential is repeated direct person to person contact with constituents. Since risk is a broadly used term, the development of a common understanding of the content and context of the information available and its appropriate (and inappropriate) uses are essential to effective communication and application of the risk information. Assistance of local and national media, as well as the Internet, is an essential component to make the information available to the broadest possible audience. The risk information is a powerful means to create a common understanding of a situation and the relative benefits of alternative approaches to manage or reduce risk.

Quantitative estimates of vulnerability to flooding and potential losses (risk) are a powerful tool to convey situational awareness to the public and to provide a common picture to stakeholders at all levels. It allows the public to make individual decisions that are within their purview, provides more knowledgeable input to dialogue with public officials, and facilitates more focused discussions and collaboration among government agencies at all levels. Understanding life-safety and economic loss potentials also provides a more comprehensive and system-wide body of knowledge to evaluate alternative approaches for managing risk.

Looking Forward

The IPET findings and lessons learned are based on the experience of a past event, Katrina, but they are also an important lens into the future. The following are strategic messages from Katrina that need to be considered in policy and practice immediately.

STRATEGY: First and foremost, the United States lacks a coherent and comprehensive strategy for water resources. Levels of protection are marginal with respect to levels of risk and investments too often are local in scope, short-term in nature, cost-benefit based, and focus on taming rather than working with natural processes. Integrating risk reduction with other critical functions such as water quality, sustainability and commerce remain an idealistic goal. It is time for a new national emphasis on holistic water policy where public safety is a mandatory component.

SYSTEMS: The hurricane protection measures in New Orleans were clearly overwhelmed by a major and rare event, but they were also below current standards in their performance. The system in place before Katrina was compromised by a long series of decisions driven by competing priorities, incremental decision making and funding, inadequate consideration of change and de-facto standards far too low to deal with the realities of modern natural hazards. The HPS could not and did not perform as a system because of these and other factors. If risk reduction measures are to be put in place they must be designed, constructed, and maintained as systems. The promise or perception of a system when it does not exist is perhaps more dangerous than no system at all.

STANDARDS: As a nation we lack clear standards for planning, design, and development of major public infrastructure for water resources. New knowledge is often too slow to be incorporated into engineering guidance, and we too often optimize based on immediate cost and accept short-term gains instead of long-term solutions. This is a national cultural malady that can only be reversed if the public demands a change in policy. Life-cycle solutions are important to our future, and we can only get there through the election cycle. The 100-year de-facto standard is far too risky for the continued vitality of our economy that is highly dependent on the viability of the public infrastructure and the continuity of the economy. The nation must go to more comprehensive risk-based standards that provide longer term solutions that combine benefits of both built and natural measures.

SUSTAINABILITY: Man-made measures alone can not sufficiently reduce risk for vulnerable areas such as New Orleans. Natural processes and attributes such as marshes, mangroves, and barrier islands need to be integral to a systems strategy for risk reduction. In combination with traditional structures and aggressive emergency management planning and execution, an enhanced natural environment would be a major component to a sustainable and effective long-term strategy to deal with the dynamics of climate, demographics, and social and economic well-being.

RESILIENCE: Of the performance of the HPS, beyond the failure of the four I-wall sections, it was the lack of resilience that stands out as a major factor in the ultimate flooding and losses. If no catastrophic breaching had occurred, the flooding and losses would have been significantly reduced, perhaps by half. Structures must be designed to withstand overtopping and to prevent catastrophic breaching. Such capability would not only have dramatically reduced the losses in New Orleans but also dramatically eased the burdens of unwatering and subsequent recovery.

RESPONSIBILITY: Risk is increasing significantly along the nation's coastlines, in part because natural hazards such as hurricanes appear to be more severe, but even more so because increasing numbers of people and property are being allowed to reside in harm's way. There is little that governments or individuals can do about the changing hazard, but there is much that can be done to manage risk by reducing exposure to the hazard. For populated flood-prone areas, compartmentalization of basins, raising first floor elevations, and flood-proofing structures can reduce exposure to losses. The simplest approach in principle is managing land use to avoid placing more people and property in areas vulnerable to hazards. While simple in principle, the dichotomy of land-use authorities between levels of government, lack of adequate standards, and the dependence on continued development has made this the correct path seldom taken. Many individuals are drawn into this web by ignorance or lack of clear information, an issue that must be addressed by all public officials.

RISK: Understanding risk is a powerful tool in helping both individuals and government agencies to make consistent and conscientious decisions concerning natural hazard risk management. The ability to quantify risk for large geographical areas and complex engineered systems is just emerging through the work in New Orleans and central California. Risk provides a much richer body of knowledge to understand and manage vulnerability to hazards as well as providing a clear common picture of the situation to all. Risk methods for regional infrastructure, if fully developed, will not only allow assessment of multiple hazards, but also allow collective consideration of life safety, direct and indirect economics and social-cultural issues, enabling customization of solutions to situations. But the evolution and application of risk to support decision making must be enabled by policy which currently does not exist. We have yet to demonstrate the public and the political will to adopt these more rigorous guidelines for risk management and mitigation.

RESEARCH: There is much more to learn. If we as a nation hope to manage risk from the most severe hazards, we need to learn how to work with rather than control nature. Research is needed to better define the actual role of natural environments in managing surge and waves;

rules of thumb are just too inaccurate. Given the challenges of continued sea level rise and subsidence and the potential for more intense storms, the art of building and sustaining natural environment is especially important. The vulnerability of natural features to large storms is a particular challenge if we are to rely on them for long-term risk reduction. The fact that there are not enough high quality natural materials to build traditional structures demands that we seek innovative alternatives. The ability to routinely monitor conditions and residual risk on a system-wide and regional basis will require much more effective sensing and analysis, particularly concerning geotechnical issues.

CHANGE: Our current policy and practice does not deal well with change. We must be more anticipatory and adaptive as changes occur in the hazard, the system or the potential consequences. All of these factors changed dramatically over the life of the hurricane protection projects in New Orleans with little capability for appropriate response. This is another symptom of short term rather than long term sustainable strategies, policies and practices for addressing a major life-safety need.

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 (including 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 and reduce risk in the future. 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 other studies such as 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 (ERP) 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 10 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 a 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 was 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 were 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, the improved information was used to drive another cycle of analysis and generate more refined results. 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 HPS, 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 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. Their fist task was to review the initial tasking from LTG Strock to the IPET and the initial IPET plan to accomplish that tasking. Beyond that, 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 joint meeting was held in February 2008 to review changes made to the IPET report in response to ERP recommendations, prior to the publication of the final versions of Volumes II through VII and the interim final of Volume I. Additional meetings have been held with subsets of the ERP to discuss and review the risk assessment work reported in Volume VIII.

The IPET-ERP 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 final feedback on the risk assessment in September 2008. These reports are available on the ASCE Web page (*www.asce.org*) as well as the IPET Web page (*https://ipet.wes.army.mil*). 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 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 December 2007. An additional meeting was held in Washington, DC, in January 2007, prior to the publication of the final versions of Volumes II through VII. A final meeting was held on 4 September 2008 to review the IPET risk assessment work prior to the publication of the final versions of Volumes I and VIII. IPET principals made formal presentations to the Committee at these meetings and engaged 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 provided four formal interim reports to the Assistant Secretary of the Army on the progress of their review. A final NRC report was released on April 24, 2009. 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 three major reports. The DRAFT final IPET 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 NRC 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 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.

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. After release of the draft final report in June 2006, IPET received additional comments and suggestions from both ERP and the NRC Committee. These recommendations resulted in additional analyses, re-examination of previous work and evaluation of the work accomplished by others to ensure that the IPET findings and lessons learned had the benefit of all information available. The results of this additional work were incorporated into the final versions of Volumes II to VII that were published in the spring of 2007. An interim final version of Volume I was also published at that time, lacking the results of the then ongoing risk assessment. A more comprehensive draft of Volume VIII, documenting the risk assessment, was prepared and released along with an updated draft of Volume I in June 2008. The final versions of these Volumes, which include an analysis of the uncertainty of the risk assessment methodology, were released June 2009. 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, including airborne LIDAR, have been corrected to the geodetic datum and have been made 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.

V**olume 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/or 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 is 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 Rensselaer Polytechnic Institute (RPI) and the U.S. Army Engineer Research and Development Center (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 HPS 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% 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%.

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

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

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

The consequence information generated by IPET was a direct input to the risk and reliability assessment and is being transferred to the Corps for application in other studies and analysis.

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 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 sub-basins and protected areas, the approach for estimating potential losses as a result of flooding as well as the risk model itself. It also presents detailed results of these analyses and the findings and lessons learned from the analysis.

The results are provided in three major forms. First the vulnerability to flooding is presented as inundation frequency depth estimates displayed as maps. The inundation depth maps show the mean depth of flooding that could occur or be exceeded at three specific exceedance frequencies (2%, 1%, and 0.2%) or return periods (50-, 100-, and 500-year). The flood depth information is provided at the highest level of resolution available with respect to the local topography. Risk is provided in terms of both mean values of expected loss of life and property losses at the specific exceedance frequencies (2%, 1%, and 0.2%) or return periods (50-, 100-, and 500-year). The loss of life and property loss risk maps show relative risk levels at the sub-basin level. In addition to being available within the IPET report and IPET web site, the risk maps have been made available in a limited interactive mode through Google Earth and in a more complete interactive mode through Microsoft Virtual Earth. The initial versions of the inundation depth maps (East Bank only) were first provided to the public in June 2007. Maps including the West Bank areas were published in July 2007, and maps showing the impact of pumping were published in March 2008.

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.

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 could 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 (2007), and the third represented the projected 100-year certified structures planned for the future. Only the pre-Katrina and 2007 scenarios are reported in the IPET report.

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 plus 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 sub-basin, 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 sub-basin prior to Katrina to those after repairs and upgrades were complete (June 2007).

This work offers the opportunity to examine risk at the census block level or aggregated to sub-basins, 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 that were incorporated in the 2007 HPS analysis included armoring existing structures, elevating levees, and use of erosion-resistant materials, stability berms, and relief wells. More sophisticated approaches included replacing I-walls with T-walls and adding surge gates and pumping stations at the ends of the outfall canals.

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.

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 3 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.

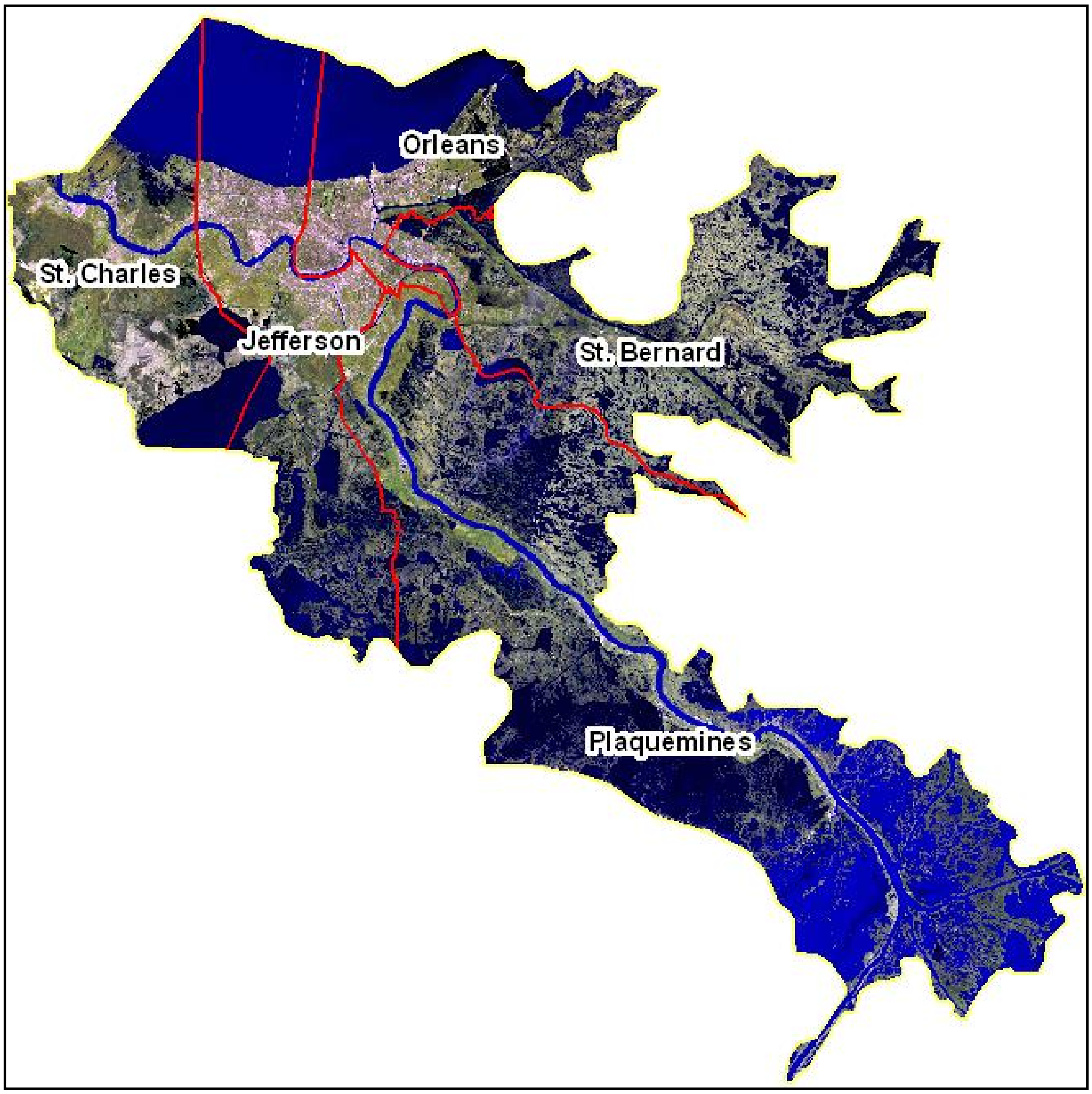

Figure 3. Principal area of analysis.

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 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 many channels that evolved for distributing water and sediment 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 IHNC 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 lakefront, 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 influenced 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 20th 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 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 the area's natural alluvial floodplain geology. The subsidence increases the flood risk, should the levees be breached or precipitation exceeds 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. Until Katrina, 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 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 when Katrina hit.

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% 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 at landfall 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% of the costs and the state and local interests paying 30%. The local interests included the State of Louisiana Department of Transportation and Development, the 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 lakefront, 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 lakefront. A number of project delays and cost increases occurred as a result of technical issues, environmental concerns, legal challenges, and local opposition to various aspects of the project.

A December 1977 court decision enjoined the Corps from constructing the barrier complexes and certain other parts of the project until a revised environmental impact statement was prepared and accepted. The Corps conducted a "Re-Evaluation Study," published in 1984, in response to the court order and examined the feasibility of providing protection mostly by means of raising and strengthening levees and floodwalls. The 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 (No. 4) and 17th Street (No. 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% complete in Orleans Parish, 70% complete in Jefferson Parish, 90% complete in the Chalmette area, and 60% 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 (see “Decision Making Chronology for the Lake Pontchartrain and Vicinity Hurricane Protection Project” authored by Douglas Woolley and Leonard Shabman and published in March 2008. This report is available from the Institute for Water Resources (*http://www.IWR.usace.army.mil*).

The System (Volumes II and III)

The HPS, outlined on the map in Figure 4, 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 5 provides a schematic of the basic geometry of these structures. Figure 6 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 6.

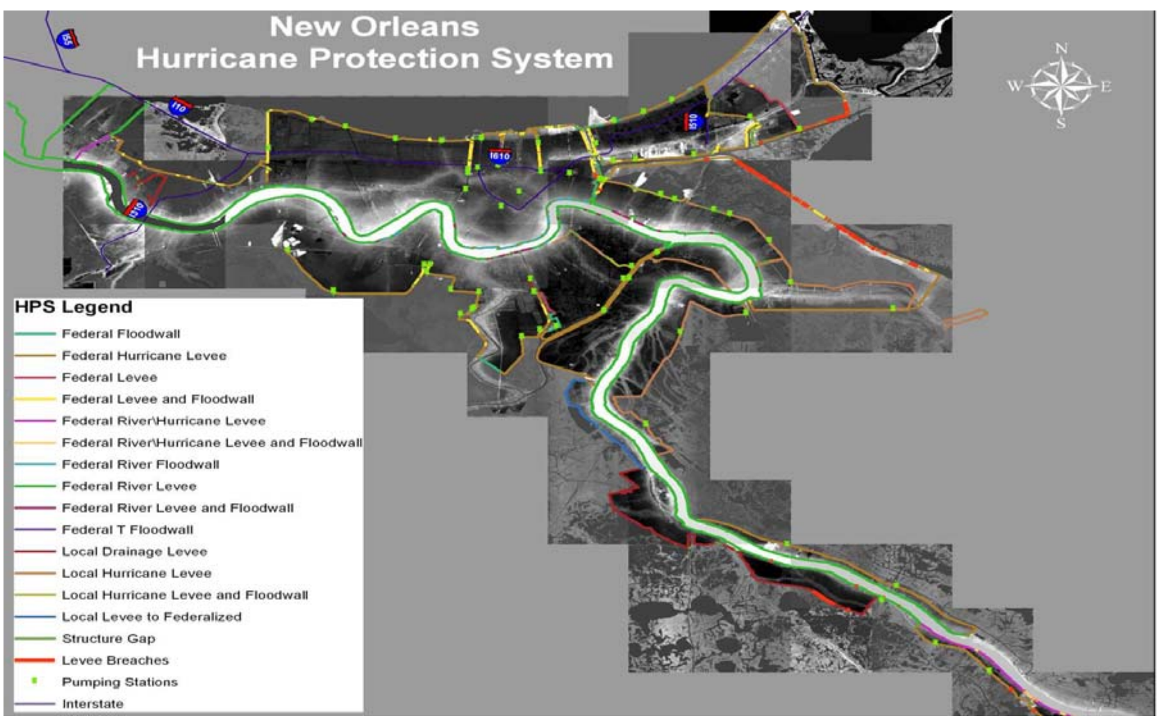

Figure 4. Outline of the New Orleans and Southeast Louisiana Hurricane Protection System.

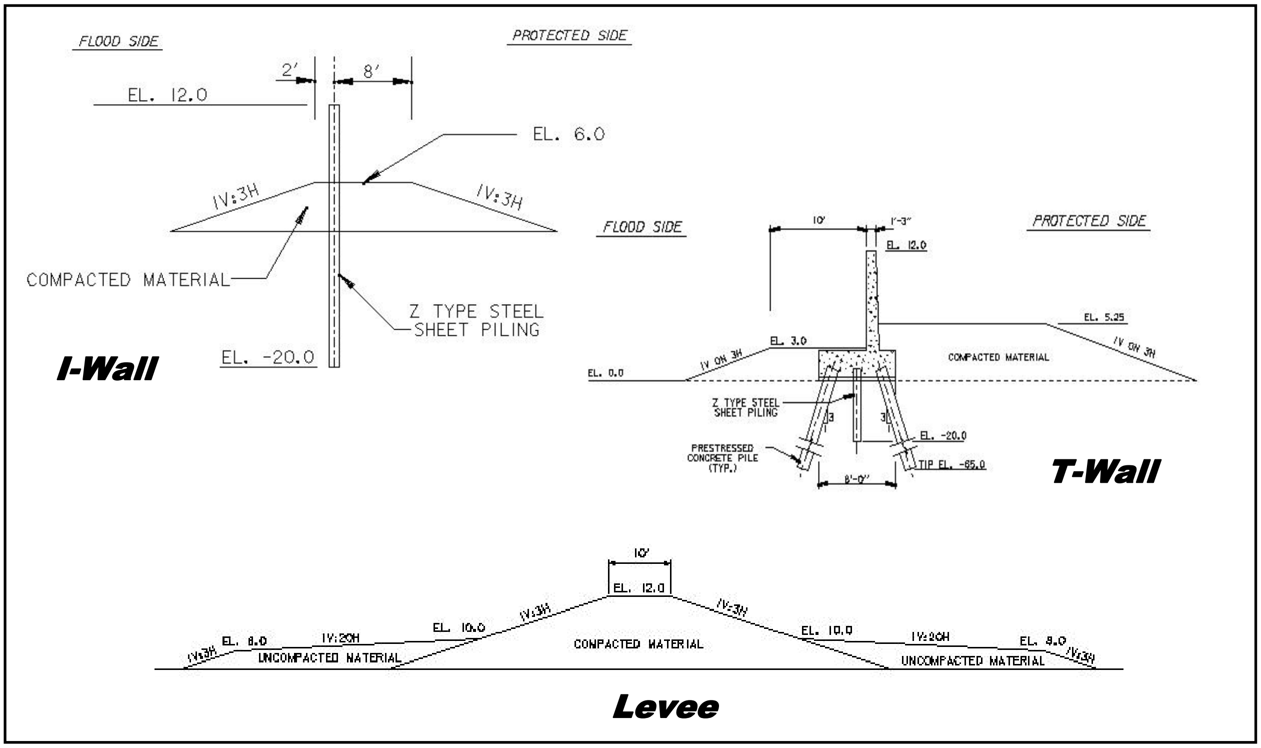

Figure 5. General schematic of major hurricane protection structures used in New Orleans and Vicinity.

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, do not explicitly include protection against overtopping. The structures were, in effect, designed to perform at water elevations up to overtopping, but not beyond. This is not atypical in flood protection measures, when cost justification is a primary decision factor. Building in resilience is well within the state-of-art of engineering practice, it is an economic decision to do so or not. 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). It is clear now that resilience to overtopping (i.e., preventing catastrophic breaching) would have dramatically reduced flooding and losses and would have been a worthwhile investment.

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.

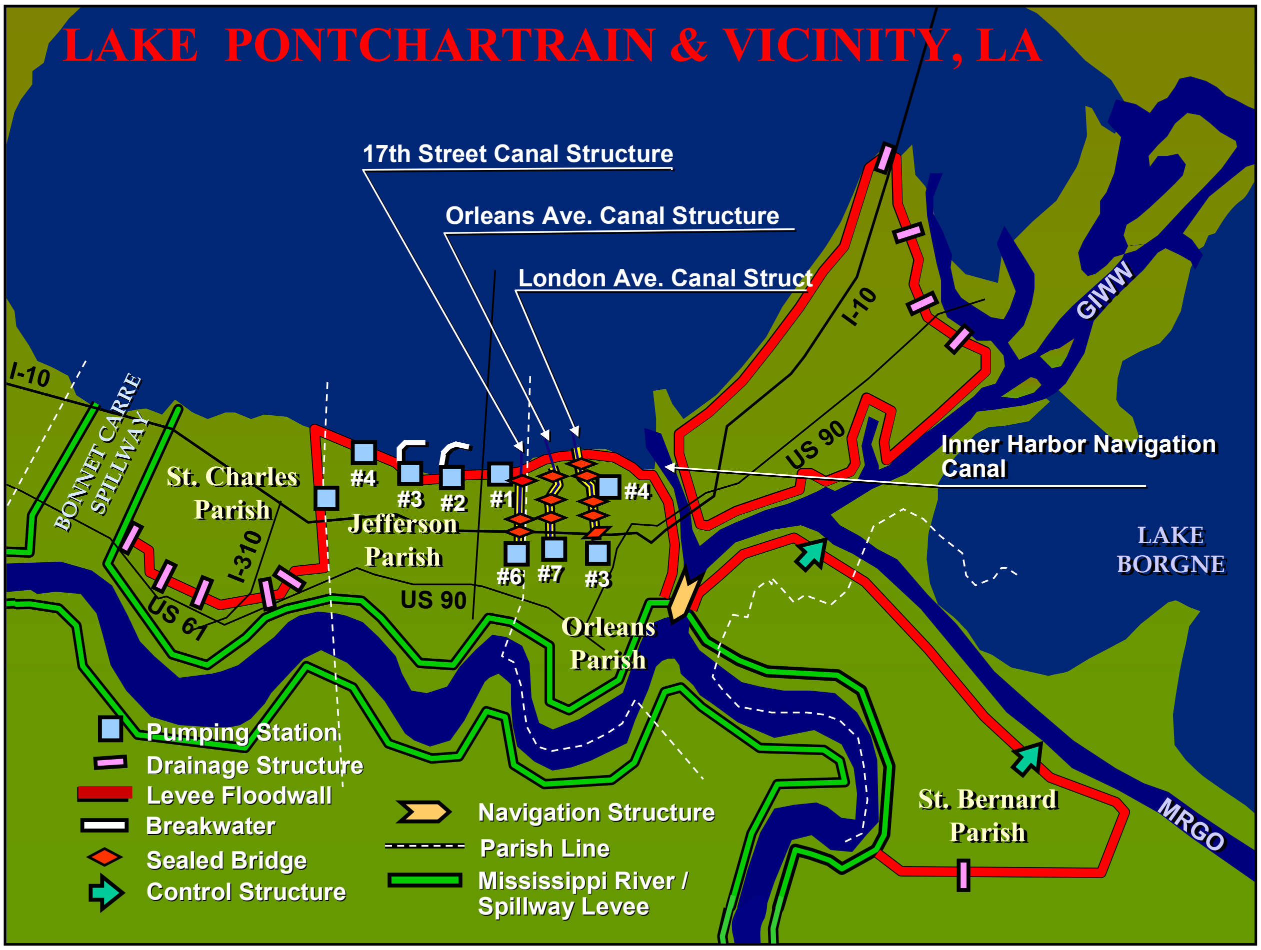

Figure 6. Map showing detailed geometry and features of the New Orleans metropolitan area.

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 7 and 8 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 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.

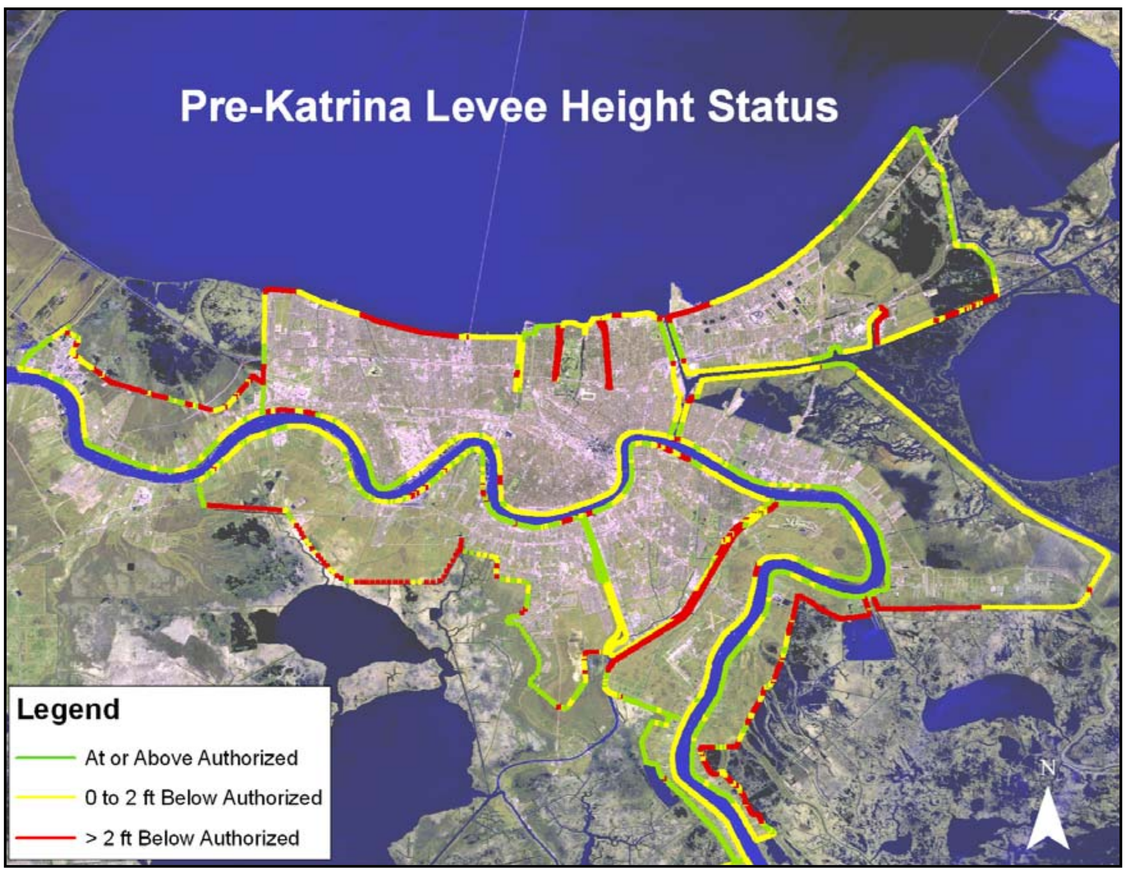

Figure 7. Map comparing pre-Katrina HPS structure elevations to authorized elevations, New Orleans metropolitan area and West Bank. Data derived from IPET risk assessment database.

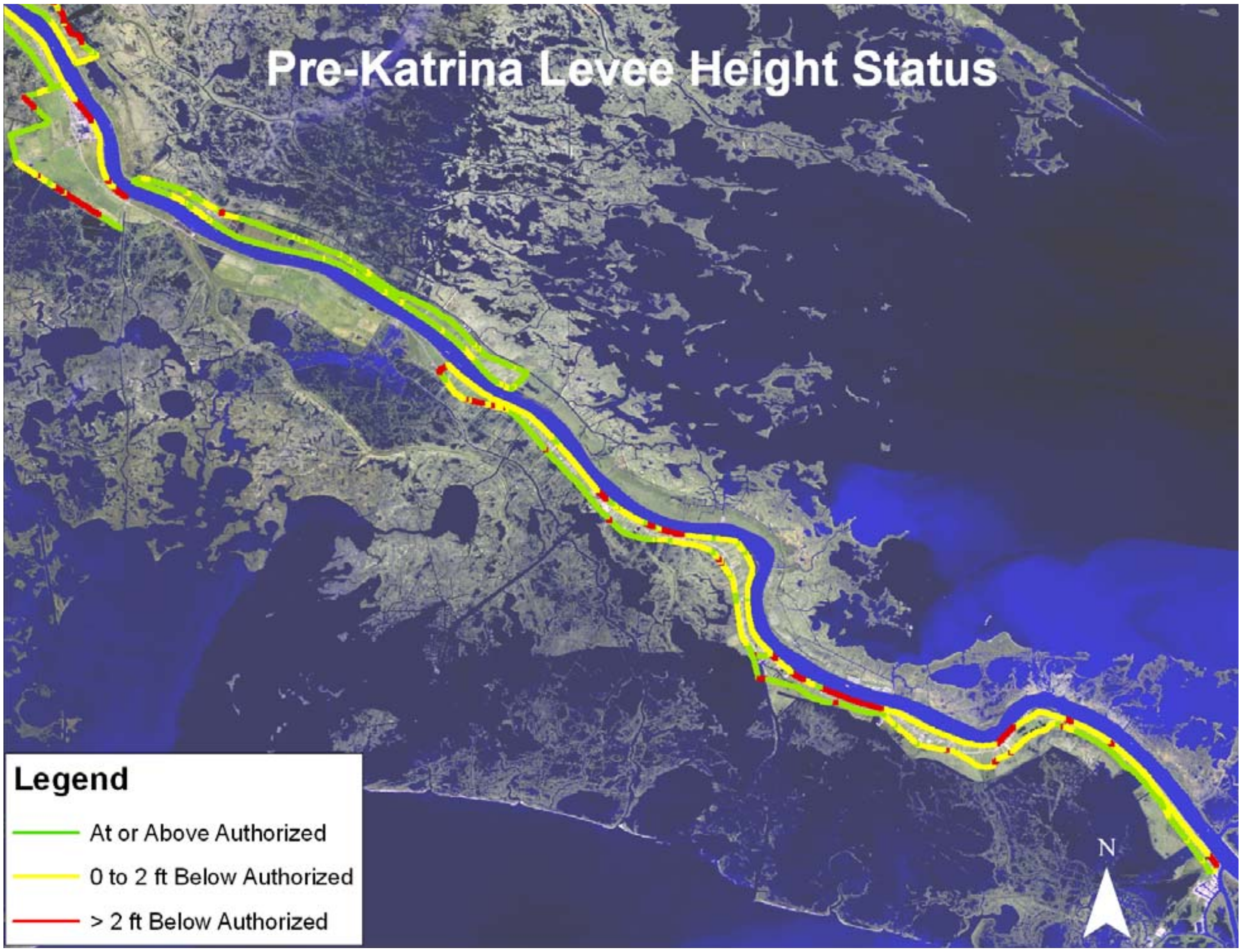

Figure 8. Map showing comparison of pre-Katrina HPS structure elevations with authorized elevations for Plaquemines Parish. Data derived from IPET risk assessment database.

The Storm (Volume IV)

The path followed by Hurricane Katrina, shown in Figure 9, 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.

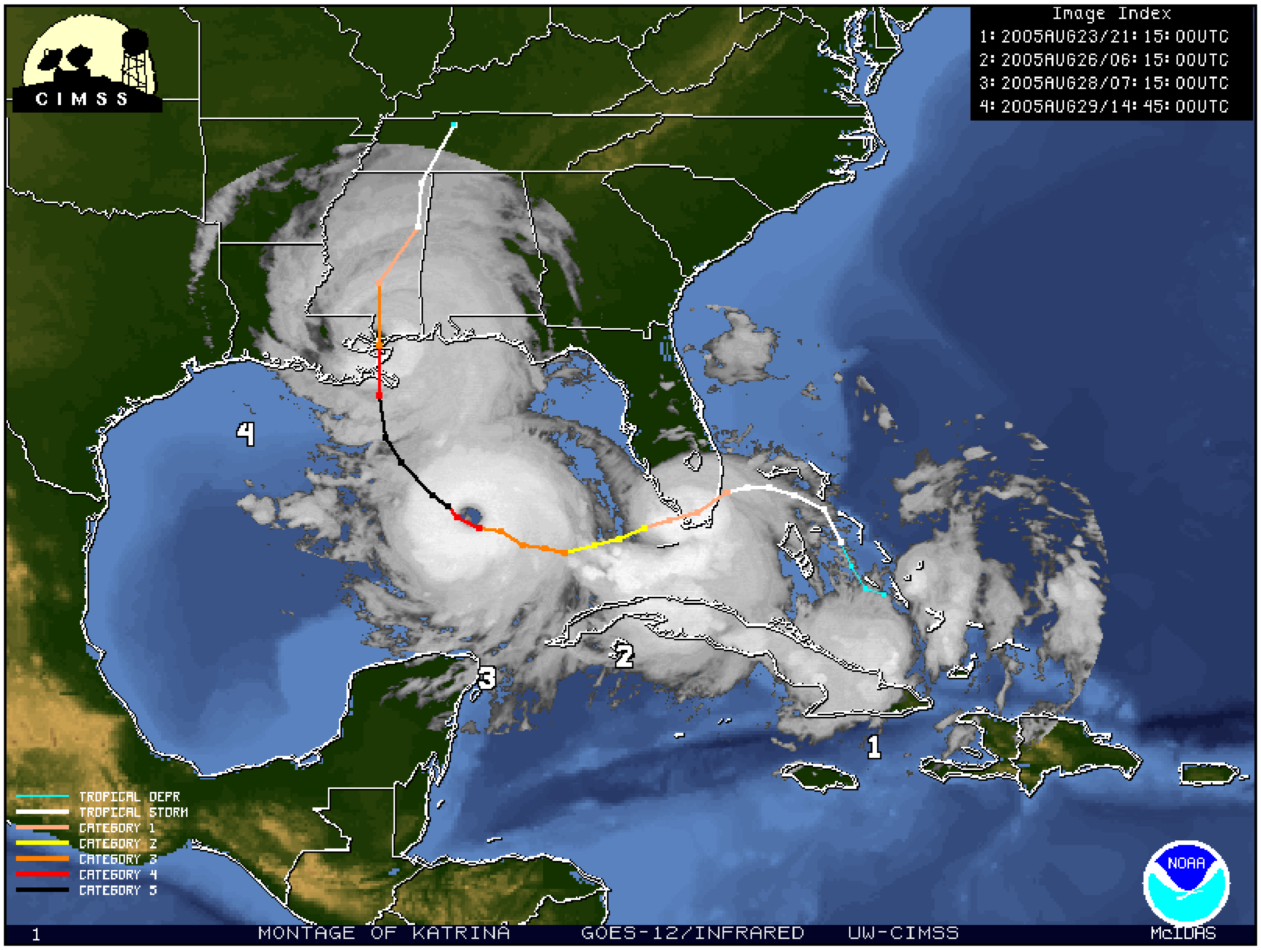

Figure 9. Hurricane Katrina path and intensity history (intensity defined based on flight-level wind speeds, as opposed to surface winds).

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 hurricane winds, 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 Katrina came record rainfall as shown in Figure 10. Over a 24-hour period, sections of New Orleans near the intersection of Lake Pontchartrain and the IHNC received over 14 inches of rainfall. The previous record was from Hurricane Betsy, which dumped up to 7 inches in the same time frame. This rainfall was to become at least 20% of the total volume of water that flooded the New Orleans metropolitan area. The east and south facing levees of New Orleans East, St. Bernard, and Plaquemines Parishes absorbed the brunt of the storm, experiencing surge and waves significantly beyond their design levels. Overtopping was common and, depending on location, persisted for hours.

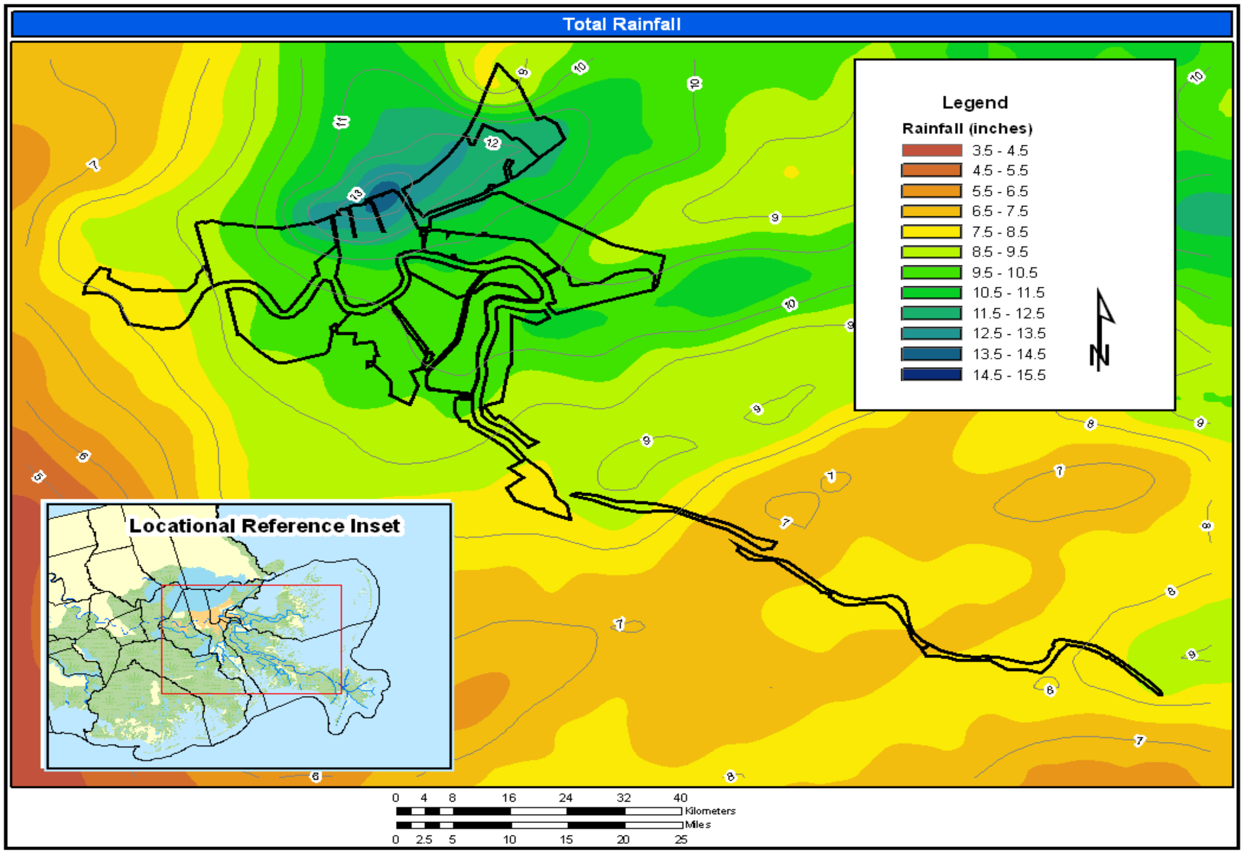

Figure 10. Hurricane Katrina rainfall totals.

Literally all of the gauging instruments to measure water conditions were destroyed by Katrina. Other than high-water marks, and the devastation, there were few measurements to confirm the actual water level time-histories resulting from the storm. The IPET used the ADCIRC model with a very high resolution computational grid to model the storm and predict the time-history of the surge levels that occurred at different locations around the region. Figure 11 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 feet along the south shore of Lake Pontchartrain to 20 feet along the Plaquemines Levees. Even enclosed areas such as the IHNC experienced water levels above 14 feet, not including waves.

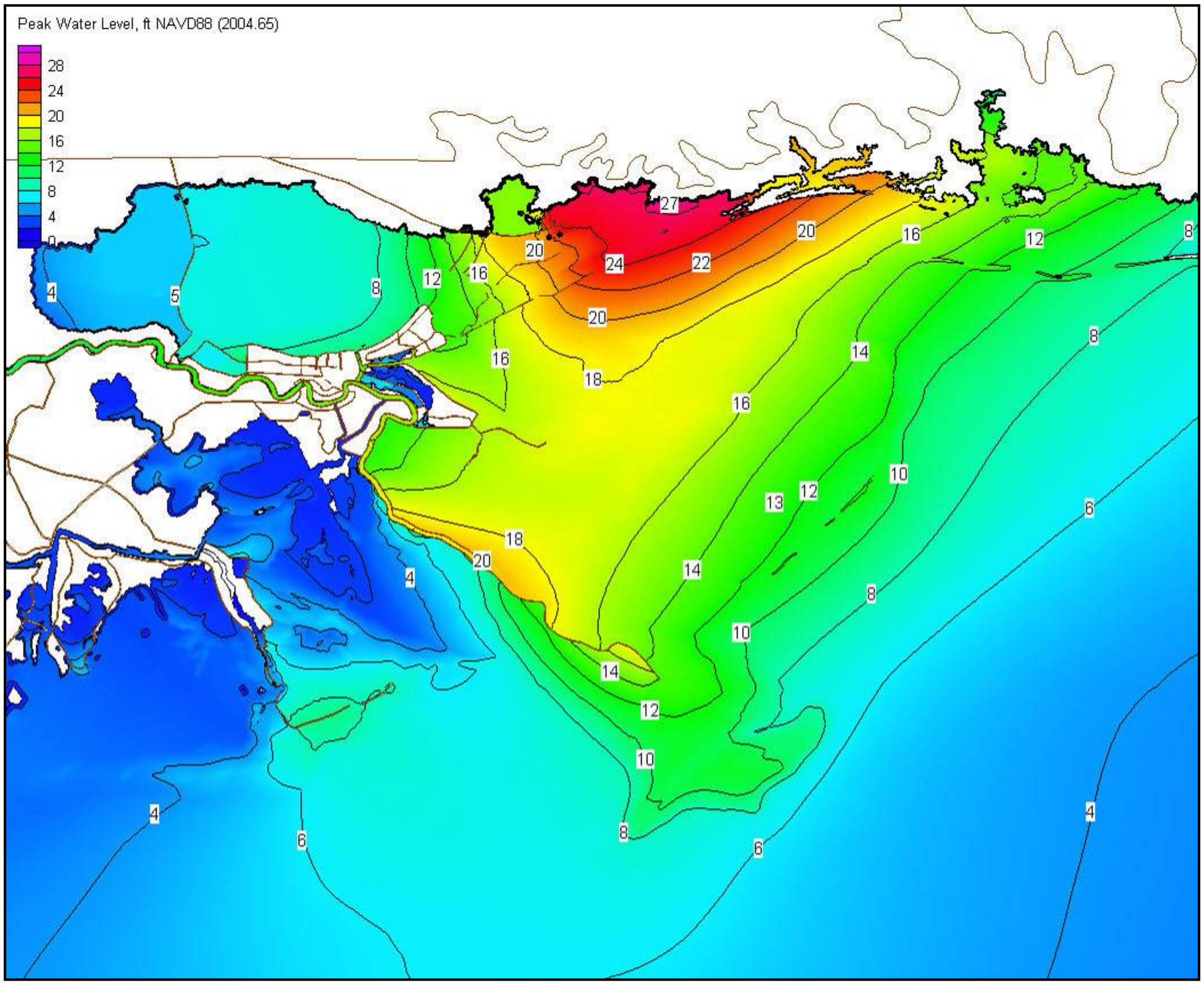

Figure 11. Maximum computed storm surge levels using the ADCIRC model, Mississippi to Louisiana region, water levels in feet NAVD88 (2004.65).

Winds from Katrina generated a record-wave environment. Again, the lack of measurements caused 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 12 to 15. 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.

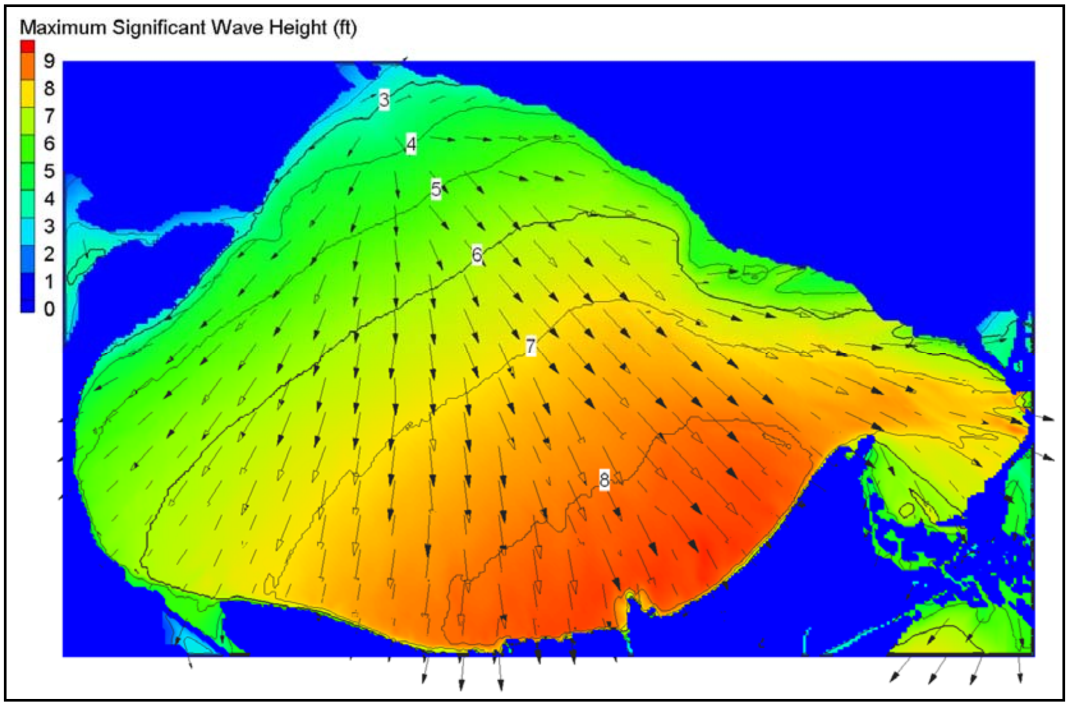

Figure 12. Lake Pontchartrain maximum modeled significant wave height and corresponding mean direction (wave heights in feet).

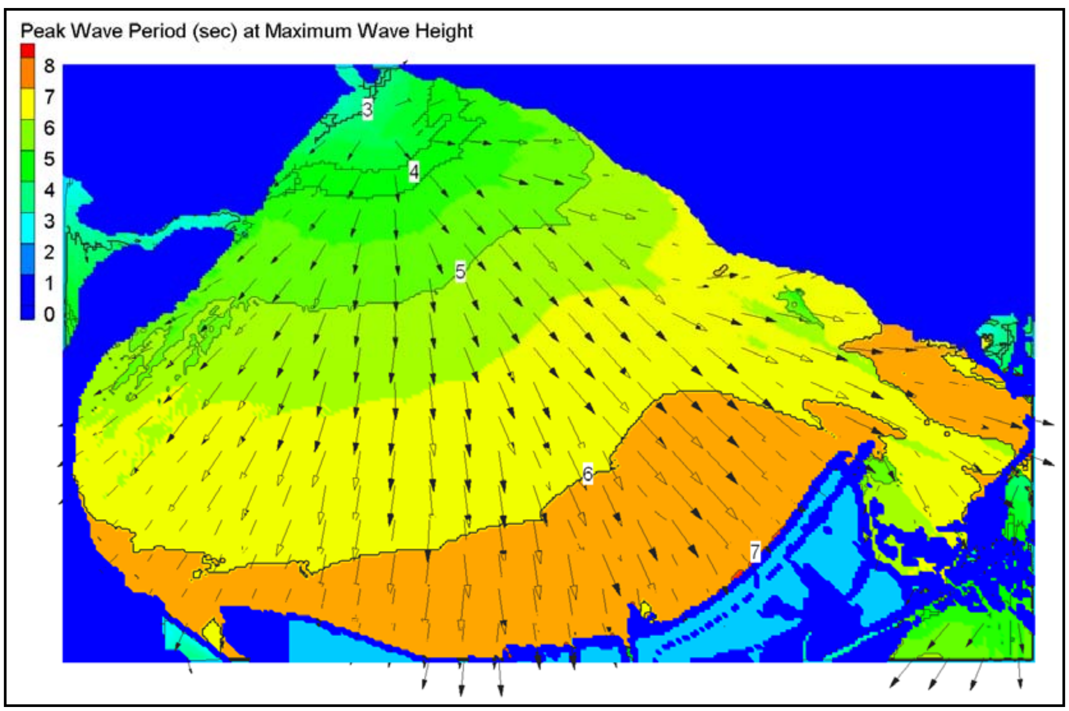

Figure 13. Lake Pontchartrain modeled peak wave period corresponding to the maximum wave height (periods in seconds).

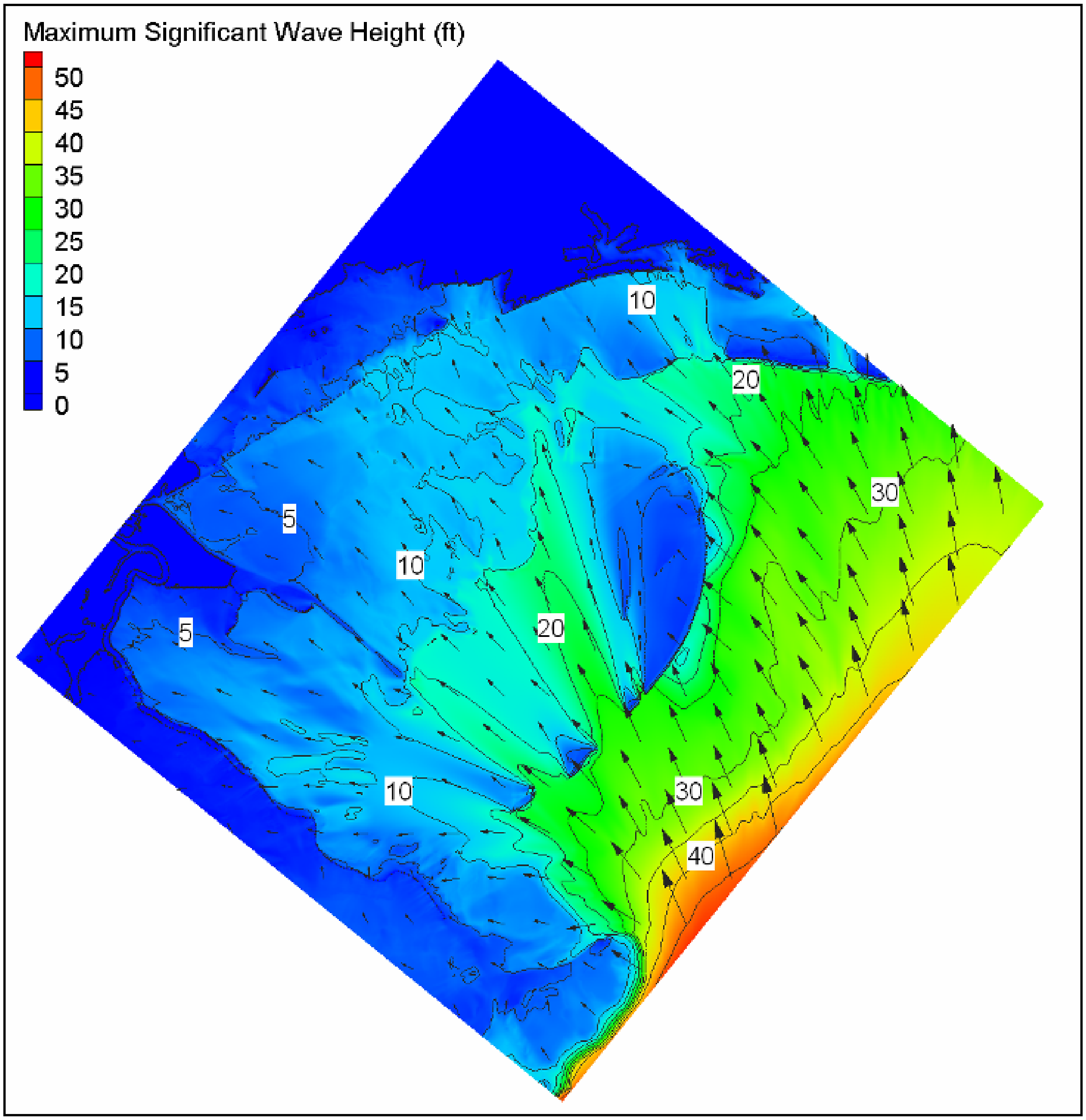

Figure 14. Southeast Louisiana maximum modeled wave height and corresponding mean direction (wave heights in feet).

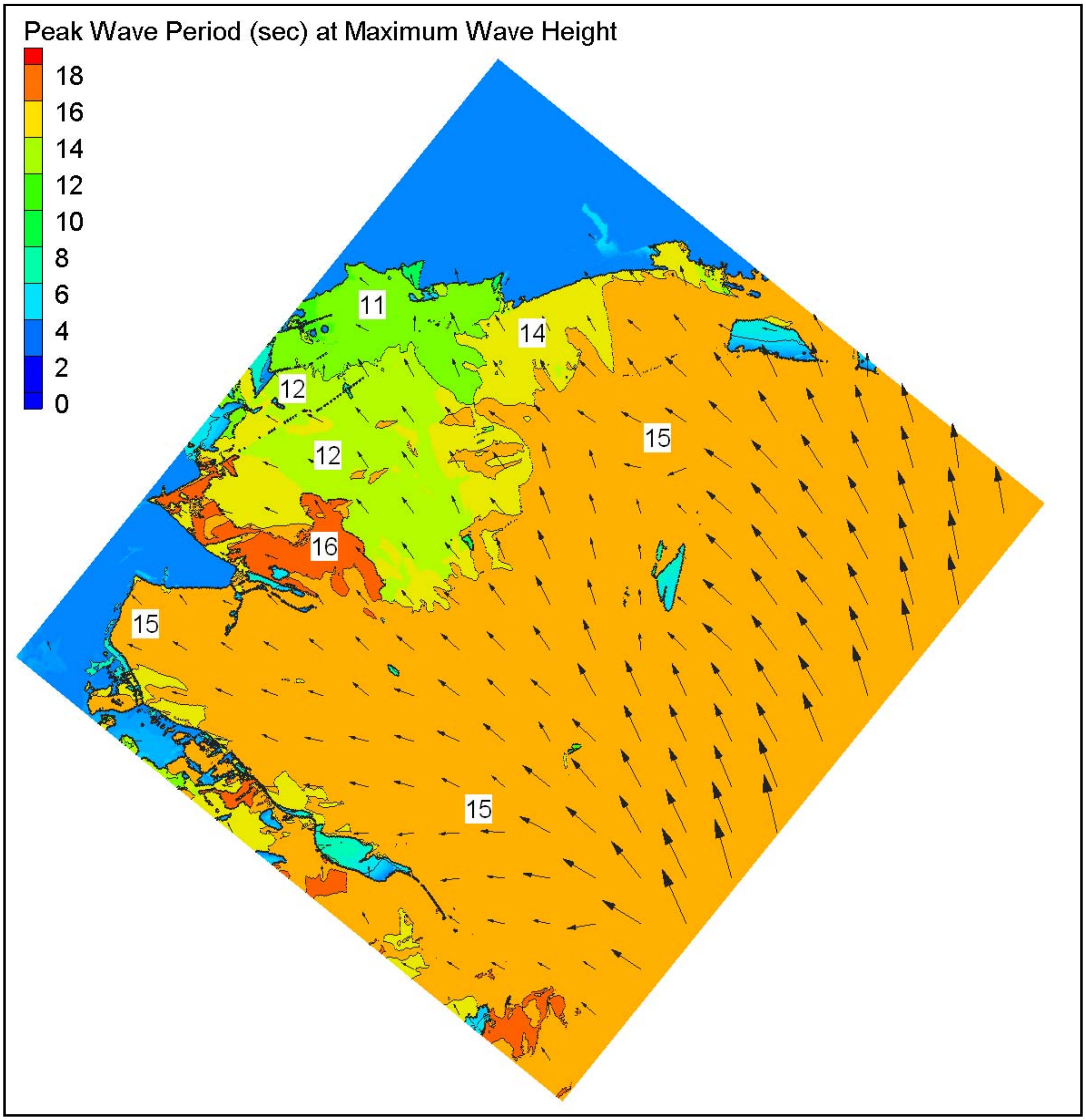

Figure 15. Southeast Louisiana modeled peak wave period corresponding to the maximum wave height (periods in seconds).

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 16 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 IV 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 feet compared to the 12 to 14 feet assumed in the design.

Figure 16. Comparison of general surge levels assumed in the SPH design (D) and estimated from Katrina (K). See Volume IV for more detailed information.

Figure 17 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 to shore and have much greater potential for runup and overtopping of HPS structures.

Figure 17. 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 (Volumes V and VI)

Figure 18 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, 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 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 8 list only 29 breaches. The difference 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.

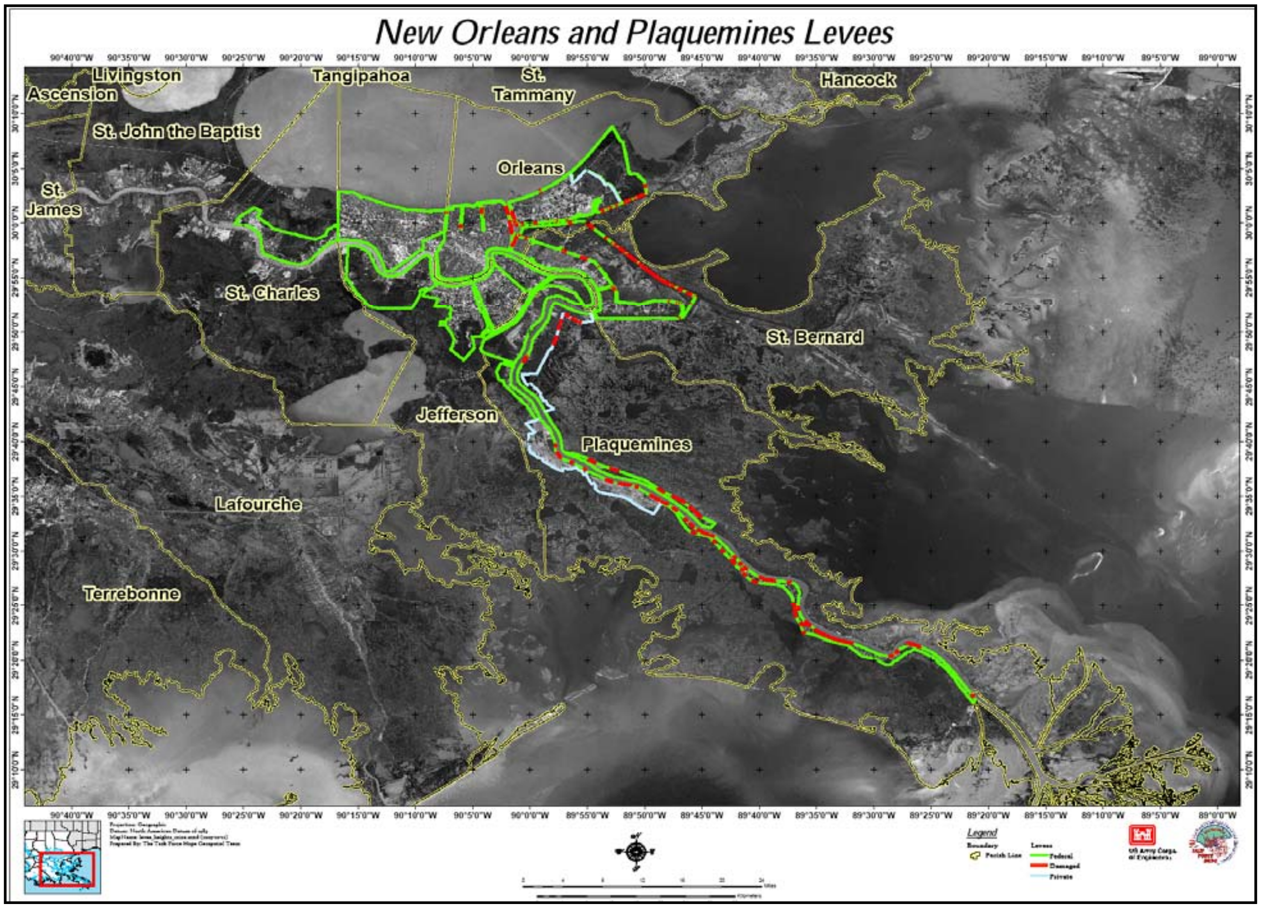

Figure 18. Locations (in red) of severe damage to hurricane protection structures resulting from Katrina.

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 19) and MRGO (Figure 20) 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 21 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 19. Example of levee along New Orleans East, GIWW, breaching from overtopping and scour of erodible materials.

Figure 20. Example of levee breach along MRGO from overtopping and scour of erodible materials.

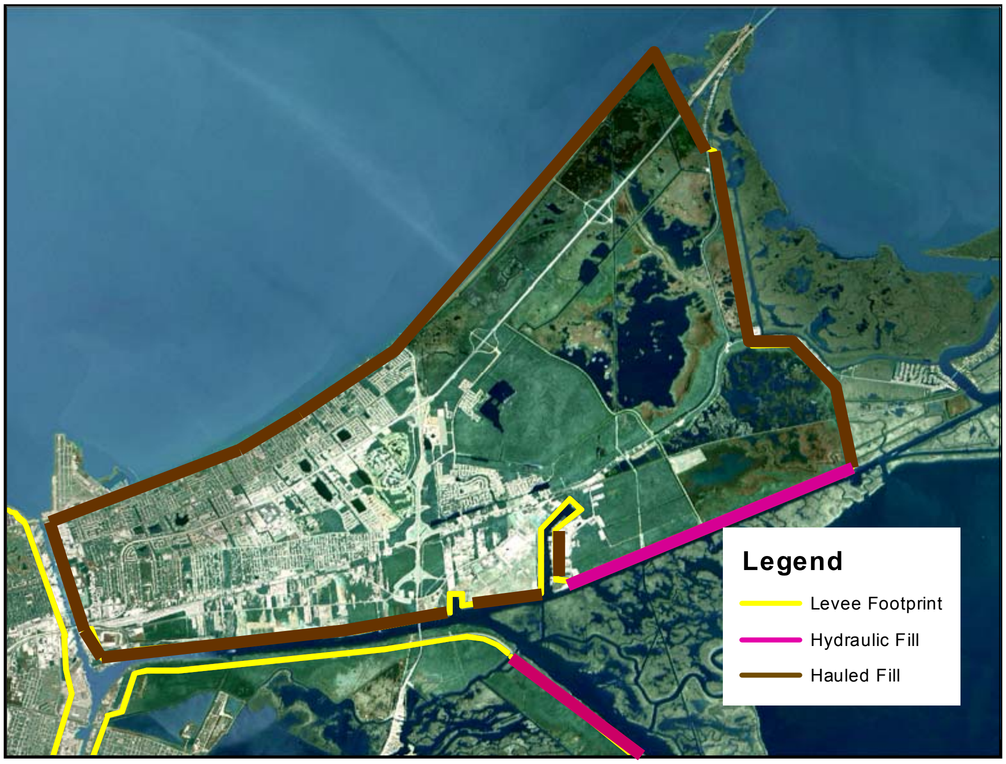

Figure 21a. Character of levee materials, New Orleans East and northern St. Bernard. This slide is incomplete for St. Bernard and shows only the hydraulic fill section along the MRGO.

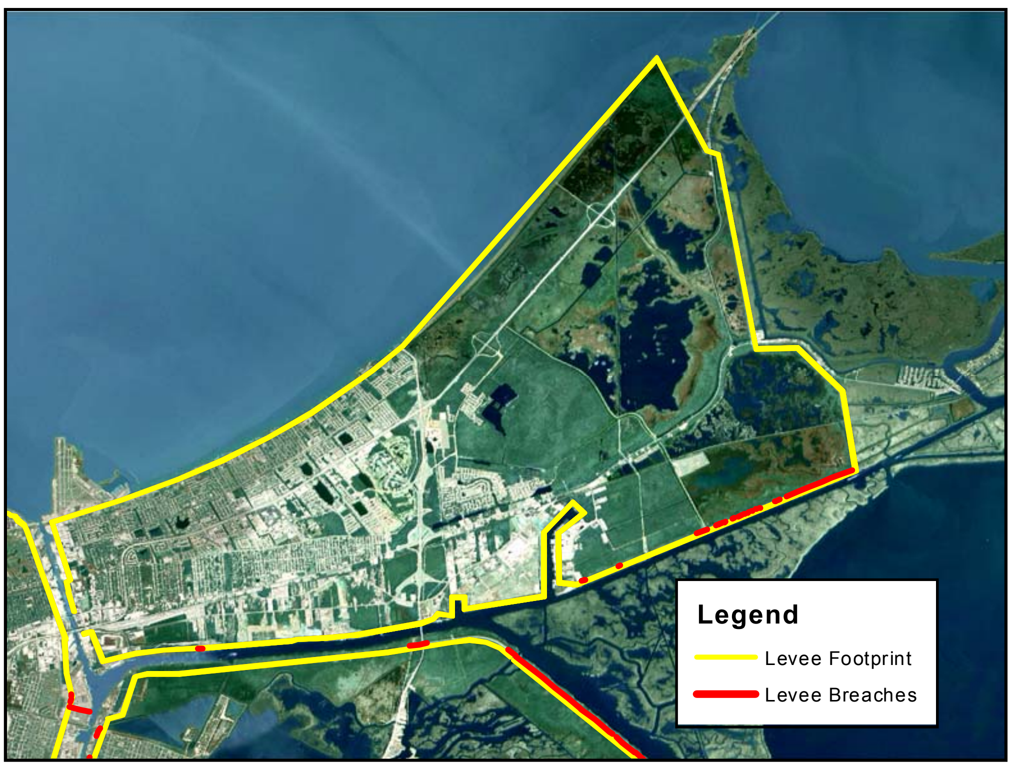

Figure 21b. Distribution of levee breaching, New Orleans East and northern St. Bernard.

Early in the morning, around 0500 hr (5 a.m. 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 to10.5 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 22 and was confirmed by field investigations of the failure plane and site conditions, separate stability analyses conducted by Virginia Tech University and ERDC, and physical testing by independent centrifuge tests at Rensselaer Polytechnic Institute and ERDC.

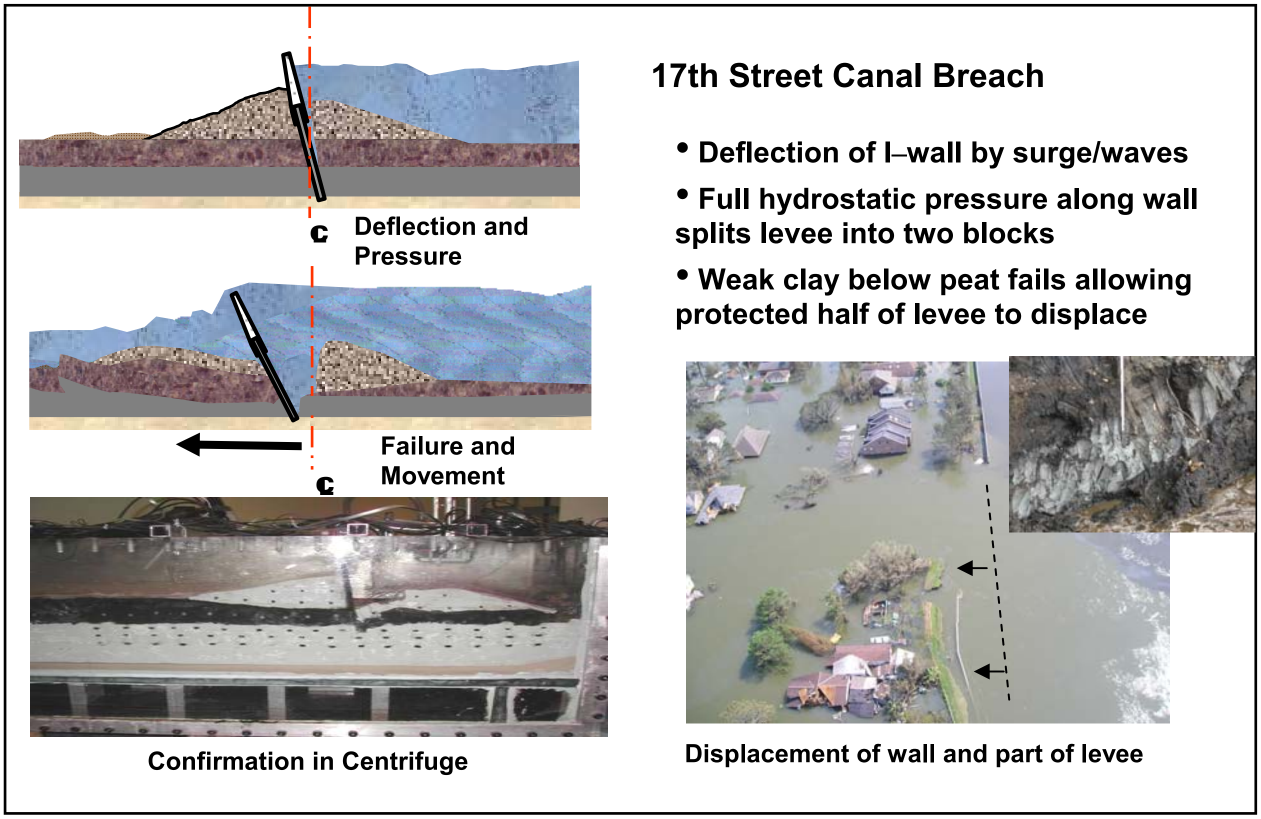

Figure 22. Depiction of failure mechanism for 17th Street and IHNC foundation failures. A crack forming along the front of the I-wall introduced high forces down the face of the sheet pile, resulting in lateral movement of the floodwall along a shear plane in the weak clay foundation.

At around 0700-0800 hr, 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 23 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 Rensselaer Polytechnic Institute 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.

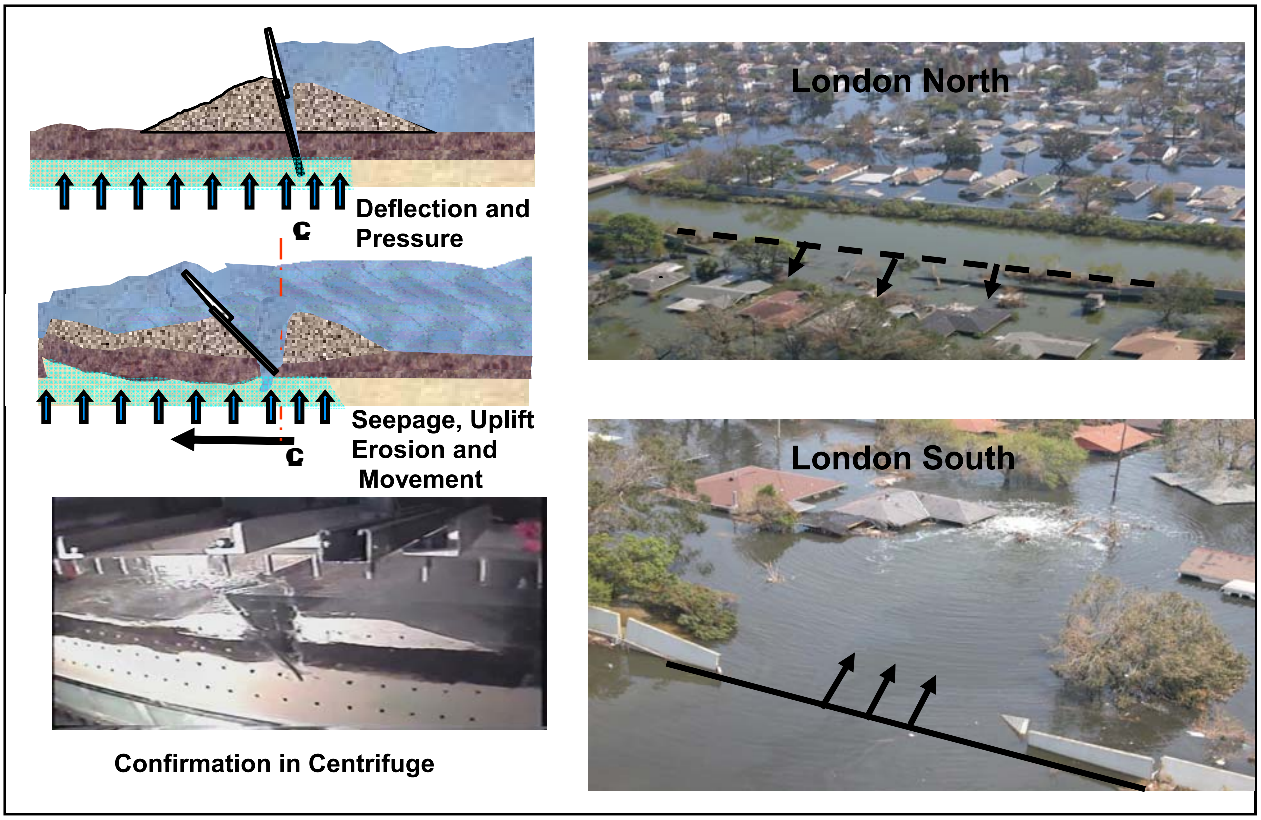

Figure 23. Depiction of London Avenue Canal north and south breaches caused by deflection of the I-wall and high uplift pressures introduced through the underlying porous sands, confirmed in centrifuge testing.

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 24 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 feet 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.

Figure 24. Example of breach along IHNC (east side) from overtopping and scour (top) and scour behind adjacent section that did not fail (bottom).

The flooding resulting from the overtopping and breaching was catastrophic. Figure 25 shows the extent and depth of flooding for the New Orleans metropolitan area where almost 80% 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 26. 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.

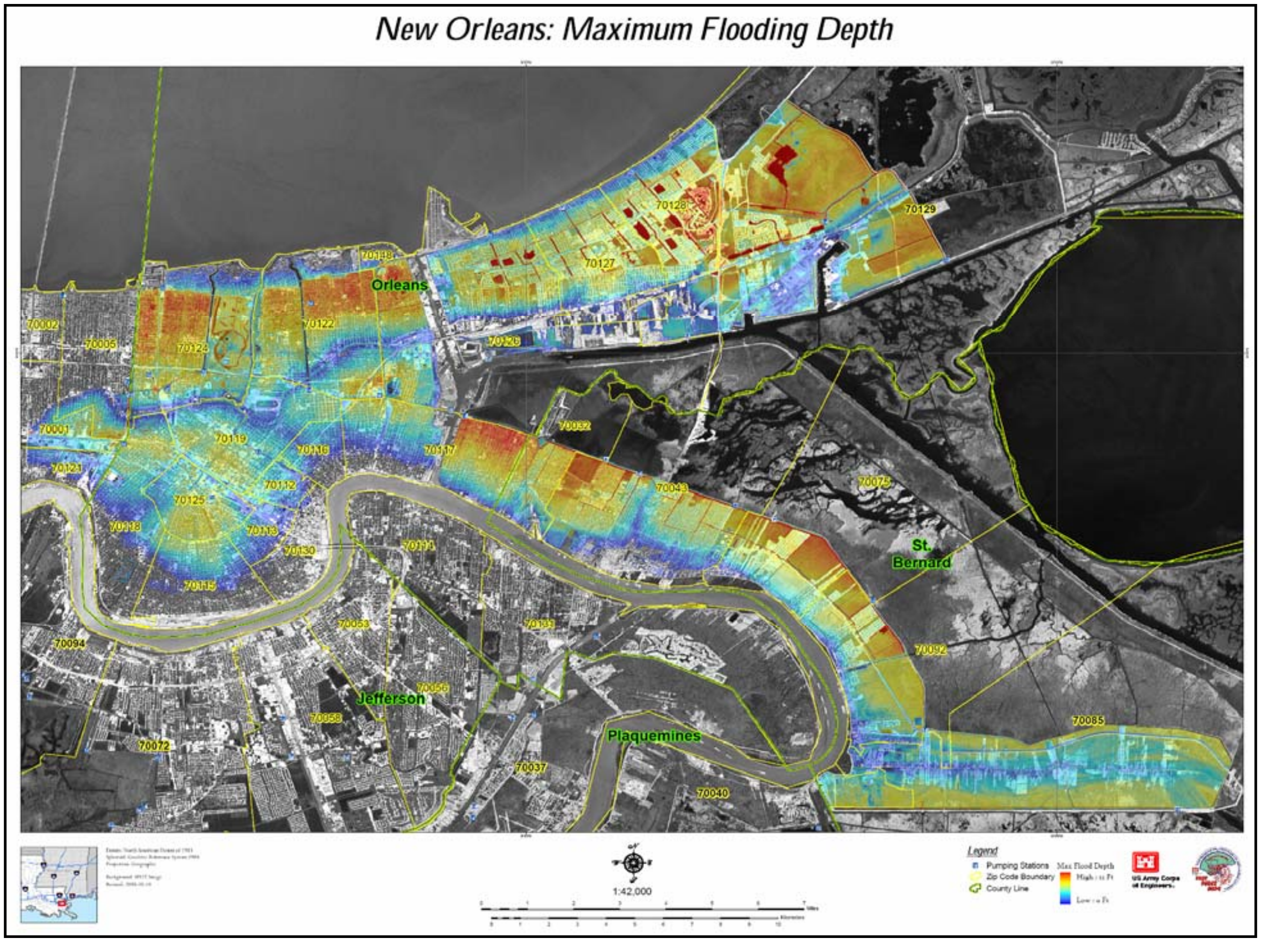

Figure 25. Map of maximum depths of flooding from Katrina. Greatest depths of flooding exceed 15 feet. Source: U.S. Army Corps of Engineers.

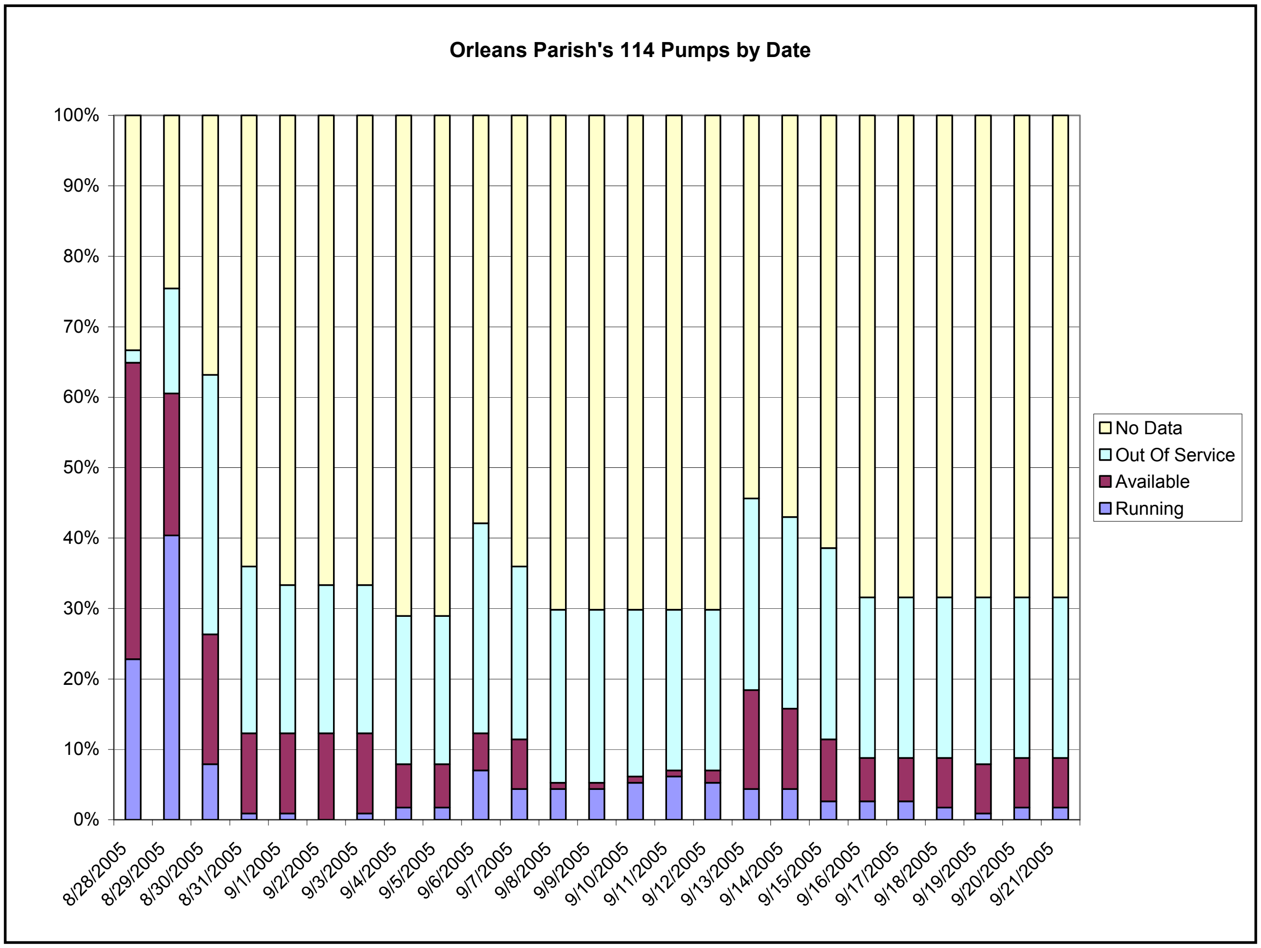

Figure 26. Example of pumping performance during Katrina.

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 27 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.

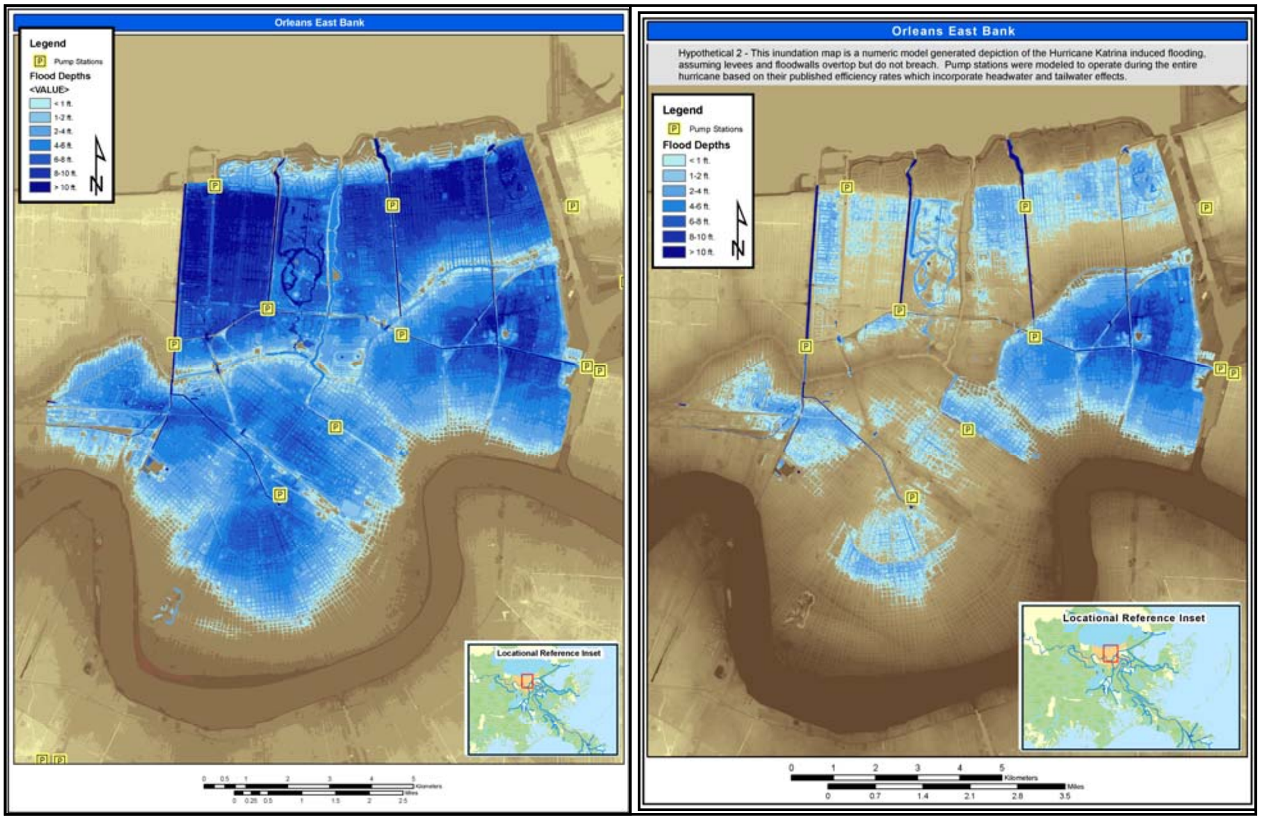

Figure 27. Comparison of flooding from Katrina (left) to hypothetical condition of no breaching and full pumping capacity (right) for Orleans East Bank.

The Consequences (Volume VII)

The consequences of the flooding were enormous, dwarfing the losses from previous disasters. Figure 28 shows residential direct property losses. Approximately 78% of the direct property losses from flooding were experienced by residential property. This is in part due to their location in some of the lowest elevations of the city. Figure 29 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 30 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 27, it is a testimony to the value of having a resilient HPS.

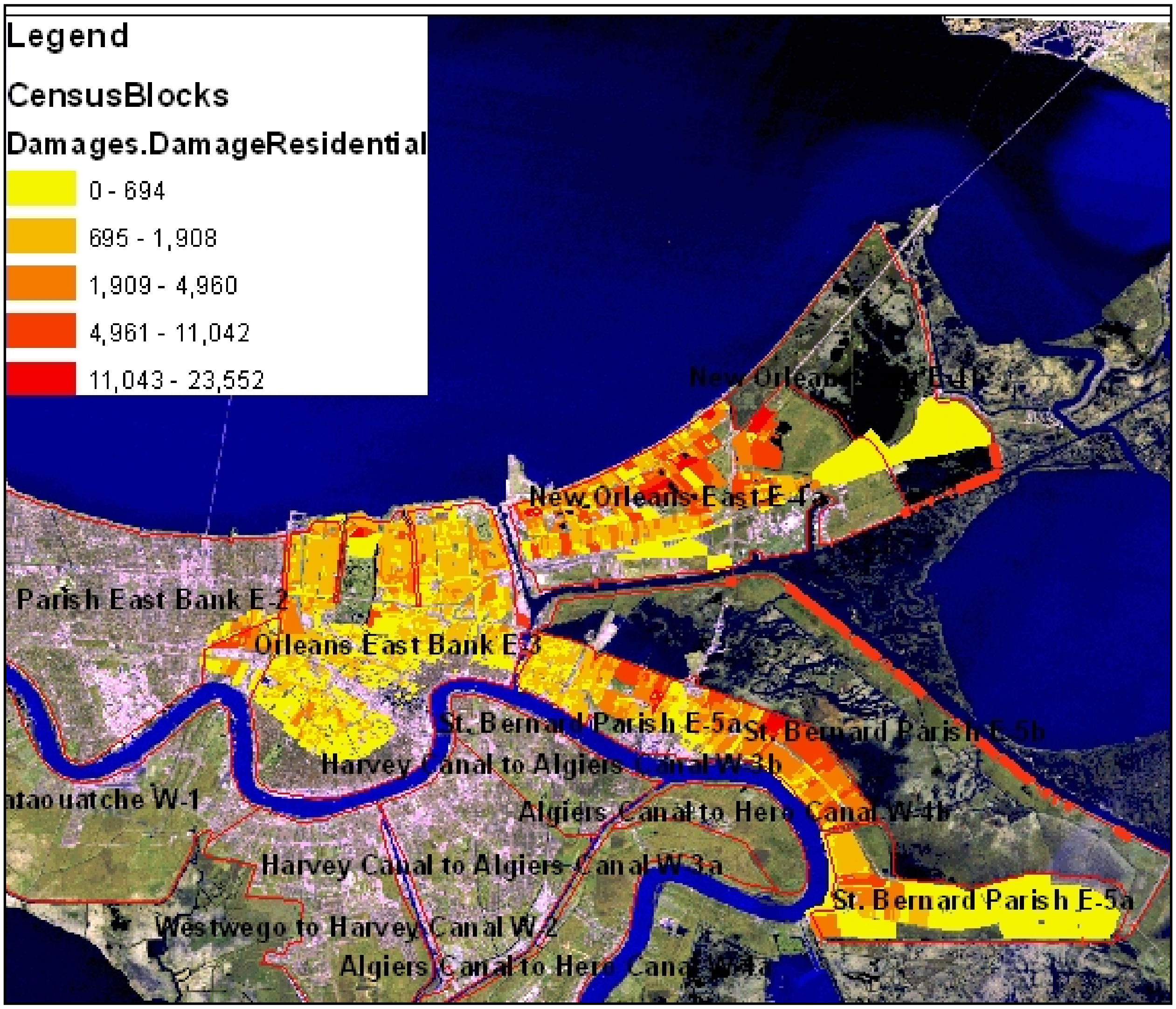

Figure 28. Distribution of Katrina-generated residential direct property damages by census block. Damages in thousands of dollars.

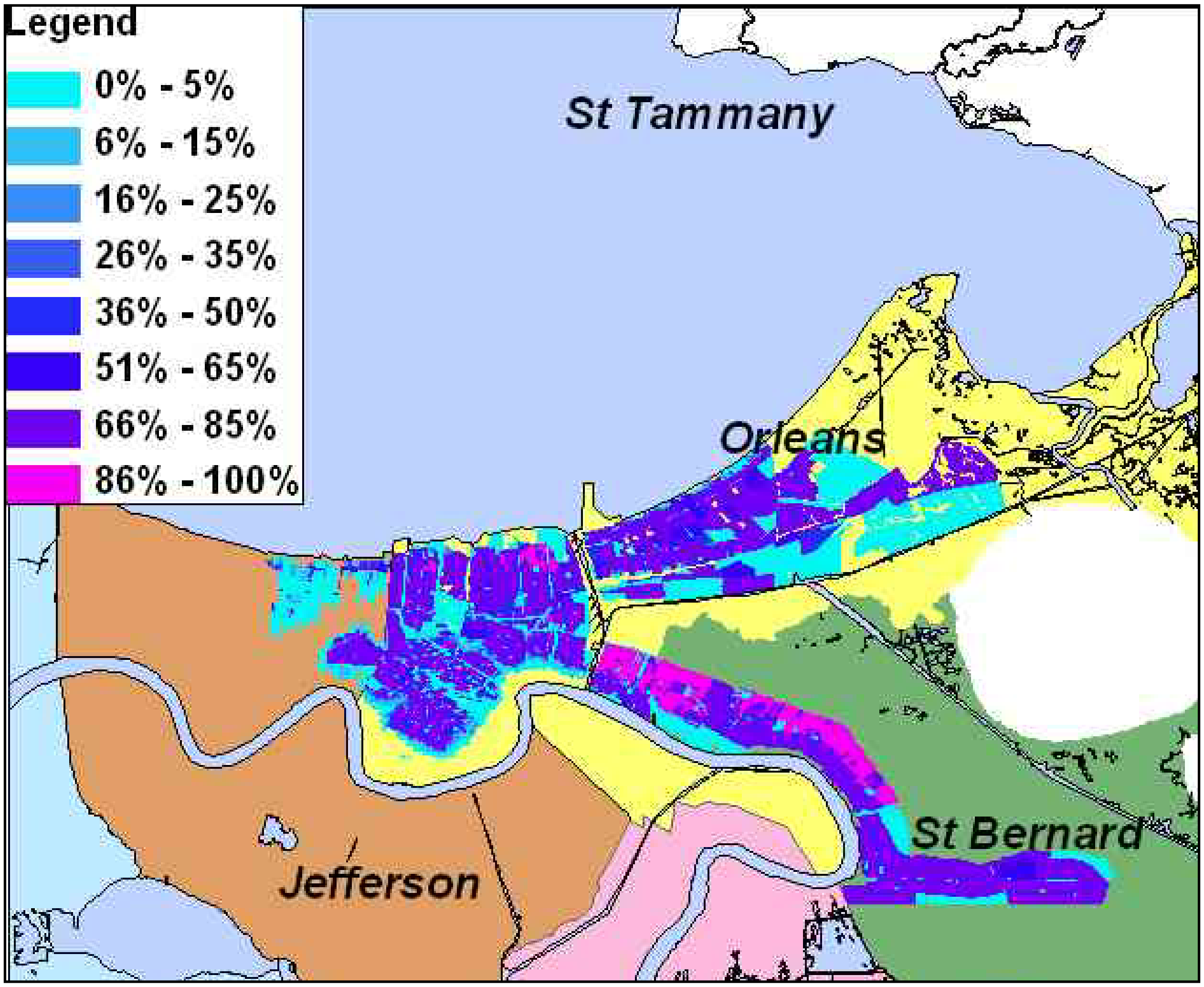

Figure 29. Distribution, by census block, of direct property damage by percent of value lost (damage/value) from Katrina.

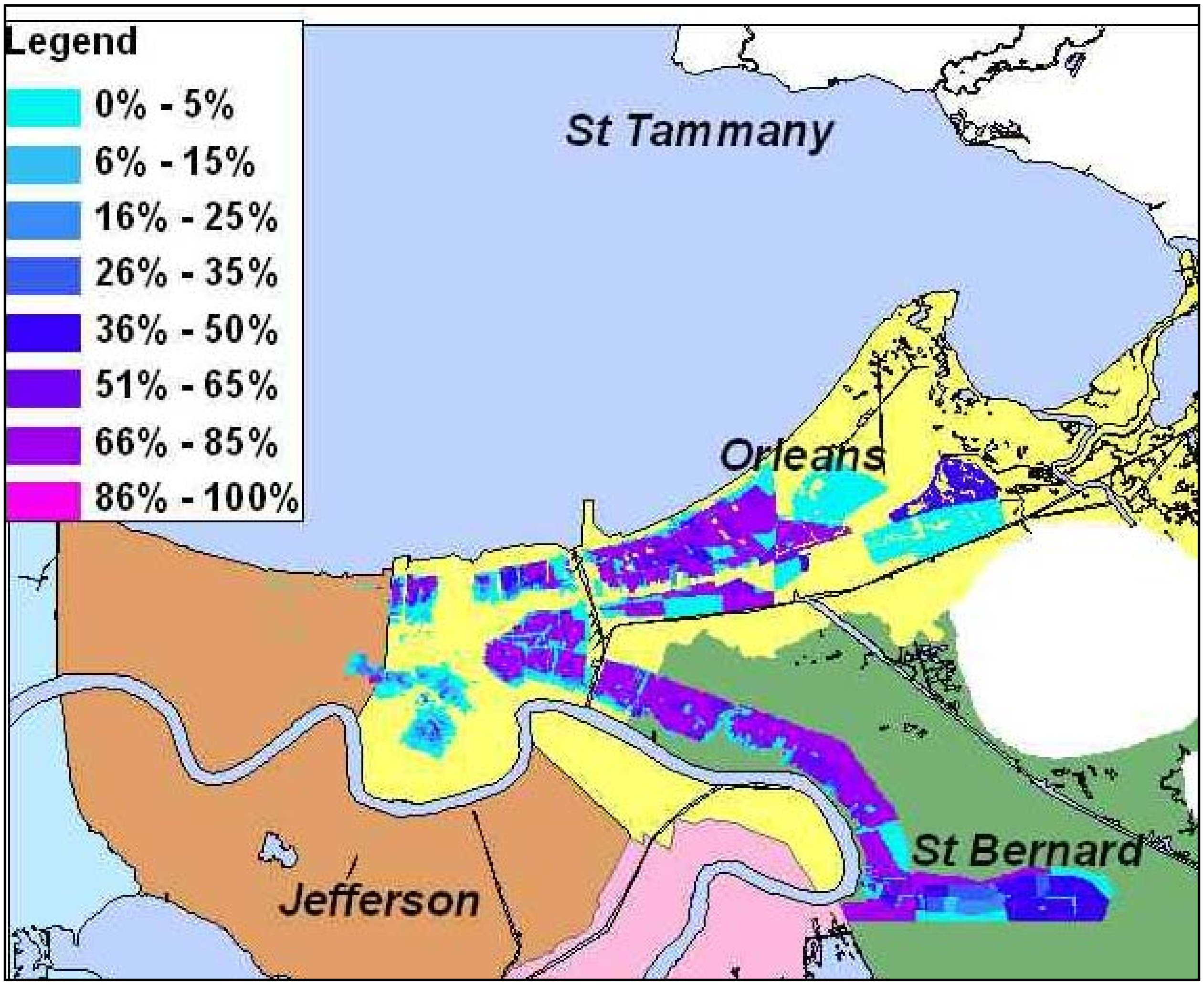

Figure 30. Hypothetical percentage property damage (damage/value) for scenario of no breaching and full pumping capacity

Loss of life in the Gulf region was staggering, with almost 1,600 fatalities accounted for and hundreds more missing and presumed dead. The New Orleans metropolitan area suffered over 1,000 storm-related deaths as of the February 2006 analysis. Only 2% 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 31 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.

Race	Female	Male	Grand Total
African American	44.6%	62.1%	53.4%
Caucasian	51.0%	35.4%	43.2%
Hispanic	3.0%	1.6%	2.3%
Other	1.4%	0.8%	1.1%

Age	Percent
0 to 5	0.3%
6 to 10	0.1%
11 to 15	0.3%
16 to 20	0.7%
21 to 30	1.1%
31 to 40	3.0%
41 to 50	8.9%
51 to 60	13.9%
61 to 75	23.7%
>75	48.0%

Source: Vital Statistics of All Bodies at St. Gabriel Morgue, 16 Feb 2006
http://www.dhh.louisiana.gov/offices/publications/pubs-192/Deceased%20Victims_2-16-2006_information.pdf

Figure 31. 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% of the total. Commercial property losses were approximately 11% of the total, while industrial losses were under 2%. Clearly, the people of New Orleans suffered the most direct losses, and these losses represent perhaps the greatest challenge to recovery, not just in terms of property damages. The extensive flooding caused a breakdown in the area's social and cultural structure, significantly complicating recovery and redevelopment. Critical social institutions such as schools and hospitals have been very slow to reopen.

Figure 32 shows an example of the pre-Katrina and post-Katrina (1 June 2006) direct economic damage – elevation relationships developed for each sub-basin. 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 sub-basin would be decreased because of the reduced exposure for economic loss.

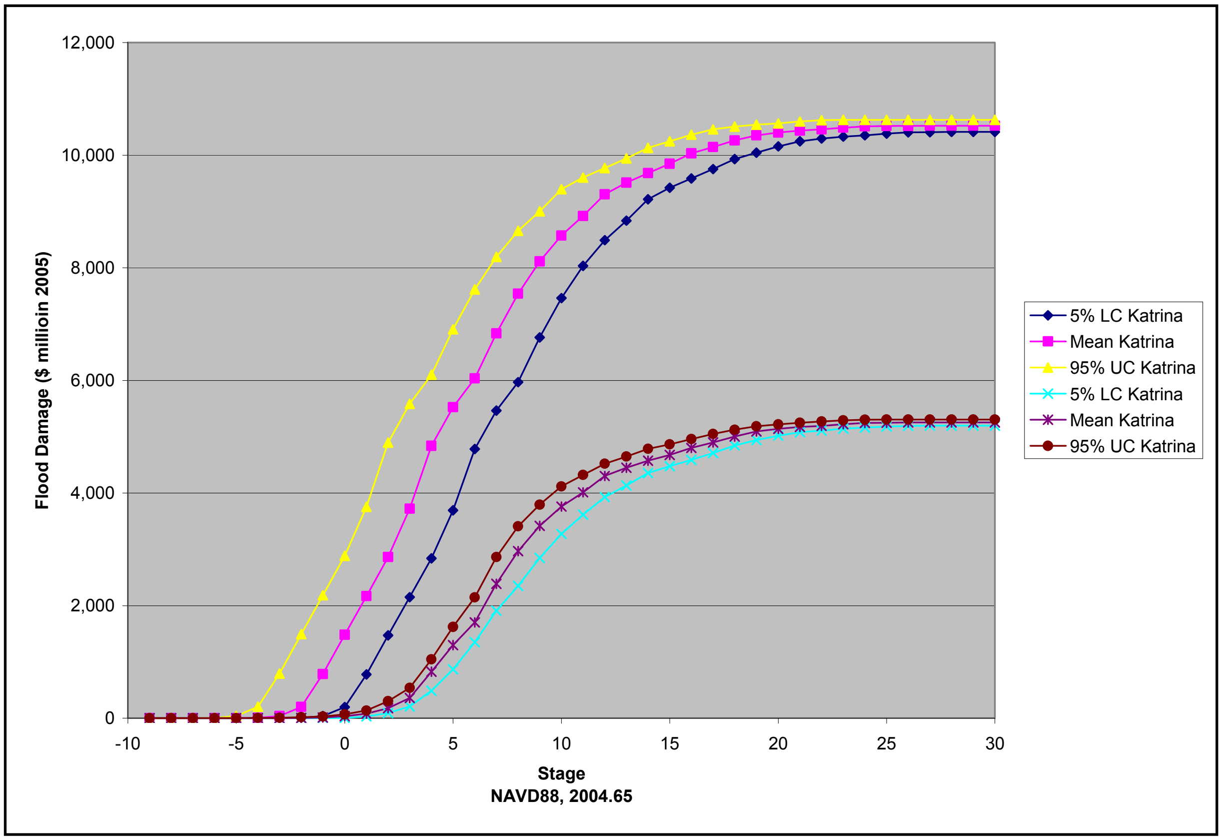

Figure 32. Comparison of flood damage – water level (in feet) relationships for pre- and post-Katrina scenarios for Orleans sub-basin 5. LC and UC represent the lower and upper confidence limits of the data.

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 33 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 U.S. Environmental Protection Agency (USEPA) 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 (USGS) 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 it 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.

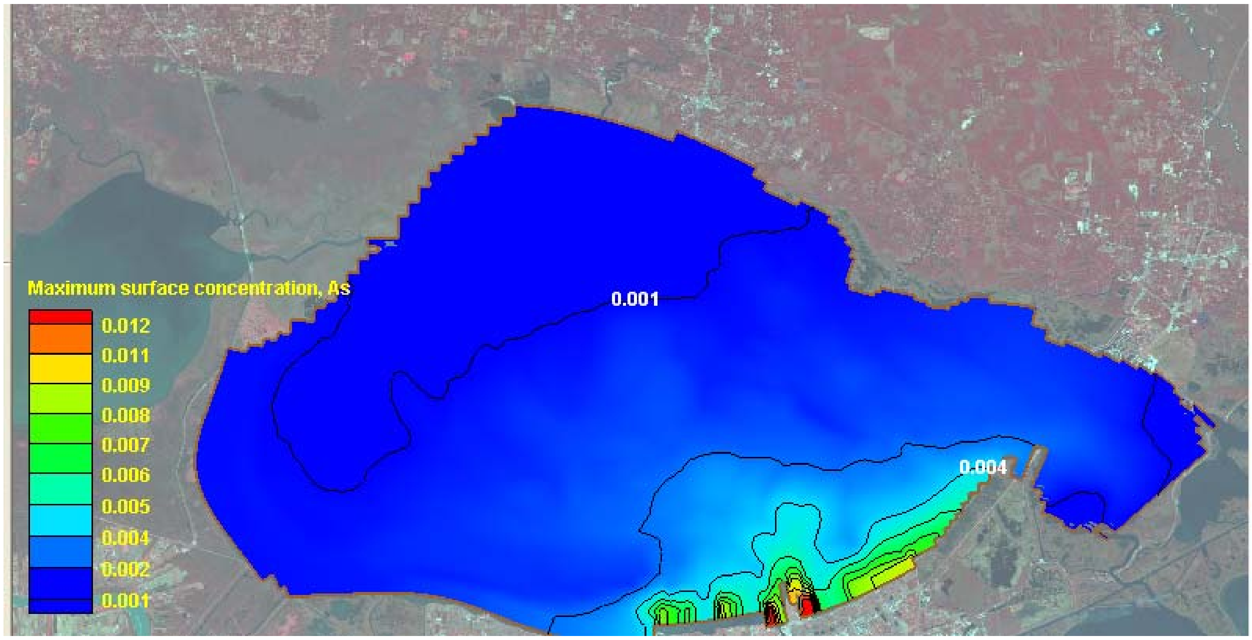

Figure 33. Maximum arsenic (As) water surface concentrations (milligrams per liter total) in Lake Pontchartrain after Katrina.

The Risk (Volume VIII)

Risk Assessment Approach

This document provides a general overview of the risk assessment performed to determine the vulnerability of New Orleans and vicinity to flooding from hurricanes and to estimate the difference in risk, by location, for the pre-Katrina HPS conditions and the post-Katrina (June 2007) HPS conditions. The risk assessment process, its application, and a presentation and discussion of results are presented in detail in Volume VIII, Engineering and Operational Risk and Reliability Analysis. This discussion is intended to be a more general treatment of the same topics without the burden of the math and details, but including presentation and discussion of the results of the work. IPET also released a supplemental report entitled "A General Description of Vulnerability to Flooding and Risk for New Orleans and Vicinity: Past, Present, and Future," available on our Web site (*https://IPET.wes.army.mil*), that provides a non-technical description of the risk assessment for the pre-Katrina, 2007, and 2011 timeframes.

The risk information provided is focused on hurricanes as the primary source. The surge and wave conditions generated by hurricanes are the principal hazard. The reliability or performance of the many components of the hurricane protection system is examined through the individual and collective performance of levees, walls, gates and closures, transitions, and pumping stations. The chance of flooding is estimated based on these factors and the rainfall associated with hurricanes. Losses are estimated based on estimated depths of flooding at different frequencies of occurrence. Rainfall from other, non-cyclonic storms is not considered, nor is flooding resulting from high flows on the Mississippi River not directly related to hurricane surge.

It is important to note that this effort involved developing and applying a prototype method to estimate risk for a large, complex, and geographically distributed system. In many respects, this is a first effort of its kind. One of the goals was to develop a methodology that would be practical to use as well as technically rigorous and provide system-wide information useful for informing individual and organizational decisions concerning hurricane risk reduction. IPET believes that this method generates reasonable and useful results. It is also clear that the results of any application of a large set of sophisticated models to a complex issue such as hurricane protection will engender significant uncertainty. A deliberate effort has been made to quantify that uncertainty to guide use of the results as well as to facilitate continued improvement in the methods. The uncertainty analysis is documented in IPET Volume VIII.

Why use risk assessment?

A significant part of the IPET effort was aimed at developing a system-wide risk assessment of the capability of the HPS to protect New Orleans against hurricane hazards. The goal of assessing risk is to facilitate rational decision making. The decisions that risk assessment supports include the following:

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

To put the post-Katrina level of risk in perspective, the IPET assessment examined risk for the HPS as it existed before Katrina and for the repaired and upgraded HPS as it existed in June 2007.

What is risk?

Risk is a concept that influences much of our lives but remains an emerging tool in many areas of water resources management. The insurance industry uses risk to set rates, businesses assess market risk, and the financial and stock markets are literally real-time risk assessments from millions of individuals who participate in the market. In water resources, risk has primarily been a tool applied to dam safety. Although similar, application of risk methods to a HPS such as the one in New Orleans is more complex because of the large geographical area; hundreds of miles of different types of structures, a wide range of conditions (soils, elevations, etc.), and the complex nature of hurricanes and the forces they can generate. It is important that the term risk and the way it is used in this study are clearly defined. One of the most difficult issues with risk is communicating the information itself.

Different people use the term "risk" in different ways. For our purposes and the analysis of risk for New Orleans, IPET defines risk as the chance of something bad happening multiplied by the consequences from that event. In New Orleans, bad equates to flooding and the consequences equate to loss of life and property. Thus, you can experience high risk from either being very vulnerable to flooding or having the potential to lose a lot when flooding occurs. Areas that have both poor protection and many people and much property exposed have the highest risk. Risk can be displayed as average annual consequences. For New Orleans the consequences considered are loss of life and loss of property. This is not to say that there will be loss of life and loss of property every year, only that the risks represent long-term averages of the potential for loss.

It is important up front to clarify that ***the 100-year flood is not a measure of risk: it is a measure of probability***. It measures the first part of risk, the chance of flooding, but not the second part, the consequences of flooding. It also does not provide information on what might happen if larger events occur. Risk incorporates the potential for flooding from the whole range of hurricane-generated water (surge and wave) levels as well as the losses that would result for different levels of flooding. There is no artificial cap on the analysis, but larger and rarer events are weighted by their lesser chance of occurring. As such, this approach to estimating vulnerability to flooding and losses is more comprehensive than approaches that rely on a single design storm or severe event such as the standard project hurricane or probable maximum hurricane.

We are influenced by and make decisions about risks every day. Insurance companies track the chance of you having an accident in your car or a fire in your home. They statistically track the potential losses from an accident or fire and use those data in combination with the chance of an accident or fire to set your insurance rates.

According to the National Highway Transportation Safety Administration (using 2004 data), an individual in the United States has an annual risk of losing his or her life in a traffic accident of 0.00015, which is 15 fatalities per 100,000 residents, or 1.4 fatalities for every 100 million miles traveled, under current patterns of driving. The chance of being in an accident is much greater, since not every accident involves fatalities. Statistics like this represent averages and are not necessarily representative of the risk one faces. For example, in Louisiana there are 2.03 fatalities per 100 million miles driven, making it higher risk than the national average. Within Louisiana, New Orleans has a traffic fatality risk 50% higher than Baton Rouge. These numbers are influenced by the amount of traffic, the condition and safety of the roads, traffic management, and simply reflect the history of accidents in the region.

We as individuals accept risk every time we get into a car. We also make risk-based decisions. We know that our risk is reduced in some vehicles compared to others. Air bags and seat belts, while not preventing accidents, reduce injury and deaths when an accident occurs. We can buy a safer car and buckle up when we drive. We can also choose to use public transport, which has a lower rate of fatalities-per-mile than do cars.

The situation is the same with hurricane protection. Risk can be reduced by having stronger physical protection and, thereby, reducing the probability of flooding; or by managing development in areas that have a high chance of being flooded, thereby reducing the consequences of flooding. We can also make personal choices such as living in an area with a lower chance of flooding, elevating our homes so the consequences of flooding are less, or having an effective evacuation plan to take ourselves out of harm's way.

Why use risk assessment for hurricane protection?

Much like risk statistics for cars, risk assessment for the New Orleans and Southeast Louisiana HPS provides a broad picture of the relative chance of a flooding in different areas of Southeast Louisiana and of the losses that could occur as a result of flooding. It is in fact more appropriate to call the HPS a storm damage risk reduction system rather than a protection system since it is impossible to "protect" against all possible threats. A risk reduction system protects people to a degree, to the level of residual risk (see Figure 1). Residual risk defines how much risk must be managed by means other than those in place.

By estimating residual risk for different locations, we know where the greatest problems are, and why. Risk varies with location due to variations in the chance of high surge and wave conditions, the strength and height of the protective structures, the elevations of the land subject to flooding, the numbers of people and structures exposed to flooding, and different emergency preparedness and response capabilities.

By understanding the sources of risk, directed action can be brought to bear against specific weaknesses. This helps save lives, minimizes property damage, and rank-orders improvement projects. Options such as evacuation planning and improved evacuation routes can be considered alongside more traditional options such as hardening pumping facilities, increasing first-floor elevations, improving land-use zoning, compartmentalizing drainage basins, armoring levees, and building safe harbors.

What risk assessment is not.

First, ***risk assessment is not forecasting***, and ***risk assessments do not reflect the impact of any single storm***. Risk assessment is a long-term look at relative vulnerability from the spectrum of storms that can occur, just as car insurance statistics look at long-term averages from the spectrum of driver experiences. Risk assessments do not predict what will happen in a given year, only what could happen based on long-term averages. Risk assessment forecasts the effects of many individual storms and aggregates the results into patterns.

Second, ***risk assessment in the current context is intended to support planning decisions***. It is not intended to support engineering decisions. A risk assessment over a large, complex geography like New Orleans requires many generalizations and assumptions, compared to the details of engineering design. Nonetheless, while risk assessment does not generate design information, it does inform design by defining hazards and suggesting alternative approaches to providing protection.

Risk Assessment Methodology

The methodology underlying the IPET risk assessment is shown in Figure 34. It has four steps.

Step 1: The hazard is the event or condition with the potential for causing an undesirable consequence. In the present context, the hazard is surge and wave conditions caused by hurricanes; it is not the hurricane themselves. To assess the hazard, it is first necessary to identify the range, character, and frequency of hurricanes that may strike the southern Louisiana coast.

IPET used state-of-the-art methods, including supercomputer models, to compute the surge and wave conditions that a wide variety of hurricanes would produce around New Orleans. This analysis led to estimates of the frequency of extreme surges and waves everywhere around the HPS. These estimates are for current climate conditions, and they do not project climate variations into the future, although continuing work is investigating the effect of potential climate change.

Step 2: System performance is the response of the HPS to the hazard, that is, to surge and wave conditions generated by the hurricanes. The system performance is assessed by modeling the reliability of the HPS under loads generated by surge and wave. This leads to an estimate of the likelihood that the HPS can withstand those loads and, correspondingly, to an estimate of the chance of flooding at various places across the city and region. This chance of flooding is sometimes called the *vulnerability*.

The reliability analysis starts with a detailed inventory of the engineering characteristics of every section of the HPS. Then, the potential for overtopping and breaching is estimated for the spectrum of surge and wave conditions forecast in the hazard assessment. Combining the potential for overtopping and breaching with the frequencies of the corresponding hazards leads to an assessment of vulnerability to flooding from the spectrum of hurricanes that are possible for the region. The calculation also includes the chance of water entering through open gates and the amount of rainfall associated with hurricanes.

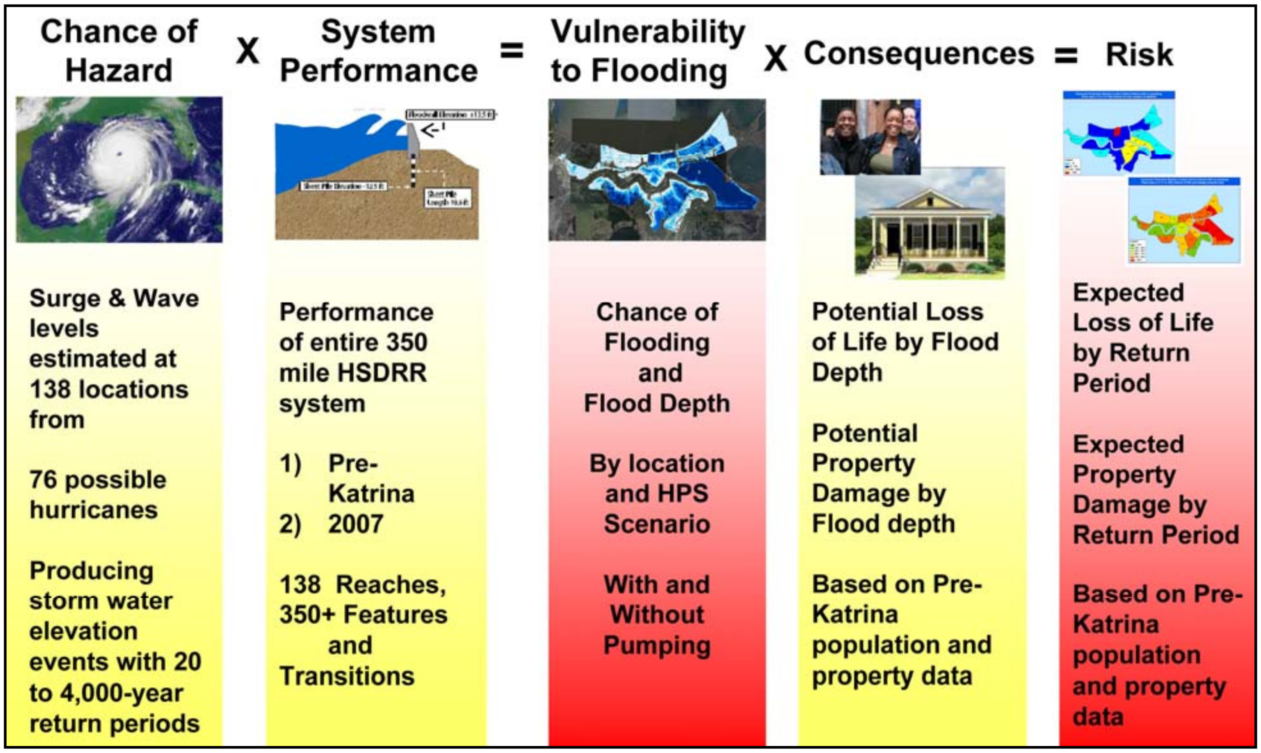

Figure 34. Risk assessment framework used in IPET analysis of New Orleans. While risk was assessed for a projected 100-year HPS design scheduled for 2011, this document only discusses the risk for the Pre-Katrina and 2007 HPS conditions.

Step 3: The consequences of flooding, measured by potential loss of life and property damage, are estimated by defining the distribution of people and structures within each sub-basin, the elevations of all structures and the surrounding land, and the value of the properties; and then by applying actuarial information and models to approximate losses.

Consequences were estimated for different depths of flooding to determine expected losses across the spectrum of hurricanes. The results are summarized for three chances of occurrence, specifically, the 1/50-, 1/100-, and 1/500-year floods. For loss of life estimation, a sophisticated simulation model was developed using geo-spatial census databases and evacuation plans. For property damage estimation, historical data from flood control and coastal protection projects across the nation were used to develop flood-depth versus damage relationships.

Step 4: Risk is calculated by combining the chance of undesirable consequences occurring with the magnitude of those consequences should they occur. This allows an estimate of risk by area, based on the character of the HPS and other measures that may influence who and what is exposed to flooding. Risk is calculated by multiplying the chance of flooding to a certain depth by the losses expected by the flooding. Losses can be expressed as potential loss of life or potential loss of property.

Risk was estimated for the HPS as it existed (1) prior to Katrina and (2) for after the repair and rebuilding of the HPS through June 2007. Risk was also assessed for a projected 100-year HPS design scheduled for 2011, but this effort is not reported in the IPET reports in that it was accomplished as a separate activity in support of the Corps of Engineers' New Orleans District design of a more robust Hurricane and Storm Damage Risk Reduction System.

Since a principal purpose of the risk assessment was to determine how risk is changing with respect to the capabilities of the HPS, both the pre-Katrina and post-Katrina risk were estimated using the pre-Katrina distribution of population and property. Using today's population and property conditions would show a dramatic reduction in risk simply because the number of people in some areas is dramatically fewer than before Katrina, not because of changes to the HPS. Maintaining the population and property data as a constant allows changes in the chance of flooding and, therefore, risk to be related to improvements in the HPS.

Defining the hurricane protection system (HPS)

Principal Assumptions

1. The risk assessment is engineering-based, requiring a detailed inventory and description of all the components of the HPS.
2. The HPS was divided into basins and sub-basins representing the major drainage areas within the protected area.
3. The perimeter of the HPS was defined by reaches (levee or floodwall sections), point features such as gates, and transitions between different structures (e.g., levee/wall, wall/levee, gates, pumping stations, drainage structures, and ramps).
4. Reaches defined sections of the HPS are expected to have similar physical, performance, and hazard characteristics.

The first step in the risk assessment was to define the drainage areas within which flooding might occur. This divided the region into parish-level drainage basins (e.g., Jefferson Parish, Orleans Main, New Orleans East), and then into sub-basins within the parishes. The boundaries are based on the location and character of the HPS structures, the topography of the protected areas, and the internal drainage system (Figure 35a).

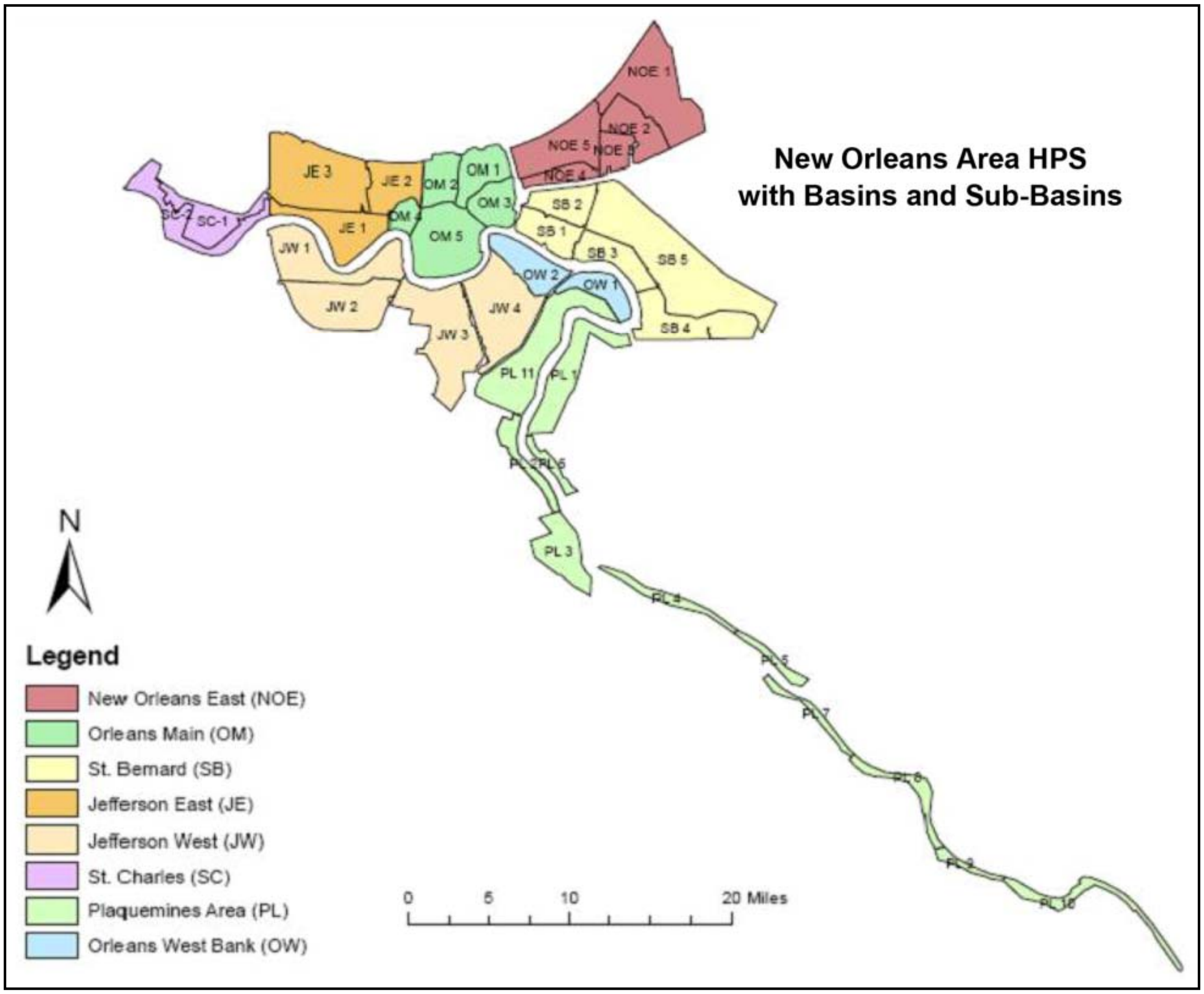

Figure 35a. Definition of drainage basins and sub-basins for risk assessment.

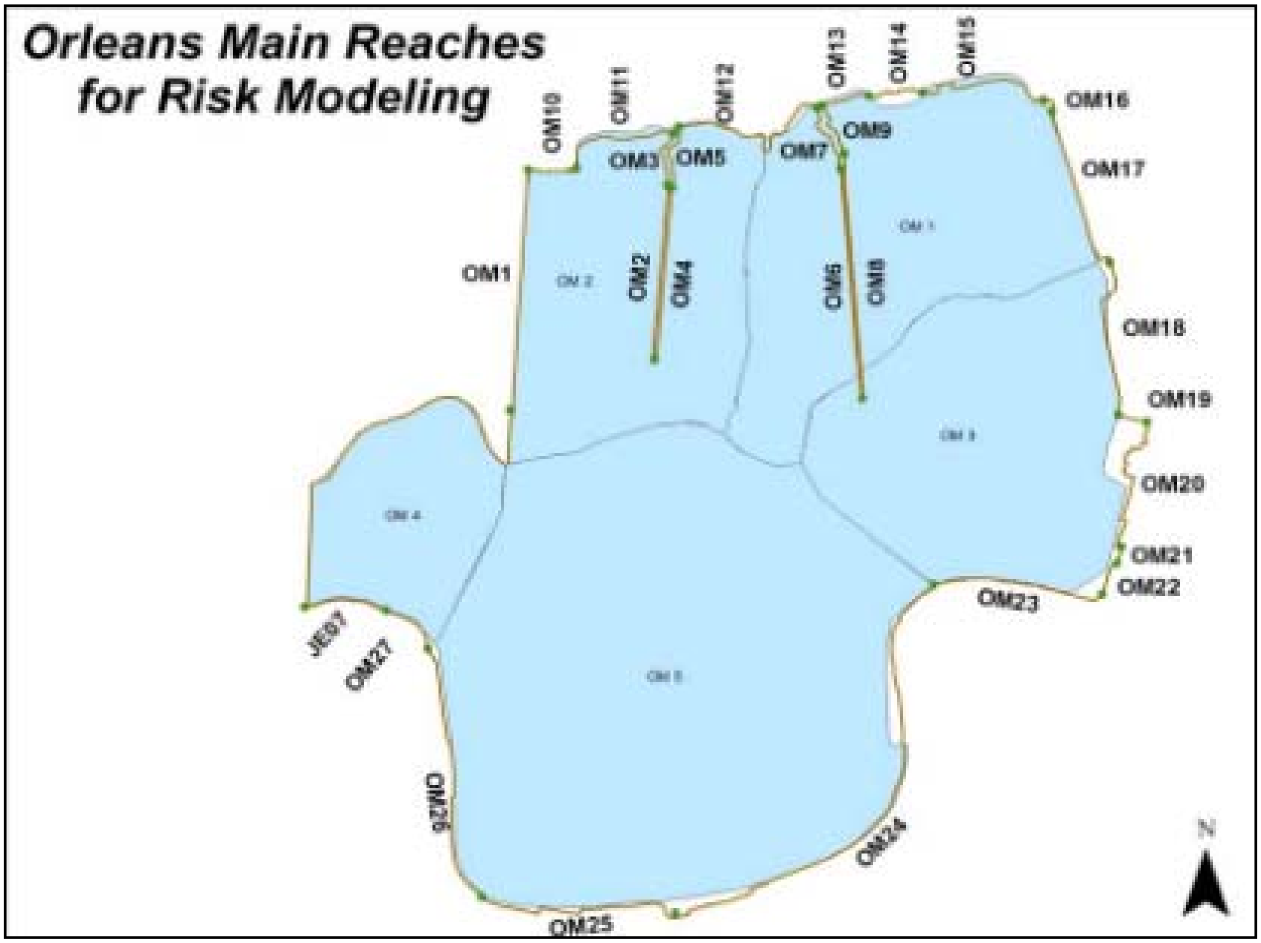

Figure 35b.Definition of reaches for Orleans Main Basin risk assessment. Reach definitions for all basins and sub-basins are given in IPET Volume VIII.

Estimating potential flooding in each protected area (by sub-basin) required that the structures and features composing the HPS be defined in enough detail so their individual and collective performance could be examined. To do so, the HPS was divided into reaches, transitions, and features. Reaches are lengths of levees or walls that have uniform elevation, strength, foundation, and hazard conditions. Reaches may be short or long, depending on the character of the structures in place. Features include such things as pumping stations and closure gates. Transitions are a change from one kind of structure to another (e.g., a levee to a concrete floodwall).

There were 135 reaches defined for the Pre-Katrina HPS and 138 defined for the 2007 HPS. The additional three reaches for the 2007 HPS (numbers 136, 137 and 138) represent the three new gate closure structures for the London Avenue, Orleans and 17th Street outfall canals. The Pre-Katrina HPS had 416 features and transitions compared to 375 for the 2007 HPS. Tables documenting the reach and feature characteristics for each basin are available in IPET Volume VIII. As an example, Figure 35b shows reach definitions for the Orleans Main Basin.

Repairs and structural enhancements made following Katrina have been factored into the data used to describe and model the 2007 HPS. Figure 36 shows the general map of the 2007 HPS and lists the repairs and enhancements that were accomplished after Katrina and modeled in the risk assessment. Table 9-1 provides a summary of reach lengths and heights for the pre-Katrina and 2007 HPS.

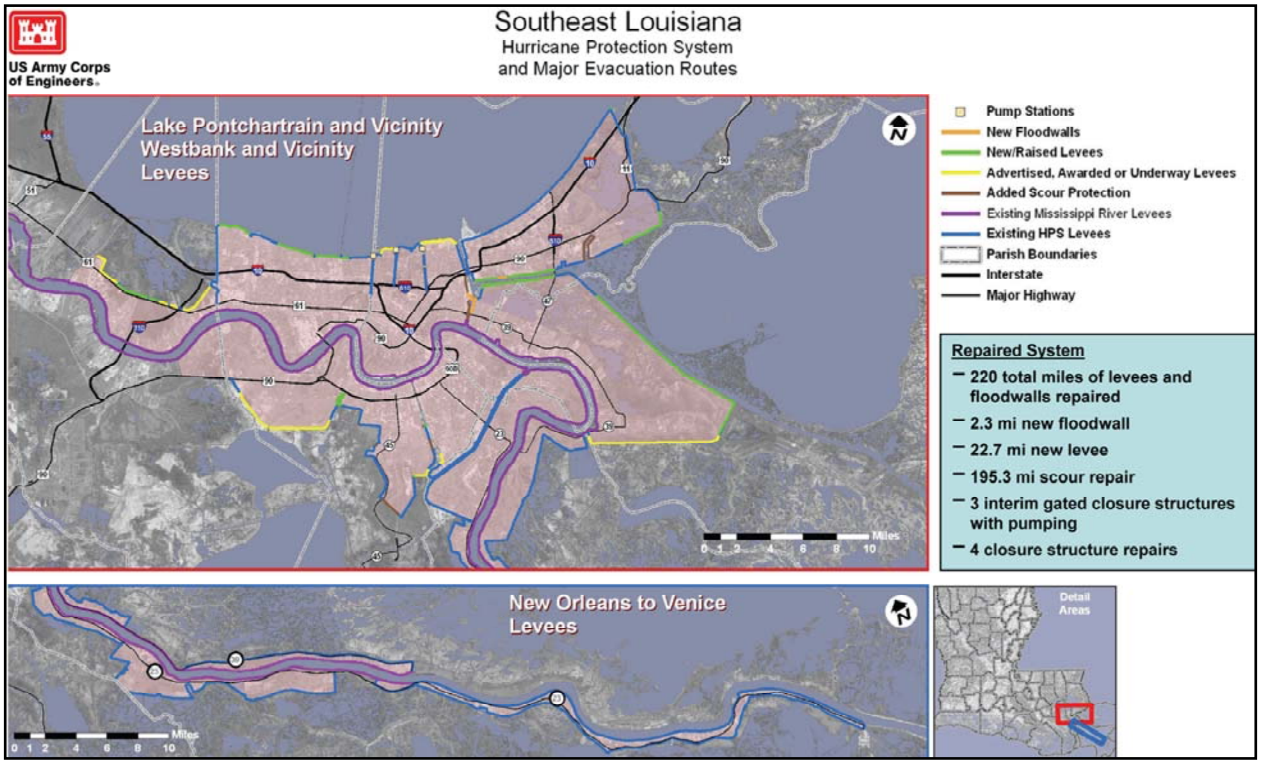

Figure 36. General configuration of 2007 HPS and list of major repairs and upgrades included in the 2007 HPS. Structures shown in yellow, indicating contracts pending for construction, were modeled in their existing June 2007 condition for this analysis. Source: U.S. Army Corps of Engineers.

Assessing the hazard

Principal Assumptions

1. The historical record is inadequate to characterize the surge and wave threat for New Orleans into the future.
2. Traditional methods of extrapolating historical data are inadequate in that they assume the past is representative of the future.
3. Storm records differ in accuracy. Prior to 1940 the data are less reliable and incomplete. This analysis was limited to post-1940 data.
4. The joint probability method, modified to provide optimal sampling, was chosen to provide a forward looking hurricane and surge and wave climatology for the IPET risk assessment and reduce the requirement for modeling thousands of storms.
5. High-resolution, physics-based models were used to improve the accuracy of surge and wave predictions.
6. A total of 152 storms were selected based on physics and climate conditions to represent the present-day hazard for New Orleans. A sample of 76 of these storms was used to drive the risk analysis.
7. The IPET "Hurricane Hazard" is a definition of the frequency of occurrence of surge and wave heights in a large number of locations around New Orleans and vicinity. Specifically, it includes complete storm hydrographs for each of the reaches of the HPS.

The relationship between surge and wave levels and how frequently they occur differs greatly around the HPS. IPET, the Corps of Engineers, FEMA, and NOAA have worked together, along with the top hurricane experts, to study the surge and wave environment of New Orleans. Collectively, these investigations have greatly advanced our understanding of hurricane forces. Today, we know considerably more about hurricanes and their effects than we did prior to Katrina.

The method developed by IPET for evaluating surge and wave hazard involves three steps. This is called, *the joint probability method – optimal sampling* method.

- The first step is to assess the frequency of hurricanes of particular description (e.g., intensity, size, maximum wind speed) coming ashore in southern Louisiana.
- The second step is to calculate the spatial pattern of winds (the wind field) arising from a hurricane with a particular description.
- The third step is to calculate the surges and waves that result from the hurricane and its wind field, and to associate them with probabilities of occurrence.

Step 1 — What hurricanes might occur? The first step requires looking at potential hurricanes. In the past, this was done by analyzing historical hurricanes and extrapolating from those records. In the original design of the New Orleans HPS in the 1960s, historical data were used to define a standard project hurricane (SPH). The SPH was a hypothetical hurricane representing "the most severe storm considered reasonably characteristic of a region." The surge created by the SPH traveling along a few select tracks was used as the basis of design. In later years, the historical record was used to artificially generate a larger sample of hurricanes, to provide multiple storms for modeling surge and wave conditions.

Experts believe these approaches are no longer the best approach, especially with the recognition of trends toward more frequent and intense hurricanes. Yet, historical hurricanes are important because they are a sample of what nature can produce, and they allow any process to be checked against known information.

A major finding of the Katrina investigations was the importance of considering both the intensity (central pressure deficit) and physical size of a storm (radius to the maximum wind speed) to surge generation. It was Katrina's combination of high intensity and large size that allowed it to create the highest surge ever experienced in North America. Figure 37 shows the pressure deficit – size relationship for historical storms. Hurricane Camille, a Category 5 storm on the Saffir-Simpson scale at landfall, was a more intense storm than Katrina (Category 3 at landfall), but Katrina was larger in diameter and generated greater surge. The Saffir-Simpson scale categorizes hurricanes by ranges of maximum wind speed, ranges of surge height, and descriptions of property damage (*http://www.nhc.noaa.gov/aboutsshs.shtml*) and is often criticized today for being simplistic.

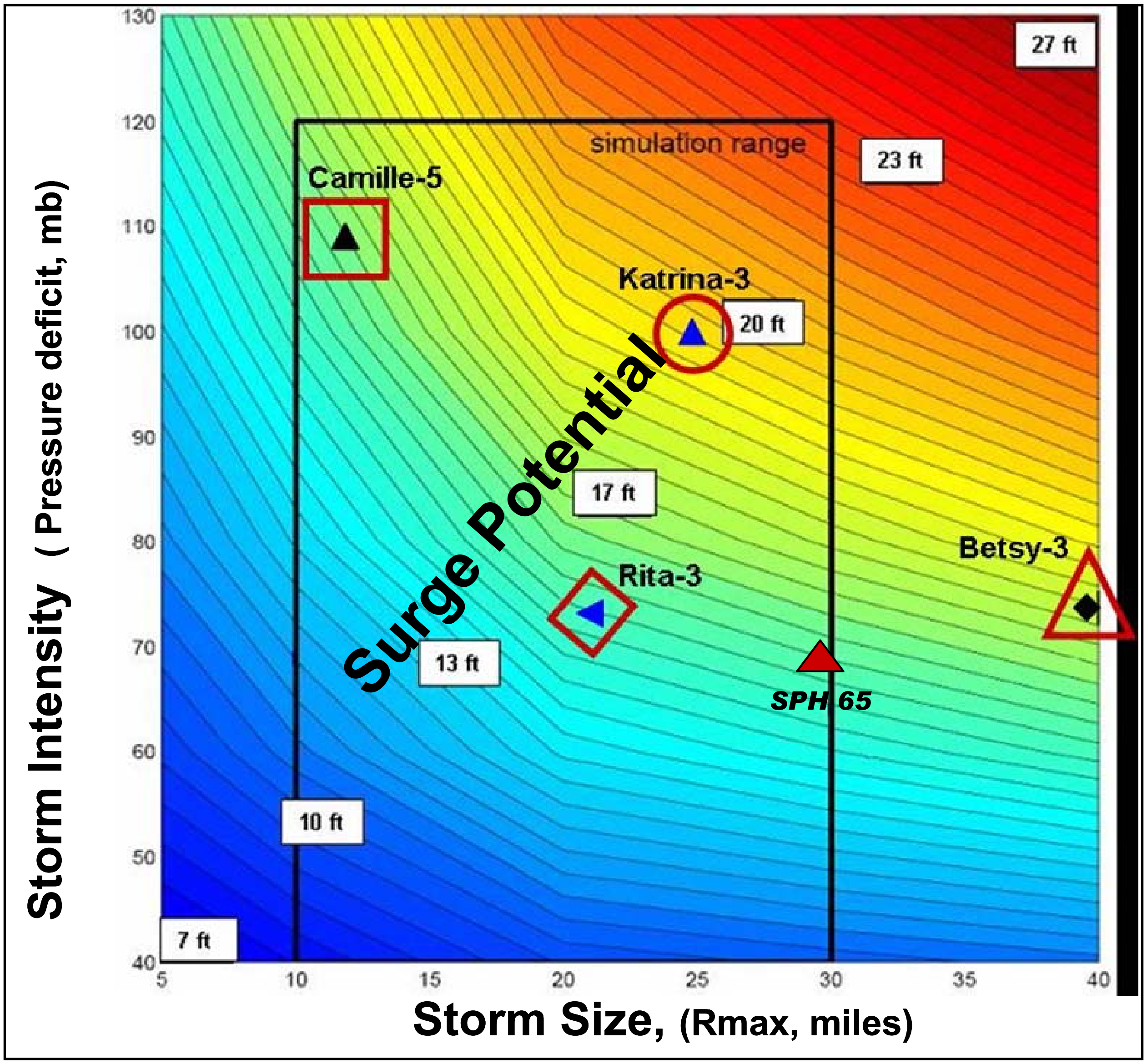

Figure 37. Relationship of intensity (central pressure deficit) to size of historical storms including their Saffir-Simpson category at landfall. This plot assumes a simple straight-line shoreline with a 1:1000 ocean bottom slope (Irish et al.[1]). As such, the data here are meant as a means to compare the surge generation potential of different storms, not to represent the surge they actually created for the specific coastline and bottom geometries in the specific locations where they struck.

The Joint Probability Method—Optimal Sampling (JPM-OS) summarizes historical information on hurricanes in a joint frequency distribution of the parameters used to characterize individual hurricanes (Table 1).

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[1] Irish, J.L., Resio, D.T., and Ratcliff, J.J. 2008: The influence of storm size on hurricane surge. *J. Phys. Oceanogr*. 38 (11), 2003-2013.

Table 1 Major Hurricane Parameters	
Parameter	**Description**
Intensity (central pressure deficit)	Usually described by the Saffir-Simpson scale, which relates category of storm to the maximum wind speed and damage effects.
Size (radius to maximum wind speed)	This is a measure of the diameter or width of the storm determined by how far away from the eye that the maximum wind speed occurs. It can also be examined by the distance to which hurricane force winds exist.
Speed (rate of forward motion)	This is simply the speed that the hurricane is traveling along its path.
Track angle (angle to shoreline azimuth)	This measures the angle of the hurricane path with respect to the shoreline.
Landfall location	This measures the distance between a point of interest and the location where the center of the hurricane strikes land.
Storm shape (Holland "B")	This measures how rapidly the winds degrade or the peakedness of the hurricane.

Storms having a variety of these characteristics were sampled from the joint probability distribution by hurricane experts to represent the spectrum of storms that could threaten New Orleans. The annual probability of each of these hypothetical storms is taken from the joint probability distribution. Using this approach, for example, Katrina was computed to be roughly a 400-year storm—on the basis of its meteorological parameters, not on the basis of its surge and waves. In total, 152 hurricanes were sampled and used in the IPET analysis; 76 of those were used to drive the formal risk analysis.

Based on the considerations of data quality, the historical data used to define the frequency of occurrence of the hurricane descriptors was limited to the 67-year span from 1940 through 2006. Although the historical database includes information back to 1851, the older data is suspect and does not describe the character of the storms before landfall, which was necessary for accurate surge and wave estimates.

Figure 38 shows pressure and size combinations used in the JPM-OS analysis. To calibrate and test the JPM-OS approach, IPET primarily used hurricanes Rita and Katrina since they represented the only storms with comprehensive data available for this purpose. This new data set defines a modern hurricane hazard, using the latest knowledge, but it does not project potential climate change impacts on storm intensity or frequency into the future. Such projections would have involved significant speculation that was beyond the scope of the IPET effort. Table 9-2 in Appendix 9 of this volume provides a summary of the characteristics of the 152 hurricanes modeled in the JPM-OS/Modeling process.

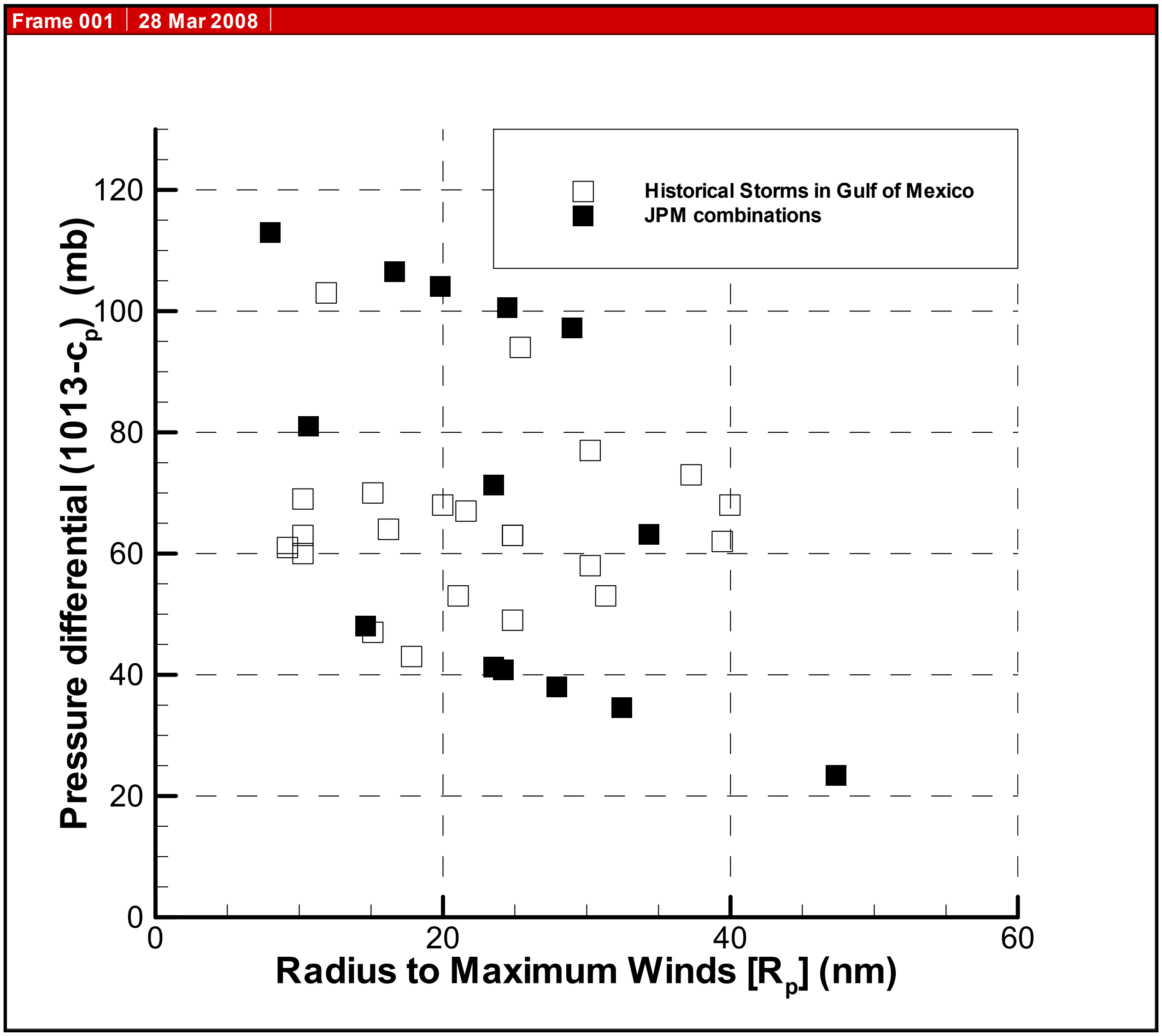


Figure 38. Plot comparing the pressure deficit-size combinations of historical and JPM-OS storms used to define the hazard for the risk assessment (Irish et al.).

Step 2 — What wind fields associated with the hurricanes? The hurricane characteristics were entered into a sophisticated atmospheric model (planetary boundary layer model) to develop a time-history of the wind and atmospheric pressure fields representing each hurricane. The winds and low atmospheric pressure generated by hurricanes are the primary forces that cause the high storm surge and large waves that reach land. The surge is built up over the life of the storm, as are the waves, making it important to model the storm for many days to accurately estimate the resulting surge and wave levels. This was the basic input to the surge and wave modeling efforts.

This large sample of storms was used to compute the surge and wave conditions that each would generate at a large number of locations, giving decision makers a larger and more comprehensive database to define the hazard, the likelihood of any location experiencing water levels of different heights.

The JPM-OS was used to generate a set of 152 storms for use in the risk assessment. These storms represent relatively common storms to those that are quite rare, providing an effective data set for evaluating risk over a wide range of conditions. Since wind, surge, and wave simulations using high resolution computer models are computationally demanding, it was important to use as few storms as possible to define the hazard, keeping the methods affordable and time efficient. Of the sample of 152 hurricanes, 76 were used to directly assess vulnerability to flooding and risk.

Step 3 — What surge and waves would occur? IPET used the same surge and wave models (ADCIRC and WAM/STWAVE) that were used to estimate water levels created by Hurricane Katrina. These models were verified in the IPET Katrina analysis (IPET Volume IV) by matching computed estimates to observed high-water marks. The models were coupled together to include the impact of energy transfer from waves that can increase surge levels (wave setup).

In this process, an estimate of the total free water elevation was determined in a stepwise process. ADCIRC was first run to determine initial surge elevations and wind field data. STWAVE was then run to estimate distributed wave conditions. The wave information was fed back into ADCIRC as an additional forcing term to consider wave setup, which is the transfer of wave radiation stress associated with the storm that increases surge levels. The result is a time-history of water elevation at each location, that is, a *hydrograph*, for each storm (Figure 39). An estimate of wave conditions by location, expressed as significant wave height and period, also resulted. Table 9-3 in Appendix 9 of this volume provides a summary of predicted water elevation data from the JPM/OS modeling process. It includes for each reach the maximum water level (without runup) for all hurricanes, water levels from Rita-like and Katrina-like hurricanes, and the water elevations associated with the 50-, 100-, 500-, and 1,000-year return periods.

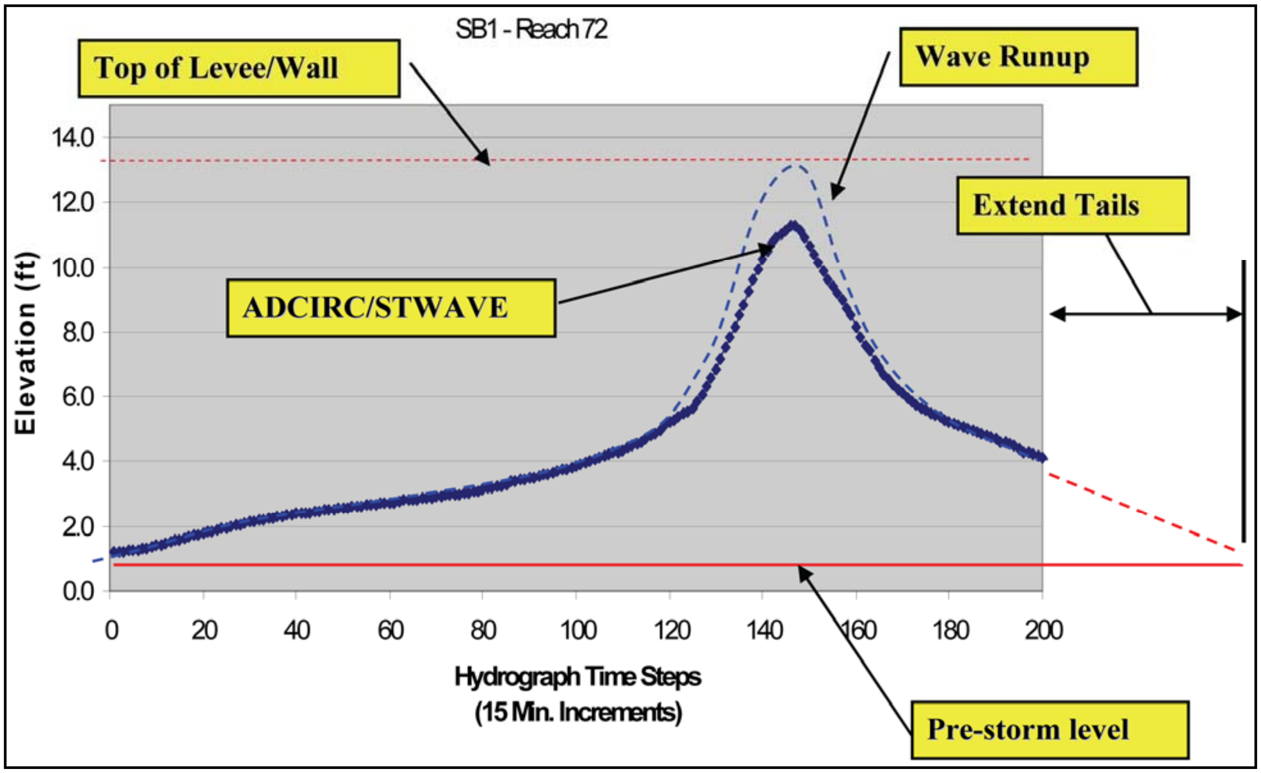


Figure 39. Illustration of storm hydrograph for a location. Graph shows specific process augmentation after ADCIRC/STWAVE simulation, which includes wave setup.

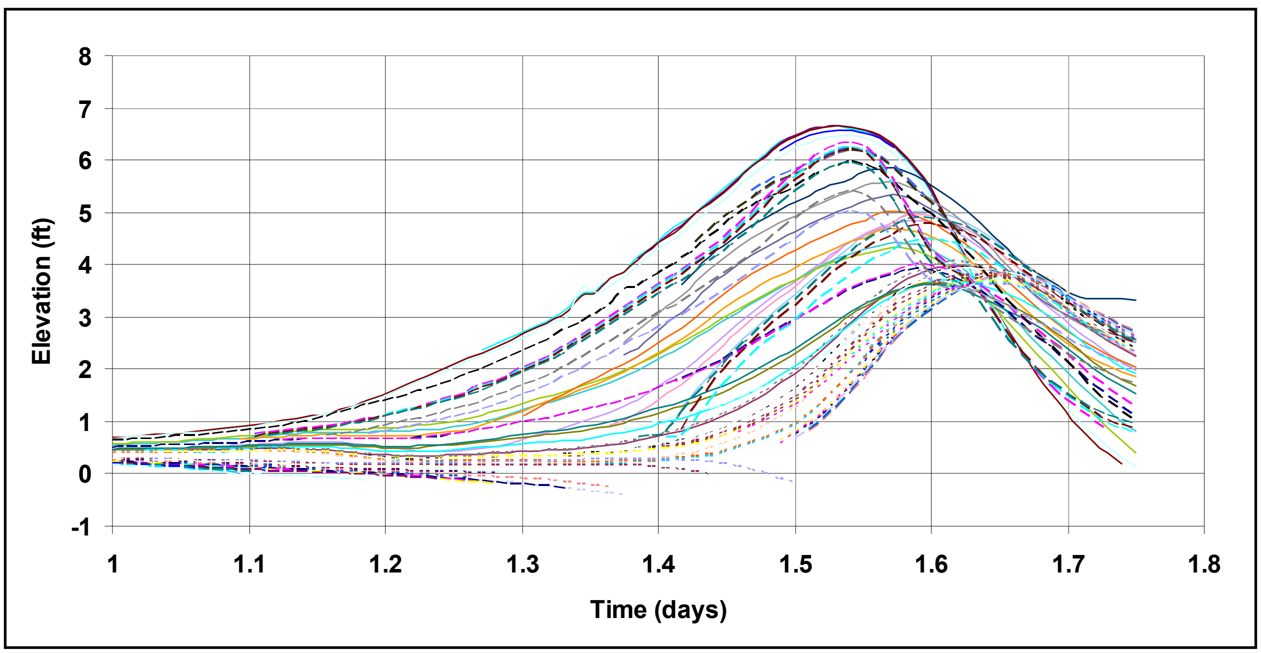


Figure 40. Example of hydrographs for a variety of locations around the HPS from a single storm.

Each storm resulted in a separate hydrograph for each section of the HPS that was evaluated in the reliability assessment (e.g., Figure 40). In a separate step, an estimate of wave runup (additional water elevation due to the impact of waves near shore interacting with individual structures) was determined to evaluate the volume of water that could enter a sub-basin by overtopping and the effect of the additional loads generated by the waves on the reliability of the HPS. Approximately 20,000 hurricane hydrographs were generated for each HPS scenario evaluated in the risk assessment. Table 9-4 in Appendix 9 of this volume provides for each reach a summary of the modeled maximum significant wave height and associated wave period information for all simulated hurricanes to include Rita-like and Katrina-like hurricanes.

It was necessary to estimate the entire hydrograph of the free water elevations for the risk assessment. Since one of the key products of the assessment is an estimate of the amount of water that would enter the protected areas by overtopping or breaching, it was essential to be able to estimate the amount of water available to flow over structures or through breaches at any given time and location. Each hydrograph was divided into 30-minute time-steps to estimate water level and water volumes for the risk assessment. Since the character of the HPS structures (height and geometry) themselves can influence the height of the water levels, separate computations were made for the pre-Katrina HPS and for the June 2007 condition of the HPS to better capture the influence of the changes between the two systems.

System Performance

The performance of the HPS when loaded by surge and waves was analyzed in four steps. First, the performance of the individual components of the system was assessed. Then, the performances of the components were combined in a systems model to account for their interactions and dependencies. Then the contributions of rainfall associated with hurricane storms and internal pumping were evaluated. Finally, the impacts of inter-basin flows were considered.

Principal Assumptions

1. Fragility relationships (the probability of failure plotted against water elevation) were developed as the fundamental descriptor of structural performance for the reliability analysis. The fragility curves were developed from all information sources available (from original design memoranda to IPET post-Katrina investigations).
2. Fragility curves defined both the traditional global stability of structures (performance for water levels to the top of wall/levee design elevations) and their performance when experiencing overtopping. Erosion of structures from overtopping was considered using empirical post-Katrina field data and erosion rates for different soil types and surface cover (such as grass).
3. A traditional event tree approach was used to estimate the likely performance of the individual features and reaches for each hurricane hydrograph resulting in estimates of the volume of water that would enter each protected sub-basin from each hurricane.
4. The significant wave height was added to the free water surface (surge plus wave setup) to estimate volumes entering protected areas.
5. Water volumes entering a sub-basin from a specific hurricane were associated with the frequency of occurrence of that hurricane.
6. The drainage inter-relationships of the sub-basins were considered with a simple model that did not represent the subsurface drainage network.
7. Idealized pumping capacities were used to estimate the degree of impact pumping could provide to reduce flood levels. These capacities do not reflect actual pumping capability.

Component reliability: Component reliability means the chance that a component of the system—a levee reach, a gate structure, a transition, and so on—will fail to perform its intended purpose as a function of the loads placed upon the component. In the present case, the intended function is to keep water out of the protected areas behind the HPS, and the loads are the water heights on the outside of the system.

The reliability of a reach or other component is summarized in a *fragility curve.* A fragility curve (Figure 41) describes the probability of failure as a function of possible water level. A value near zero means little chance of failure; a value of one means certain failure. To perform a reliability analysis of a reach within the HPS, it is essential to understand subsurface geologic conditions, the design of the structures, how the reach was constructed, and how it has been maintained.

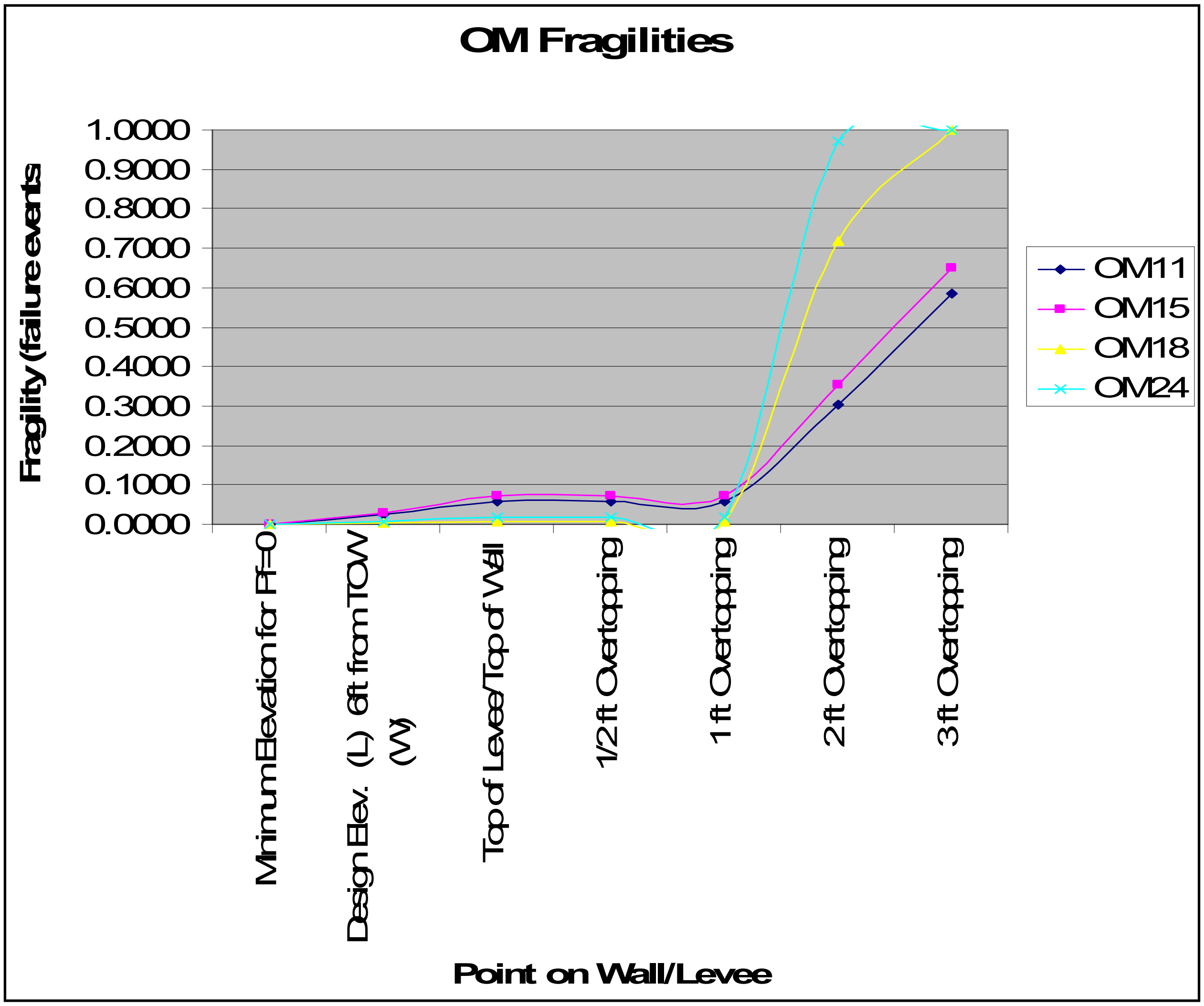


Figure 41. Fragility curves (mean values) for a sample of reaches in the Orleans Main (OM) Basin. OM11 and 15 are along the south shore of Lake Pontchartrain, OM18 is on the west side of the IHNC, and OM24 is a portion of the Mississippi River main line levee.

The bottom section of the fragility curve (lower water elevations) represents the period of time when the water level is below the crest of the structure. If failure occurs at this time, it is because the structure was not strong enough to resist the forces created by the water. As water nears the crest, waves begin to overtop the structure and introduce the possibility of erosion on the back side of the structure. Erosion can lead to breaching of an earth levee by washing away soils and creating a breach through which more water can flow, creating more erosion and eventual failure. For a floodwall, overtopping can cause erosion of the soils behind the wall leading to a loss of stability and eventual failure. Overtopping was the cause of all but four of the catastrophic breaches during Katrina.

Fragility curves were developed for each reach and feature so that the reliability of these components could be estimated. Separate curves were developed for the reach and features of the pre-Katrina HPS and for the June 2007 condition of the HPS to determine the changes in vulnerability to flooding for each basin and sub-basin based on the repairs and upgrades to the HPS since Katrina. Fragility curves for each reach are documented in IPET Volume VIII.

Systems reliability: The assessments of hazards as manifest in hydrographs and wave loadings, and of component reliability as manifested in fragility curves, are brought together in an event tree (Figure 42). The event tree characterizes the interactions of loads, responses, and potential inundation. The event tree charts all the possible ways the many components of the HPS might perform under a given hurricane scenario, and it provides a vehicle for logically calculating the corresponding probabilities of different levels of flooding. These probabilities are weighted over all the 76 hurricane scenarios to arrive at annual probabilities of flooding from the set of possible storms sampled using the JPM-OS methodology.

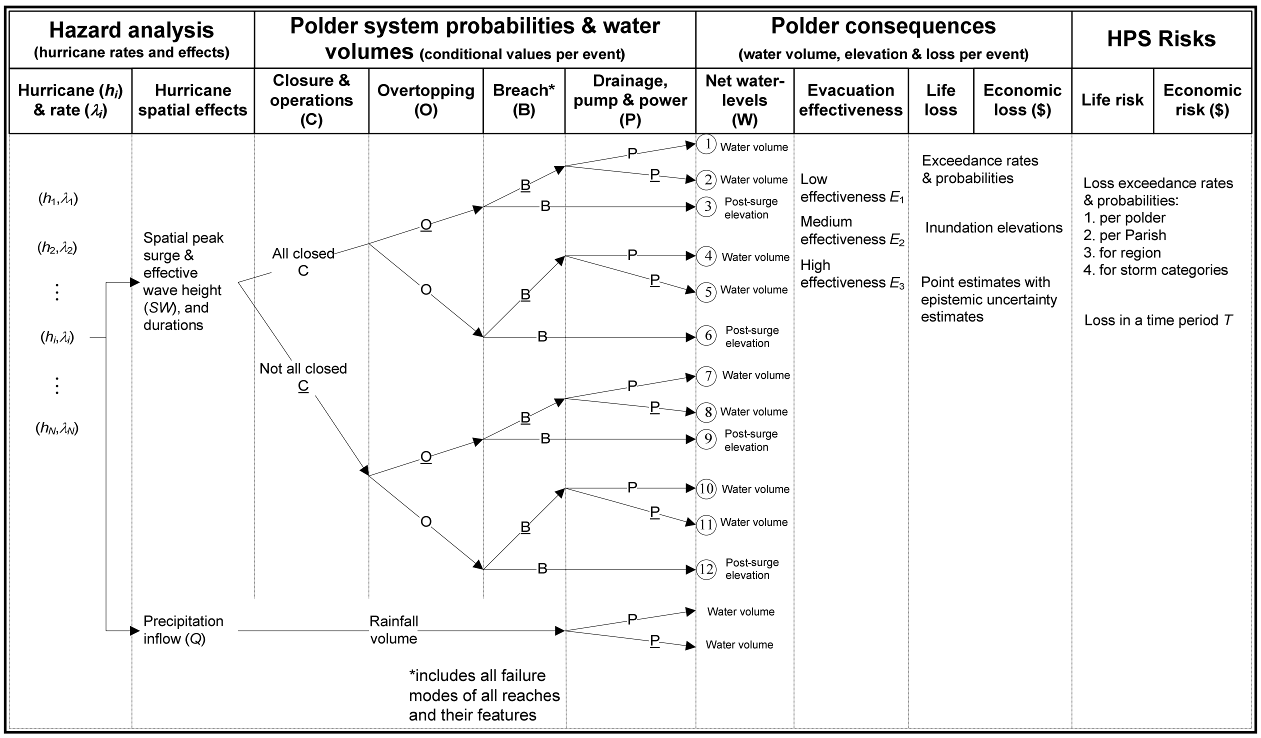


Figure 42. Sample event tree calculations for volumes of water entering protected areas.

Rainfall and pumping: The rainfall volumes that would be associated with each of the 76 hurricanes defining the hazard were estimated based on NASA data that correlates rainfall intensity and volume with hurricane characteristics. The total rainfall volume entering each sub-basin was computed for each hurricane and is documented in IPET Volume VIII. Rainfall was assumed to occur for periods of 8 to 12 hours, depending on the character of the storm. By adding the additional water volumes from rainfall, a total volume of water, for each storm, was determined for each sub-basin.

Pumping impact was considered using the following basic process:

- Determine total sub-basin design pumping capacity.
- Determine rainfall duration per storm from intensity curves (generally 8 to 12 hours).

- Determine volume of rain and runoff appropriate to each sub-basin.
- Assume pumps will perform at the assumed capacity (0%, 50% or 100%).
- Determine volume of water that pumps could evacuate per storm at the selected capacity.
- Subtract pump volume from rainfall to determine net volume.
- If net volume is a positive value, replace rainfall with net volume.
- If net volume is a negative value, replace rainfall with net volume = zero.

The pumping capacities used were the design ("name plate") capacities for all pumps that evacuate water from each sub-basin. ***These capacities are "ideal" values and do not reflect the current or projected actual operational capacities,*** which are highly dependent on the operational efficiency of the pumps and the condition and capability of the internal drainage system to get water to the pumping stations. Table 9-5 in Appendix 9 of this volume provides a summary of sub-basin pumping ideal or name-plate capacities used as a basis for the pumping analysis.

Sub-basin interflow: Once the estimates are made for the volume of water that would enter each sub-basin from a given storm, the topographic relationships between adjacent sub-basins are considered to model the flow of water between the sub-basins as it would naturally. This does not include modeling of the intricate drainage system of canals, conduits, etc., that also provides a means for water to move between areas. That detail of modeling is not feasible in the IPET risk assessment process.

Estimates of potential flooding: By considering the topography of each sub-basin, it is possible to develop a curve that represents the volume of water that would be stored in the basin for different water elevations (e.g., Figure 43). Curves have been generated for each of the sub-basins. Using this relationship, the estimated volume of water entering a sub-basin from each storm can be converted to an approximate water elevation. This elevation represents an estimate of the elevation of flooding from that hurricane, and it is associated with a corresponding probability based on the event tree analysis.

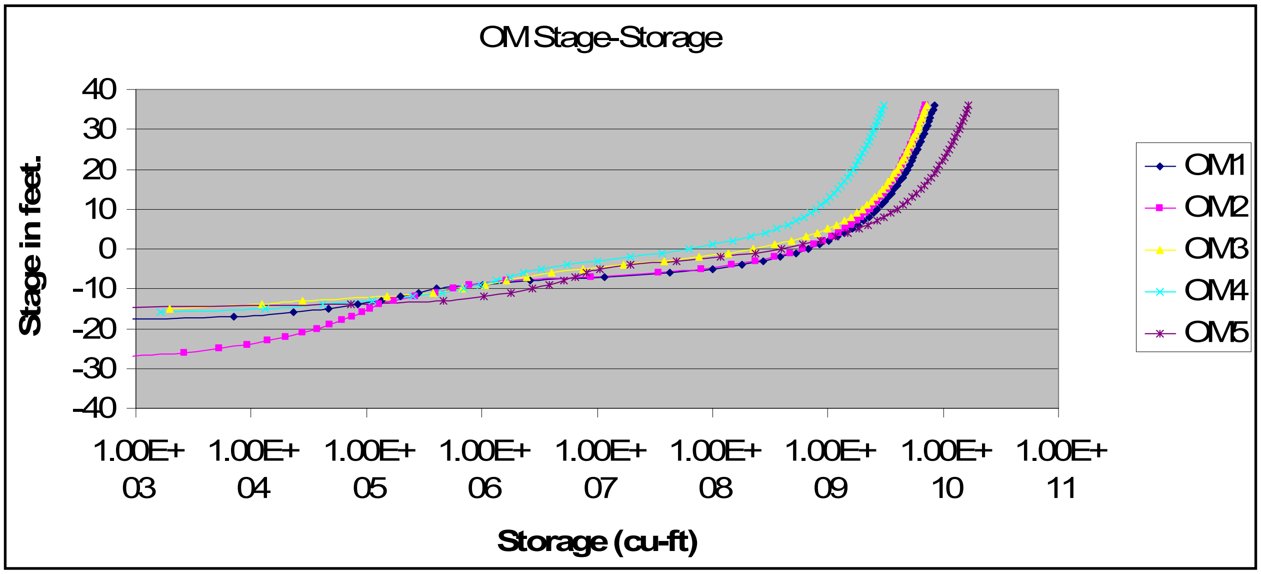


Figure 43. Example of relationship between the volume of water in a sub-basin (storage) and the resulting water elevation for OM sub-basins.

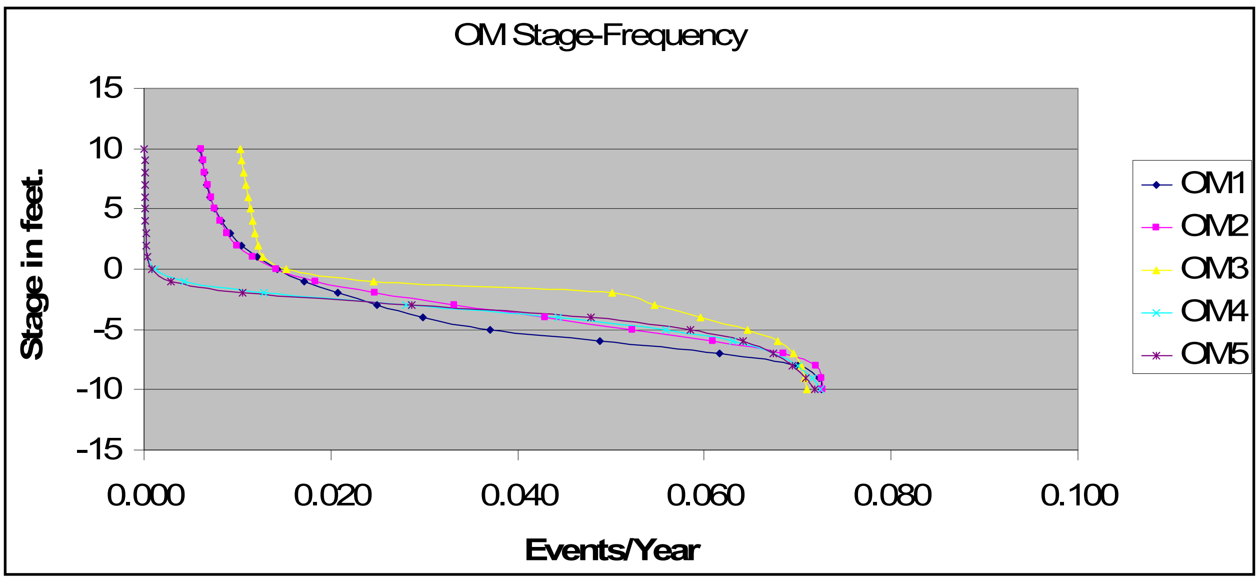


Figure 44. Example of water elevation – frequency of occurrence (exceedence) relationships for OM sub-basins. These curves do not include the impact of flow of water between sub-basins by natural drainage, which is considered separately.

The curves typified by those in Figure 44 are the basis for generating maps showing vulnerability to flooding. For example, given the volume of water for a sub-basin that equates to a chance of occurrence of 1% in any given year, Figure 44 can be used to determine the water elevation representing the 1% flood for that basin.

The flood with a 1% chance of occurring in any given year is commonly referred to as the “100-Year” flood; 100 years is the reciprocal of a probability of 0.01 per year and is called the *return period*. Many people find this designation confusing. Table 2 provides a reference for interpreting what return periods mean in a practical sense.

Table 2.
Relationship between terms used to describe probabilities and chance of events.

Recurrence Interval	Probability of Occurring in any Year		% Chance of Occurring in:		
"X-Year"	"1 in X"	"%"	30 years (mortgage)	78 years (Average U.S. lifespan)	100 years
500	1 in 500	0.2	5.8	14.5	18
100	1 in 100	1	26	54	63
50	1 in 50	2	45	79	86
25	1 in 25	4	64	96	98
10	1 in 10	10	96	99.9	100

Consequences

The estimation of consequences for Katrina and the fundamental assumptions and processes developed to estimate losses for other flooding scenarios are described in IPET Volume VII, *The Consequences*. The losses considered for this analysis are based on the pre-Katrina distribution of population and property and pre-Katrina property values. This results in all reductions in risk being attributed to the changes in the HPS, not to changes in exposure of property or people. This was a deliberate decision made to avoid speculation on and the uncertainty of rates and distribution of redevelopment and recovery. Consequences were estimated using the processes described in detail in IPET Volume VII, *The Consequences*. There are a few differences that will be highlighted here.

Principal Assumptions

1. Flood elevation – loss relationships used for the risk assessment represented the population and property distribution (and property values) prior to Katrina.
2. The loss relationships were aggregate for each sub-basin.
3. The loss of life estimates were computed in concert with those described in IPET Volume VII, *The Consequences*, and used LIFESim model to estimate population at risk and a probability distribution of possible evacuation effectiveness that was modeled after the Katrina experience to estimate fatalities.
4. Economic losses were estimated using 2005 property values.

The relationships used to determine expected losses for a given flood frequency (elevation) are shown schematically in Figure 45. Expected losses for various water elevations were determined for each sub-basin. Economic losses are based on the structure elevations, geographic distribution, and property value at the census block level. Loss of life was estimated using pre-Katrina population demographics by census block through the use of two computer models.

Life loss was estimated using the LIFESim Modeling System (McClelland and Bowles 2002[1]). This models how people in flooded areas redistribute vertically in buildings in relation to depth of inundation and classifies population demographics into one of flood lethality zones. LIFESim was run without considering evacuation.

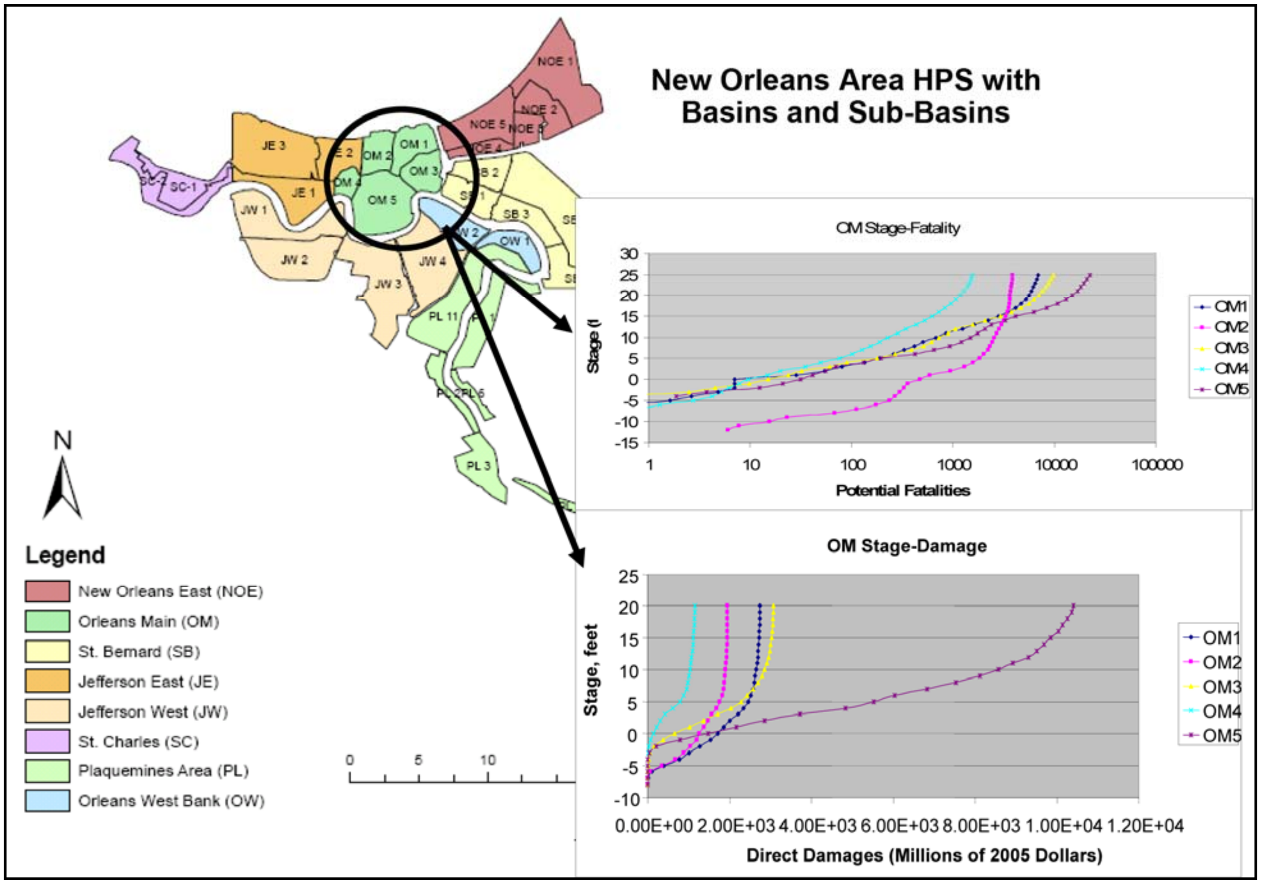


Figure 45. Example relationships for loss of life – water elevation and loss of property – water elevations for the Orleans Main sub-basins.

A Monte Carlo Uncertainty Model was then used to estimate immediate loss of life using fatality rate probability distributions (McClelland 2000[2]) accounting for evacuation effectiveness as a random variable. Evacuation was assumed to have a triangular probability distribution (65%, 80%, 95%). This was based in part on post-storm research on evacuation by Tulane University, which cited estimates of 70%-80%. This resulted in a conservative estimate of

[1] McClelland, D.M. and Bowles, D.S. (2002), "EstimatingLife Loss for Dam Safety Risk Assessment - A Review and New Approach." Institute for Water Resources, U S Army Corps of Engineers, Alexandria, VA.

[2] McClelland, D. M.(2000), Personal Communication of Updated Probability Distribution for Fatality Rates for Each Flood Zone, November 30.

fatalities in comparison to those experienced in Katrina. (Model estimates are likely to be higher than those experienced during Katrina.)

Next an estimate was made of the delayed fatalities among those who survived the initial inundation but were not rescued. The rescue effectiveness was accounted for as a random variable that varied between 99.5% and 100% in the Safe Flood Lethality Zone and between 95% and 100% in the Compromised and Chance Flood Lethality Zones.

Risk

Risk for loss of life and property damages can be estimated using the flood water level associated with specific frequencies of occurrence (2%, 1%, and 0.2%) and the loss – stage relationships. The information derived from this step is an average representing the most likely value. Since all the estimates have a level of uncertainty, the actual value may be higher or lower. The uncertainty of these and other parameters presented in this report has been studied and is presented in Volume VIII.

Principal Assumptions

1. Risk was assessed using the mean values of flood inundation elevations for 0.2%, 0.1%, and 2% frequencies of occurrence.
2. Losses were estimated with the mean values of loss estimates for each flood elevation.
3. Economic risk is portrayed as percentage of total value lost as well as actual value lost to represent two important dimensions of economic losses. The percentage of value ties into the ability of the area to recover and the degree of damages. The actual loss values represent the magnitude of economic stress and extent of re-investment necessary to recover.
4. A simplified pumping model was used that lumped all the pump capacities in a given sub-basin into a single pump. The actual reliability of the pumps was not considered, and a percentage of the total capacity was used to demonstrate the impact that pumping could have on inundation levels.

Risk Assessment Results

Vulnerability to flooding

The flood water elevations for specific events, such as the 2% (1/50), 1% (1/100) or 0.2% (1/500) -year floods can be determined by aggregating the information from all of the hurricanes modeled. For the purposes of this analysis, only the 76 hurricane scenarios modeled of the 152 hurricanes were assigned frequencies of occurrence and used in the risk estimation. The flood elevations determined by this process for three pumping scenarios, (0%, 50%, and 100% of ideal pumping capacities) are presented in Tables 9-6 to 9-8, respectively, in Appendix 9. Note that the 2%, 1%, and 0.2% elevations are represented in these charts as the 50-, 100-, and 500-year elevations, respectively.

The elevations derived from this process were plotted on maps to show the extent of flooding at each frequency of occurrence. Note, these are the frequencies of occurrence of flooding, not of hurricanes. The 100-year flood does not necessarily occur from the 100-year hurricane.

Hurricane floodplain maps. There are a number of ways to portray hurricane flood data. The first is to plot the area inundated or flooded at different frequencies of occurrence such as the 2% (50-year), 1% (100-year), and 0.2% (500-year). Figures 44 to 49 show a variety of floodplain maps for the Orleans Main Basin. They cover the pre-Katrina and June 2007 HPS conditions assuming three pumping capacities, none, 50%, and 100%.

Figures 46 and 47 show 50-, 100-, and 500-year inundations for the pre-Katrina and 2007 HPS, respectively, with no pumping. The darkest blue represents the areas that have a 2% chance of flooding each year (50-year floodplain). The medium blue represents areas having a 1% chance each year of flooding (100-year floodplain) and the light blue represents areas having a 0.2% chance of flooding each year (500-year floodplain).

The same modeling approach can include the impact of pumping stations operating at different levels of capacity. For this analysis, a simplified pumping model was used. For each drainage area, the pumping capacity of all of the individual pumps supporting that area was combined to generate a single “representative” pump station. The impacts of having that pump operating at 50% and 100% of full capacity were computed and the water volumes that would be removed by the representative pump station were subtracted from the total rainfall volumes for each storm. The new net volume was input to the risk model.

Figures 48 and 49 show the pre-Katrina and current HPS floodplains assuming 50% pumping capacity, while Figures 50 and 51 show the pre-Katrina and 2007 HPS floodplains for 100% pumping capacity *(100% pumping will never be achieved).* Note: Pumping computations do not model the actual performance of the individual pumps and drainage system. They give an estimate of the potential impact of pumping if the performance (volume of water removed) is achieved.

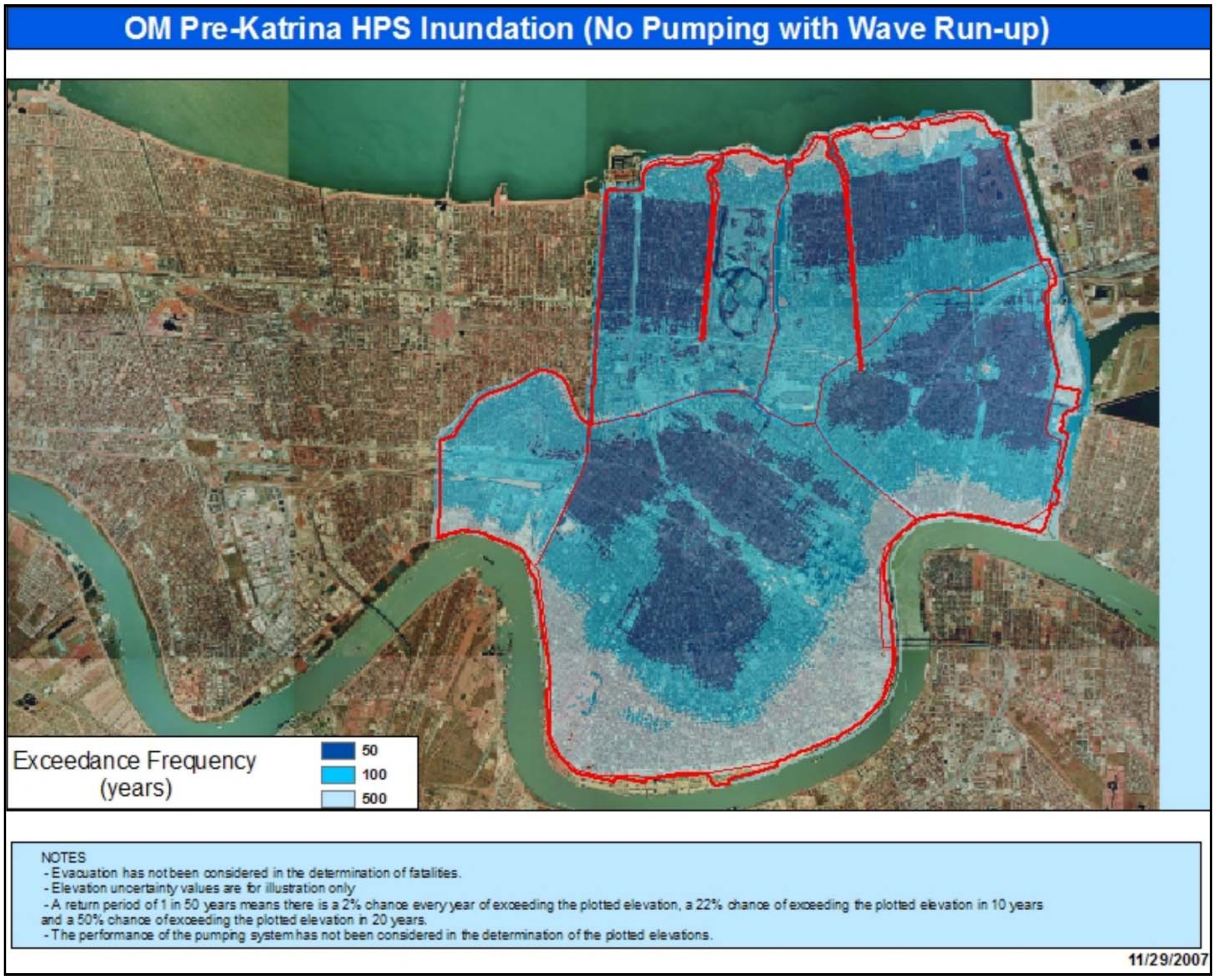


Figure 46. Inundation frequency map for pre-Katrina HPS conditions for the Orleans Main Basin. The dark blue represents the 50-year floodplain, the medium blue the 100-year floodplain, and the light blue the 500-year floodplain. No pumping.

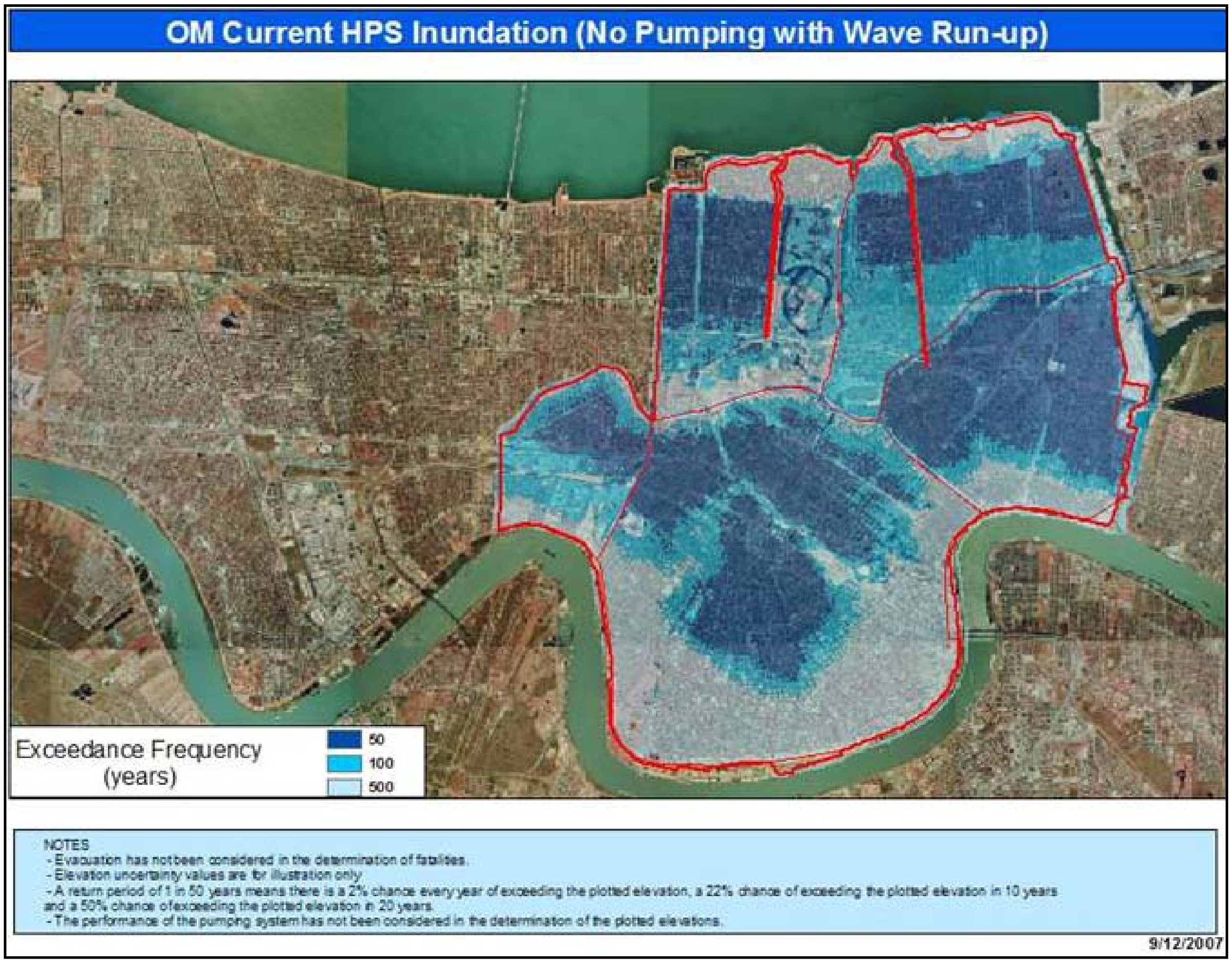


Figure 47. Inundation frequency map for 2007 HPS conditions for the Orleans Main Basin. The dark blue represents the 50-year floodplain, the medium blue the 100-year floodplain, and the light blue the 500-year floodplain. No pumping.

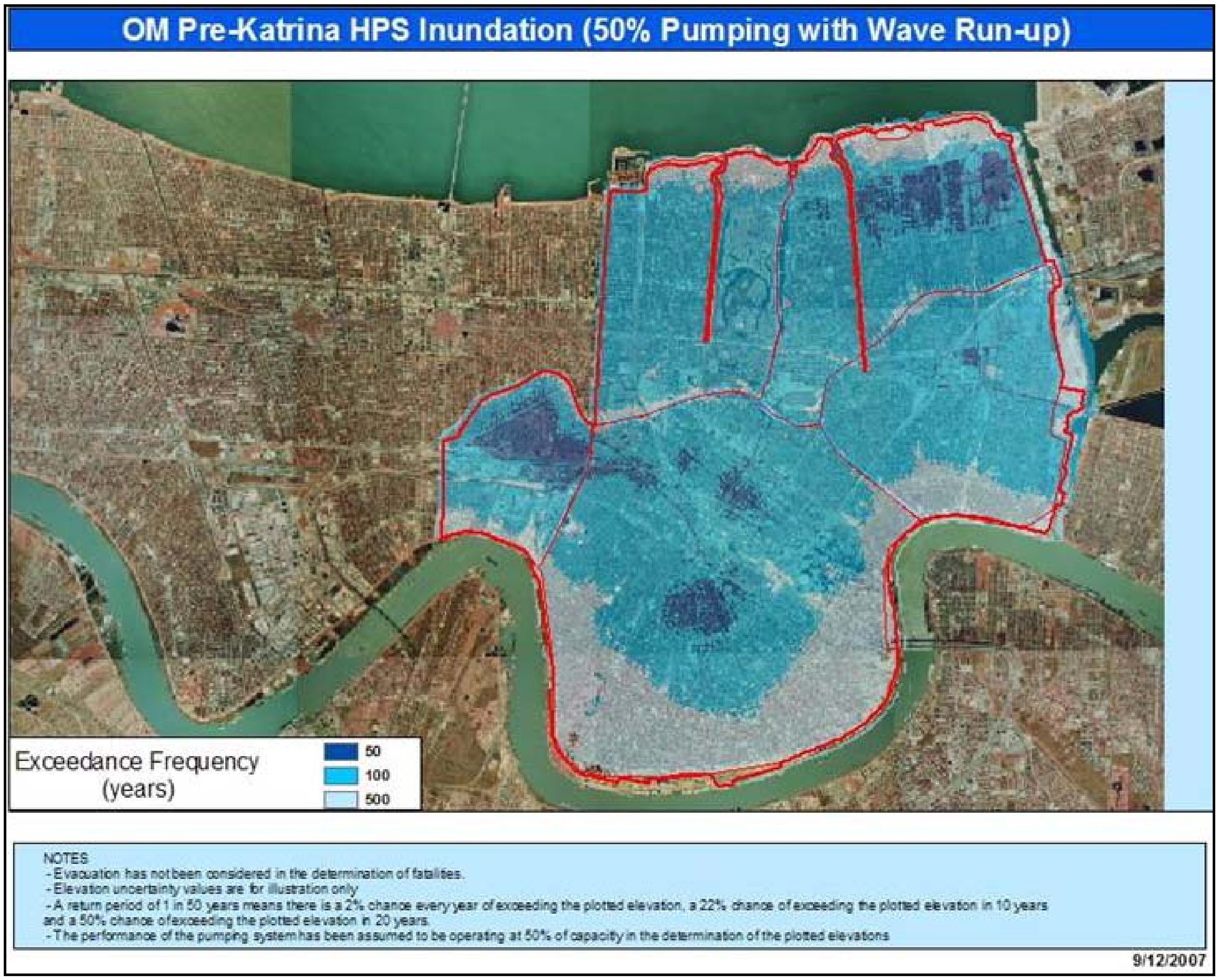


Figure 48. Inundation frequency map for pre-Katrina HPS conditions including impact of 50% pumping capacity for the Orleans Main Basin. The dark blue represents the 50-year floodplain, the medium blue the 100-year floodplain, and the light blue the 500-year floodplain.

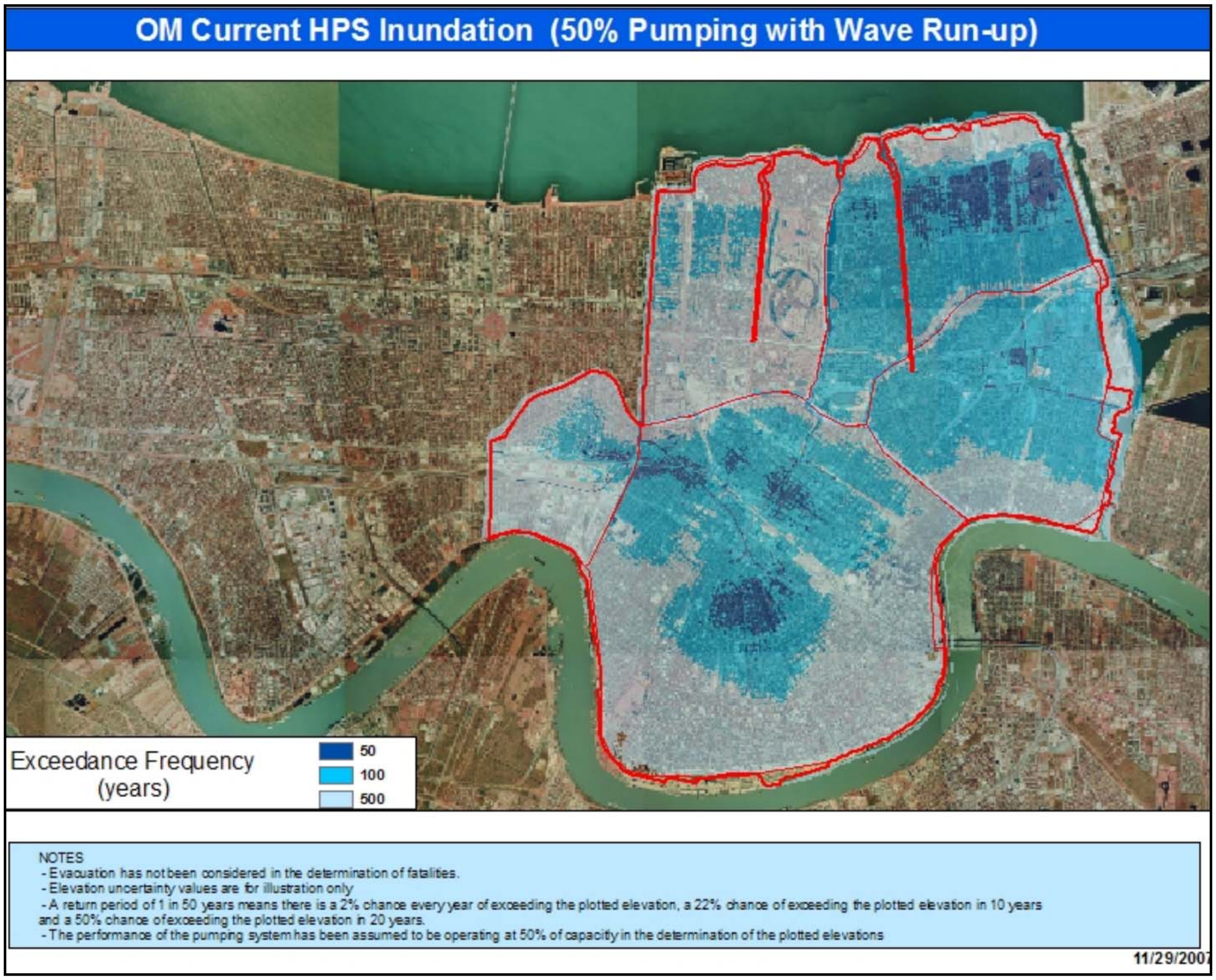


Figure 49. Inundation frequency map for 2007 HPS conditions with 50% pumping capacity for the Orleans Main Basin. The dark blue represents the 50-year floodplain, the medium blue the 100-year floodplain, and the light blue the 500-year floodplain.

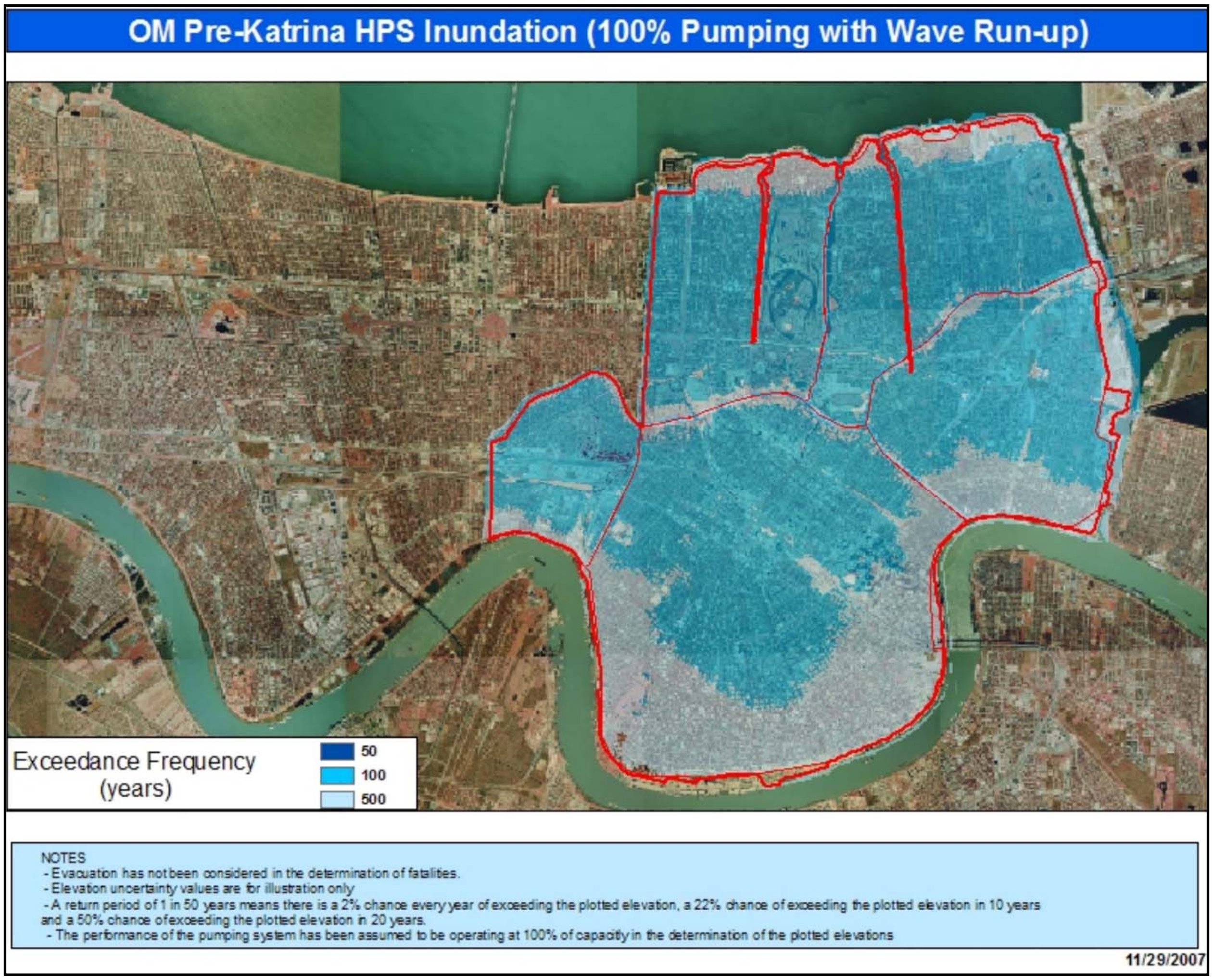


Figure 50. Inundation frequency map for pre-Katrina HPS with 100% pumping capacity (ideal) for the Orleans Main Basin. The dark blue represents the 50-year floodplain, the medium blue the 100-year floodplain, and the light blue the 500-year floodplain.

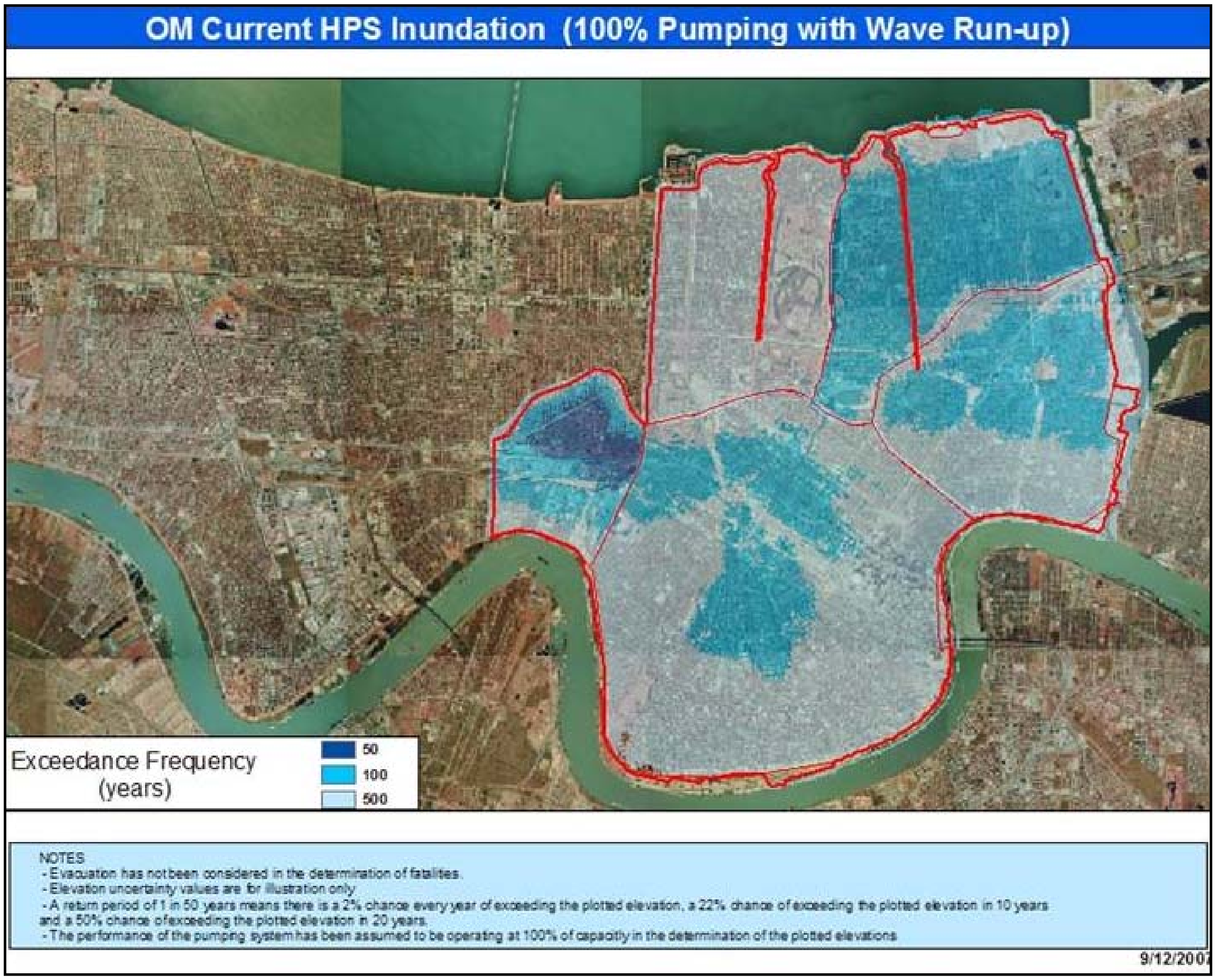


Figure 51. Inundation frequency map for 2007 HPS conditions with 100% pumping capacity (ideal) for the Orleans Main Basin. The dark blue represents the 50-year floodplain, the medium blue the 100-year floodplain, and the light blue the 500-year floodplain.

Flood depth frequency maps. A second type of map was generated to display the potential depth of flooding at different return periods (frequencies). These maps are called hurricane flood depth frequency maps. This map is based on flood depths as illustrated in Figure 52. Individual maps display the estimated depth of flooding by location for a single floodplain frequency. An example of maps for the 50-, 100-, and 500-year floodplains is shown for the Orleans Main Basin in Figure 53.

These maps are created by overlaying the water elevation, representing a frequency of flood event, on the local topography. By subtracting the land elevation from the water elevation at each point, an estimate of water depth is obtained. This does not represent flood depth with respect to the first-floor elevation of local structures, but depth of water above the ground surface. It should also be considered a general estimate because of the resolution of the ground elevation data (approximately ± 1 ft) and the uncertainty in the estimated flood elevations.

Depth maps are displayed in 2-foot increments because of the limits of the data. If the depth category is 0-2 feet, there is little chance of significant flooding, especially for structures with some height above ground level. Darker blue areas represent deeper flooding and higher potential for serious losses. The map legend and graphics display a greater than 8 foot depth category to simplify the display, and the assumption was made that flooding beyond that level represented severe consequences.

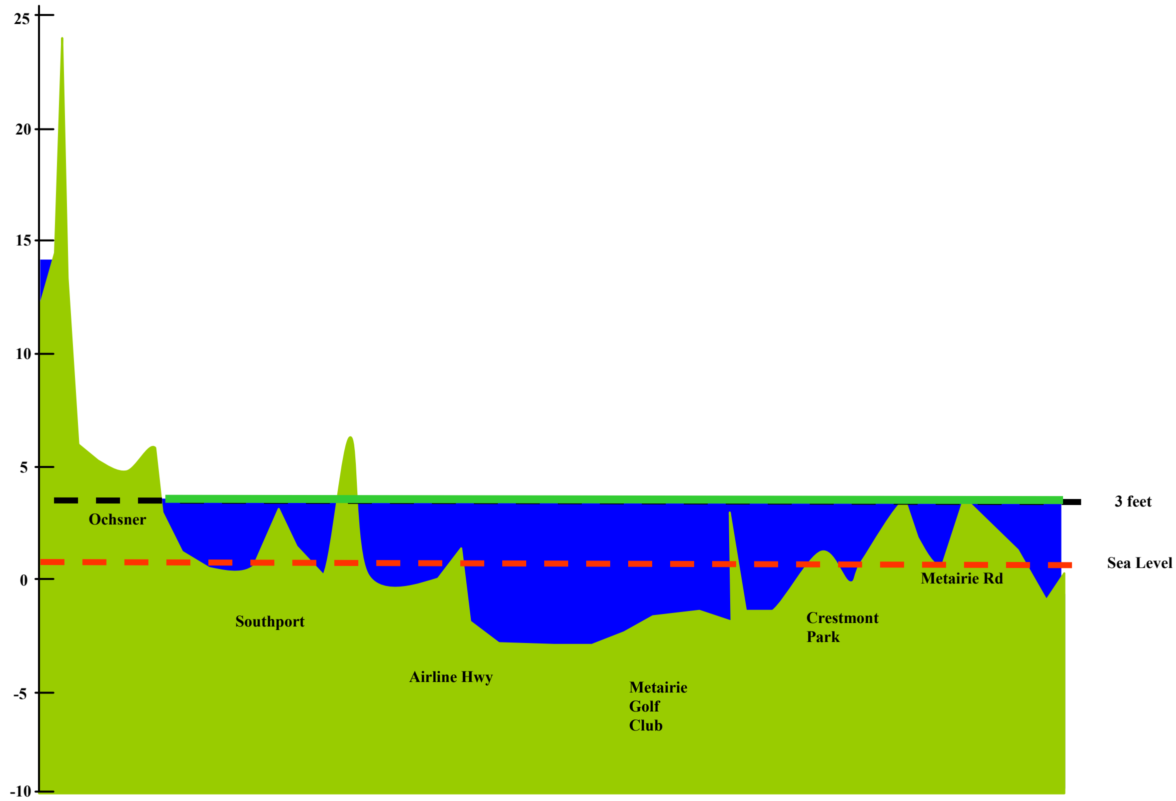


Figure 52. Flood depth information desired by local officials to better understand and communicate vulnerability.

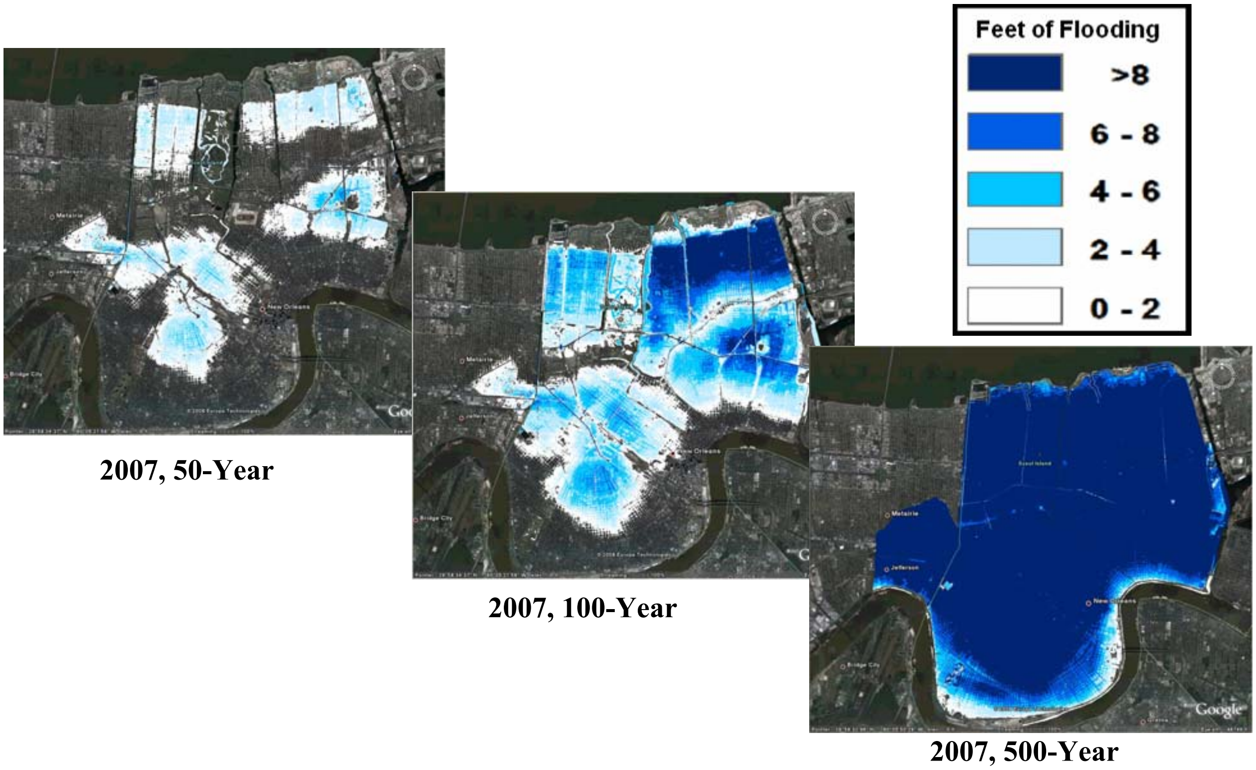


Figure 53. Examples of flood depth frequency maps for 50-, 100-, and 500-year hurricane floodplains in Orleans Main Basin for the 2007 HPS. Shades of blue display the estimated depth of flooding in 2-foot increments for the return frequency. No pumping.

The maps in Figures 54 to 56 provide a "big picture" perspective of flooding vulnerability of greater New Orleans, for different flood frequencies, and for the pre-Katrina and 2007 HPS and the three pumping scenarios. Detailed maps for each of the individual major basins are provided in Volume VIII. Appendix 10 provides the individual maps used in the above composite figures.

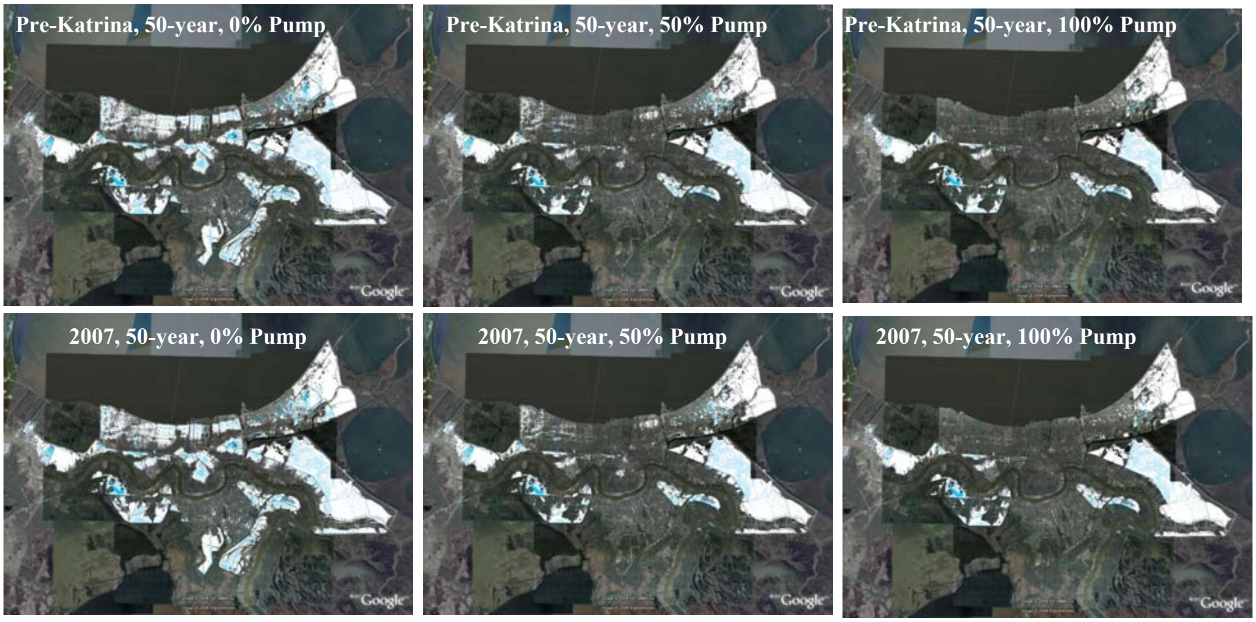


Figure 54. Flood depth frequency maps for 50-year hurricane floodplain, showing impact of different pumping capacities. The label on each map indicates the HPS, floodplain frequency, and percentage pumping capacity modeled.

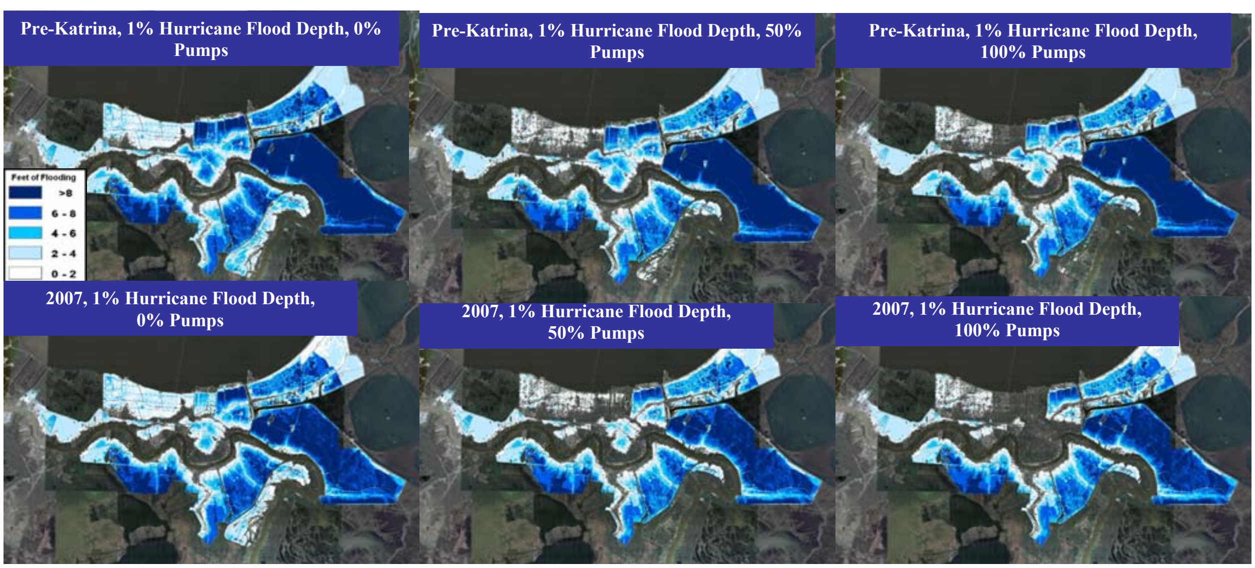


Figure 55. Flood depth frequency maps for 100-year hurricane floodplain, Orleans Main Basin. The label on each map indicates the HPS, floodplain frequency, and percentage pumping capacity modeled.

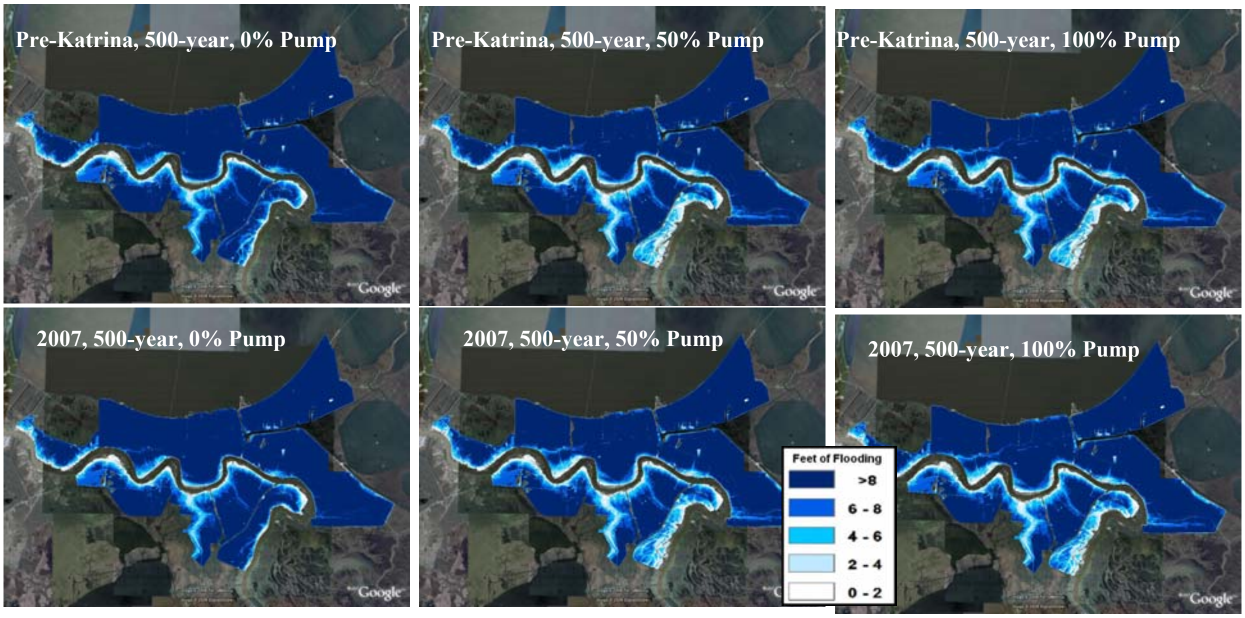


Figure 56. Flood depth frequency maps for 500-year hurricane floodplain, showing impact of different pumping capacities. The label on each map indicates the basin, HPS, floodplain frequency, and percentage pumping.

Flood depth frequency maps display the depth of flooding equaled or exceeded at a specific flood return period or frequency of occurrence. Maps are presented for 50-, 100-, and 500-year return periods or 2%, 1%, and 0.2% frequencies of occurrence.

Flood depth results of analysis

The assessments made here represent a "big picture" look at the information in the flood depth frequency maps presented here and in IPET Volume VIII, *Engineering and Operational Risk and Reliability Analysis*. It is focused on a systems-wide look at the vulnerability to flooding and the probable sources of flooding. A more in-depth basin by basin analysis is provided in Volume VIII.

The primary findings are presented for the entire region modeled and the individual major basins as described in Figure 35. A full risk assessment was conducted only for the northern part of Plaquemines Parish (sub-basin PL11, Belle Chasse).

Because the sub-basins that comprise each basin are interconnected, especially with higher levels of water (flooding) and this interconnectivity is only partially modeled, it is not recommended that the flooding vulnerability data be examined in isolation for individual sub-basins.

The following findings have been determined from analysis of the maps. These findings are consistent with the more detailed findings presented in Volume VIII.

50-Year flood event: New Orleans is widely vulnerable to light to moderate flooding at the 50-year or 2% frequency of occurrence level if significant pumping capacity is not available.

There is no significant difference in the flood elevations between the pre-Katrina and 2007 HPS at the 50-year (2%) frequency of occurrence. This is likely due to the dominance of rainfall as the source of water at this level of event. As such, thunderstorms and tropical storms, not hurricanes, are the dominant threat to New Orleans at this return period.

Pumping operating at a capacity that is equivalent to or greater than 50% of the ideal (or nameplate) capacity of the sub-basins can have a dramatic impact in reducing the flood elevations at the 50-year or 2% frequency of occurrence in a number of the basins modeled. There is a small benefit in NOE and a significant benefit in OM, portions of JE, JW, and PL.

The impact of pumping is directly related to the total volume of water that must be managed; therefore, pumping is most effective when flooding is not extensive or deep.

100-Year flood event: Without pumping, the majority of the New Orleans area remains vulnerable to moderate to deep flooding (greater than 4 feet) at the 100-year or 1% frequency of occurrence. The areas with least vulnerability are Jefferson Parish East and St. Charles Parish, where flood threats are moderate.

The improvements in the HPS from pre-Katrina to the 2007 HPS have provided significantly reduced flood levels in a few areas, notably portions of Orleans Main (OM2 and OM4) and moderate reductions in the 1% flood level in St. Bernard (SB) and Plaquemines (PL11).

Improvements in Orleans Main are largely due to the presence of the new gates and temporary pumps at the ends of the outfall canals. Continued vulnerability of the areas adjacent to the IHNC can be attributed to the remaining pre-Katrina elevations and significant fragility of the I-walls along the IHNC. Strengthening of the I-walls with stability berms and relief wells has improved the performance of the structures in the IHNC, but they remain unable to cope with surge conditions created by large storms.

Pumping capacity equal to or greater than the 50% ideal capacity modeled can have a significant impact on the 100-year or 1% flood elevations. Primary areas that benefit the most are OM and JE. The sub-basins adjacent to the IHNC remain vulnerable to flooding even when pumping is considered.

The West Bank area remains highly vulnerable to flooding in 2007 and pumping will likely have little impact until all of the fundamental protective structures are completed.

500-Year flood event: Virtually all of New Orleans region remains highly vulnerable to deep and catastrophic flooding at the 500-year or 0.2% flood frequency. The vast majority of the region would experience flooding of greater than 8 feet.

There is essentially no difference in the flooding vulnerability at this frequency of occurrence between the pre-Katrina and 2007 HPS.

Pumping has no impact at this level of flooding for either the pre-Katrina or the 2007 HPS because of the large amount of overtopping and the fragility of portions of the HPS.

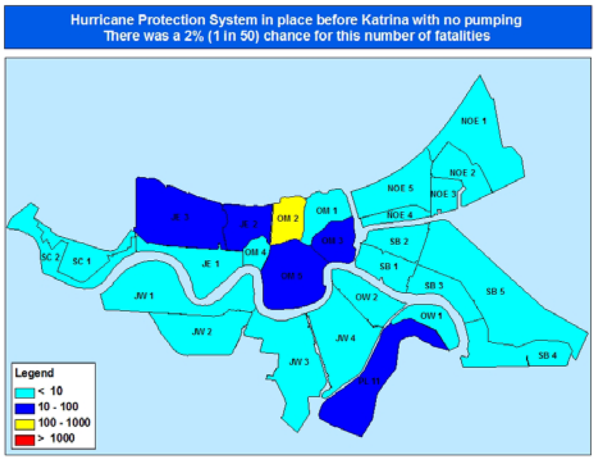
Loss of life risk

The estimates of potential loss of life are provided in Tables 9-9 to 9-11 of Appendix 9 in this volume. The losses are by sub-basin for each HPS (pre-Katrina and 2007) and the three pumping capacities (0%, 50%, and 100% of ideal capacity) modeled. The values in these tables were derived by combining the flood elevations for each frequency of occurrence in the loss-water elevation relationships for each sub-basin. The color codes in the tables represent different categories of loss of life as illustrated below.

Potential Fatalities	
Color Scale	
Less Than 10	(cyan)
10 to 100	(blue)
100 to 1000	(yellow)
More than 1000	(red)

The values presented in the tables are the most likely or mean values. Each has a level of uncertainty that is discussed in IPET Volume VIII. In the case of loss of life, the uncertainties are substantial because of the lack of basic information to relate loss of life to location during Katrina. These results, while calibrated somewhat by what happened in Katrina, are largely influenced by the assumptions made in the LIFESim model. Since evacuation was considered by a conservative approach, the estimates of potential fatalities given here are likely conservative (typically higher) than would be experienced with a level of evacuation experienced during Katrina. These estimates should be viewed as an index of potential loss of life rather than a specific estimate of actual fatalities. For example, for the pre-Katrina no-pumping condition, significant loss of life is projected for the OM2 (Lakeview) sub-basin for the 50-year flood event. This is counter to the experience in New Orleans for historical flooding caused by large rainfall events. The fact that the majority of the sub-basins have low estimated values for loss of life at the 50-year flood levels is appropriate and meaningful. The fact that the 50-year estimates are quite low compared to those for the 100-year and 500-year flood levels is also appropriate as is the reduction in potential loss of life when significant pumping is considered.

The data in Tables 9-9 to 9-11 (Appendix 9) represent estimates of mean potential loss of life risk at the specific frequency of occurrences cited in the tables. These data have been mapped using the same color code used in the tables to provide a visual graphical presentation of the relative risk for the New Orleans area. The loss of life risk maps derived from these data are presented in Figures 57 to 63. Figures 57 to 62 provide comparisons between the pre-Katrina HPS and 2007 HPS at the 50-, 100-, and 500-year flood frequencies for 0% and 50% of ideal pumping capacities. Figure 63 provides a direct comparison of the 2007 HPS loss of life risk for 0% and 50% of ideal pumping capacity at the 100-year (1%) flood frequency.



Pre-Katrina, 50-year, 0% pumping

2007, 50-year, 0% pumping

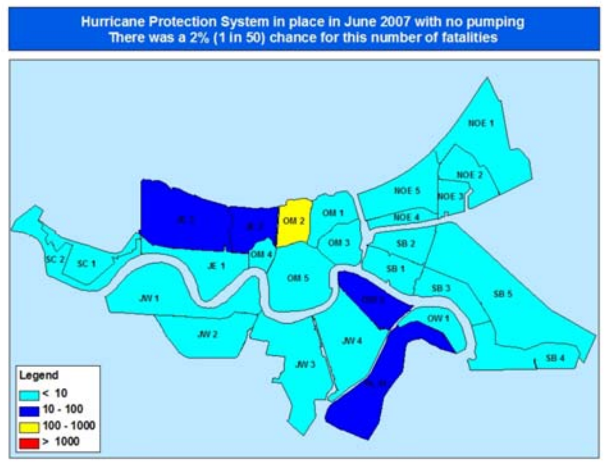
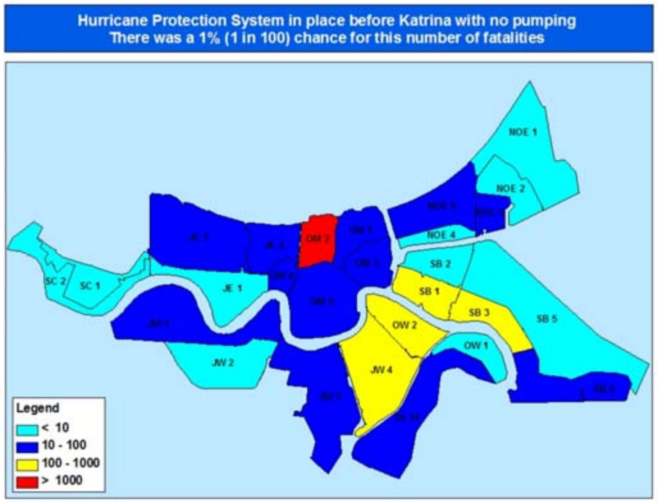


Figure 57. Loss of life risk maps comparing pre-Katrina HPS and 2007 HPS for 50-year (2%) flood frequency, no pumping. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.



Pre-Katrina, 100-year, 0% pumping

2007, 100-year, 0% pumping

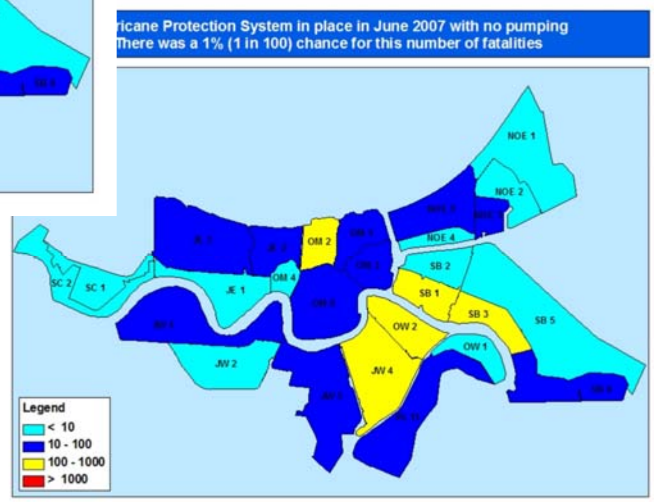
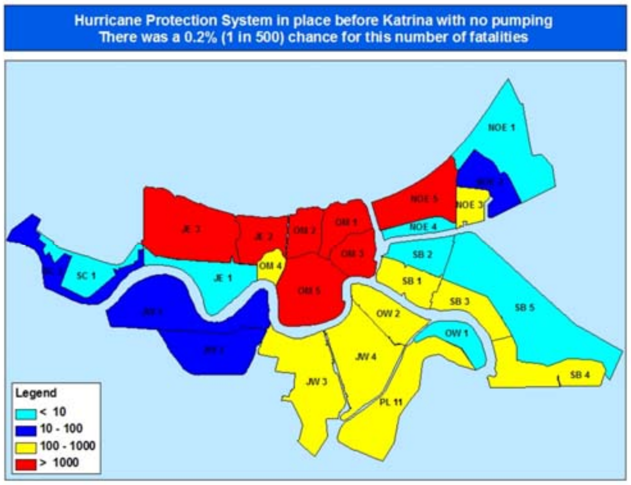


Figure 58. Loss of life risk maps comparing pre-Katrina HPS and 2007 HPS for 100-year (1%) flood frequency, no pumping. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.



Pre-Katrina, 500-year, 0% pumping

2007, 500-year, 0% pumping

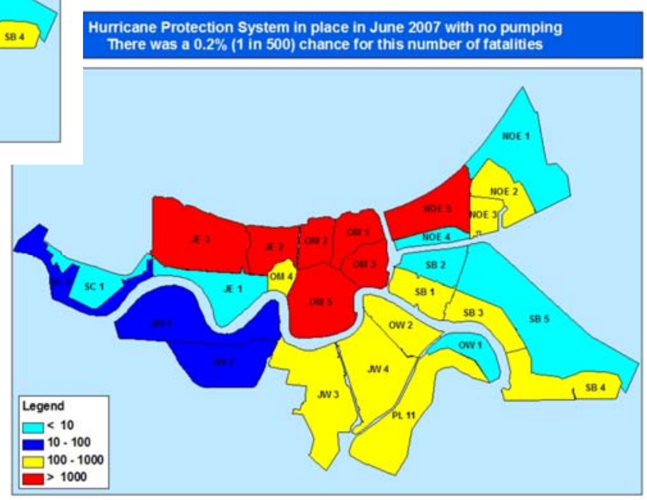
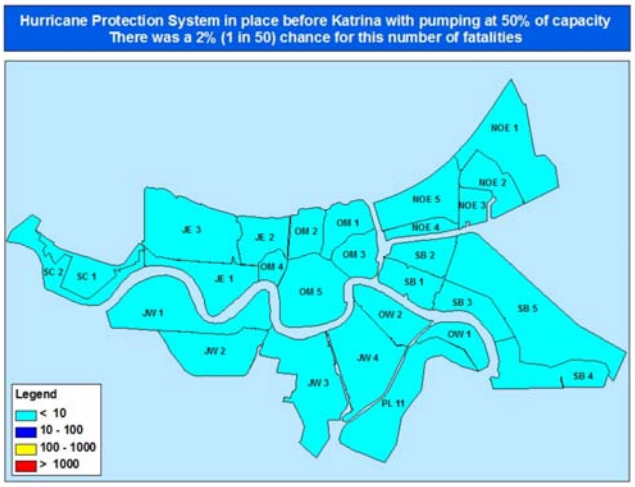


Figure 59. Loss of life risk maps comparing pre-Katrina HPS and 2007 HPS for 500-year (0.2%) flood frequency, no pumping. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.



Pre-Katrina, 50-year, 50% pumping

2007, 50-year, 50% pumping

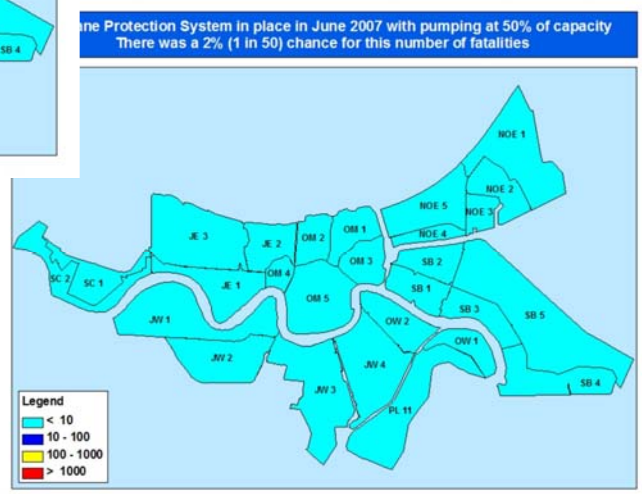
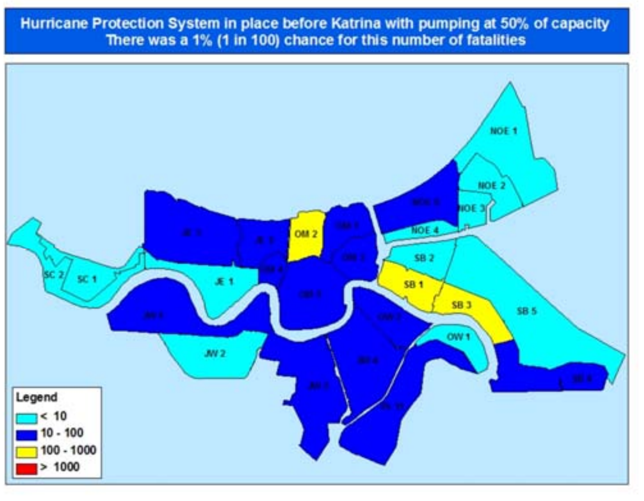


Figure 60. Loss of Life Risk Maps comparing Pre-Katrina HPS and 2007 HPS for 50-Year (2%) Flood Frequency, 50% pumping. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.



Pre-Katrina, 100-year, 50% pumping

2007, 100-year, 50% pumping

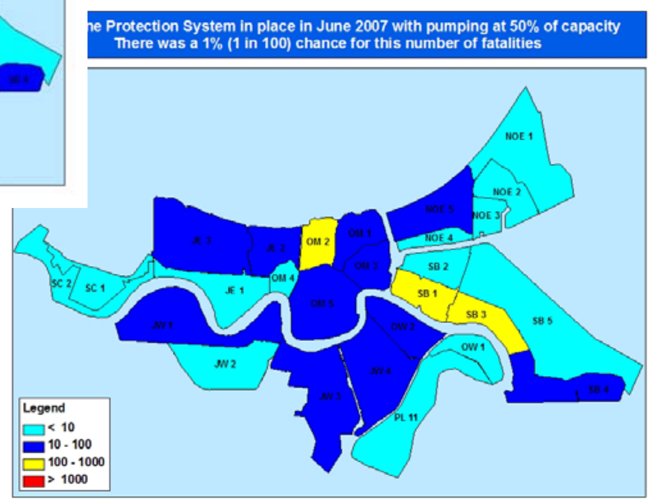
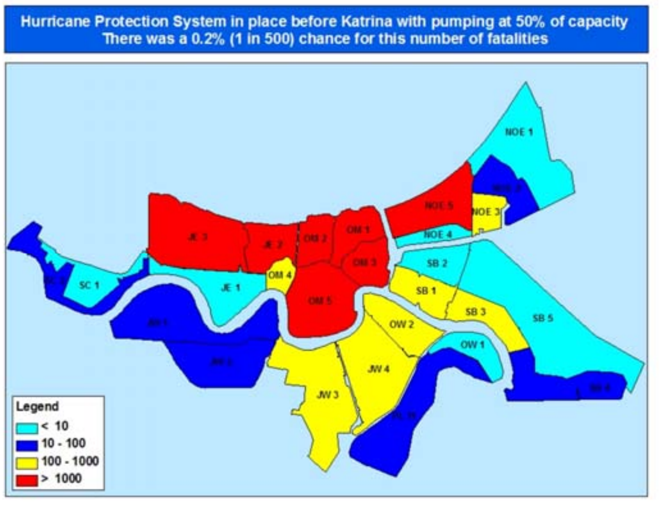


Figure 61. Loss of life risk maps comparing pre-Katrina HPS and 2007 HPS for 100-year (1%) flood frequency, 50% pumping. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.



Pre-Katrina, 500-year, 50% pumping

2007, 500-year, 50% pumping

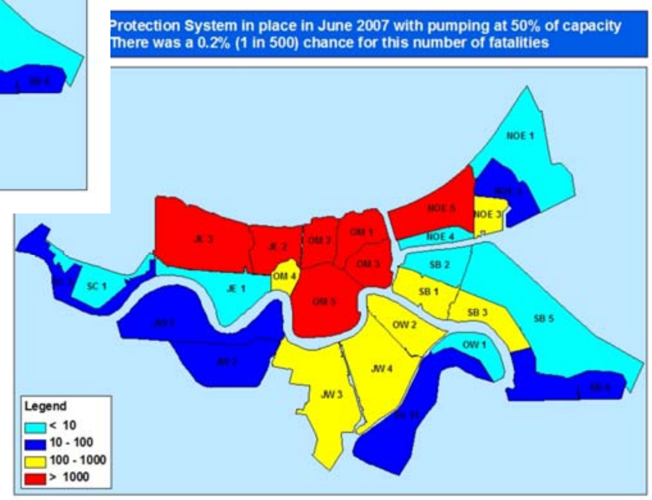


Figure 62. Loss of life risk maps comparing pre-Katrina HPS and 2007 HPS for 500-year (0.2%) flood frequency, 50% pumping. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.

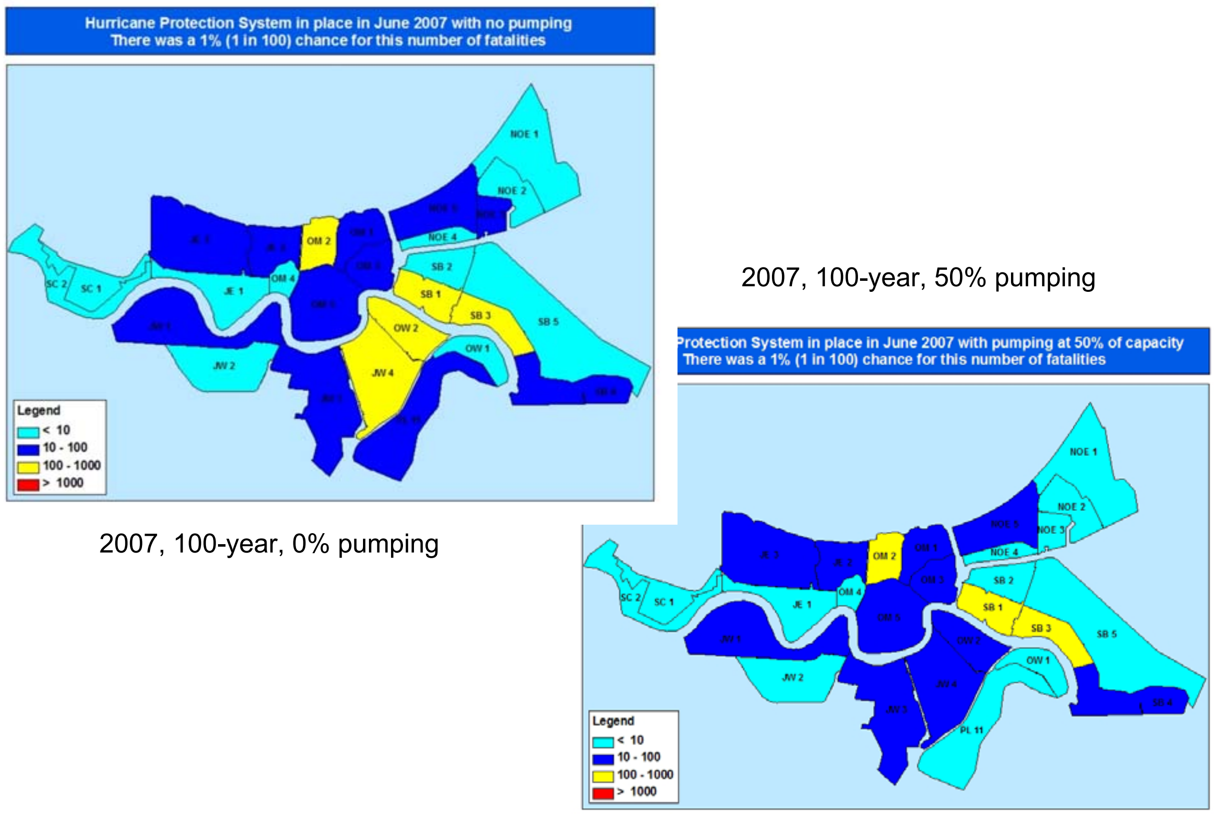


Figure 63. Loss of life risk maps for 0% and 50% ideal pumping capacity, 2007 HPS, 100-year (1%) flood frequency. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.

Table 3 presents a summary of the loss of life estimates for the entire region as a function of the HPS and level of pumping. This shows that the loss of life, given the assumptions in the analysis, is somewhat improved for the 2007 HPS at the 100-year frequency of occurrence, but little different at the 50- and 500-year frequencies. There is no difference between the HPS at the 50-year level because that flooding is dominantly from rainfall. For the 500-year level, there is such extensive flooding that the improvements made for the 2007 HPS have little impact. These numbers also show that pumping can have a significant impact on loss of life if an operational capability comparable to the 50% ideal capacity modeled can be achieved. ***Remember that these results are based on the pre-Katrina distribution of population and property and do not reflect the current or any future situation. In addition, these values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative, making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.***

Table 3. Loss of life summary statistics for entire region modeled (× 1000).					
Level	**50-Year**		**100-Year**		**500-Year**
	Pre-K	**2007**	**Pre-K**	**2007**	
No Pumping	0.4	0.4	3.7	2.6	45
50% Pumping	0.3	0.3	2.6	1.1	29
100% Pumping	0.2	0.2	2.5	.9	27

Loss of life risk findings

50-Year event: Pre-Katrina potential for loss of life risk was extreme in OM2 sub-basin and very high in portions of JE, JW, PL, and OW.

The 2007 HPS (without pumping) reduced loss of life risk in the majority of OM and JE and portions of QW, JW, NOE, and PL north. Loss of life risk remains high in OM2 due primarily to the IHNC vulnerability.

Pumping at an operational capacity equal to or greater than the 50% ideal capacity modeled reduces loss of life risk to the lowest category at the 50-year (2%) flood frequency.

100-Year event: At the 100-year flood frequency (1%), pre-Katrina potential for loss of life risk was extreme for OM2 and very high for SB and portions of OW and JW.

The 2007 HPS, without pumping, reduces loss of life risk for OM2 but has little impact elsewhere.

Pumping at an operational capacity equal or greater than the 50% ideal capacity modeled would reduce loss of life risk in portions of OW, JE, and PL north.

500-Year event: The 500-year (0.2%) flood frequency presents an extremely high potential for loss of life risk for all of OM, most of JE, and a large portion of NOE, SB, OW, and JW for both pre-Katrina HPS and the 2007 HPS.

Areas with lower loss of life risk are primarily areas with lower populations exposed to flooding. Pumping makes no difference in loss of life risk at the 500-year flood frequency for either HPS.

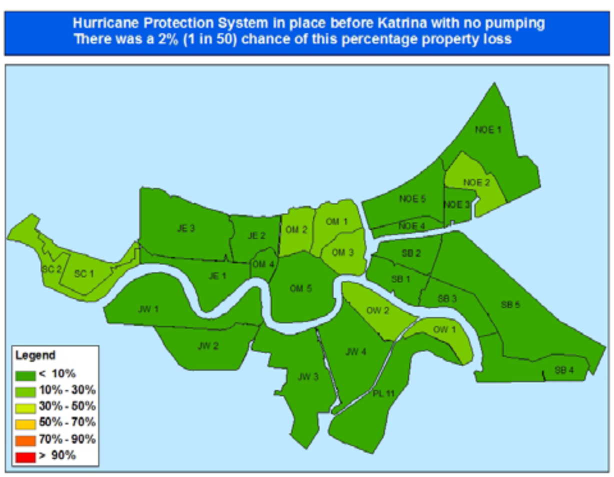
Property loss risk

The estimates of potential economic loss due to direct property damages are provided in Tables 9-12 to 9-14 in Appendix 9 of this volume. The losses are presented by sub-basin for each HPS (pre-Katrina and 2007) and the three pumping capacities (0%, 50%, and 100% of ideal capacity) modeled. The values in these tables are derived by combining the flood elevations for each frequency of occurrence in the loss – water elevation relationships for each sub-basin. Table 4 provides a basin-wide summary of economic risk estimates.

Figures 64 to 70 are maps providing a graphical portrayal of the data in Tables 9-12 to 9-14 (Appendix 9). The maps show estimated economic risk in terms expected losses as a percentage of total value, for the 50-, 100-, and 500-year flood frequencies and the pre-Katrina and 2007 HPS. Thus, economic risk is presented in two contrasting ways, the actual dollar (2005) losses in the tables and the percentage of total value on the maps. The map representations were chosen to normalize the influence of high-cost structures in the risk estimates. Figure 70 shows a side by side comparison of the 100-year economic risk for the pre-Katrina HPS and the 2007 HPS with no pumping considered.

Table 4.
Summary statistics of the property loss risk for the pre-Katrina and 2007 HPS and for the 0%, 50%, and 100% pumping options, ($B).

Level	Pre-Katrina 50-Year	2007 50-Year	Pre-Katrina 100-Year	2007 100-Year	500-Year (Both)
No Pumping	4.7	4.7	43	40	74
50% Pumping	1.2	1.2	31	26	72
100% Pumping	1.0	1.0	29	24	72



Pre-Katrina, 50-year, no pumping

Pre-Katrina, 50-year, 50% pumping

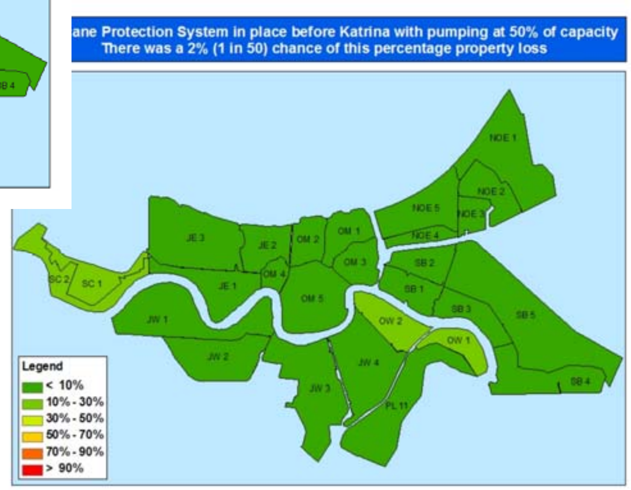


Figure 64. Property loss risk for 50-year (2%) flood frequency, pre-Katrina HPS.

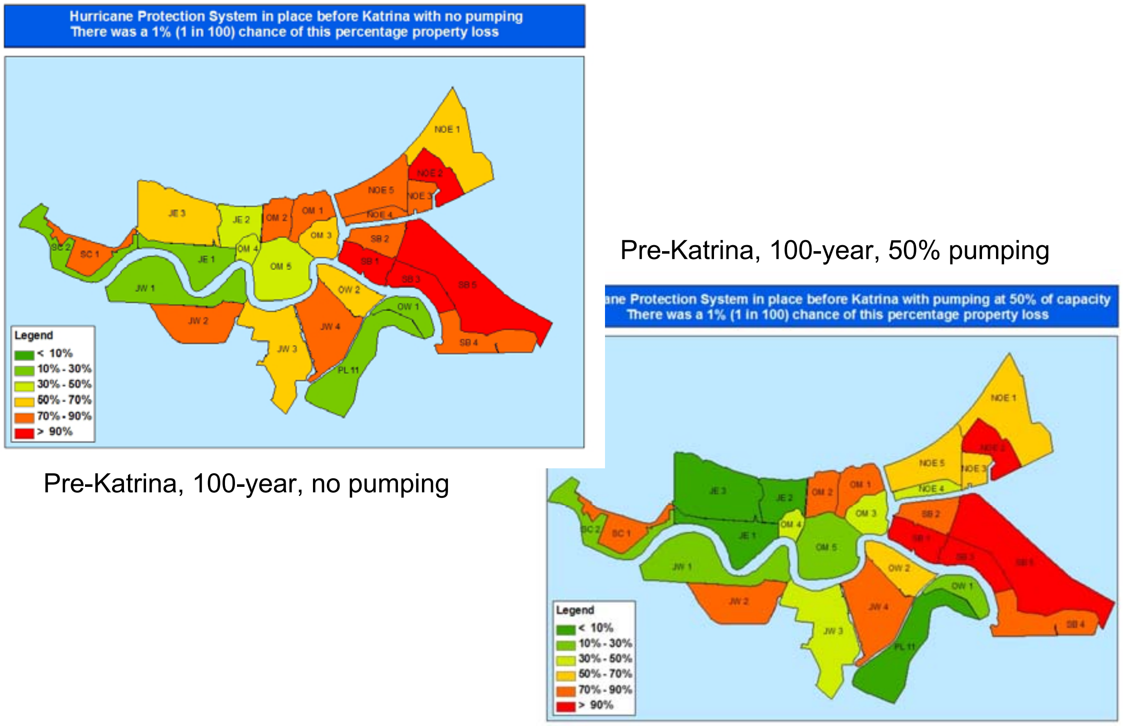


Figure 65. Property loss risk for 100-year (1%) flood frequency, pre-Katrina HPS.

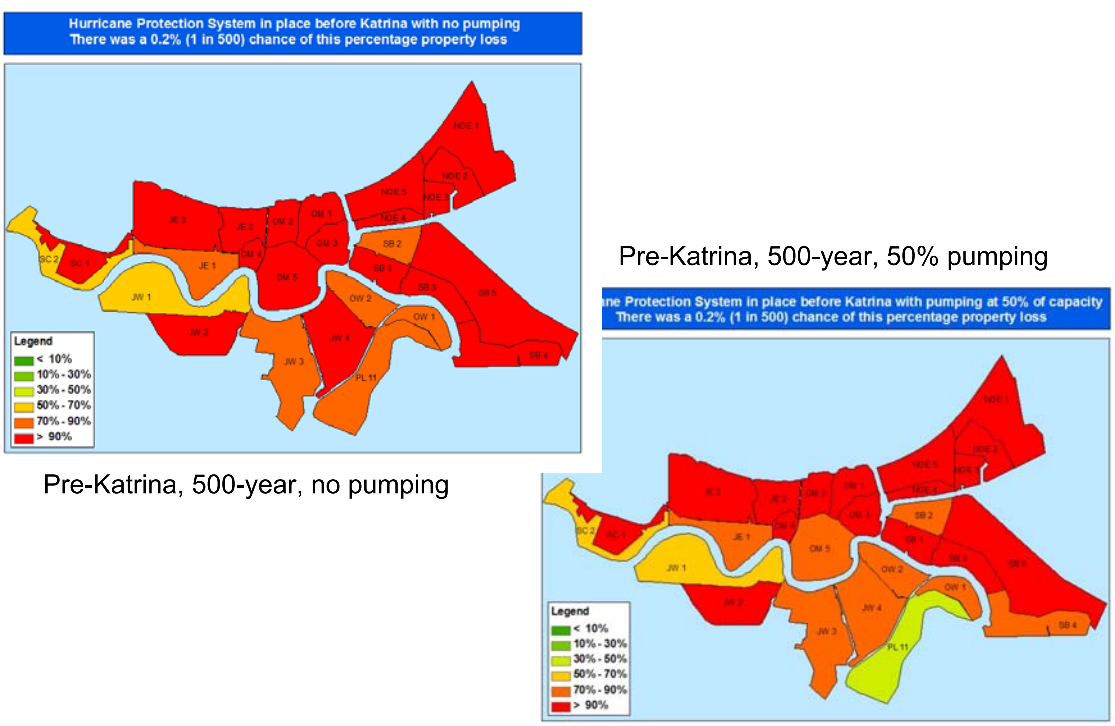


Figure 66. Property loss risk for 500-year (0.2%) flood frequency, pre-Katrina HPS.

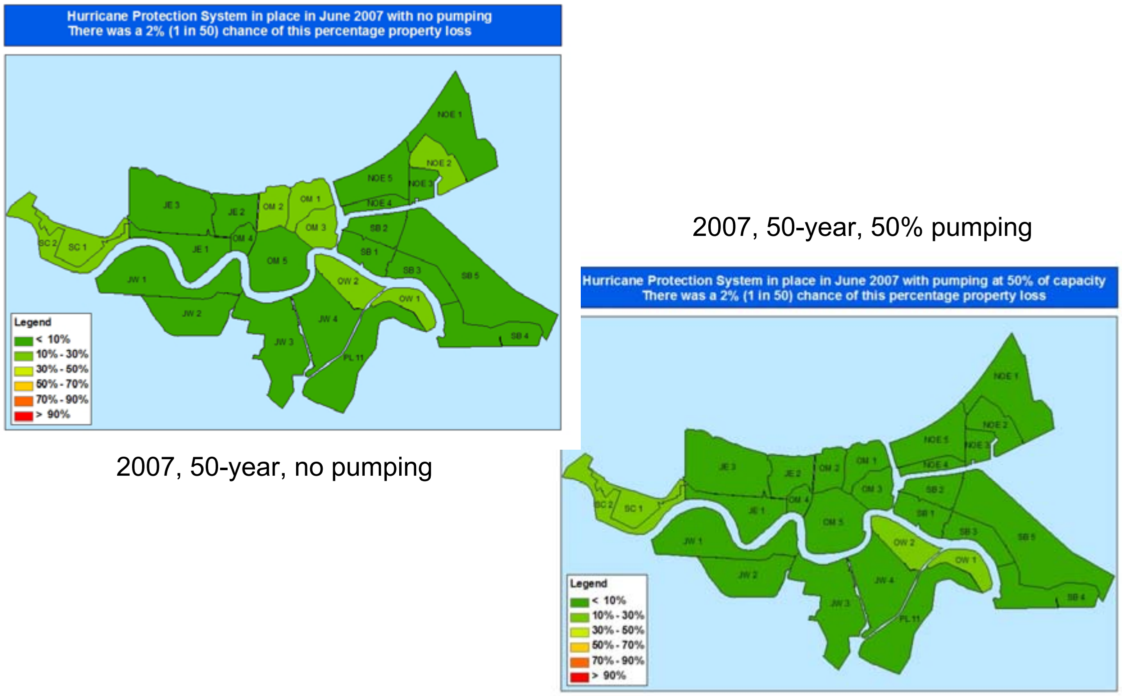


Figure 67. Property loss risk for 50-year (2%) flood frequency, 2007 HPS.

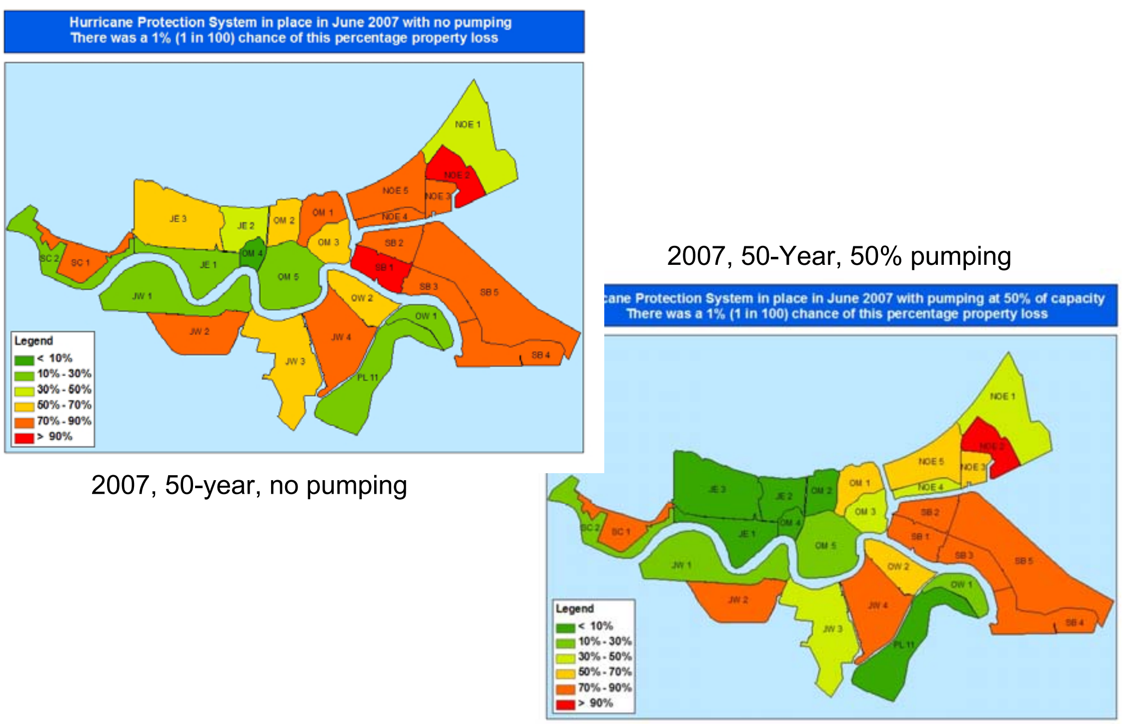
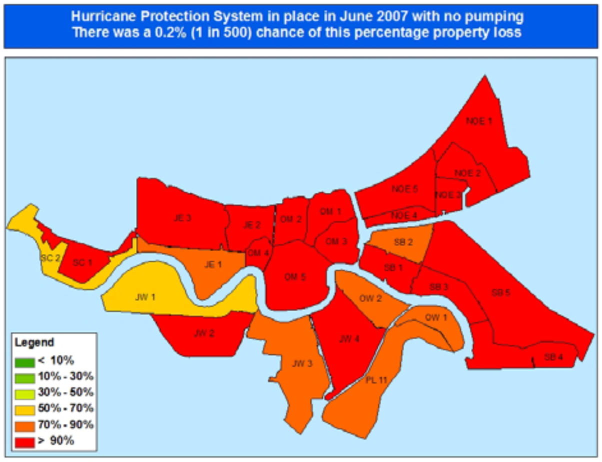


Figure 68. Property loss risk for 100-year (1%) flood frequency, 2007 HPS.



2007, 500-year, no pumping

2007, 500-year, 50% pumping

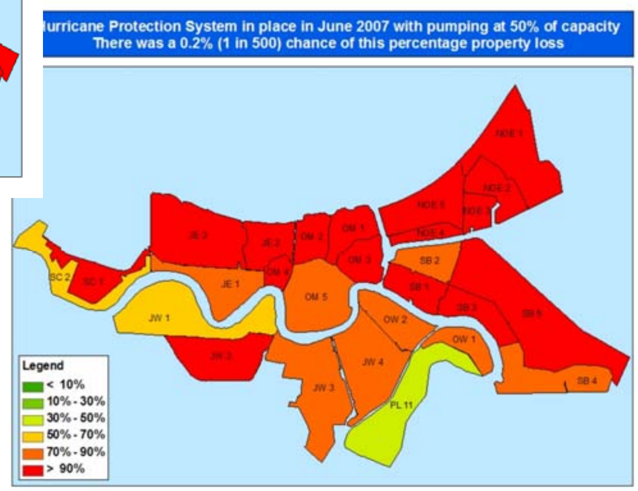
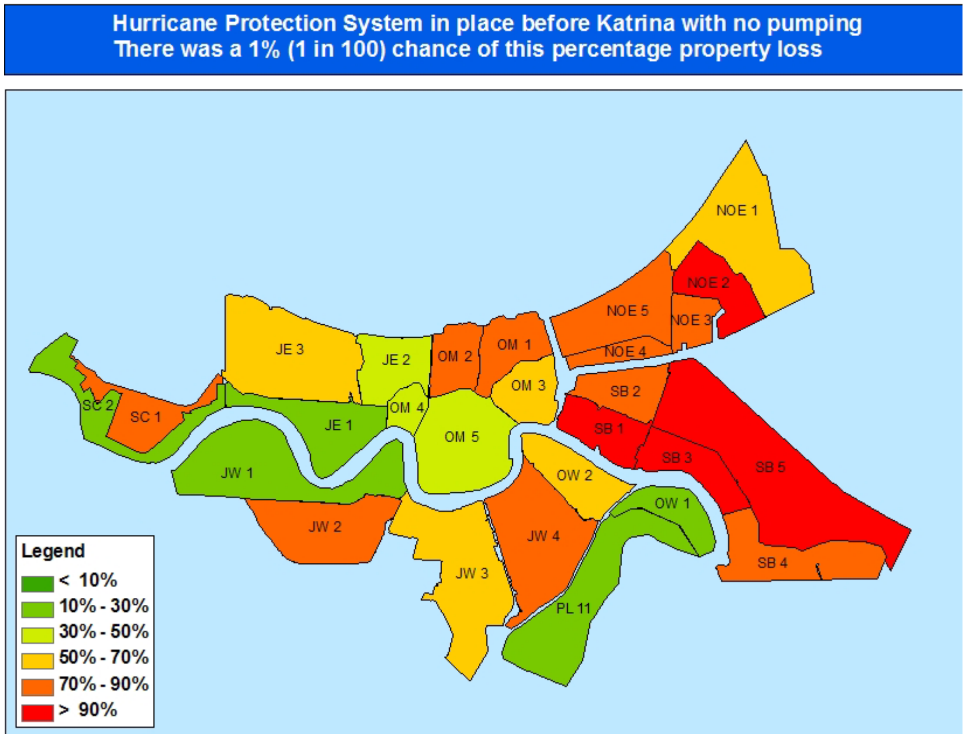
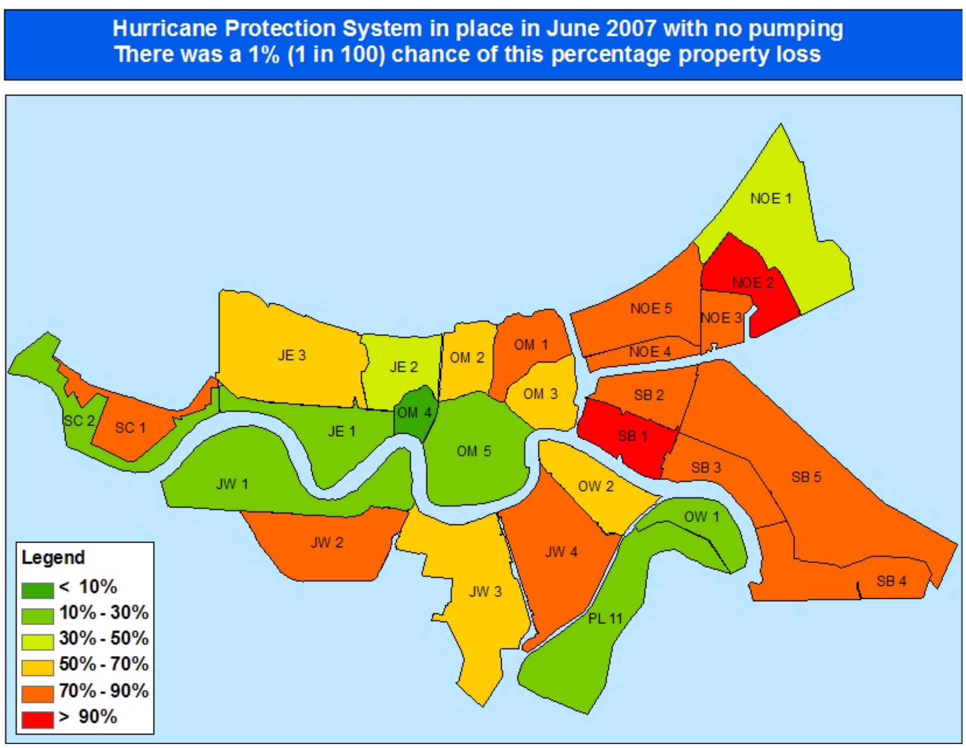


Figure 69. Property loss risk for 500-year (0.2%) flood frequency, 2007 HPS.



Pre-Katrina, 100-year, 0% pumping



2007, 100-year, 0% pumping

Figure 70. Comparison of 100-year property loss risk, no pumping, for pre-Katrina HPS and 2007 HPS.

Table 4 shows that the 2007 HPS does provide a small reduction overall in the property loss risk in comparison to the pre-Katrina HPS. It also shows that there is no difference in property loss risk between the two HPS at the 50- and 500-year frequencies. The 50-year level is dominantly rainfall flooding and the 500-year level has extensive flooding regardless of which HPS is in place. ***Remember that these results are based on the pre-Katrina distribution of population and property and do not reflect the current or any future situation.***

Property loss risk findings

50-Year event: Property loss risk is relatively low for the 50-year (2%) flood frequency, being below 10% of total value in most areas and from 10% to 20% in areas of Orleans Main near the canals and Orleans West.

Property loss risk maps for pre-Katrina and 2007 HPS are essentially the same at this return period. Pumping at operational capacities equal to or greater than the 50% ideal value modeled would reduce all of the sub-basins to the lowest category with the exception of OW which remains the same.

100-Year event: Prior to Katrina, with the exception of a portion of Jefferson East, Jefferson West, and northern Plaquemines, property loss risk was very high across New Orleans at the 100-year or 1% flood frequency. In most cases property would experience damages greater than half of its total value in this type of flood event.

The 2007 HPS provides a risk reduction in three of the five sub-basins of Orleans Main, those nearest the IHNC remaining at higher risk levels. There is also some reduction in St. Bernard but none on the West Bank or in New Orleans East.

Without pumping, in 2007, moderate to high risk to property losses exists in most of New Orleans East, St. Bernard, and the West Bank.

Pumping at an operational capacity equal to or greater than the ideal 50% capacity modeled would provide significant property loss risk reduction in all of Jefferson East and Orleans Main, and in portions of New Orleans East. Property loss risk remains high elsewhere with the exception of northern part of Plaquemines.

500-Year event: The economic risk for the 500-year (0.2%) flood frequency is extremely high in all areas. There is essentially no change in property loss risk at this level between the pre-Katrina HPS and 2007 HPS.

Pumping capacity has little impact on the direct property loss risk at this level of flooding.

Uncertainty Analyses

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 HPS. 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. This is traditional due diligence when conducting a complex deterministic analysis. In addition, a formal uncertainty analysis was accomplished as a component of the risk and reliability assessment, tracking the levels of uncertainty in for the hazard (hurricane generated surge and wave levels), the system performance (reliability of the levees, floodwalls and other component of the HPS) and the resulting flood elevations estimated in the analysis. 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. In the following paragraphs a qualitative discussion of sources of uncertainty in the general data and models used for the overall forensic analysis is given followed by a summary of the formal uncertainty analysis for the risk assessment.

Uncertainty Sources by Component

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 make 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 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.

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.

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 were 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 gauges external to the protection system were destroyed by the storm. Only one gauge, at the Corps lock where the IHNC meets the Mississippi River, provided any significant water elevation 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 gauge 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.

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 the time frame of overtopping and breaching activities by location. Interviews with many eye witnesses and a variety of other information sources such as stopped clocks, were integrated to generate a most plausible timeline for the major overtopping, breaching, and flooding events. This timeline best fits all of the information available, but that information is by no means comprehensive for all locations.

Analysis of the floodwall behaviors required characterization of the subsurface conditions at each breach site, as well as for 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 re-distribution of flood waters among adjacent sub-basins is included in the computation of extent and depth of flooding with time. However, the extensive sub-surface drainage system that carries water to the pumping stations that can also be a source of flow between sub-basins was not modeled.

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 databases 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 databases 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 redevelopment 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 were 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. These data are presented in Volume VII, Consequences. There is significantly more uncertainty in the loss of life relationships than in the property loss relationships.

The Risk Uncertainty

The IPET risk analysis generates best-estimates of the frequencies of inundation resulting from severe storms and the response of the HPS to those storms. These frequencies reflect the inherent randomness of events, manifesting as variability over space and time. In the language of risk analysis, this variability is called *aleatory uncertainty* and reflects the randomness of nature. There is also, however, uncertainty introduced by the assumptions and estimates made in the process of modeling. In the language of risk analysis, this is called *epistemic uncertainty* and reflects our incomplete understanding or information describing the processes being modeled. This epistemic uncertainty leads to "error bands" about the best-estimates of the frequencies of inundation. An important part of the IPET risk analysis was an effort to quantitatively assess these error bands.

Understanding epistemic uncertainty and its sources is important to understanding the limits of the risk products developed and the areas where additional development would best improve those products. While aleatory uncertainty is inherent in nature and in principle irreducible, epistemic uncertainty stems from inadequate knowledge, and thus can be reduced with additional research.

Approach: The objective of the uncertainty analysis was to identify the primary contributors to epistemic uncertainty and to calculate the uncertainty—i.e., error-bands—on the best-estimates of the 100-year inundations. The 100-year inundations were chosen because they are the focus of near-term efforts to upgrade the HPS. The IPET risk model itself was not set up to propagate epistemic uncertainties directly through the analysis; therefore, a parallel modeling approach was taken.

The principal sources of epistemic uncertainty for 100-year inundation levels were identified as being, (1) hurricane occurrence frequencies, (2) the magnitudes of surges and waves resulting from given hurricanes, and (3) the reliability of levees and floodwalls to surge and wave loadings. Considering that the New Orleans basins are mostly enclosed, well-defined areas, it was judged that the epistemic uncertainty in volume-stage relationships is small. Similarly, the uncertainty in rainfall associated with hurricanes was judged to be small for the 100-year scenarios.

Hurricane occurrence frequencies. In the risk analysis, 76 hurricanes, each based on a combination of principal descriptors of hurricanes and an associated frequency of occurrence, were used. The joint probability model approach to characterizing the descriptors was used to assess storm frequencies, and the statistical error in estimating the joint probability model was used to quantify epistemic uncertainty in storm frequencies.

The magnitudes of surges and waves. For each hurricane the temporal (i.e., hydrographs) and spatial field of surge and wave actions (i.e., how the hydrographs vary with location) were estimated using ADCIRC and STWAVE. The uncertainty analysis evaluated the parameter uncertainties entering the two codes and calibrated the predictions of surge and wave against field observations of high water levels made after Katrina.

Reliability of levees and floodwalls. As part of the uncertainty analysis, an event tree was developed for each basin within the HPS. This event tree was designed to assess the performance of the levee and floodwall system (whereas, the overall risk assessment also included pumping stations and gate closures). The sequences in the event tree define all the possible combinations of levee and floodwall performance states for all reaches in the HPS. Calculations are made on a reach-by-reach basis and aggregated by drainage basin. An estimate of the epistemic uncertainty in the fragility curves (relationships that show the expected performance of a reach, in terms of probability of failure, for a range of water elevations) for each reach was made, accounting for the uncertainty in engineering models and model parameters.

Results: The full description of the uncertainty analysis and results are presented in Appendix 11 of IPET Volume VIII, *Engineering and Operational Risk and Reliability Assessment*. The results are summarized here in Tables 5 through 8, in two major metrics, the mean frequency of failure and 100-year flood depths. Mean frequency of failure is a key parameter in that it describes how often a basin would be expected to experience breaching and resultant severe flooding. The 100-year flood levels are a measure of the severity of the flooding and associated losses.

For the Pre-Katrina HPS, for each basin, with the exception of St. Charles Parish, the uncertainty in hurricane hazard and the magnitudes of surge and wave are the primary contributors to uncertainty in inundation. For St. Charles, uncertainty in levee fragility is the primary contributor to uncertainty in inundation.

For the 2007 HPS, the uncertainty in the hurricane hazard and the magnitudes of surge and waves is again the primary contributor to the uncertainty in the frequency of levee system failure. The relative contribution of the uncertainty in levee fragility is slightly higher than it was in the pre-Katrina HPS, principally because many levee reaches have been heightened and strengthened. In St. Charles and Orleans West, the uncertainty in levee fragility is the principal contributor to the uncertainty in inundation.

Contrasting the Pre-Katrina and 2007 HPS, the mean frequency of failure decreases for all basins, as exhibited in the best-estimate risk assessment. The results on uncertainty in the estimates do not take into account pumping capability, closure of gates, or certain other factors, but IPET believes that trends in results are nonetheless valid.

The standard deviations of the uncertainty for inundation depth point out the difficulty in estimating values with a series of complex models, some of which have few measured data to confirm their accuracy (e.g., the return periods of large storms and resulting surge and wave levels). Note, these uncertainties pertain to the absolute depth of flooding and are thus much more sensitive to potential errors than is the simple frequency of flooding, which typically exhibit error bands less than about a multiple of 5. The error bands are in fact similar to those computed in most risk assessments of complex systems. It is typical for error bands between the 5% and 95% limits of confidence to be about an order of magnitude.[1]

Due to the fact that little data exist to validate the accuracy of surge estimates from large storms, IPET had to relay on high water marks only for Katrina. This drives the uncertainty for hurricane surge estimates to large values. This, of course, simply points to the need for more research and data monitoring to drive down the uncertainty. The best-estimate inundations and risk remain both useful and credible, but their absolute values are associated with large uncertainties.

Finally, although there is considerable uncertainty, the "best-estimate" is still the *best* estimate. It represents the statistically most likely value for failure frequency or for inundation depth. The values we observe in the future could differ from these best-estimates, but the probability that they do so declines rapidly away from the best-estimate. In is important to note that the large uncertainty for complex systems is not a property of the risk modeling; it is a property of the engineering modeling that goes into the risk modeling. The epistemic uncertainties that are quantified herein are no different than the "errors" that a deterministic analysis ought to be accounting for (although they seldom do) in an error analysis and for which we apply factors of safety to compensate.

Table 5. Comparison of Uncertainty in Frequency of Levee System Failure by Basin for Pre-Katrina HPS and 2007 HPS

Basin	Logarithmic Standard Deviation on the Frequency of Failure		Contribution to the Total Uncertainty			
			Pre-Katrina		2007	
	Pre-Katrina	2007	Fragility	Hurricane	Fragility	Hurricane
NOE	0.353	0.369	0.125	0.875	0.150	0.850
JE	0.473	0.506	0.330	0.670	0.281	0.719
SC	0.689	0.828	0.696	0.304	0.844	0.156
OM	0.371	0.419	0.190	0.810	0.332	0.668
SB	0.392	0.412	0.328	0.672	0.287	0.713
PLN	0.304	0.341	0.108	0.892	0.209	0.791
PLS	0.301	0.330	0.099	0.901	0.171	0.829
JW	0.316	0.347	0.125	0.875	0.287	0.713
OW	0.435	0.625	0.382	0.618	0.734	0.266

[1] Kurowicka, D. and Cooke, R. (2006). *Uncertainty Analysis With High Dimensional Dependence Modeling,* John Wiley and Sons, London, 284pp.

Table 6. Comparison of Failure Modes to Frequency of Levee and Floodwall Failure				
Basin	2007 HPS		PRE-KATRINA	
	Overtopping	Stability	Overtopping	Stability
NOE	0.231	0.769	0.407	0.593
JE	0.060	0.940	0.324	0.676
SC	0.267	0.733	0.452	0.548
OM	0.166	0.834	0.047	0.953
SB	0.219	0.781	0.102	0.898
PLN	0.233	0.767	0.580	0.420
PLS	0.279	0.721	0.571	0.429
JW	0.024	0.976	0.684	0.316
OW	0.047	0.953	0.550	0.450

Table 7. Epistemic Uncertainty in The Estimate of the 100-year Flood Depth	
BASIN	STANDARD DEVIATION (FT)
JE	4.7
OM	4.7
SB	6.2
SC	3.1

Table 8. Epistemic Uncertainty in The Estimate Failure Frequency: Statistics of the epistemic distribution of failure frequency

Basin		Mean	Median	lnSD	lnCOV	P(5%)	P(95%)	P(95%) /P(05%)
PreKatrina	NOE	3.49E-02	3.28E-02	0.353	(0.10)	1.83E-02	5.87E-02	3.21
	JE	1.56E-02	1.39E-02	0.473	(0.11)	6.39E-03	3.04E-02	4.76
	SC	1.86E-02	1.47E-02	0.689	(0.16)	4.71E-03	4.57E-02	9.72
	OM	3.33E-02	3.11E-02	0.371	(0.11)	1.69E-02	5.73E-02	3.40
	SB	3.36E-02	3.11E-02	0.392	(0.11)	1.63E-02	5.94E-02	3.65
	PLN	5.47E-02	5.22E-02	0.304	(0.10)	3.16E-02	8.63E-02	2.73
	PLS	5.55E-02	5.30E-02	0.301	(0.10)	3.23E-02	8.72E-02	2.70
	JW	4.88E-02	4.64E-02	0.316	(0.10)	2.76E-02	7.82E-02	2.84
	OW	3.11E-02	2.83E-02	0.435	(0.12)	1.38E-02	5.80E-02	4.20
2007	NOE	3.06E-02	2.86E-02	0.369	(0.10)	1.56E-02	5.26E-02	3.38
	JE	8.46E-03	7.44E-03	0.506	(0.10)	3.23E-03	1.72E-02	5.31
	SC	8.48E-03	6.02E-03	0.828	(0.16)	1.54E-03	2.36E-02	15.37
	OM	2.81E-02	2.57E-02	0.419	(0.11)	1.29E-02	5.14E-02	3.99
	SB	2.81E-02	2.58E-02	0.412	(0.11)	1.31E-02	5.09E-02	3.89
	PLN	3.90E-02	3.68E-02	0.341	(0.10)	2.10E-02	6.46E-02	3.08
	PLS	4.33E-02	4.10E-02	0.33	(0.10)	2.38E-02	7.07E-02	2.97
	JW	2.41E-02	2.25E-02	0.375	(0.10)	1.21E-02	4.17E-02	3.45
	OW	9.37E-03	7.71E-03	0.625	(0.13)	2.75E-03	2.16E-02	7.87

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 feet 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 feet below the intended elevation. Updating of the reference elevation points for the region, although under way at that time, 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 feet 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 HPS 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. I-walls were the dominant floodwall structures with only selected areas, such as at transitions to major structures (e.g. 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 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. 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 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 based on 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 at the four locations.

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 SPH 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 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. While the original plans for protection were indeed a systems approach, the actual hurricane protection in New Orleans was designed and developed in a piecemeal fashion, subjected to a number of compromises related to physical and fiscal restraints, 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. In addition, the pump stations were not a formal part of the HPS and were not intended to be a principal component of the overall hurricane response capability.

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 29 August 2005. 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 feet). 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 feet along the east side of the HPS, substantially higher, up to 5 or 6 feet, 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 feet were generated within the GIWW/MRGO canal entering the IHNC from the east. The IHNC design assumed 1-foot waves. Detailed hydrodynamic analyses showed that dynamic forces were a significant portion (20% – 30%) 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 breached due to erosion determined that all breaches were caused by erosion of the crest and back face.

The southeast trending leg of the 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 relic 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 Canal 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 feet by 35 years of subsidence, contributed to the amount of overtopping that occurred.

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

In spite of being subjected to 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% 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% of the flooding in Orleans East Bank. The remainder was due to the heavy rainfall (up to 14 inches in 24 hours) 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 cubic feet per second. 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% of deaths being people over the age of 60. There were over 1,000 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% ($16 billion) of which was attributed to residential losses. The next largest component was the 11.5% ($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% of its population and St. Bernard Parish nearly 80%. 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 it 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 varies considerably across the New Orleans area, particularly at the 100-year return period. The level of risk is clearly associated with both the potential for flooding and the population and property exposed. The depth of flooding is clearly tied to land elevation, making high density residential areas at low elevations the most risky places to live.

New Orleans remains vulnerable to flooding from large storms. The loss of life and property loss values included herein are believed to be conservative (higher than actual) based on the methods and assumptions used in their development. However, they represent a consistent and quantitative estimate of the level of residual risk that New Orleans faces. At less than 50-year return periods, most flooding is due to rainfall, not hurricane surge and waves. With no pumping, some flooding and losses are possible but they pale in comparison to the potential losses at higher return periods. At the 100-year return period (1%), New Orleans is vulnerable to moderate to deep (>4 ft) flooding in many areas. There are some significant reductions in vulnerability to flooding due to the outfall canal gates but areas near the IHNC and on the West Bank remain the most vulnerable due to low structure elevations or incomplete structures (West Bank).

Pumping can have a significant impact in reducing flooding. If operational pumping capacities equal to or greater than the ideal capacities modeled are available, significant reductions in flooding vulnerability can be achieved at the 50- and 100-year return periods. This will require an efficient drainage system to get water to the pumps and reliable pumping capabilities during large storm events. Pumping would have little or no impact on flood levels at the 500-year (0.2%) return period.

All of New Orleans is highly vulnerable to catastrophic flooding at the 500-year return period. While the repairs and strengthening of the HPS have provided benefits and reduced flooding vulnerability in some locations at the 100-year level (1%), a larger event such as the 500-year (0.2%) event would cause extensive and deep flooding literally everywhere. It is instructive to remember that the 500-year flood has an almost 1 in 7 chance of occurring in the average lifetime and an almost 1 in 5 chance of occurring in 100 years.

The principal source of uncertainty in the risk assessment was the estimation of the hurricane hazard. There was also considerable uncertainty in the reliability analysis, which carried over into the estimates of flood inundation elevations for the 100-year flood event.

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 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 HPS 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 – Optimal 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 feet at Biloxi, MS. In the vicinity of Biloxi, the surge produced by Camille was 15.8 feet, 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 wind field 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 HPS in Southeast Louisiana is very long and expansive, having a highly irregular layout. These factors, coupled with a translating counterclockwise 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 is still well off the coast. During Katrina, 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 conditions and wave contributions to surge 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 feet due east from the tip of the Mississippi River delta to 20 to 25 feet just north of the Chandeleur Island chain, with peak wave periods of approximately 15 to 16 seconds. Considerable wave breaking took place seaward of the Chandeleur Islands. High resolution (as fine as 300 feet) 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 feet, 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 feet 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% 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 locations where oscillatory wave motions were minimized.

The Performance (see Volumes 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, HPS should be deliberately designed and built as integrated systems to enhance reliability and provide consistency in levels of protection. Components such as the interior drainage and pumping need to be an integral part of the system because of the important role they can play in limiting the amount and duration of flooding. Resilience in pumping capacity is especially important.

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

Damages and loss of life were both directly tied to depth of flooding, which in turn is inversely tied to the elevation of the location or sub-basin. Areas with lower elevations experienced the most severe losses and, 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 most practical means to reduce risk is to keep people and property out of flood prone areas. While this may seem an obvious thought, it is in fact difficult to achieve within the reality of our current political system. The current de-facto 100-year guideline used for the National Flood Insurance Program is a base-line objective that inadvertently fosters development in areas that have almost the same chance of flooding as those in the adjacent floodplain. Current policies, insurance tools and development patterns do not support a risk-based approach.

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.

The definition of the hurricane hazard was the most demanding and complex technical challenge. While it was clear that the historical record was not sufficient, most alternatives were either simple extrapolations of the historical data or too computationally intensive to be practical tools. The JPM-OS method used exploited the value of historical data in conjunction with modern high-resolution, physics-based models and high-performance computing to provide a more comprehensive definition of the current and future hurricane generated surge and wave hazard that New Orleans faces.

The reliability analysis for a large distributed system is challenged by the vast amount of geologic, structural design, and condition data that must be considered. This includes the task of dividing the HPS into reaches of uniform performance potential; estimating the fragility of each reach, transition, and feature; and handling the complex issue of overtopping and erosion impact on HPS performance.

The loss of life estimation methods are conservative in the approach taken to model evacuation. Consequences were limited to pre-Katrina population and property conditions, but they required extrapolation of loss of life through the LIFESim model. This was essential because of both the scarcity and lack of availability of fatality information that allowed correlation of fatalities to location of and the situation leading to the fatalities. The LIFESim model was run assuming no evacuation. While evacuation was considered using a second modeling process, the fatalities estimated by this process are likely conservative (larger) than those experienced with the level of evacuation experienced during Katrina.

The overall process used to estimate vulnerability to flooding and risk (property and loss of life) generated reasonable results when compared to losses from historical events. It is important to note that single events like Katrina may not severely impact an entire region. As such, the total direct losses estimated at a specific return period for the entire region may be significantly higher than that for a single event. Also, substantial uncertainties can be expected in the application of this type of method because of the large data sets, sophisticated models, and many steps required.

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

Pumping and a bona fide system in place are critical to risk reduction. Surge and waves are not the only source of flood waters. Rainfall can add a significant volume that is literally trapped by the same HPS structures designed to keep other sources of water (surge and waves) out. Drainage and pumping are an import component of an overall systems approach to reduce vulnerability to flooding.

There is always risk. No amount of effort will eliminate risk. It is critical to monitor and communicate the residual risk so that individuals and public officials can make effective decisions to manage it. Much additional work is necessary to evolve and improve risk assessment methods for regional water systems. This is important work that requires research and changes in engineering practice and policy.

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 and storm damage risk reduction 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. The risk-based approach 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 1940 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 and representiveness of the historical record.

Risk assessments for large and complex systems typically have large uncertainties associated with the results. It is important to understand that these uncertainties are not the result of the risk assessment, but result from the data and models used in the assessment process, which are largely the same fundamental tools and inputs used for non-probabilistic deterministic analyses. The difference is that the deterministic approach does not give the investigator knowledge of either the size or sources of uncertainty. The probabilistic approach provides the statistically most likely values for results, which is the best estimate given knowledge available. It also provides an understanding of the sources of greatest uncertainty that allows subsequent development to focus on reducing the largest sources. The risk assessment methodology used for New Orleans is a prototype that needs considerable continued development. The ‘spread sheet’ approach, while straight forward and requiring little developmental effort, was inefficient, lacked transparency for examining intermediate results and required an extensive amount of review and verification. A method based on modern simulation techniques and efficient analytical (code) architecture would be a great improvement.

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 levees 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 re-emphasize 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 a priority issue, 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 significant benefits.

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 $25 million and direct access to the unique experimental facilities of ERDC 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 ERP 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.

Following release of the IPET Draft Final Report on 1 June 2006, review comments were provided by the ASCE ERP 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 Canal breach site and for one site on the IHNC. 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 factor 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 MRGO. The UCB report, and numerous media accounts attributed 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
Rafael L. Bras	Massachusetts Institute of Technology
Greg J. Holland	National Center for Atmospheric Research
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	Deltares / Delft Hydraulics
Thomas D. O'Rourke	Cornell University
Andrew J. Whittle	Massachusetts Institute of Technology
Robin L. Dillon-Merrill	Georgetown 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 TFG 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 SPH 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 TFG.

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 TFG 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, TFG, TFH, 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 one gets an inexperienced contractor that does more harm than good. TFG will know if heat straightening caused cracking if there is 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; pumping 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.

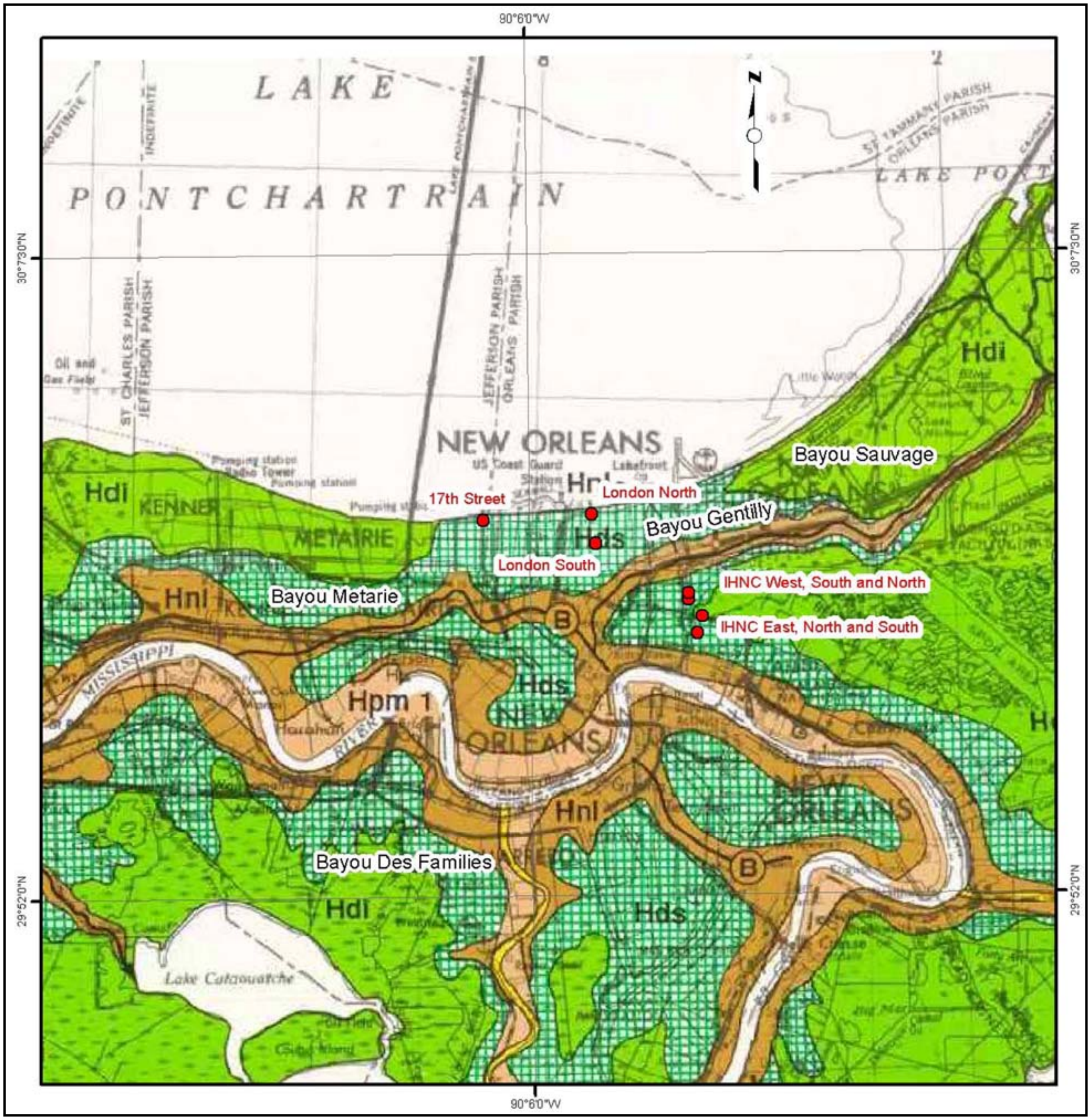


Figure 5-1. General map of the New Orleans area geology showing the limits of the different surface depositional environments (Saucier 1994). Map symbols are as follows: H = Holocene, d = deltaic, i = interdistributary, s = inland swamp, nl = natural levee, pm1 = point bar (most recent meander belt),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

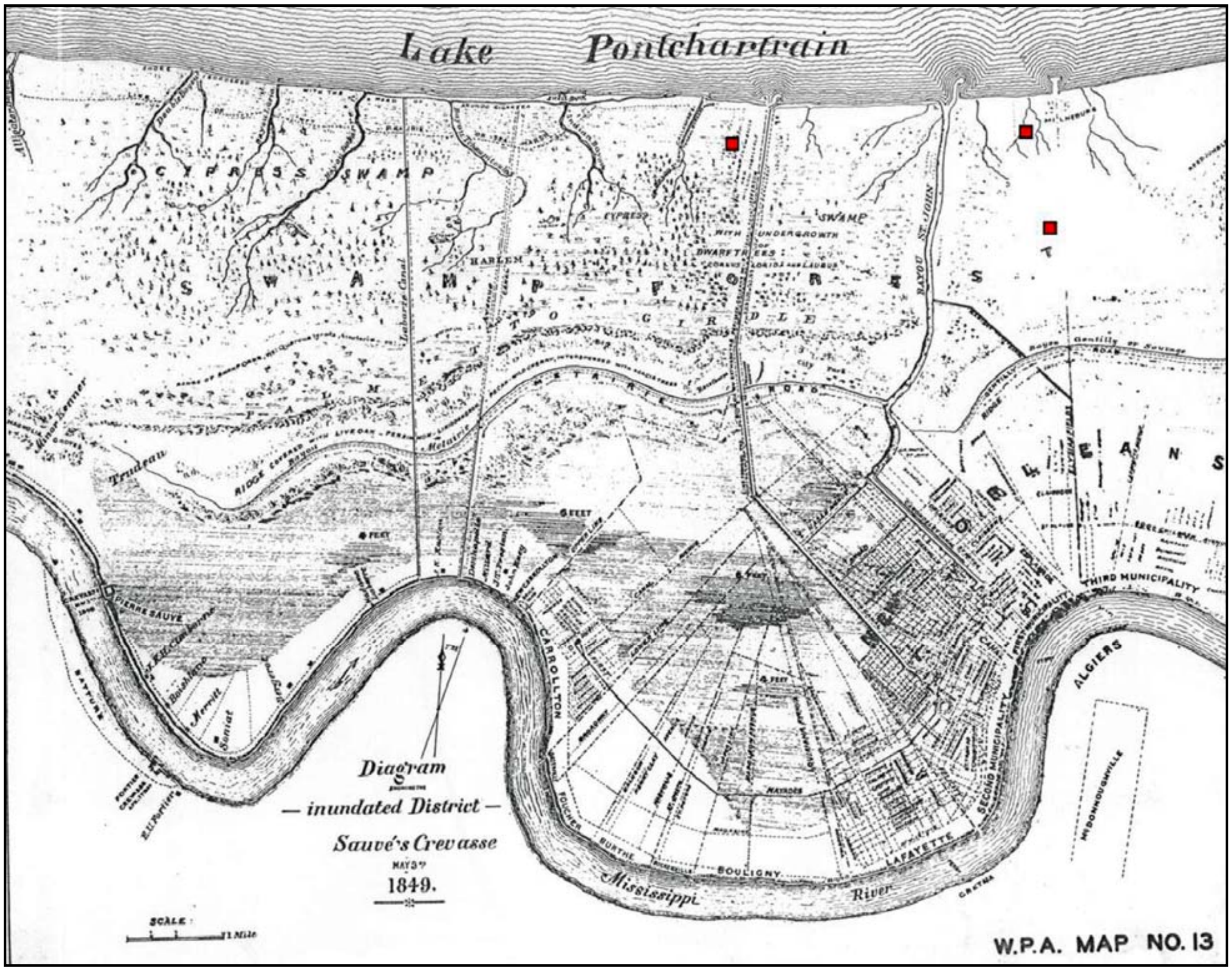


Figure 5-2. New Orleans area map from 1849 showing the locations of the Bayous Metairie and Gentilly distributary channel, the cypress swamps north of the city, and locations of 17th Street, London North, and South Canal breaches (marked by red squares, beginning from left to right and going clockwise).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

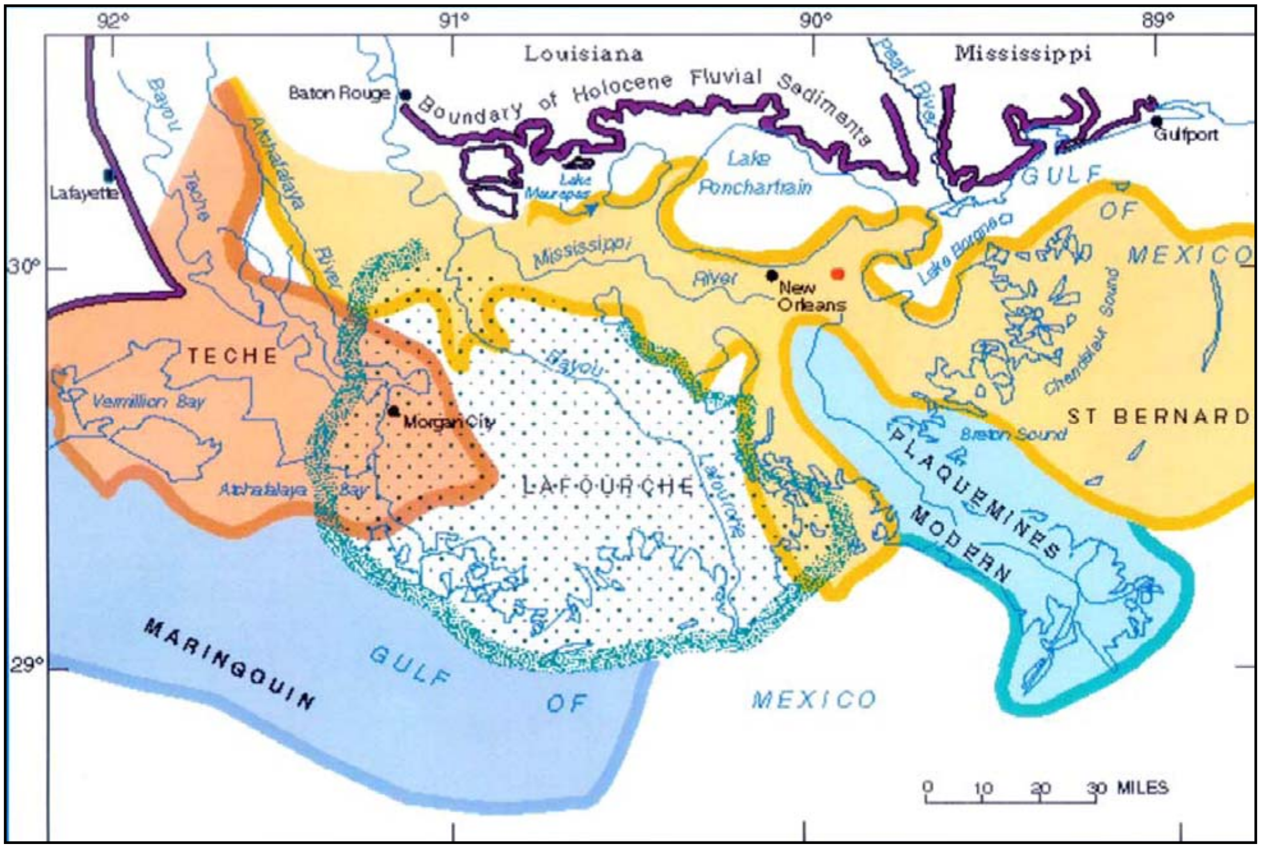


Figure 5-3a. Holocene deltas of the Mississippi River (after Frazier 1967).

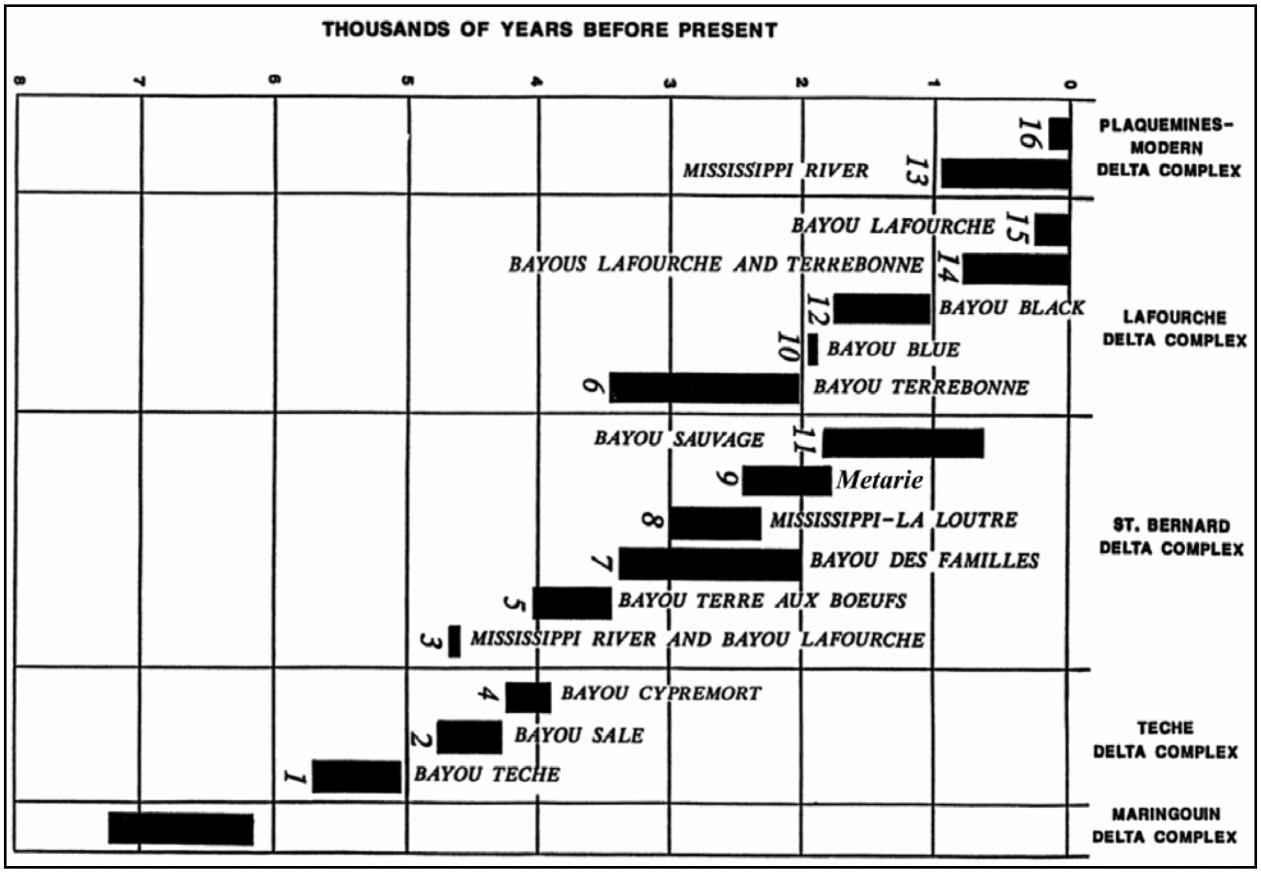


Figure 5-3b. Chronology of major Holocene distributary channels (after Frazier 1967).

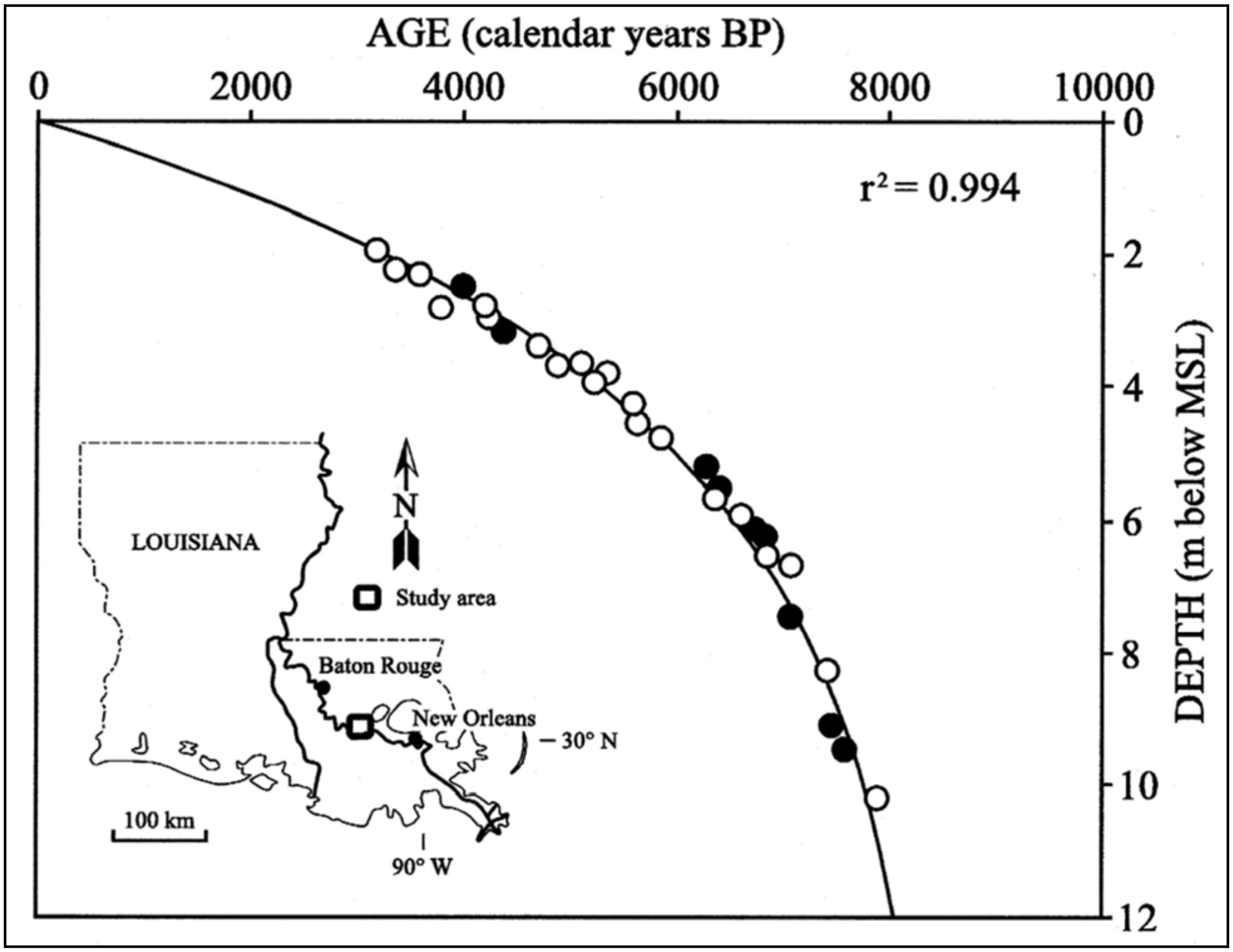


Figure 5-4. Holocene sea level curve for the eastern Mississippi River deltaic plain based on carbon-14 dating of basal peats at the transgressive Holocene and Pleistocene contact (Törnqvist et al. 2004).

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 (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 space borings, and a dense network of elevation benchmarks are needed to determine whether Holocene movement in deltaic sediments is 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 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 USACE geology website for the LMV to obtain maps and cross sections at *lmvmapping.erdc.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; Kolb and Van Lopik 1965).

DEPOSITIONAL TYPES	LITHOLOGY PERCENT (0 25 50 75 100)	REMARKS
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.
INTRA DELTA		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; Kolb and Van Lopik 1965).

DEPOSITIONAL TYPES	NATURAL WATER CONTENT PERCENT DRY WEIGHT (0, 50, 100, 150, 200)	UNIT WEIGHT LB/CU FT (60, 80, 100, 120, 140)	SHEAR STRENGTH [1] COHESIVE STRENGTH LB/SQ FT (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 costal 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.

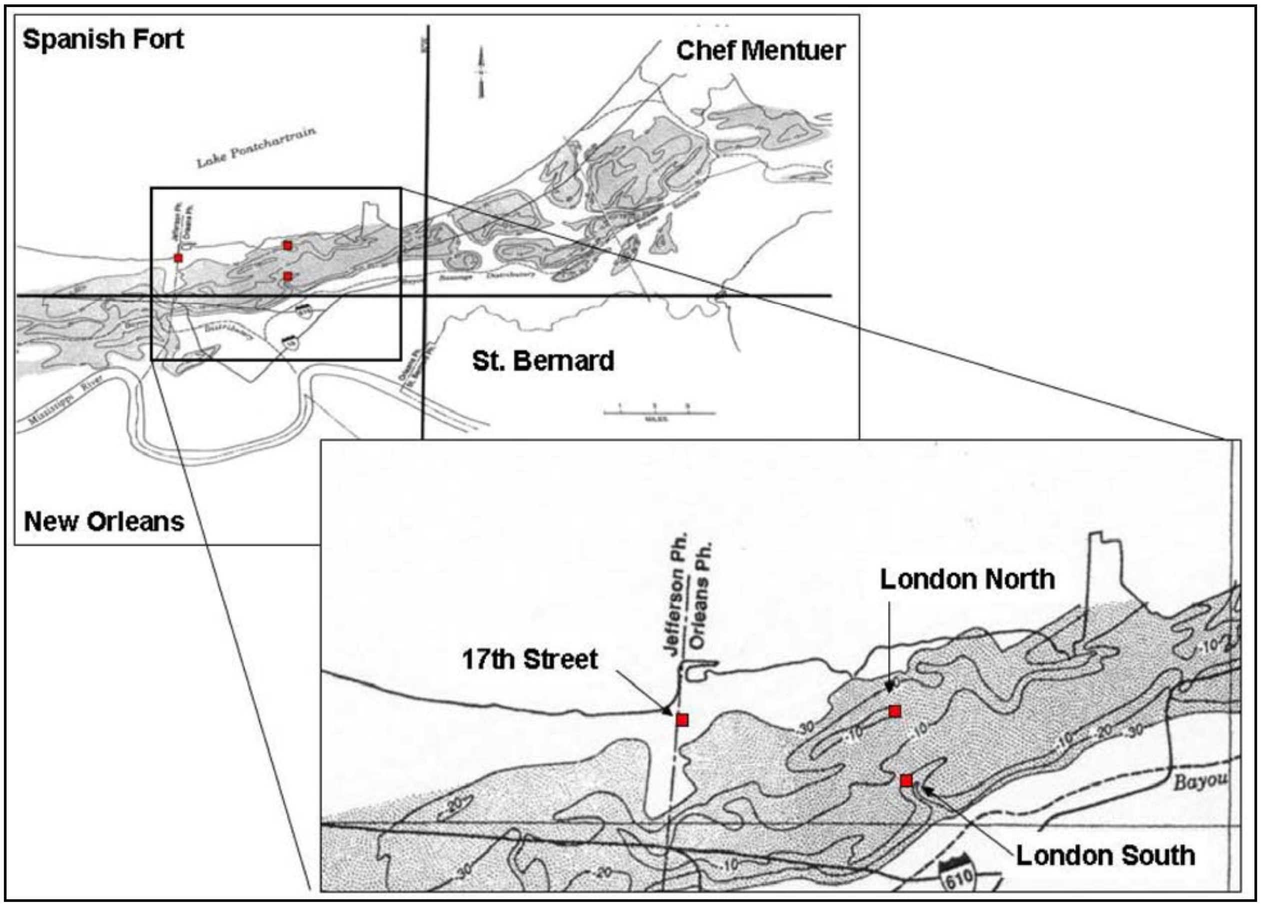


Figure 5-5. Contour map of the buried Pine Island Beach with elevations in ft MSL (Saucier 1994).

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 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 Missisisippi 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 lakefront 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; 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.

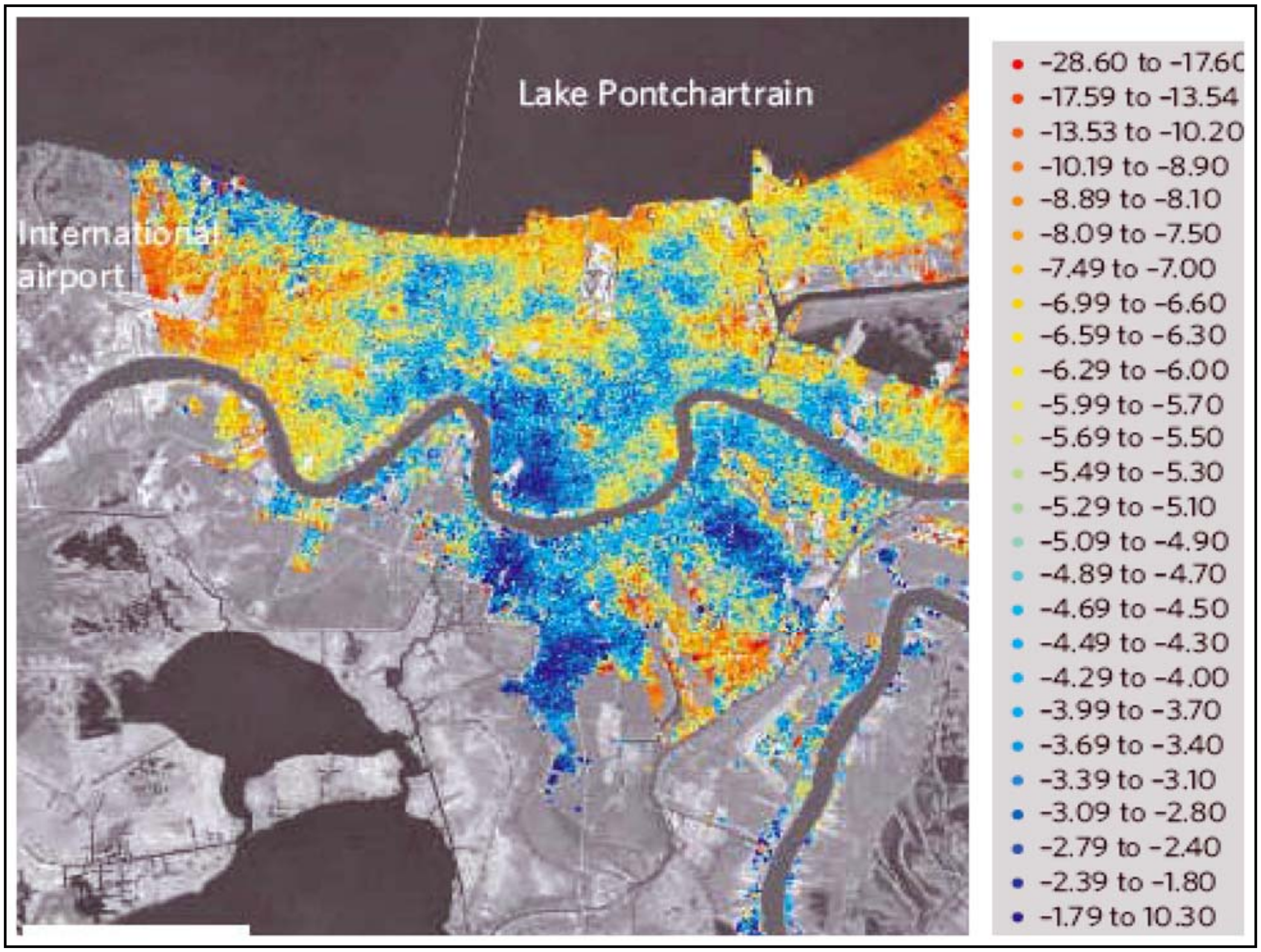


Figure 5-6. New Orleans area subsidence rates in millimeters per year, based on 33 Radarsat satellite scenes from 2002 and 2005 (Dixon et al. 2006). Rates are generally highest near the Lake Pontchartrain shoreline. Lake front area contains dredge fill from early 1900s. This area also corresponds to 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).

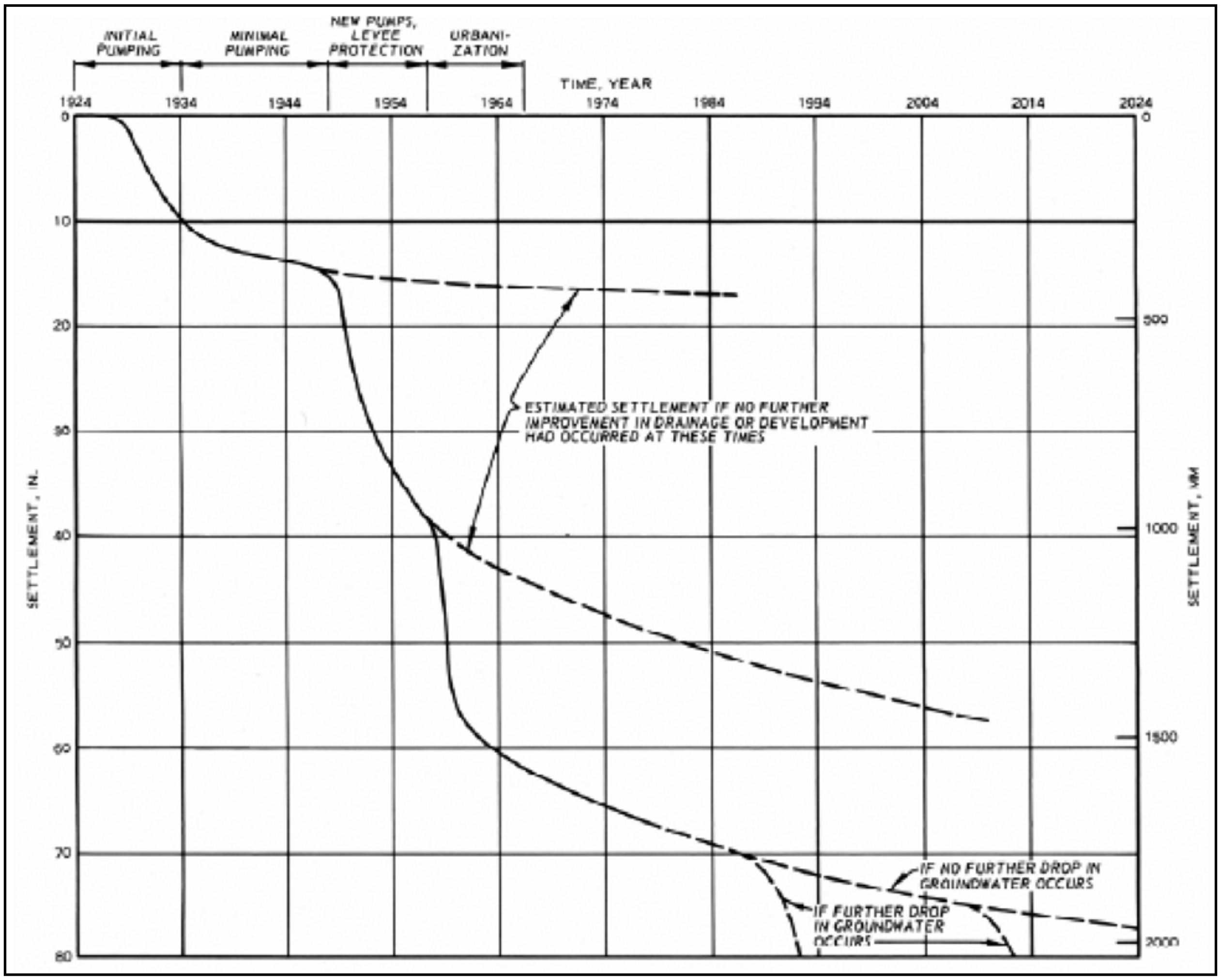


Figure 5-7. Estimated settlement history in the Kenner area due to dewatering of near surface organic sediments by drainage canals and pumping (from Kolb and Saucier (1982) using unpublished data by Traughber and Gore). Dewatering of organic sediments causes volume reduction in these sediments and results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

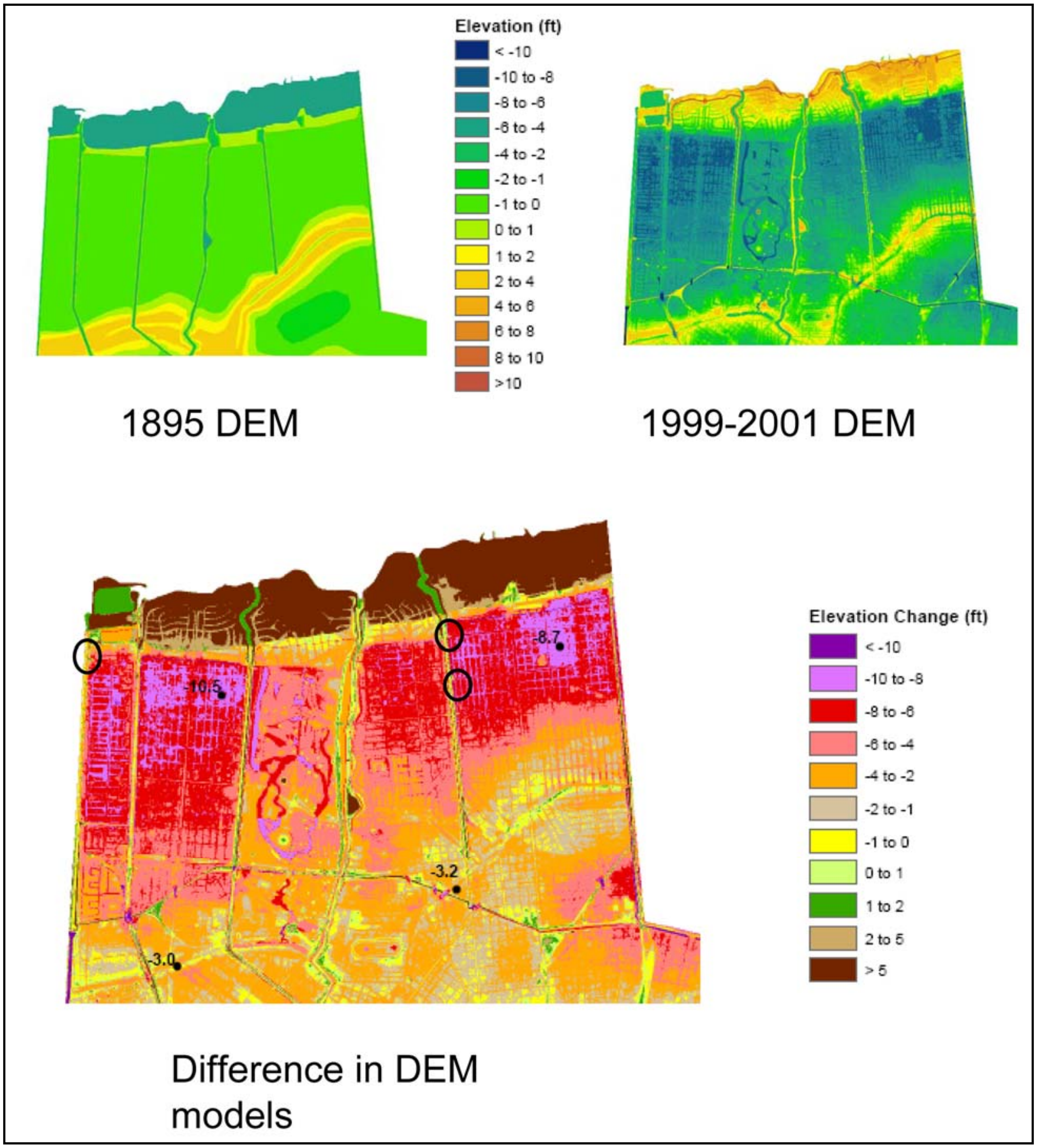


Figure 5-8. Changes in ground surface elevation between 1895 and 2001 (URS 2006). Comparison is based on 1895 historic topographic map and 1999-2001 digital elevation models (DEMs). Locations of failures are identified by open circles, from left to right are 17th Street Canal, London Canal North breach (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 stabilize 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 they probably accurately reflect the latter stages of the subsidence curve in Figure 5-7 in areas that have undergone dewatering.

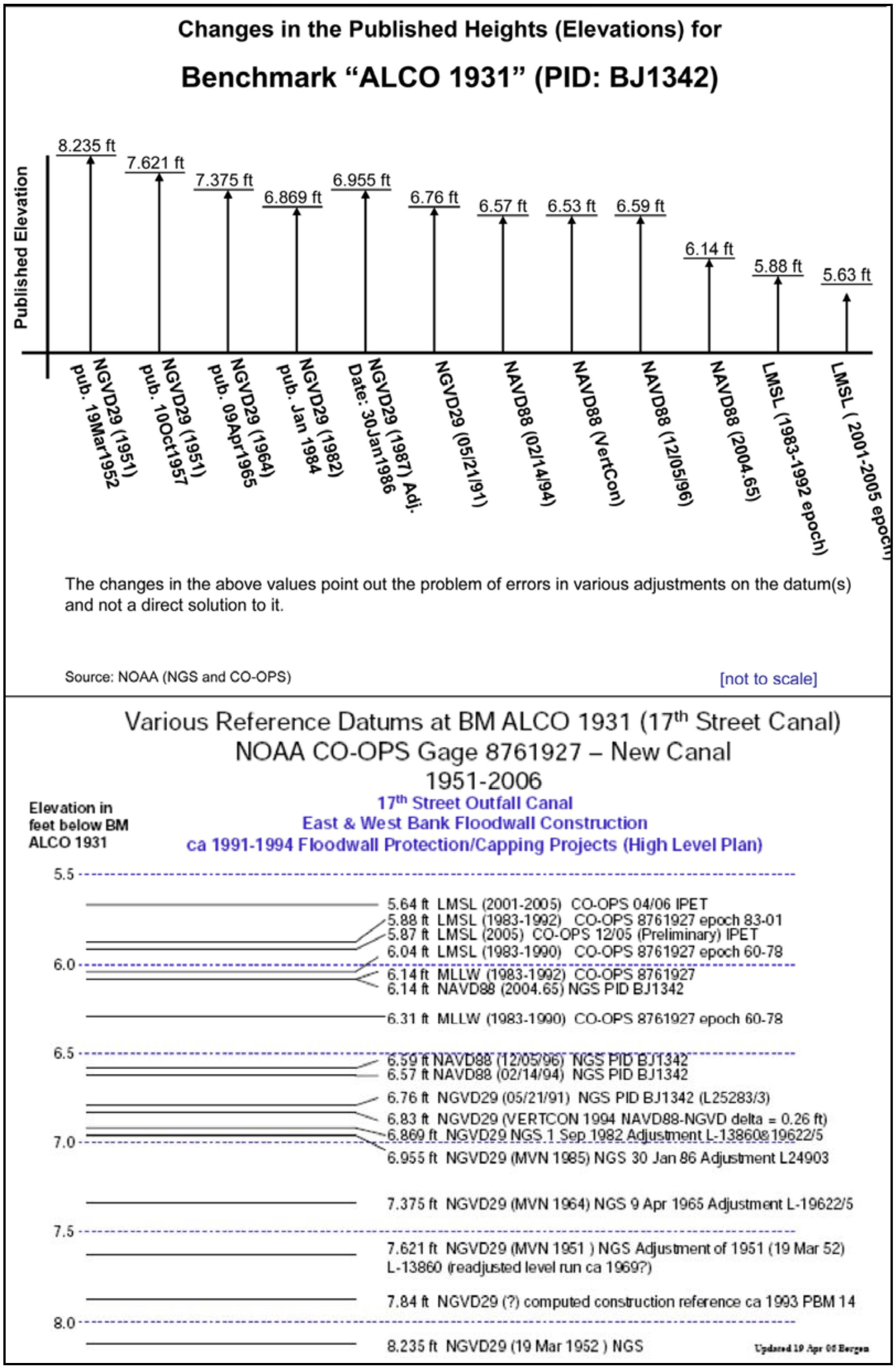


Figure 5-9. Changes in elevation reported for the ALCO benchmark, near the Hammond Highway Bridge at 17th Street Canal (from IPET, Volume II, Figures 69 and 33, respectively).

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 they 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 IPET Volume VIII, *Engineering and Operational Risk and Reliability Analysis*.

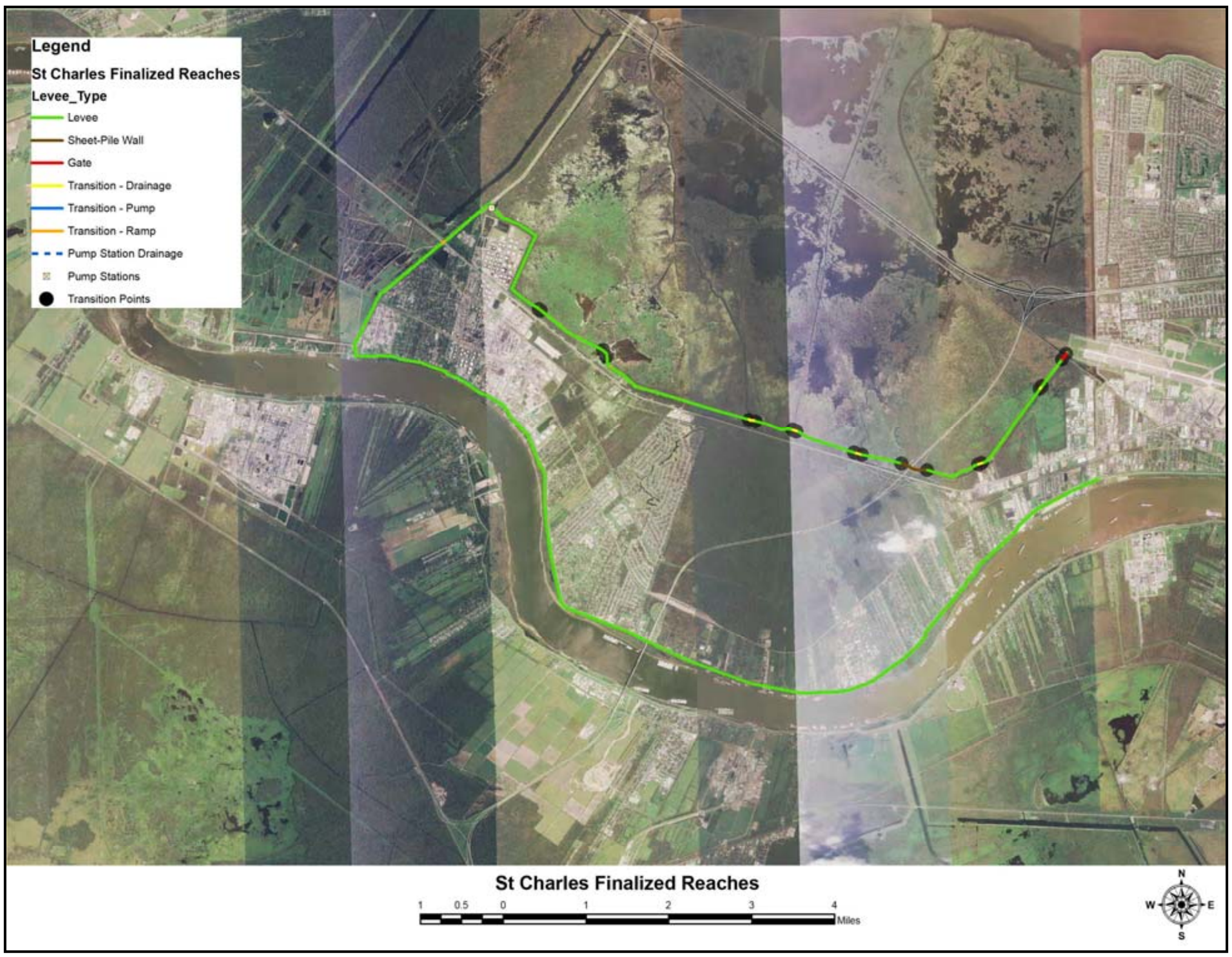

Figure 6-1. St. Charles.

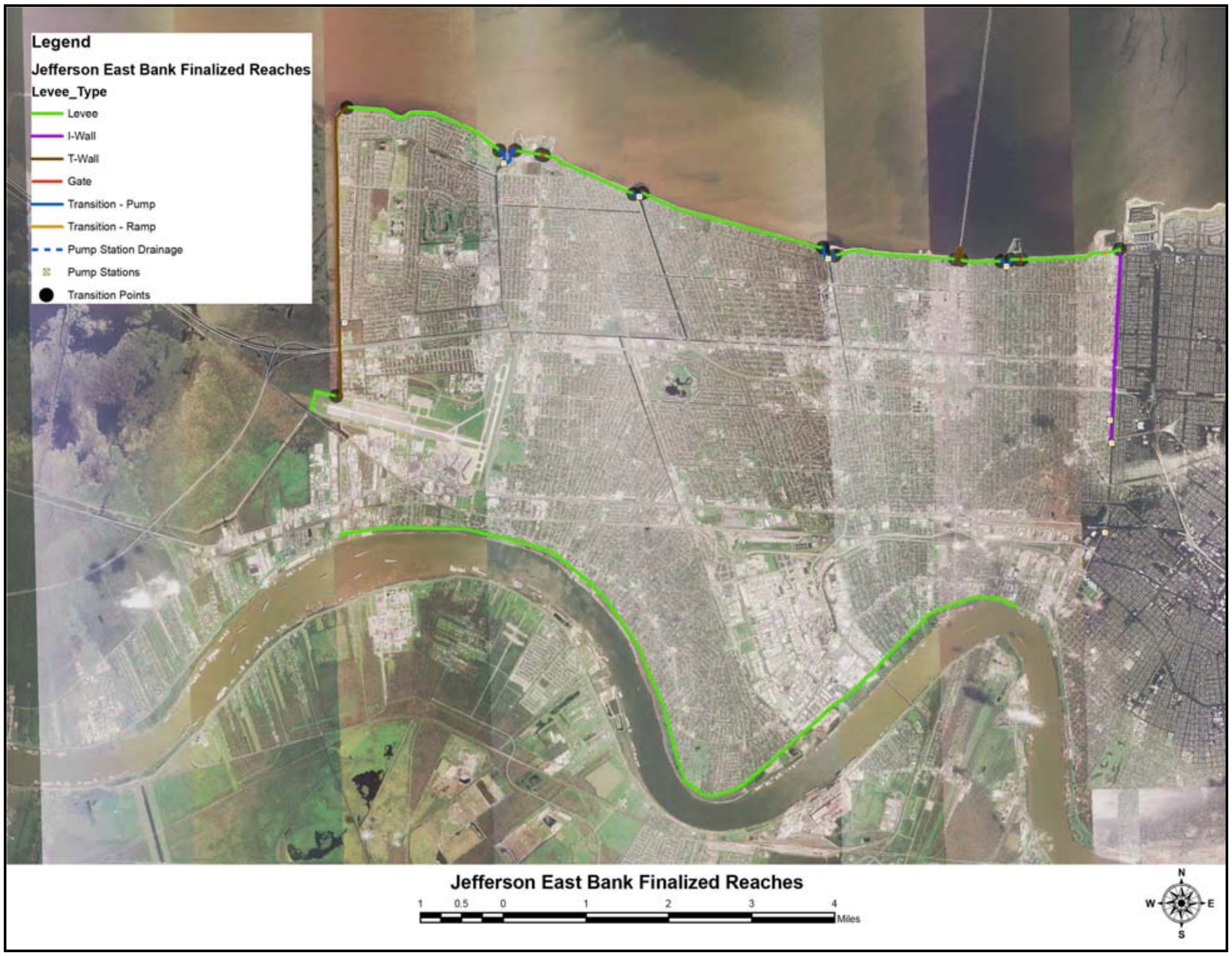

Figure 6-2. Jefferson East Bank.

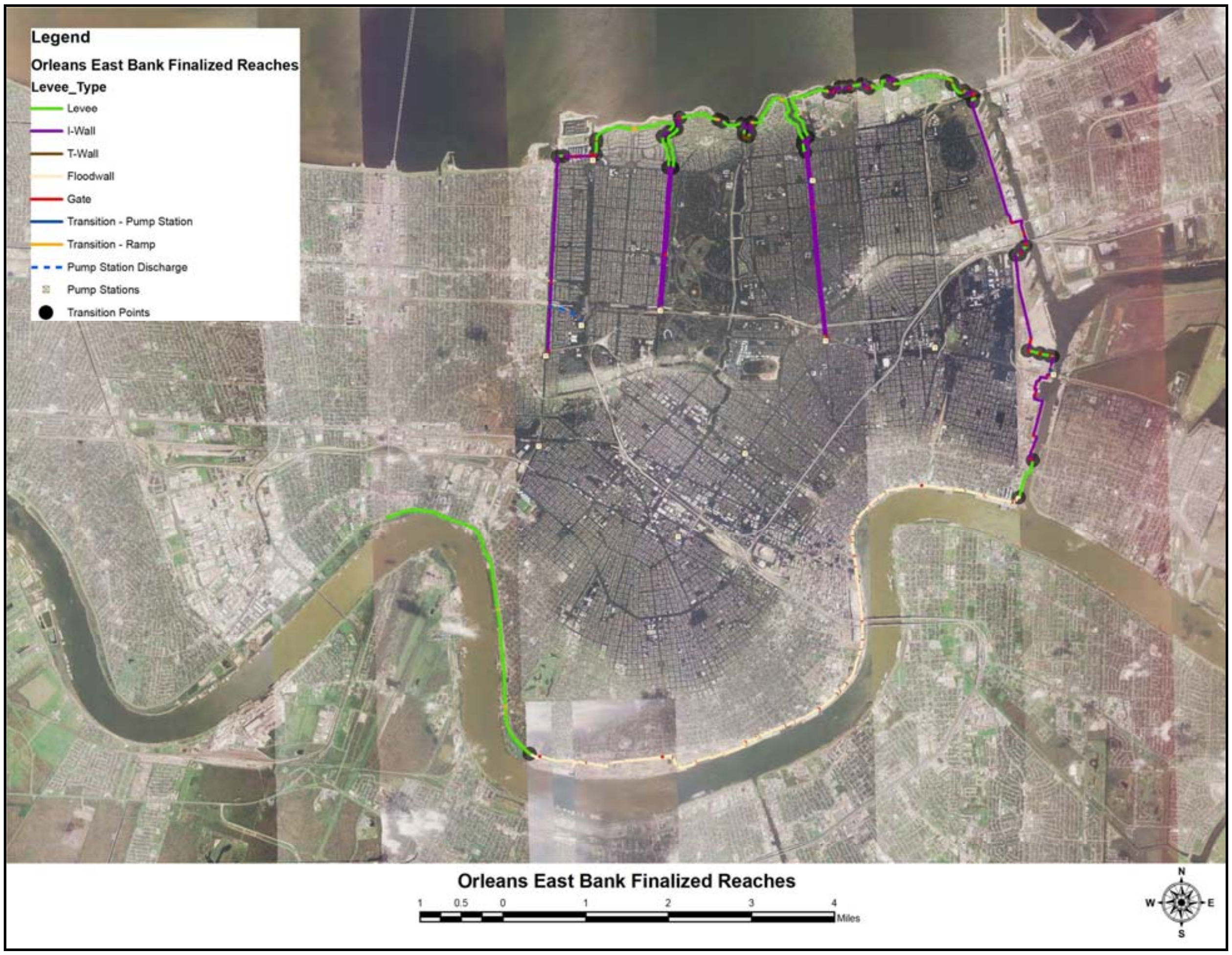

Figure 6-3. Orleans East Bank.

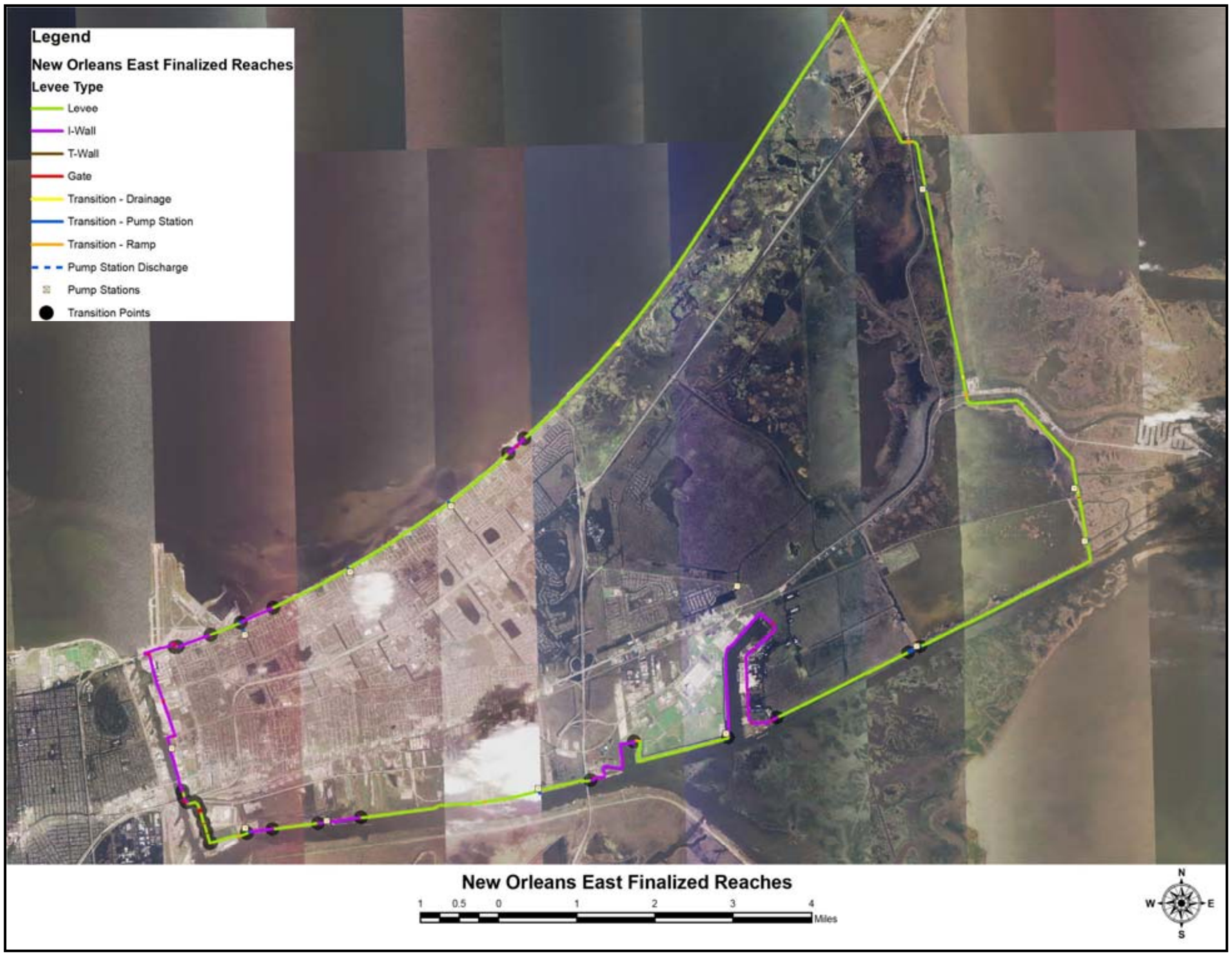

Figure 6-4. New Orleans East.

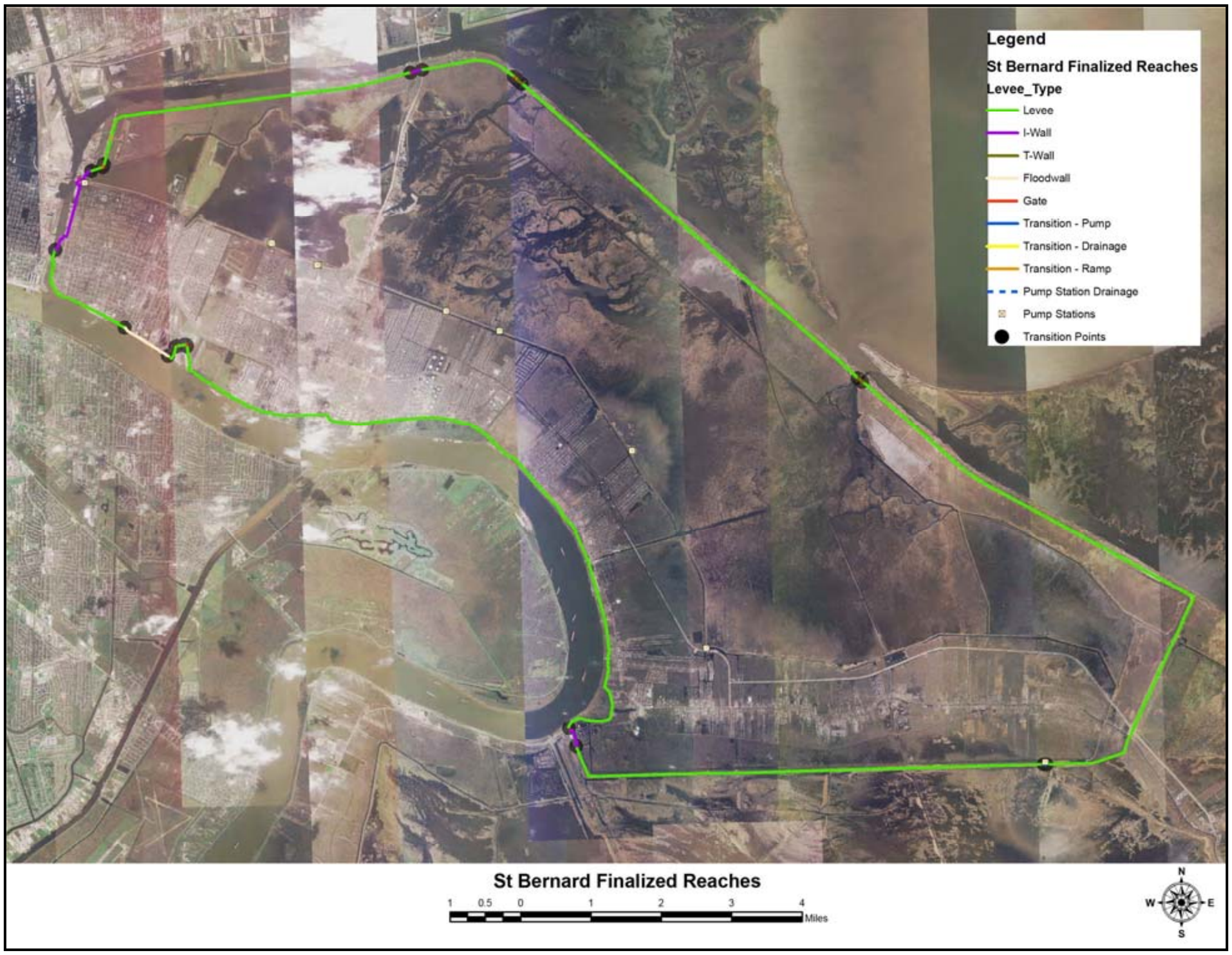

Figure 6-5. St. Bernard.

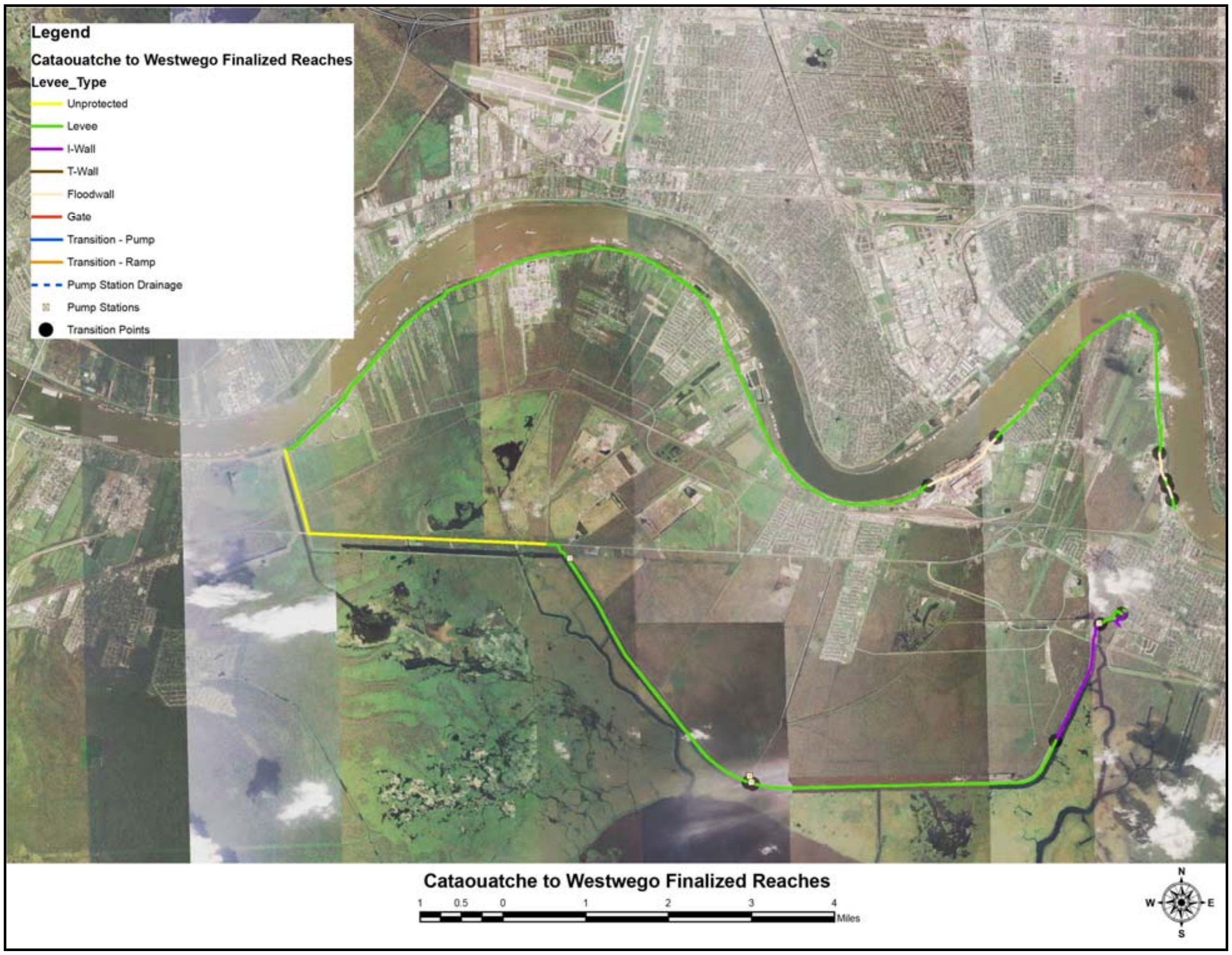

Figure 6-6. Westwego to Harvey Canal.

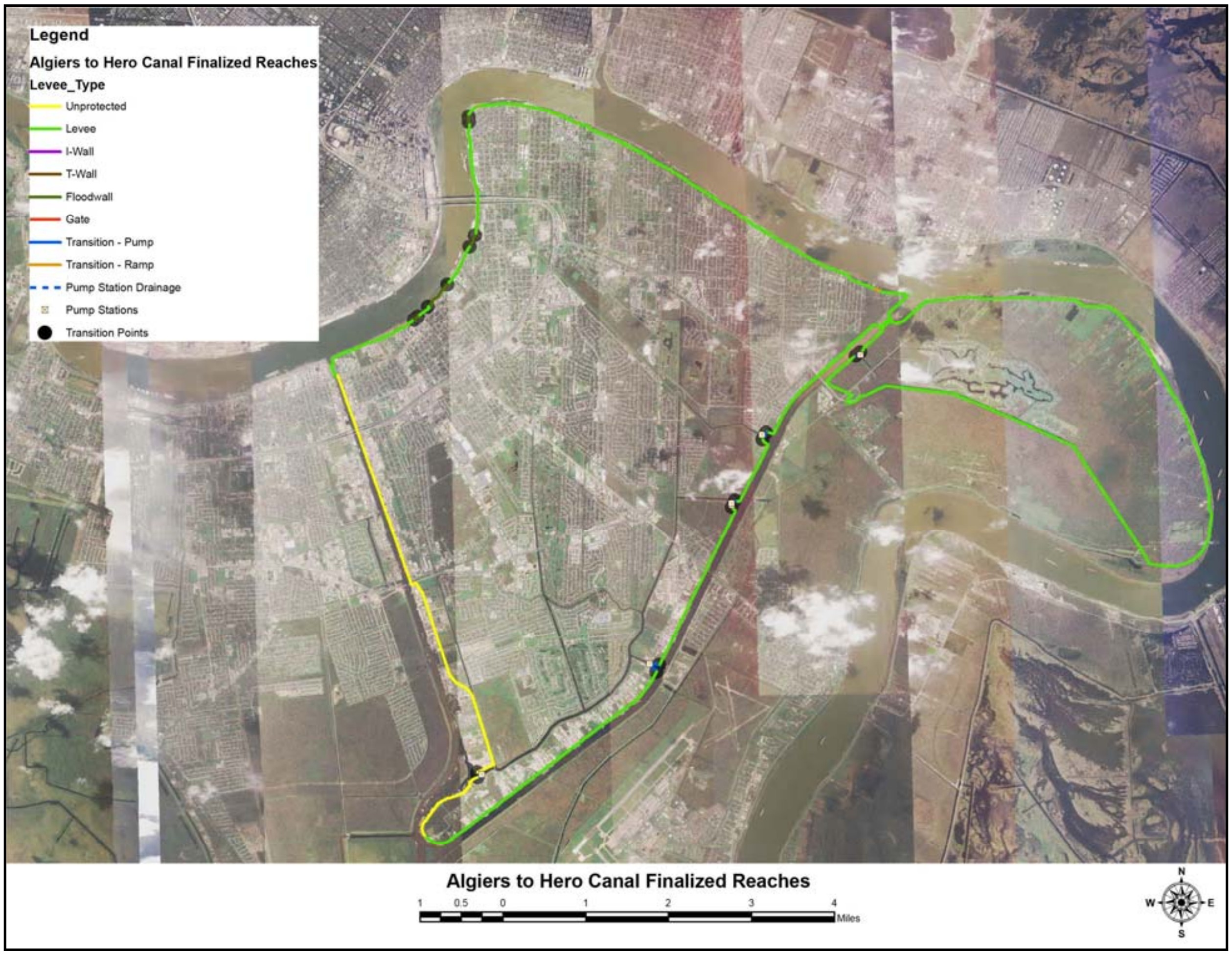

Figure 6-7. Algiers to Hero Canal.

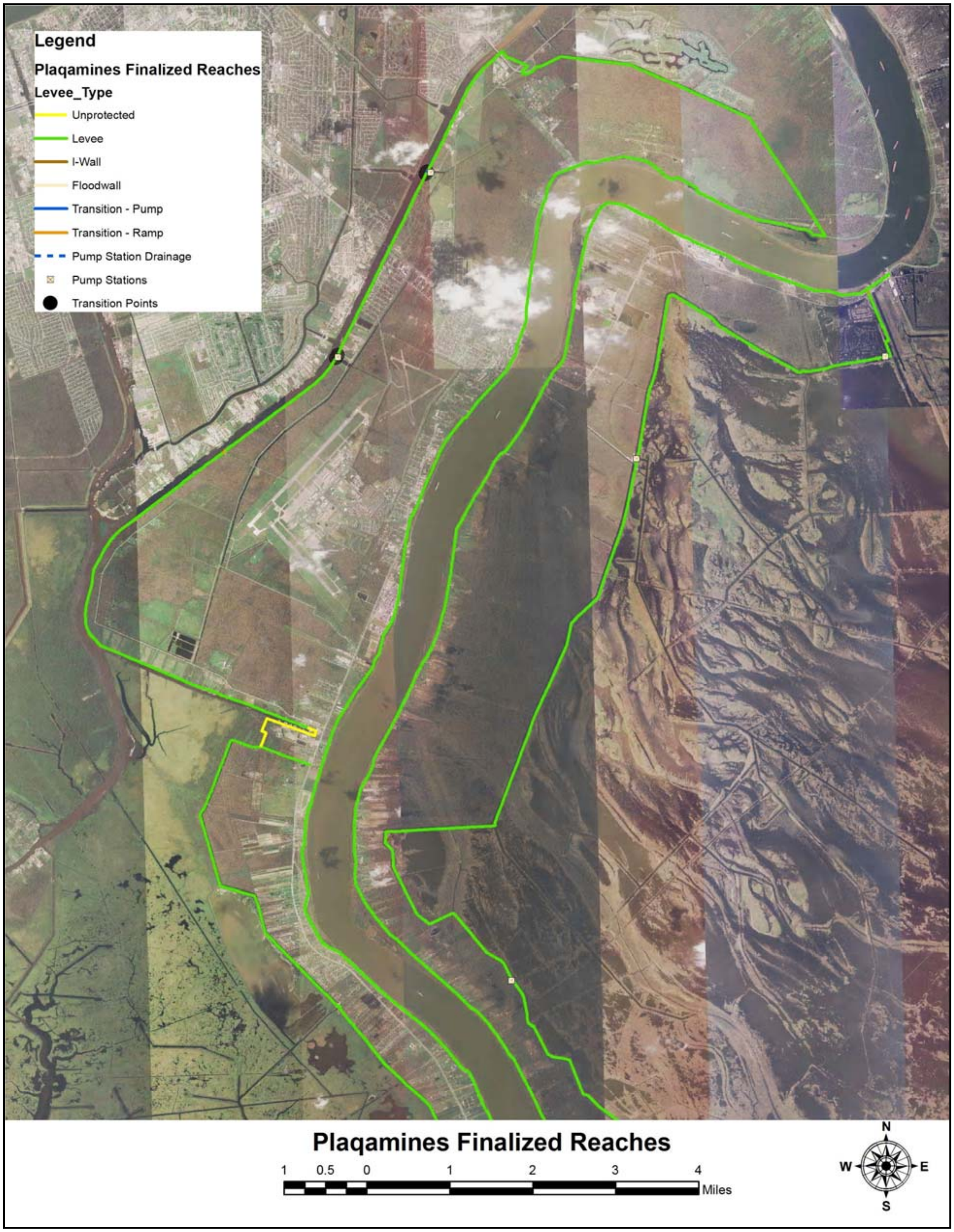

Figure 6-8. Plaquemines 1.

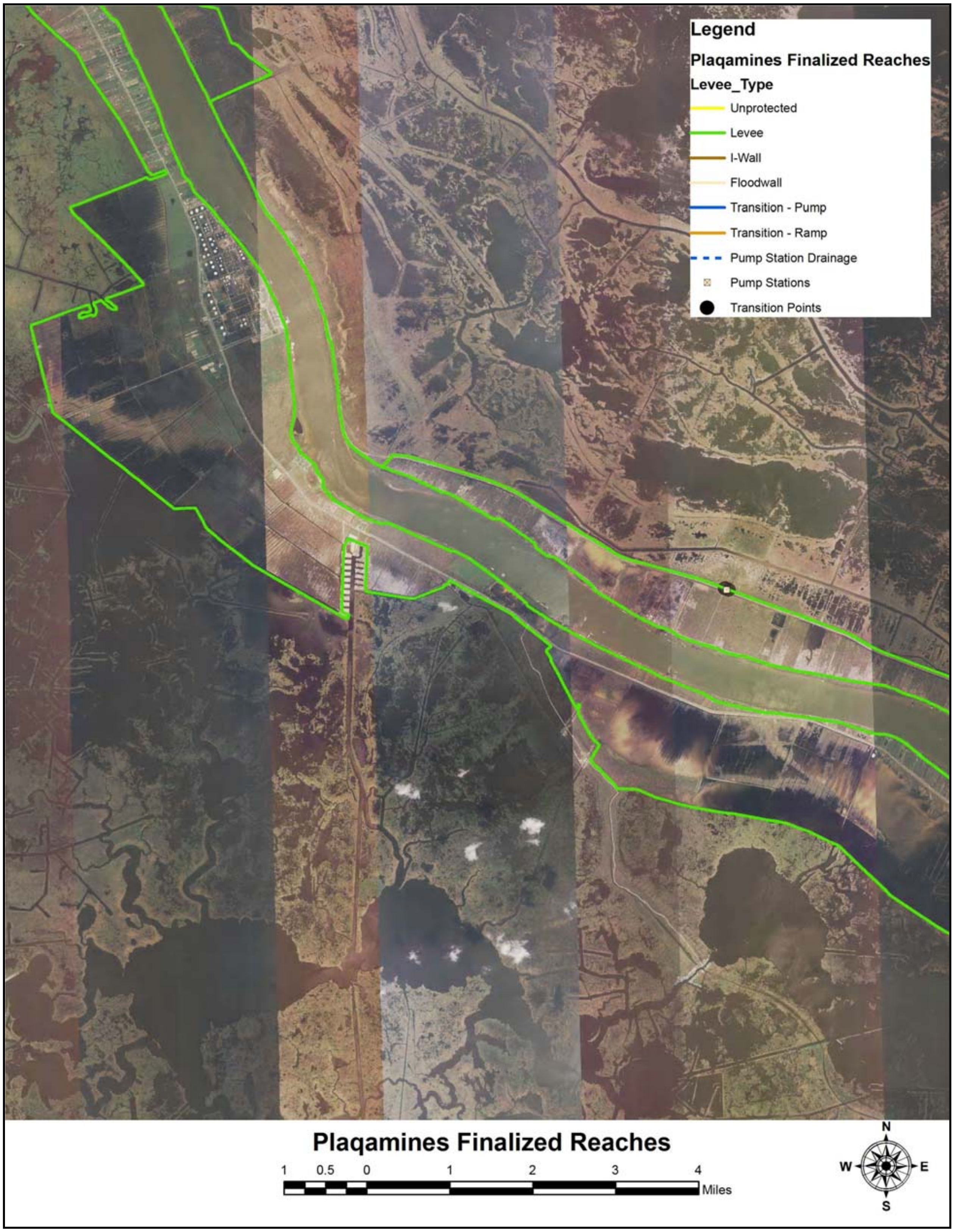

Figure 6-9. Plaquemines 2.

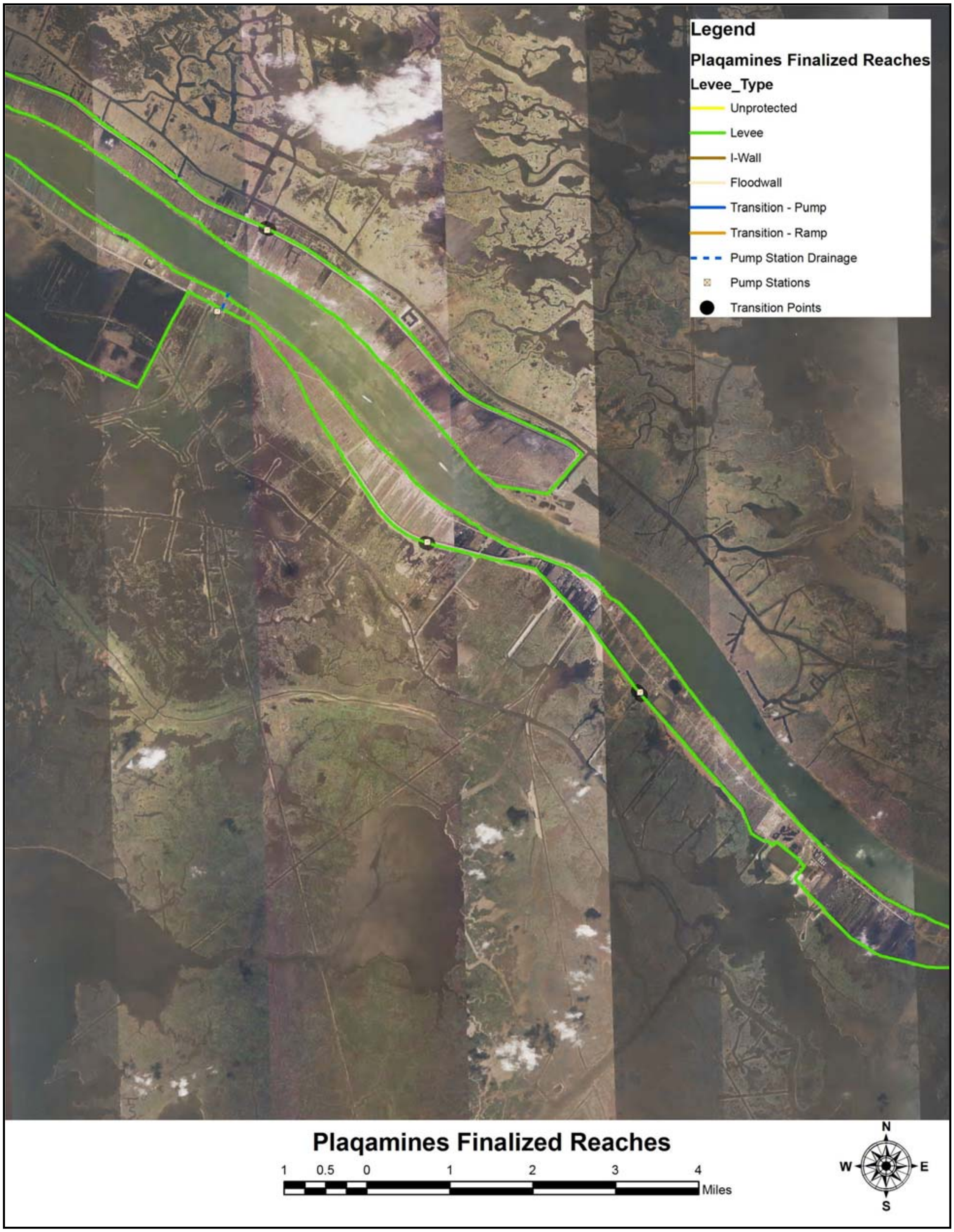

Figure 6-10. Plaquemines 3.

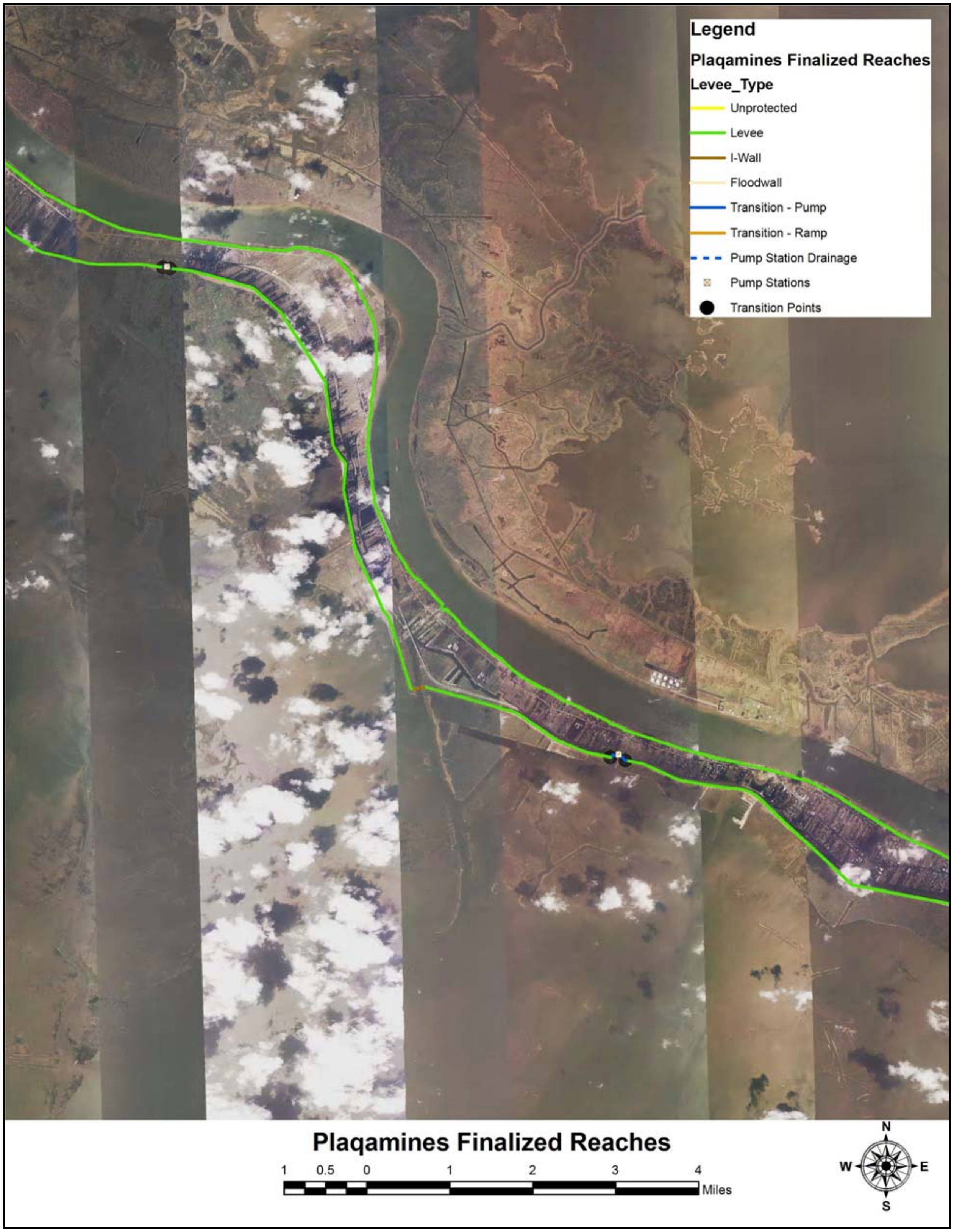

Figure 6-11. Plaquemines 4.

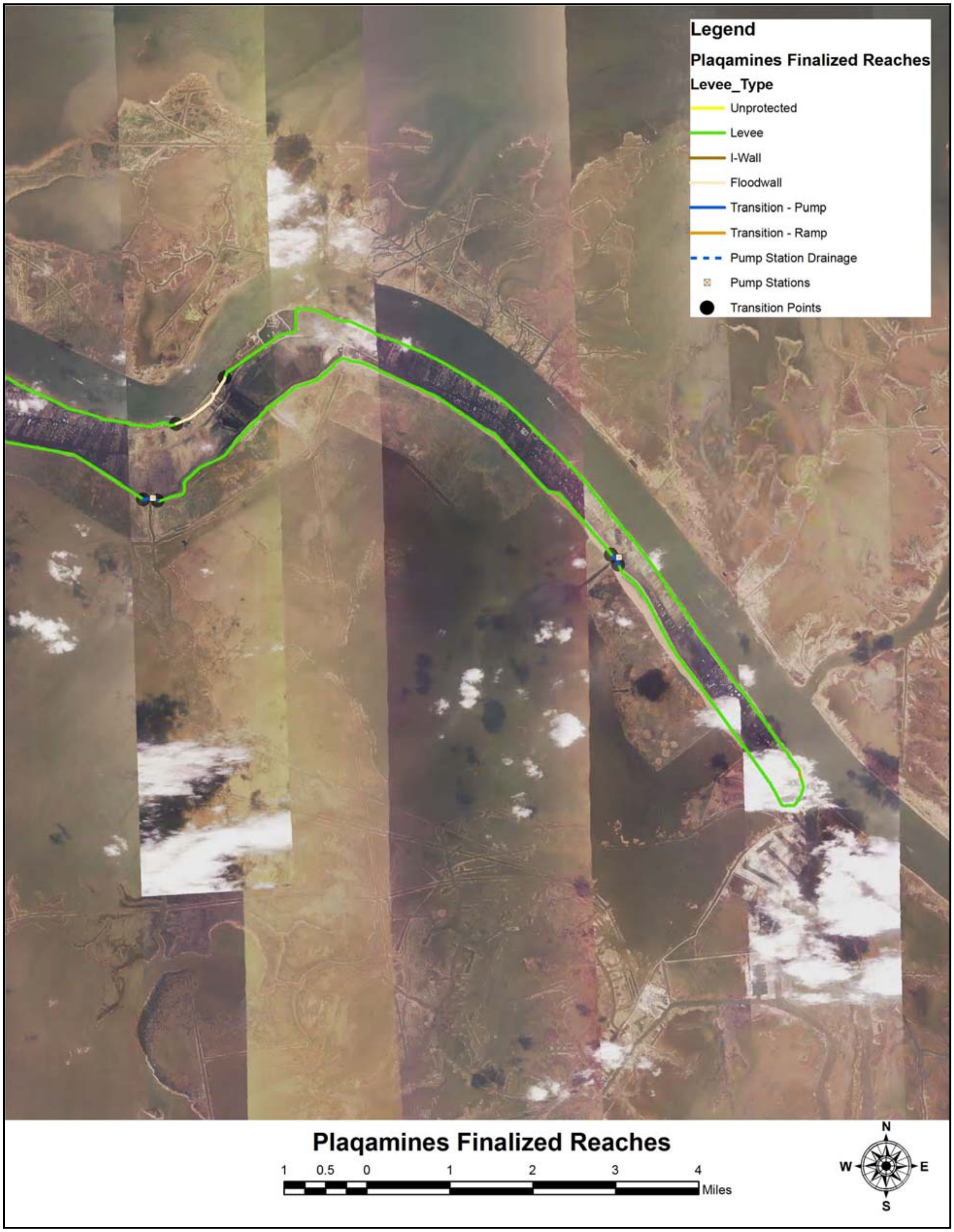

Figure 6-12. Plaquemines 5.

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.

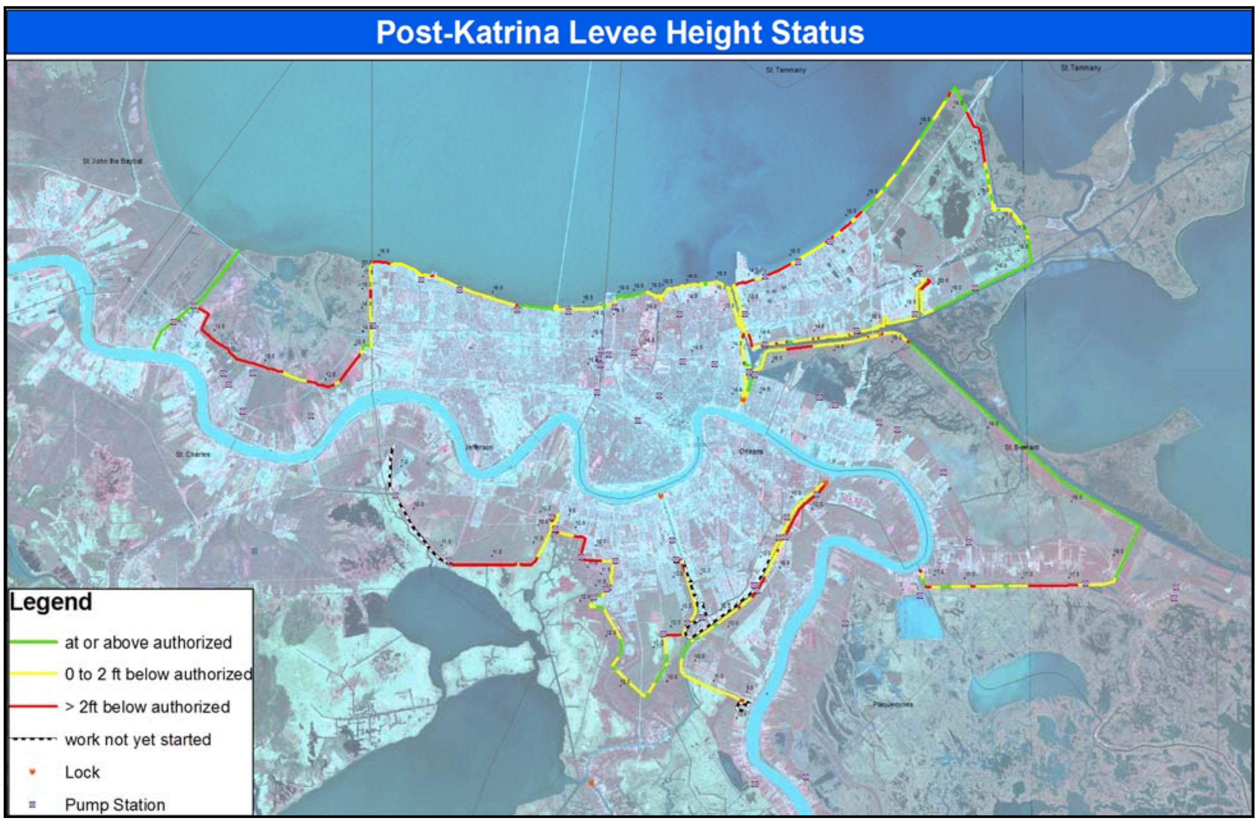

Figure 7-1. Comparison of repaired structure elevations (post-Katrina) to authorized elevations for northern portion of the hurricane protection system. (Source, New Orleans District.)

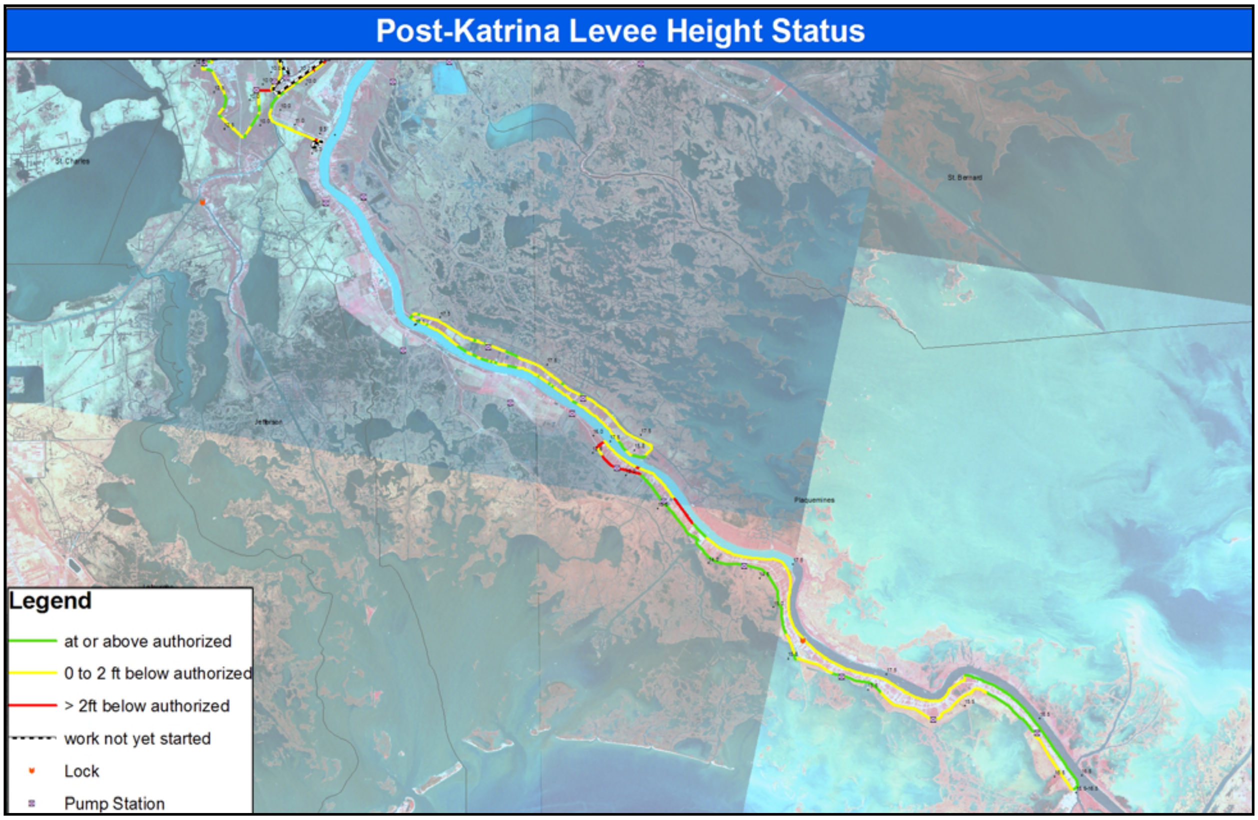

Figure 7-2. Comparison of repaired structure elevations (post-Katrina) to authorized elevations for the southern portions of the hurricane protection system. (Source, New Orleans District.)

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 8-1describes 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.

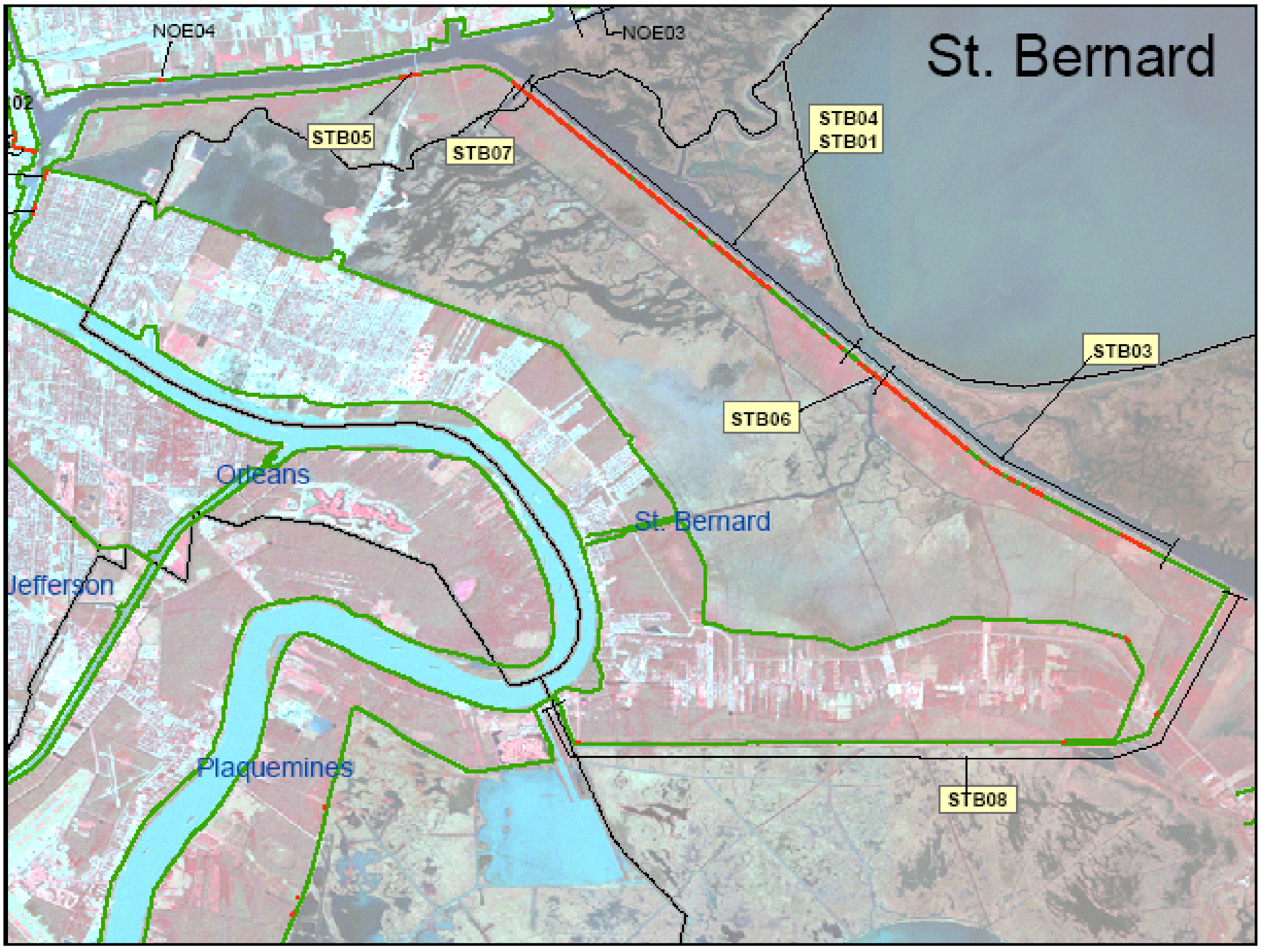

Figure 8-3. Distribution of breaches, St. Bernard.

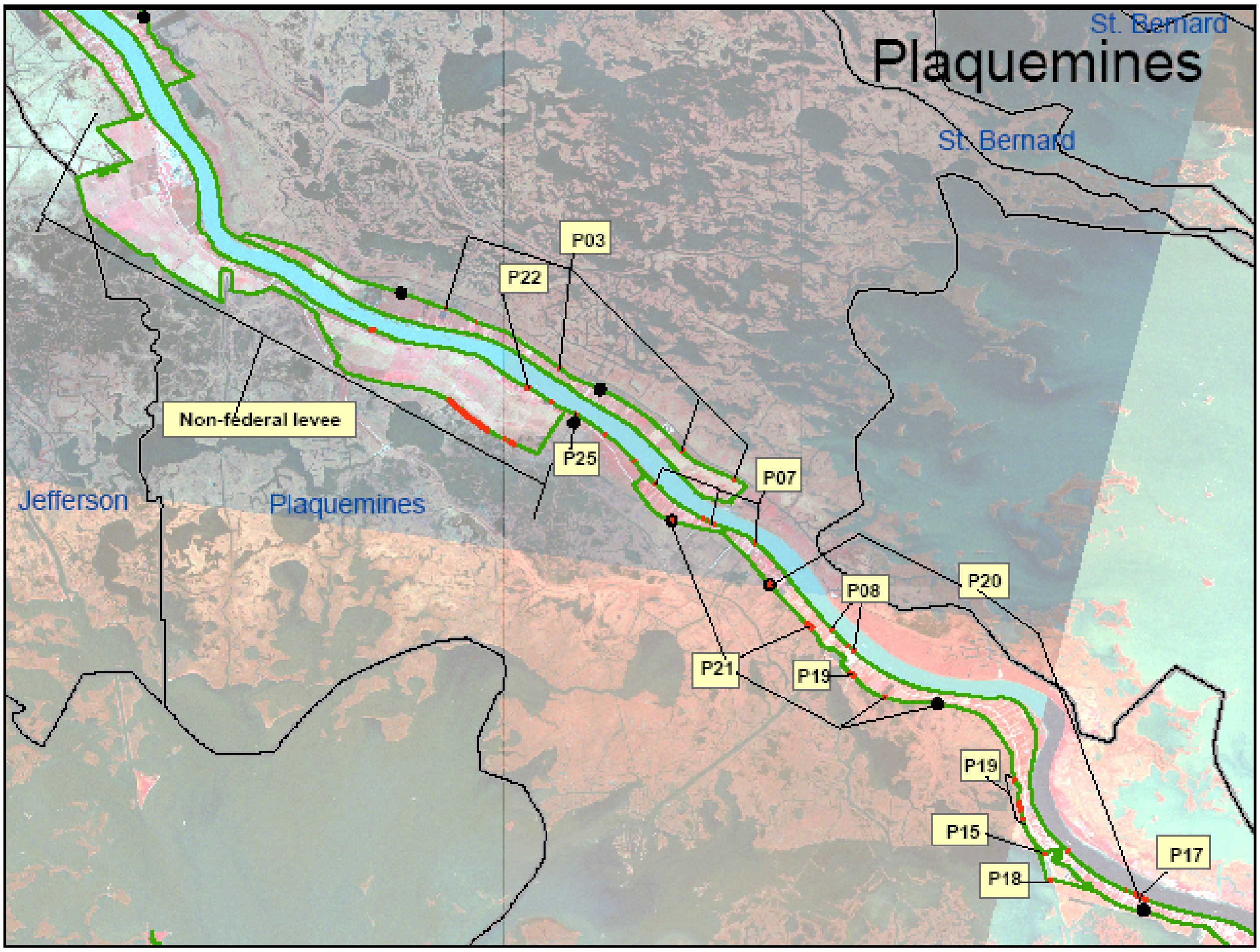

Figure 8-4. Distribution of breaches, Plaquemines.

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 yd 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

Table 8-1. Character of Breach Sites and General Repairs			
Breach/Project ID	**Breach Location Description**	**Damage Description**	**Repair Description**
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 sour 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 riprap, 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.

Table 8-1. Character of Breach Sites and General Repairs			
Breach/Project ID	**Breach Location Description**	**Damage Description**	**Repair Description**
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 back side 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 sour hole extends to -21 ft 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.
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.

Table 8-1. Character of Breach Sites and General Repairs			
Breach/Project ID	**Breach Location Description**	**Damage Description**	**Repair Description**
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 sheet-pile 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.

Table 8-1. Character of Breach Sites and General Repairs			
Breach/Project ID	**Breach Location Description**	**Damage Description**	**Repair Description**
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.

Appendix 9
Risk Assessment Supporting Data

This appendix provides tables of fundamental data that support the documentation and discussion of the risk assessment provided in the overview main text of IPET Volume I. More detailed information is available in IPET Volume VIII, *Engineering and Operational Risk and Reliability Analysis*. This information provides some numerical context to the graphics and dialogue in the description of the risk assessment methodology and results.

Table 9-1. Reach elevations (top of structure) and lengths used in risk assessment for Pre-Katrina and 2007 HPS. Elevations referenced to NAVD 88 (2004.65).

Reach	Length (ft)	Reach Name	Pre-Katrina HPS (ft)	2007 HPS (ft)
1	2,405	NOE 1	12.0	10.8
2	250	NOE 2	10.0	10.8
3	2,325	NOE 3	12.0	10.8
4	2,330	NOE 4	13.0	10.8
5	2,270	NOE 5	14.0	10.8
6	19,110	NOE 6	13.0	13.0
7	1,475	NOE 7	13.0	13.0
8	2,725	NOE 8	13.0	13.0
9	32,900	NOE 9	18.5	18.2
10	5,830	NOE 10	15.0	13.8
11	13,325	NOE 11	11.0	14.0
12	8,910	NOE 12	15.0	15.0
13	9,185	NOE 13	16.0	15.8
14	2,615	NOE 14	17.0	16.0
15	4,470	NOE 15	18.0	18.0
16	13,045	NOE 16	15.5	18.0
17	10,570	NOE 17	16.8	18.0
18	10,760	NOE 18	18.0	17.9
19	9,320	NOE 19	17.9	17.9
20	7,905	NOE 20	17.0	16.0
21	5,520	NOE 21	17.0	16.0
22	385	NOE 22	14.0	16.0
23	15,320	NOE 23	14.0	13.9
24	2,910	NOE 24	12.5	13.8
25	3,230	NOE 25	13.5	13.8
26	1,640	NOE 26	14.0	13.8

Reach	Length (ft)	Reach Name	Pre-Katrina HPS (ft)	2007 HPS (ft)
27	2,750	NOE 27	14.0	13.8
28	4,100	NOE 28	12.5	13.0
29	11,185	NOE 29	13.0	13.5
30	6,745	JE1	12.5	12.8
31	5,915	JE2	13.0	13.9
32	4,945	JE3	12.5	13.9
33	36,430	JE4	15.0	16.5
34	19,925	JE5	16.0	16.5
35	12,300	JE6	13.0	15.5
36	4,205	JE7	24.5	25.3
37	53,090	JE8	25.5	25.4
38	2,595	JE9	6.0	9.6
39	17,500	SC1	11.0	11.0
40	11,710	SC2	10.0	13.0
41	23,190	SC3	10.0	10.0
42	70,465	SC4	27.0	27.9
43	9,280	SC5	21.0	20.5
44	3,795	SC6	17.0	20.3
45	12,740	OM1	13.0	15.5
46	9,280	OM2	14.0	14.0
47	3,155	OM3	14.0	14.0
48	9,110	OM4	14.0	14.0
49	3,610	OM5	14.0	14.7
50	12,130	OM6	13.5	13.5
51	3,880	OM7	13.5	13.5
52	12,765	OM8	13.5	13.5
53	3,030	OM9	13.5	13.5
54	2,925	OM10	13.0	12.0
55	6,310	OM11	18.5	18.0
56	9,940	OM12	17.0	17.0
57	2,380	OM13	17.5	16.5
58	3,220	OM14	19.5	16.5
59	7,605	OM15	17.0	16.5
60	1,155	OM16	14.0	14.4
61	9,095	OM17	12.5	13.5
62	9,170	OM18	12.5	13.8
63	1,490	OM19	11.0	15.0
64	8,390	OM20	13.0	13.8
65	875	OM21	21.0	20.1
66	1,980	OM22	21.0	21.5
67	8,915	OM23	21.8	22.5

Reach	Length (ft)	Reach Name	Pre-Katrina HPS (ft)	2007 HPS (ft)
68	25,450	OM24	22.2	23.6
69	10,780	OM25	22.5	24.3
70	14,180	OM26	24.0	24.8
71	3,350	OM27	25.0	25.8
72	6,570	SB1	13.0	15.0
73	1,115	SB2	13.0	13.3
74	26,995	SB3	13.5	13.6
75	84,195	SB4	17.5	20.0
76	44,650	SB5	15.0	15.7
77	25,545	SB6	20.1	22.0
78	26,950	SB7	20.1	21.2
79	15,885	SB8	20.1	20.5
80	870	SB9	20.9	22.0
81	22,000	PL1	6.0	9.5
82	41,525	PL2	9.0	8.5
83	57,470	PL3	18.0	18.1
84	50,610	PL4	8.0	8.5
85	36,605	PL5	17.0	16.4
86	60,615	PL6	6.0	6.4
87	25,865	PL7	17.0	15.7
88	17,170	PL8	9.5	11.2
89	39,195	PL9	15.5	16.2
90	27,100	PL10	12.5	13.5
91	19,120	PL11	12.2	13.6
92	13,774	PL12	11.8	12.7
93	6,635	PL13	12.2	13.8
94	49,470	PL14	15.5	16.3
95	6,160	PL15	14.0	14.9
96	26,710	PL16	14.0	15.0
97	78,500	PL17	14.0	14.7
98	79,100	PL18	14.5	15.0
99	22,740	PL19	14.5	13.9
100	51,200	PL20	16.5	16.6
101	32,235	PL21	16.5	15.6
102	50,475	PL22	15.0	17.3
103	29,050	PL23	15.0	17.5
104	62,810	PL24	10.5	12.0
105	30,940	PL25	10.5	12.4
106	61,710	PL26	18.5	18.6
107	25,225	PL27	18.5	17.0
108	21,496	CW1	3.0	6.5

Reach	Length (ft)	Reach Name	Pre-Katrina HPS (ft)	2007 HPS (ft)
109	13,947	CW2	8.0	7.8
110	24,047	CW3	8.0	7.0
111	8,180	CW4	6.0	9.0
112	1,730	CW5	4.0	4.0
113	320	CW6	8.0	8.0
114	1,495	CW7	9.0	9.0
115	85,639	CW8	24.0	26.3
116	3,060	WH1	9.0	9.0
117	11,240	WH2	8.5	8.0
118	16,370	WH3	10.0	9.8
119	22,135	WH4	13.0	12.5
120	6,690	WH5	13.0	12.0
121	16,120	WH6	9.0	9.0
122	26,700	WH7	8.0	8.0
123	9,510	WH8	5.0	5.0
124	1,165	WH9	13.0	24.8
125	20,710	WH10	23.0	24.2
126	40,198	HA1	22.0	22.0
127	14,550	HA2	22.0	23.2
128	28,337	HA3	5.0	5.0
129	44,000	HA4	9.0	8.3
130	920	HA5	20.0	16.0
131	26,040	HA6	22.0	20.1
132	920	HA7	20.0	16.0
133	5,050	HA8	6.0	9.5
134	10,745	HA9	9.0	8.0
135	1,165	HA10	13.0	24.8
136	190	17th St Gate	Na	16.50
137	215	Orleans Gate	Na	18.00
138	160	London Ave Gate	Na	18.00

Table 9-2. Characteristics of hurricanes used in the joint probability method definition of the hazard. The first 76 hurricanes, those assigned a storm frequency, were used for risk computations. Note, hurricane 62 is deleted and hurricane 77 is added to total 76. The storm frequencies shown are based on joint probabilities of the individual hurricane characteristics and may differ from traditional values determined from historical records or from central pressure alone.

Sequential number - IPET R&R Storm	Storm Frequency	Central pressure at landfall (P0)	Radius to maximum winds at landfall (Rp)	Forward speed at landfall (Vf)	Track angle at landfall wrt vertical (A)	Track	Lat	Long
1	7.90E-04	960	11	11	0	1	24.43	-79.1
2	9.19E-04	960	21	11	0	1	24.43	-79.1
3	4.92E-04	960	35.6	11	0	1	24.43	-79.1
4	2.50E-03	930	8	11	0	1	24.43	-79.1
5	2.73E-03	930	17.7	11	0	1	24.43	-79.1
6	2.30E-03	930	25.8	11	0	1	24.43	-79.1
7	1.13E-03	900	6	11	0	1	24.43	-79.1
8	1.39E-03	900	14.9	11	0	1	24.43	-79.1
9	3.46E-04	900	21.8	11	0	1	24.43	-79.1
10	7.90E-04	960	11	11	0	2	24.42	-78.6
11	9.19E-04	960	21	11	0	2	24.42	-78.6
12	4.92E-04	960	35.6	11	0	2	24.42	-78.6
13	2.50E-03	930	8	11	0	2	24.42	-78.6
14	2.73E-03	930	17.7	11	0	2	24.42	-78.6
15	2.30E-03	930	25.8	11	0	2	24.42	-78.6
16	1.13E-03	900	6	11	0	2	24.42	-78.6
17	1.39E-03	900	14.9	11	0	2	24.42	-78.6
18	3.46E-04	900	21.8	11	0	2	24.42	-78.6
19	7.90E-04	960	11	11	0	3	24.42	-78.5
20	9.19E-04	960	21	11	0	3	24.42	-78.5
21	4.92E-04	960	35.6	11	0	3	24.42	-78.5
22	2.50E-03	930	8	11	0	3	24.42	-78.5
23	2.73E-03	930	17.7	11	0	3	24.42	-78.5
24	2.30E-03	930	25.8	11	0	3	24.42	-78.5
25	1.13E-03	900	6	11	0	3	24.42	-78.5
26	1.39E-03	900	14.9	11	0	3	24.42	-78.5
27	3.46E-04	900	21.8	11	0	3	24.42	-78.5
28	7.90E-04	960	11	11	0	4	24.4	-77.9
29	9.19E-04	960	21	11	0	4	24.4	-77.9
30	4.92E-04	960	35.6	11	0	4	24.4	-77.9
31	2.50E-03	930	8	11	0	4	24.4	-77.9

Sequential number - IPET R&R Storm	Storm Frequency	Central pressure at landfall (P0)	Radius to maximum winds at landfall (Rp)	Forward speed at landfall (Vf)	Track angle at landfall wrt vertical (A)	Track	Lat	Long
32	2.73E-03	930	17.7	11	0	4	24.4	-77.9
33	2.30E-03	930	25.8	11	0	4	24.4	-77.9
34	1.13E-03	900	6	11	0	4	24.4	-77.9
35	1.39E-03	900	14.9	11	0	4	24.4	-77.9
36	3.46E-04	900	21.8	11	0	4	24.4	-77.9
37	7.90E-04	960	11	11	0	5	24.43	-78.9
38	9.19E-04	960	21	11	0	5	24.43	-78.9
39	4.92E-04	960	35.6	11	0	5	24.43	-78.9
40	2.50E-03	930	8	11	0	5	24.43	-78.9
41	2.73E-03	930	17.7	11	0	5	24.43	-78.9
42	2.30E-03	930	25.8	11	0	5	24.43	-78.9
43	1.13E-03	900	6	11	0	5	24.43	-78.9
44	1.39E-03	900	14.9	11	0	5	24.43	-78.9
45	3.46E-04	900	21.8	11	0	5	24.43	-78.9
46	3.50E-04	960	18.2	11	-45	1	24.54	-80.9
47	3.90E-04	960	24.6	11	-45	1	24.54	-80.9
48	7.16E-04	900	12.5	11	-45	1	24.54	-80.9
49	5.48E-04	900	18.4	11	-45	1	24.54	-80.9
50	3.50E-04	960	18.2	11	-45	2	24.83	-80.8
51	3.90E-04	960	24.6	11	-45	2	24.83	-80.8
52	7.16E-04	900	12.5	11	-45	2	24.83	-80.8
53	5.48E-04	900	18.4	11	-45	2	24.83	-80.8
54	3.50E-04	960	18.2	11	-45	3	25.38	-80.8
55	3.90E-04	960	24.6	11	-45	3	25.38	-80.8
56	7.16E-04	900	12.5	11	-45	3	25.38	-80.8
57	5.48E-04	900	18.4	11	-45	3	25.38	-80.8
58	3.50E-04	960	18.2	11	-45	4.1	26.08	-80.8
59	3.90E-04	960	24.6	11	-45	4.1	26.08	-80.8
60	7.16E-04	900	12.5	11	-45	4.1	26.08	-80.8
61	5.48E-04	900	18.4	11	-45	4.1	26.08	-80.8
63	2.50E-04	960	24.6	11	45	1	21.28	-90
64	3.02E-04	900	12.5	11	45	1	21.28	-90
65	2.01E-04	900	18.4	11	45	1	21.28	-90
66	1.54E-04	960	18.2	11	45	2	21.3	-90
67	2.50E-04	960	24.6	11	45	2	21.3	-90
68	3.02E-04	900	12.5	11	45	2	21.3	-90
69	2.01E-04	900	18.4	11	45	2	21.3	-90

Sequential number - IPET R&R Storm	Storm Frequency	Central pressure at landfall (P0)	Radius to maximum winds at landfall (Rp)	Forward speed at landfall (Vf)	Track angle at landfall wrt vertical (A)	Track	Lat	Long
70	1.54E-04	960	18.2	11	45	3	21.27	-90.1
71	2.50E-04	960	24.6	11	45	3	21.27	-90.1
72	3.02E-04	900	12.5	11	45	3	21.27	-90.1
73	2.01E-04	900	18.4	11	45	3	21.27	-90.1
74	1.54E-04	960	18.2	11	45	4	21.28	-90
75	2.50E-04	960	24.6	11	45	4	21.28	-90
76	3.02E-04	900	12.5	11	45	4	21.28	-90
77	2.01E-04	900	18.4	11	45	4	21.28	-90
Total	**7.45E-02**							
62		960	18.2	11	45	1	21.28	-90
78		960	17.7	6	0	1	24.43	-78.9
79		900	17.7	6	0	1	24.43	-78.9
80		960	17.7	6	0	2	24.42	-78.4
81		900	17.7	6	0	2	24.42	-78.4
82		960	17.7	6	0	3	24.42	-78.3
83		900	17.7	6	0	3	24.42	-78.3
84		960	17.7	6	0	4	24.4	-77.7
85		900	17.7	6	0	4	24.4	-77.7
86		960	17.7	6	0	5	24.42	-78.7
87		900	17.7	6	0	5	24.42	-78.7
88		930	17.7	6	-45	1	26.94	-80.9
89		930	17.7	6	-45	2	27.09	-80.9
90		930	17.7	6	-45	3	27.52	-80.9
91		930	17.7	6	-45	4.1	28.21	-80.9
92		930	17.7	6	45	1	20.66	-92.3
93		930	17.7	6	45	2	20.75	-92.6
94		930	17.7	6	45	3	20.91	-92.8
95		930	17.7	6	45	4	21.17	-93
96		930	17.7	17	0	1	24.43	-79.1
97		930	17.7	17	0	2	24.42	-78.6
98		930	17.7	17	0	3	24.42	-78.5
99		930	17.7	17	0	4	24.4	-77.8
100		930	17.7	17	0	5	24.43	-78.9
101		930	17.7	17	-45	1	23.29	-80.8
102		930	17.7	17	-45	2	23.68	-80.9
103		930	17.7	17	-45	3	24.27	-80.8
104		930	17.7	17	-45	4.1	24.94	-80.7

Sequential number - IPET R&R Storm	Storm Frequency	Central pressure at landfall (P0)	Radius to maximum winds at landfall (Rp)	Forward speed at landfall (Vf)	Track angle at landfall wrt vertical (A)	Track	Lat	Long
105		930	17.7	17	45	1	21.28	-90
106		930	17.7	17	45	2	21.27	-90.1
107		930	17.7	17	45	3	21.27	-90.1
108		930	17.7	17	45	4	21.26	-90.1
109		960	17.7	11	0	1.5	24.42	-78.8
110		900	17.7	11	0	1.5	24.42	-78.8
111		960	17.7	11	0	2.5	24.42	-78.5
112		900	17.7	11	0	2.5	24.42	-78.5
113		960	17.7	11	0	3.5	24.41	-78.3
114		900	17.7	11	0	3.5	24.41	-78.3
115		960	17.7	11	0	4.5	24.43	-79.1
116		900	17.7	11	0	4.5	24.43	-79.1
117		960	17.7	11	-45	1.5	24.76	-81.2
118		960	17.7	11	-45	1.5	25.15	-81.1
119		960	17.7	11	-45	2.5	25.79	-81.2
120		900	17.7	11	-45	2.5	24.76	-81.2
121		900	17.7	11	-45	3.5	25.15	-81.1
122		900	17.7	11	-45	3.5	25.79	-81.2
123		960	17.7	11	45	1.5	21.29	-90
124		900	17.7	11	45	1.5	21.29	-90
125		960	17.7	11	45	2.5	21.29	-90
126		900	17.7	11	45	2.5	21.29	-90
127		960	17.7	11	45	3.5	21.28	-90
128		900	17.7	11	45	3.5	21.28	-90
129		960	17.7	6	0	1.5	24.42	-78.6
130		900	17.7	6	0	1.5	24.42	-78.6
131		960	17.7	6	0	2.5	24.42	-78.3
132		900	17.7	6	0	2.5	24.42	-78.3
133		960	17.7	6	0	3.5	24.41	-78.1
134		900	17.7	6	0	3.5	24.41	-78.1
135		960	17.7	6	0	4.5	24.43	-78.9
136		900	17.7	6	0	4.5	24.43	-78.9
137		930	17.7	6	-45	1.5	26.93	-81.3
138		930	17.7	6	-45	2.5	27.23	-81.2
139		930	17.7	6	-45	3.5	27.79	-81.2
140		930	17.7	6	45	1.5	20.71	-92.5
141		930	17.7	6	45	2.5	20.83	-92.7

Sequential number - IPET R&R Storm	Storm Frequency	Central pressure at landfall (P0)	Radius to maximum winds at landfall (Rp)	Forward speed at landfall (Vf)	Track angle at landfall wrt vertical (A)	Track	Lat	Long
142		930	17.7	6	45	3.5	21.04	-92.9
143		930	17.7	17	0	1.5	24.42	-78.8
144		930	17.7	17	0	2.5	24.42	-78.5
145		930	17.7	17	0	3.5	24.41	-78.2
146		930	17.7	17	0	4.5	24.43	-79.1
147		930	17.7	17	-45	1.5	23.64	-81.3
148		930	17.7	17	-45	2.5	24.08	-81.1
149		930	17.7	17	-45	3.5	23.73	-81
150		930	17.7	17	45	1.5	21.27	-90.1
151		930	17.7	17	45	2.5	21.27	-90.1
152		930	17.7	17	45	3.5	21.27	-90.1

Table 9-3. Summary of JPM-OS/Modeling process predicted mean water surface elevations for each reach. Elevations include surge and wave setup but do not include waves or runup. Data is shown for Rita-like and Katrina-like hurricanes, maximum for all hurricanes, and the water elevations associated with the 50-, 100-, 500-, and 1,000-year return periods. Reference NAVD (2004.65).

Reach	Katrina-Like (ft)	Rita-Like (ft)	Max All storms (ft)	Surge Height in Feet by Reach and Return Period, 2007 HPS			
				50-Year	100-Year	500-Year	1,000-Year
NOE1	9.8	0.0	13.72	8.3	9.4	12.3	12.9
NOE2	9.8	0.0	13.72	8.4	9.5	12.3	12.9
NOE3	9.7	0.0	13.69	8.4	9.5	11.9	12.9
NOE4	9.4	0.0	13.63	1.2	9.4	11.8	12.9
NOE5	9.0	4.4	13.67	8.3	9.3	11.2	12.1
NOE6	8.8	4.4	14.02	8.3	9.4	11.0	11.9
NOE7	9.1	4.4	14.23	8.3	9.3	11.0	11.7
NOE8	9.1	4.4	14.27	8.3	9.3	11.0	11.7
NOE9	9.6	4.4	14.65	8.4	9.6	11.3	11.8
NOE10	10.2	4.4	14.82	8.6	9.7	11.9	12.7
NOE11	10.4	4.3	16.77	8.8	10.3	13.1	13.9
NOE12	10.8	4.3	17.42	9.8	11.5	13.6	14.2
NOE13	11.8	4.2	17.89	10.7	12.0	14.1	15.2
NOE14	13.9	4.4	20.11	12.9	15.1	17.3	18.4
NOE15	15.1	6.3	21.53	14.3	16.7	19.1	20.2
NOE16	16.1	6.3	22.35	15.2	17.5	20.1	21.2
NOE17	17.1	6.6	22.65	15.8	18.2	21.1	22.0
NOE18	17.5	6.7	21.32	16.5	18.9	21.1	21.9
NOE19	17.5	6.8	21.32	16.7	19.2	21.1	21.9
NOE20	17.8	6.8	22.00	16.6	19.1	21.1	21.9
NOE21	17.6	6.8	21.67	16.6	18.6	21.1	21.9
NOE22	16.9	6.7	20.82	16.3	17.6	19.7	20.0
NOE23	15.9	6.6	19.84	15.5	16.5	17.7	18.0
NOE24	15.4	6.5	19.00	15.0	15.8	16.8	17.0
NOE25	15.2	0.0	18.62	14.9	15.7	16.8	17.0
NOE26	15.1	6.4	18.34	14.8	15.6	16.8	17.0
NOE27	15.0	0.0	18.12	14.8	15.6	16.7	17.0
NOE28	14.4	0.0	17.34	14.0	14.7	15.8	16.0
NOE29	12.7	0.0	16.00	11.5	12.3	13.7	14.0
JE1	13.7	4.2	15.71	10.0	11.9	15.8	16.6
JE2	13.1	4.3	15.23	9.5	11.4	15.0	15.7
JE3	12.1	4.4	14.46	9.2	10.8	14.0	14.7
JE4	11.3	4.4	13.71	8.9	10.3	13.0	13.7
JE5	11.2	4.4	12.94	8.7	10.1	12.5	12.8

Reach	Katrina-Like (ft)	Rita-Like (ft)	Max All storms (ft)	Surge Height in Feet by Reach and Return Period, 2007 HPS			
				50-Year	100-Year	500-Year	1,000-Year
JE6	11.2	4.3	12.42	8.9	10.5	13.4	13.8
JE7	13.3	5.5	20.85	12.4	14.3	16.0	16.7
JE8	13.3	5.6	20.75	12.5	14.3	16.0	16.7
JE9	13.7	4.2	15.57	10.1	11.7	15.8	16.6
SC1	12.8	4.6	16.10	10.1	12.6	15.7	16.6
SC2	13.4	4.4	16.24	10.5	12.5	15.8	16.9
SC3	13.6	4.2	16.08	10.1	12.4	15.3	15.9
SC4	13.0	5.7	20.60	12.5	14.3	16.0	16.9
SC5	11.3	0.0	16.65	9.8	12.5	15.6	16.1
SC6	10.9	4.8	16.18	10.1	12.3	15.5	15.9
OM1	11.2	4.3	12.47	8.9	10.5	13.4	13.7
OM2	11.6	4.3	13.24	8.8	10.3	13.4	13.8
OM3	10.8	4.3	13.23	8.5	9.6	12.4	12.8
OM4	11.6	4.3	13.25	8.8	10.3	13.4	13.8
OM5	10.7	4.3	13.24	8.5	9.6	12.3	12.7
OM6	11.3	4.3	13.79	8.7	9.9	13.3	13.9
OM7	10.4	4.3	13.39	8.4	9.4	12.3	12.9
OM8	11.3	4.3	13.72	8.6	9.9	13.3	13.9
OM9	10.4	4.3	13.39	8.4	9.4	12.3	12.9
OM10	11.0	4.3	13.17	8.6	9.8	12.4	12.7
OM11	10.6	4.4	13.17	8.4	9.6	12.1	12.6
OM12	10.4	4.3	13.33	8.4	9.5	12.2	12.8
OM13	10.0	4.4	13.40	8.3	9.4	12.2	12.8
OM14	9.9	4.4	13.44	8.3	9.3	12.2	12.8
OM15	9.7	4.4	13.55	8.2	9.2	11.9	12.9
OM16	9.8	0.0	13.67	8.2	9.2	12.3	12.9
OM17	12.4	0.0	15.46	11.1	11.9	13.6	13.9
OM18	14.6	0.0	17.14	14.3	15.0	16.0	16.9
OM19	15.2	0.0	17.45	14.8	15.6	16.8	17.0
OM20	15.3	6.3	18.09	14.7	15.6	16.8	17.0
OM21	15.5	6.3	18.20	14.7	15.6	17.0	17.9
OM22	15.6	6.3	18.22	14.8	15.7	17.5	18.0
OM23	13.6	5.4	21.05	13.1	14.5	16.3	17.3
OM24	13.7	5.4	21.04	13.1	14.6	16.3	17.3
OM25	13.8	5.5	21.06	12.7	14.5	16.5	17.3
OM26	13.5	5.5	20.91	12.6	14.3	16.0	16.8
OM27	13.3	5.5	20.83	12.4	14.2	16.0	16.7
SB1	15.3	6.3	18.07	14.7	15.6	16.8	17.0
SB2	15.2	0.0	18.05	14.6	15.5	16.8	17.0

Reach	Katrina-Like (ft)	Rita-Like (ft)	Max All storms (ft)	Surge Height in Feet by Reach and Return Period, 2007 HPS			
				50-Year	100-Year	500-Year	1,000-Year
SB3	15.5	6.5	19.25	15.0	15.8	16.9	17.5
SB4	18.0	6.2	23.03	14.9	17.1	20.2	20.9
SB5	12.9	8.0	23.25	16.0	18.4	20.9	21.6
SB6	13.8	5.4	21.02	13.1	14.5	16.2	17.4
SB7	13.9	5.3	20.80	13.1	14.5	16.2	17.3
SB8	14.3	5.3	20.82	13.1	14.5	16.4	17.4
SB9	15.5	6.3	18.18	14.7	15.7	17.0	17.9
PL1	2.7	4.3	11.83	5.7	7.2	7.9	8.0
PL2	2.7	4.2	12.78	5.6	7.6	9.0	9.7
PL3	15.1	5.3	22.07	14.1	15.5	17.7	18.6
PL4	3.6	4.2	17.28	5.9	8.6	12.2	13.4
PL5	16.5	0.0	22.63	14.6	16.0	19.3	20.2
PL6	3.6	4.5	17.74	7.3	9.3	14.1	14.7
PL7	17.1	0.0	22.54	14.8	16.6	19.4	20.3
PL8	7.4	4.1	20.94	8.7	12.5	16.0	16.9
PL9	18.4	4.9	22.59	14.8	18.0	21.2	21.7
PL10	9.4	4.3	20.94	10.2	13.3	17.3	18.2
PL11	11.4	4.1	20.43	11.8	13.7	18.0	18.9
PL12	12.5	3.9	20.75	11.4	13.8	18.8	19.7
PL14	19.0	4.8	22.55	15.1	18.6	21.8	23.4
PL15	11.7	3.5	19.27	10.2	12.7	18.0	18.7
PL13	12.0	3.7	19.89	10.5	13.0	17.9	18.8
PL16	13.4	3.8	19.01	10.5	12.9	18.4	19.9
PL17	18.2	3.3	20.84	10.4	12.6	20.2	21.0
PL18	14.9	4.1	21.31	14.2	16.1	20.5	21.3
PL19	18.5	4.6	23.53	15.5	18.2	22.7	23.9
PL20	17.5	5.2	22.24	14.7	16.9	19.6	20.4
PL21	18.1	5.0	22.28	14.7	17.3	20.0	21.1
PL22	18.7	6.7	24.20	14.9	17.1	20.3	20.8
PL23	19.8	6.9	24.87	16.6	19.2	21.9	22.9
PL24	10.8	8.4	25.21	15.4	18.8	21.8	22.5
PL25	16.0	8.1	24.88	15.8	17.6	20.2	20.9
PL26	15.2	5.3	22.06	14.1	15.5	17.8	18.6
PL27	16.5	5.3	22.39	14.6	16.3	19.2	19.9
CW1	0.0	4.5	11.44	5.4	6.4	8.2	8.8
CW2	2.3	4.4	11.88	5.4	7.2	8.2	8.8
CW3	2.4	4.3	12.79	5.4	7.2	8.3	8.8
CW4	2.6	4.3	12.29	5.3	7.2	8.2	8.7
CW5	2.6	4.3	12.29	5.3	7.2	8.2	8.7

Reach	Katrina-Like (ft)	Rita-Like (ft)	Max All storms (ft)	Surge Height in Feet by Reach and Return Period, 2007 HPS			
				50-Year	100-Year	500-Year	1,000-Year
CW6	2.6	4.3	12.29	5.3	7.2	8.2	8.7
CW7	2.6	4.3	12.29	5.3	7.2	8.2	8.7
CW8	13.2	5.6	20.72	12.5	14.3	16.0	16.7
WH1	2.6	4.3	12.29	5.3	7.2	8.2	8.7
WH2	0.0	4.3	12.04	5.3	7.2	8.2	8.7
WH3	2.5	4.1	12.11	4.8	6.7	8.0	8.5
WH4	0.0	4.1	12.91	4.7	7.1	8.3	8.8
WH5	0.0	0.0	12.94	1.1	7.1	9.0	9.7
WH6	2.0	0.0	12.40	1.1	6.6	9.9	10.7
WH7	2.7	4.2	11.15	5.6	7.6	9.0	9.6
WH8	2.7	4.3	11.16	5.7	7.6	9.1	9.7
WH9	1.2	1.2	11.20	2.8	2.9	3.0	3.0
WH10	13.8	0.0	21.05	12.6	14.5	16.5	17.3
HA1	13.8	0.0	21.06	13.1	14.5	16.3	17.4
HA2	13.7	5.4	20.98	13.1	14.5	16.0	16.8
HA3	2.7	4.2	11.11	5.6	7.6	9.1	9.7
HA4	2.7	4.2	12.68	5.6	7.2	7.9	8.0
HA5	2.7	4.3	11.77	5.7	7.2	7.9	8.0
HA6	13.9	5.3	20.80	13.1	14.5	16.2	17.3
HA7	2.7	4.3	11.77	5.7	7.2	7.9	8.0
HA8	2.7	4.3	11.73	5.7	7.2	7.9	8.0
HA9	2.7	4.3	11.68	5.7	7.2	7.9	8.0
HA10	1.2	1.2	11.20	2.8	2.9	3.0	3.0
CL1	11.0	4.3	13.20	8.6	9.8	12.2	12.7
CL2	10.5	4.4	13.29	8.4	9.5	11.9	12.5
CL3	10.2	4.4	13.35	8.4	9.4	12.2	12.6

Table 9-4. Summary of STWAVE generated Maximum Significant Wave Height (Hs) and Associated Wave Period (Tm) by reach from 152 hurricanes modeled. A value of 0 in this table represents no significant wave conditions. A value of 0.0 represents no water, surge or waves, the data base.

Reach	Max Hs (ft) (152 storms)	Max Tm (sec) (152 storms)	Katrina Hs (ft)	Katrina Tm (sec)	Rita Hs (ft)	Rita Tm (sec)
NOE1	12.3	5.9	2.1	3.9	0	0
NOE2	0.0	0.0	0.0	0.0	0	0
NOE3	0.0	0.0	0.0	0.0	0	0
NOE4	0.1	0.6	0.0	0.0	0	0
NOE5	8.2	6.3	4.4	4.6	1.5	2.7
NOE6	7.2	5.5	3.5	3.9	1.2	2.4
NOE7	8.8	5.3	2.5	4.0	0.3	2.6
NOE8	7.0	5.2	3.7	3.9	1.3	2.5
NOE9	5.8	4.6	3.8	3.9	1.7	2.8
NOE10	3.3	3.4	2.2	2.9	0.9	2.2
NOE11	9.2	5.3	4.7	4.2	1.5	2.9
NOE12	7.9	5.0	4.7	4.1	1.8	2.8
NOE13	0	0	0	0	0	0
NOE14	7.4	4.7	4.4	4.0	1.0	2.4
NOE15	6.7	4.5	4.6	3.9	1.9	2.9
NOE16	4.2	3.7	3.4	3.5	1.8	3.0
NOE17	0.1	0.5	0.0	0.0	0.0	0.0
NOE18	3.0	4.0	3.0	4.0	3.0	4.0
NOE19	3.0	4.0	3.0	4.0	3.0	4.0
NOE20	3.0	4.0	3.0	4.0	3.0	4.0
NOE21	3.0	4.0	3.0	4.0	3.0	4.0
NOE22	3.0	4.0	3.0	4.0	3.0	4.0
NOE23	3.0	4.0	3.0	4.0	3.0	4.0
NOE24	3.0	4.0	3.0	4.0	3.0	4.0
NOE25	3.0	4.0	3.0	4.0	3.0	4.0
NOE26	3.0	4.0	3.0	4.0	3.0	4.0
NOE27	3.0	4.0	3.0	4.0	3.0	4.0
NOE28	3.0	4.0	3.0	4.0	3.0	4.0
NOE29	3.0	4.0	3.0	4.0	3.0	4.0
JE1	0	0	0	0	0	0
JE2	7.2	7.9	4.6	5.7	0.2	0.6
JE3	3.2	3.4	2.5	3.1	0.7	2.1
JE4	10.9	6.9	8.8	6.3	3.2	4.1
JE5	11.6	7.1	9.3	6.4	2.2	3.4
JE6	3.0	4.0	3.0	4.0	3.0	4.0
JE7	1.4	2.3	1.4	2.3	1.4	2.3

Reach	Max Hs (ft) (152 storms)	Max Tm (sec) (152 storms)	Katrina Hs (ft)	Katrina Tm (sec)	Rita Hs (ft)	Rita Tm (sec)
JE8	0	0	0	0	0	0
JE9	6.8	9.7	4.4	6.8	0.1	0.3
SC1	0.0	0.0	0.0	0.0	0.0	0.0
SC2	4.0	5.0	2.9	4.5	0.5	2.6
SC3	0.4	0.5	0.1	0.2	0.0	0.0
SC4	1.7	2.5	1.7	2.4	1.6	2.4
SC5	0	0	0	0	0	0
SC6	0	0	0	0	0	0
OM1	3.0	4.0	3.0	4.0	3.0	4.0
OM2	3.0	4.0	3.0	4.0	3.0	4.0
OM3	3.0	4.0	3.0	4.0	3.0	4.0
OM4	3.0	4.0	3.0	4.0	3.0	4.0
OM5	3.0	4.0	3.0	4.0	3.0	4.0
OM6	3.0	4.0	3.0	4.0	3.0	4.0
OM7	3.0	4.0	3.0	4.0	3.0	4.0
OM8	3.0	4.0	3.0	4.0	3.0	4.0
OM9	3.0	4.0	3.0	4.0	3.0	4.0
OM10	0	0	0	0	0	0
OM11	14.4	7.1	9.9	6.1	2.2	3.2
OM12	8.3	6.1	5.6	5.0	1.3	2.6
OM13	5.5	5.1	3.6	4.1	1.1	2.3
OM14	13.8	6.6	8.1	5.3	2.0	3.0
OM15	5.7	5.3	3.4	4.1	1.0	2.3
OM16	4.9	5.8	1.6	3.8	0	0
OM17	3.0	4.0	3.0	4.0	3.0	4.0
OM18	3.0	4.0	3.0	4.0	3.0	4.0
OM19	3.0	4.0	3.0	4.0	3.0	4.0
OM20	3.0	4.0	3.0	4.0	3.0	4.0
OM21	3.0	4.0	3.0	4.0	3.0	4.0
OM22	3.0	4.0	3.0	4.0	3.0	4.0
OM23	1.4	2.4	1.3	2.4	1.2	2.4
OM24	0.2	2.2	0.0	1.9	0.2	2.2
OM25	0.4	2.8	0.2	2.7	0.1	2.5
OM26	0	0	0	0	0	0
OM27	1.3	2.1	1.1	2.0	0.8	1.9
SB1	3.0	4.0	3.0	4.0	3.0	4.0
SB2	3.0	4.0	3.0	4.0	3.0	4.0
SB3	3.0	4.0	3.0	4.0	3.0	4.0
SB4	9.4	5.3	6.8	4.9	1.8	3.6
SB5	13.4	10.5	0.8	3.4	0.1	1.4

Reach	Max Hs (ft) (152 storms)	Max Tm (sec) (152 storms)	Katrina Hs (ft)	Katrina Tm (sec)	Rita Hs (ft)	Rita Tm (sec)
SB6	1.6	2.6	1.5	2.5	1.4	2.4
SB7	0.0	0.0	0.0	0.0	0.0	0.0
SB8	0	0	0	0	0	0
SB9	3.0	4.0	3.0	4.0	3.0	4.0
PL1	0.0	0.0	0.0	0.0	0.0	0.0
PL2	0.0	0.0	0.0	0.0	0.0	0.0
PL3	0.2	3.7	0.2	3.4	0.1	2.7
PL4	0	0	0	0	0	0
PL5	2.0	6.7	0.8	3.6	0	0
PL6	0	0	0	0	0	0
PL7	2.5	4.2	2.4	4.2	0	0
PL8	0	0	0	0	0	0
PL9	2.8	5.4	2.2	5.0	0.5	2.8
PL10	0	0	0	0	0	0
PL11	0	0	0	0	0	0
PL12	0	0	0	0	0	0
PL14	0.0	0.0	0.0	0.0	0.0	0.0
PL15	0	0	0	0	0	0
PL13	0.0	0.0	0.0	0.0	0.0	0.0
PL16	8.6	9.2	3.2	8.3	0.1	5.5
PL17	0	0	0	0	0	0
PL18	1.2	3.9	0.9	3.6	1.1	2.9
PL19	0	0	0	0	0	0
PL20	0.0	0.0	0.0	0.0	0.0	0.0
PL21	0.5	4.9	0.5	4.6	0.5	2.8
PL22	0	0	0	0	0	0
PL23	0	0	0	0	0	0
PL24	0	0	0	0	0	0
PL25	0.1	0.5	0.0	0.0	0.0	0.0
PL26	0.0	2.2	0.0	0.6	0.0	0.0
PL27	0.0	0.0	0.0	0.0	0.0	0.0
CW1	0	0	0	0	0	0
CW2	0.0	0.0	0.0	0.0	0.0	0.0
CW3	0	0	0	0	0	0
CW4	0	0	0	0	0	0
CW5	0	0	0	0	0	0
CW6	0	0	0	0	0	0
CW7	0	0	0	0	0	0
CW8	0.0	0.0	0.0	0.0	0.0	0.0
WH1	0	0	0	0	0	0

Reach	Max Hs (ft) (152 storms)	Max Tm (sec) (152 storms)	Katrina Hs (ft)	Katrina Tm (sec)	Rita Hs (ft)	Rita Tm (sec)
WH2	0	0	0	0	0	0
WH3	0.0	0.0	0.0	0.0	0.0	0.0
WH4	0	0	0	0	0	0
WH5	0.0	0.0	0	0	0	0
WH6	0.0	0.0	0.0	0.0	0	0
WH7	0.0	0.0	0.0	0.0	0.0	0.0
WH8	3.0	4.0	3.0	4.0	3.0	4.0
WH9	0	0	-999.0	0	0	0
WH10	0	0	-999.0	0	0	0
HA1	0.1	7.5	0.0	0.0	0	0
HA2	0	0	-999.0	0	0	0
HA3	3.0	4.0	3.0	4.0	3.0	4.0
HA4	0.0	0.0	0.0	0.0	0.0	0.0
HA5	0	0	-999.0	0	0	0
HA6	0.3	2.9	0.3	2.8	0.2	2.9
HA7	0	0	0	0	0	0
HA8	0.0	0.0	0.0	0.0	0.0	0.0
HA9	0	0	0	0	0	0
HA10	3.0	4.0	3.0	4.0	3.0	4.0
CL1	8.0	6.3	5.1	5.3	0.5	2.1
CL2	3.0	4.0	3.0	4.0	3.0	4.0
CL3	3.0	4.0	3.0	4.0	3.0	4.0

Table 9-5. Pumping capacities, in cubic feet per second, used in modeling impact of pumping on flood water levels and range of rainfall volumes (million cubic feet) from the 152 hurricanes modeled. These capacities are based on the summation of the ideal capacities for all pumps in a given drainage sub-basin. The rainfall resulting from the 152 hurricanes varied from about 1 inch in 24 hours to over 17 inches in 24 hours. The maximum and minimum rainfall volumes reflect the least and greatest volumes received by each drainage sub-basin from all of the hurricanes.

Sub-basin	Area		Min Rainfall Volume (Mcf)	Max Rainfall Volume (Mcf)	Pump Capacity (cfs)
	sq mi	acres			
Orleans Main					
OM1	7.86	5032	2.9	168	3720
OM2	6.56	4201	2.3	149	14020
OM3	7.13	4562	2.9	164	8420
OM4	3.11	1989	1.0	703	0
OM5	17.55	11229	6.3	398	10324
Basin Totals					**36484**
New Orleans East					
NOE1	22.14	14169	1.1	487	0
NOE2	8.82	5648	4.9	185	750
NOE3	4.52	2893	4.4	93	60
NOE4	3.78	2419	1.8	84	782
NOE5	14.39	9212	6.7	308	3200
Basin Totals					**4792**
St. Bernard					
SB1	7.95	5091	3.6	166	4964
SB2	7.76	4966	3.7	167	0
SB3	8.59	5495	4.7	186	2727
SB4	14.04	8987	8.7	308	1446
SB5	37.87	24236	2.3	836	0
Basin Totals					**9137**
Jefferson East					
JE1	12.20	7810	3.4	278	160
JE2	8.76	5604	2.8	202	8905
JE3	23.71	15173	6.1	530	11597
Basin Totals					**20662**
Jefferson West					
JW1	16.57	10603	4.5	384	0
JW2	17.61	11270	4.5	303	3401
JW3	23.19	14840	8.6	541	10218
JW4	20.82	13326	8.2	443	9962
Basin Totals					**23581**

Sub-basin	Area		Min Rainfall Volume (Mcf)	Max Rainfall Volume (Mcf)	Pump Capacity (cfs)
	sq mi	acres			
St. Charles					
SC1	9.19	5882	2.1	259	
SC2	10.86	6950	1.7	202	
Basin Totals					**0**
Plaquemines					
PL1	12.71	8135	6.7	447	2019
PL2 / PL 11	4.74	3032	9.8	625	720
Basin Totals					**14121**
Orleans West Bank					
OW1	6.36	4073	3.5	143	0
OW2	9.50	6080	4.2	203	0
Basin Totals					**0**

Table 9-6. Flood elevations in feet by sub-basin for no pumping scenario. Reference to NAVD 88 (2004.65).

Sub-basin	Analysis Results Without Pumping and With Wave Runup					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
OW1	-1	-1	1	1	6	6
OW2	-3	-3	4	4	8	8
NOE1	0	0	2	1	12	13
NOE2	-4	-4	2	2	12	13
NOE3	-4	-4	2	2	12	13
NOE4	-1	-1	4	4	12	13
NOE5	-8	-8	-1	-1	12	13
OM1	-5	-5	3	3	14	14
OM2	-5	-5	3	-2	14	14
OM3	-1	-1	3	3	14	14
OM4	-1	-1	3	-1	14	14
OM5	-1	-1	3	1	14	14
SB1	-1	-1	12	10	14	14
SB2	1	1	12	10	14	14
SB3	0	0	12	10	14	14
SB4	2	2	12	10	14	14
SB5	3	3	12	10	14	14
JE1	3	3	4	4	14	14
JE2	-4	-4	-3	-3	14	14
JE3	-5	-5	-3	-3	14	14
JW1	0	0	4	4	8	8
JW2	-4	-4	4	4	8	8
JW3	-2	-2	4	4	8	8
JW4	-5	-5	4	4	8	8
PL11	-2	-2	0	-1	6	9
SC1	2	2	4	4	10	10
SC2	4	4	5	5	10	10

Table 9-7. Flood elevations in feet by sub-basin for 50% pumping scenario. Reference to NAVD 88 (2004.65).

Sub-basin	Results with 50% Pumping and With Wave Runup					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
OW1	-1	-1	0	0	6	6
OW2	-3	-3	3	3	8	8
NOE1	0	0	2	1	12	13
NOE2	-5	-5	1	1	11	12
NOE3	-5	-5	1	1	11	12
NOE4	-2	-2	2	2	11	12
NOE5	-9	-9	-2	-2	11	12
OM1	-7	-7	2	1	12	12
OM2	-12	-12	1	-7	11	11
OM3	-6	-6	2	1	12	12
OM4	-5	-5	3	-2	13	13
OM5	-4	-4	2	0	12	12
SB1	-5	-5	11	8	12	12
SB2	1	1	12	9	13	13
SB3	-1	-1	11	8	12	12
SB4	1	1	11	9	12	12
SB5	3	3	12	10	13	13
JE1	2	2	3	3	12	12
JE2	-12	-12	-5	-5	12	12
JE3	-6	-6	-5	-5	12	12
JW1	0	0	4	4	8	8
JW2	-5	-5	3	3	7	7
JW3	-5	-5	3	3	7	7
JW4	-12	-12	3	3	7	7
PL11	-12	-12	-4	-8	1	2
SC1	2	2	4	4	10	10
SC2	4	4	5	5	10	10

Table 9-8. Flood elevations in feet by sub-basin for 100% pumping scenario. Reference to NAVD 88 (2004.65)

Sub-basin	Results with 100% Pumping and with Wave Runup					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
OW1	-1	-1	0	0	6	6
OW2	-3	-3	3	3	8	8
NOE1	0	0	2	1	12	13
NOE2	-5	-5	1	1	11	12
NOE3	-5	-5	1	1	11	12
NOE4	-3	-3	2	2	11	12
NOE5	-11	-11	-2	-2	11	12
OM1	-12	-12	2	1	12	12
OM2	-12	-12	0	-12	10	10
OM3	-12	-12	1	-1	11	11
OM4	-5	-5	3	-2	13	13
OM5	-12	-12	1	-2	12	12
SB1	-12	-12	11	8	12	12
SB2	1	1	12	9	13	13
SB3	-3	-3	11	8	12	12
SB4	1	1	11	9	12	12
SB5	3	3	12	10	13	13
JE1	2	2	3	3	12	12
JE2	-12	-12	-12	-12	11	11
JE3	-10	-10	-5	-5	12	12
JW1	0	0	4	4	8	8
JW2	-5	-5	3	3	7	7
JW3	-12	-12	3	3	7	7
JW4	-12	-12	3	3	7	7
PL11	-12	-12	-5	-12	1	2
SC1	2	2	4	4	10	10
SC2	3	3	4	4	10	10

Table 9-9. Summary of mean values of expected loss of life by sub-basin for no pumping situation. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.

Potential Fatalities	
Color Scale	
Less Than 10	(cyan)
10 to 100	(blue)
100 to 1000	(yellow)
More than 1000	(red)

Sub-basin	No Pumping					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
JE1	0	0	0	0	3	3
JE2	37	37	50	50	5,886	5,886
JE3	31	31	93	93	17,136	17,136
JW1	4	4	31	31	63	63
JW2	0	0	6	6	40	40
JW3	1	1	42	42	195	195
JW4	1	1	132	132	607	607
NOE1	0	0	0	0	0	0
NOE2	0	0	1	1	91	154
NOE3	0	0	13	13	298	524
NOE4	0	0	0	0	2	2
NOE5	4	4	63	63	6,528	7,945
OM1	2	2	80	80	2,217	2,217
OM2	237	237	1,289	329	3,179	3,179
OM3	10	10	61	61	2,079	2,079
OM4	8	8	35	8	530	530
OM5	21	21	70	41	3,262	3,262
OW1	0	0	0	0	1	1
OW2	6	6	101	101	420	420
PL11	28	28	33	31	180	247
SB1	-	-	915	888	915	915
SB2	-	-	-	-	-	-
SB3	-	-	561	561	646	646
SB4	0	0	82	49	107	107
SB5	0	0	3	3	3	3
SC1	-	-	-	-	1	1
SC2	1	1	1	1	23	23
Totals	391	391	3,663	2,585	44,411	46,184

Table 9-10. Summary of mean values of expected loss of life by sub-basin for 50% pumping situation. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.

Sub-basin	50% Pumping					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	Current	Pre-K	Current	Pre-K	Current
JE1	-	-	0	0	3	3
JE2	-	-	23	23	3,716	3,716
JE3	9	9	31	31	9,678	9,678
JW1	4	4	31	31	63	63
JW2	0	0	5	5	24	24
JW3	0	0	33	33	138	138
JW4	-	-	83	83	418	418
NOE1	0	0	0	0	0	0
NOE2	0	0	1	1	56	91
NOE3	-	-	9	9	228	298
NOE4	0	0	0	0	2	2
NOE5	2	2	45	45	5,111	6,528
OM1	1	1	54	29	1,241	1,241
OM2	6	6	586	113	2,683	2,683
OM3	-	-	32	24	1,055	1,055
OM4	3	3	35	6	438	438
OM5	2	2	56	31	2,075	2,075
OW1	0	0	0	0	1	1
OW2	6	6	52	52	420	420
PL11	1	1	16	1	37	41
SB1	-	-	901	393	915	915
SB2	-	-	-	-	-	-
SB3	-	-	561	136	561	561
SB4	0	0	66	34	82	82
SB5	0	0	3	3	3	3
SC1	-	-	-	-	1	1
SC2	1	1	1	1	23	23
Totals	33	33	2,625	1,054	28,971	30,497

Table 9-11. Summary of mean values of expected loss of life by sub-basin for 100% pumping situation. These values should be considered an index of potential loss of life, not actual fatalities. Assumptions for evacuation were conservative making the fatality estimates relatively larger than would be expected if effective evacuation is achieved.

Sub-basin	100% Pumping					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	Current	Pre-K	Current	Pre-K	Current
JE1	-	-	0	0	3	3
JE2	-	-	-	-	2,584	2,584
JE3	-	-	31	31	9,678	9,678
JW1	4	4	31	31	63	63
JW2	0	0	5	5	24	24
JW3	-	-	33	33	138	138
JW4	-	-	83	83	418	418
NOE1	0	0	0	0	0	0
NOE2	0	0	1	1	56	91
NOE3	-	-	9	9	228	298
NOE4	0	0	0	0	2	2
NOE5	-	-	45	45	5,111	6,528
OM1	-	-	54	29	1,241	1,241
OM2	6	6	472	6	2,560	2,560
OM3	-	-	24	10	888	888
OM4	3	3	35	6	438	438
OM5	-	-	41	12	2,075	2,075
OW1	0	0	0	0	1	1
OW2	6	6	52	52	420	420
PL11	1	1	10	1	37	41
SB1	-	-	901	393	915	915
SB2	-	-	-	-	-	-
SB3	-	-	561	136	561	561
SB4	0	0	66	34	82	82
SB5	0	0	3	3	3	3
SC1	-	-	-	-	1	1
SC2	0	0	1	1	23	23
	19	19	2,458	921	27,549	29,075

Table 9-12. Summary of mean values of expected direct property losses by sub-basin for no pumping situation ($1000).

Sub-basin	Analysis Results Without Pumping and With Wave Runup					
	50-Year Elevations		100-Year Elevations		500-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
OW1	23	23	39	39	170	170
OW2	412	412	2,405	2,405	3,105	3,105
NOE1	0	0	8	6	12	12
NOE2	19	19	123	123	143	143
NOE3	8	8	510	510	668	671
NOE4	0	0	49	49	61	62
NOE5	43	43	4,561	4,561	6,022	6,026
OM1	402	402	2,209	2,209	2,718	2,718
OM2	348	348	1,573	1,040	1,945	1,945
OM3	376	376	1,709	1,709	3,010	3,010
OM4	68	68	420	68	1,111	1,111
OM5	785	785	3,721	2,167	9,680	9,680
SB1	196	196	2,617	2,542	2,677	2,677
SB2	-	-	25	24	26	26
SB3	71	71	2,456	2,298	2,510	2,510
SB4	0	0	497	465	516	516
SB5	2	2	43	41	44	44
JE1	420	420	1,093	1,093	5,728	5,728
JE2	471	471	2,190	2,190	6,278	6,278
JE3	515	515	6,174	6,174	12,081	12,081
JW1	0	0	230	230	542	542
JW2	5	5	393	393	426	426
JW3	122	122	3,660	3,660	5,625	5,625
JW4	23	23	5,551	5,551	6,437	6,437
SC1	19	19	113	113	132	132
SC2	390	390	485	485	1,355	1,355
Totals	4,718	4,718	42,856	40,147	73,020	73,028

Table 9-13. Summary of mean values of expected direct property losses by sub-basin for 50% pumping situation ($1000).

Sub-basin	Results with 50% Pumping and With Wave Runup					
	50-Year Elevations		100-Year Elevations		50-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
OW1	23	23	28	28	170	170
OW2	412	412	2,205	2,205	3,105	3,105
NOE1	0	0	8	6	12	12
NOE2	1	1	121	121	143	143
NOE3	0	0	416	416	667	668
NOE4	0	0	33	33	60	61
NOE5	5	5	4,121	4,121	6,007	6,022
OM1	8	8	2,012	1,864	2,689	2,689
OM2	-	-	1,377	2	1,922	1,922
OM3	1	1	1,365	1,031	2,953	2,953
OM4	3	3	420	28	1,096	1,096
OM5	7	7	2,860	1,483	9,306	9,306
SB1	-	-	2,582	2,403	2,617	2,617
SB2	-	-	25	24	25	25
SB3	4	4	2,393	2,077	2,456	2,456
SB4	-	-	491	439	497	497
SB5	2	2	43	41	44	44
JE1	218	218	420	420	5,122	5,122
JE2	-	-	52	52	6,243	6,243
JE3	116	116	515	515	12,062	12,062
JW1	0	0	230	230	542	542
JW2	1	1	383	383	416	416
JW3	0	0	2,750	2,750	5,466	5,466
JW4	-	-	5,236	5,236	6,272	6,272
SC1	19	19	113	113	132	132
SC2	390	390	485	485	1,355	1,355
-	1,209	1,209	30,684	26,506	71,379	71,396

Table 9-14. Summary of mean values of expected direct property losses by sub-basin for 100% pumping situation ($1000).

Sub-basin	Results with 100% Pumping and With Wave Runup					
	50-Year Elevations		100-Year Elevations		50-Year Elevations	
	Pre-K	2007	Pre-K	2007	Pre-K	2007
OW1	23	23	28	28	170	170
OW2	412	412	2,205	2,205	3,105	3,105
NOE1	0	0	8	6	12	12
NOE2	1	1	121	121	143	143
NOE3	0	0	416	416	667	668
NOE4	0	0	33	33	60	61
NOE5	0	0	4,121	4,121	6,007	6,022
OM1	-	-	2,012	1,864	2,689	2,689
OM2	-	-	1,261	-	1,910	1,910
OM3	-	-	1,031	376	2,910	2,910
OM4	3	3	420	28	1,096	1,096
OM5	-	-	2,167	200	9,306	9,306
SB1	-	-	2,582	2,403	2,617	2,617
SB2	-	-	25	24	25	25
SB3	0	0	2,393	2,077	2,456	2,456
SB4	-	-	491	439	497	497
SB5	2	2	43	41	44	44
JE1	218	218	420	420	5,122	5,122
JE2	-	-	-	-	6,216	6,216
JE3	0	0	515	515	12,062	12,062
JW1	0	0	230	230	542	542
JW2	1	1	383	383	416	416
JW3	-	-	2,750	2,750	5,466	5,466
JW4	-	-	5,236	5,236	6,272	6,272
SC1	19	19	113	113	132	132
SC2	290	290	390	390	1,355	1,355
-	969	969	29,394	24,419	71,297	71,313

Appendix 10
Inundation Depth Frequency Maps

This appendix provides the individual inundation frequency maps prepared as a part of the IPET Risk and Reliability Assessment for New Orleans. Maps for the pre-Katrina and 2007 HPS are presented for the entire region modeled with the exception of the lower portions of Plaquemines Parish. Maps are provided for the 2% (1/50), 1% (1/100) and 0.2% (1/500) return periods and for 0%, 50%, and 100% of ideal pumping capacity. Lower Plaquemines was not included because of insufficient data to allow a full risk assessment. Details on the preparation of these maps are provided in IPET Final Report, Volume VIII, *Engineering and Operational Risk and Reliability Analysis*.

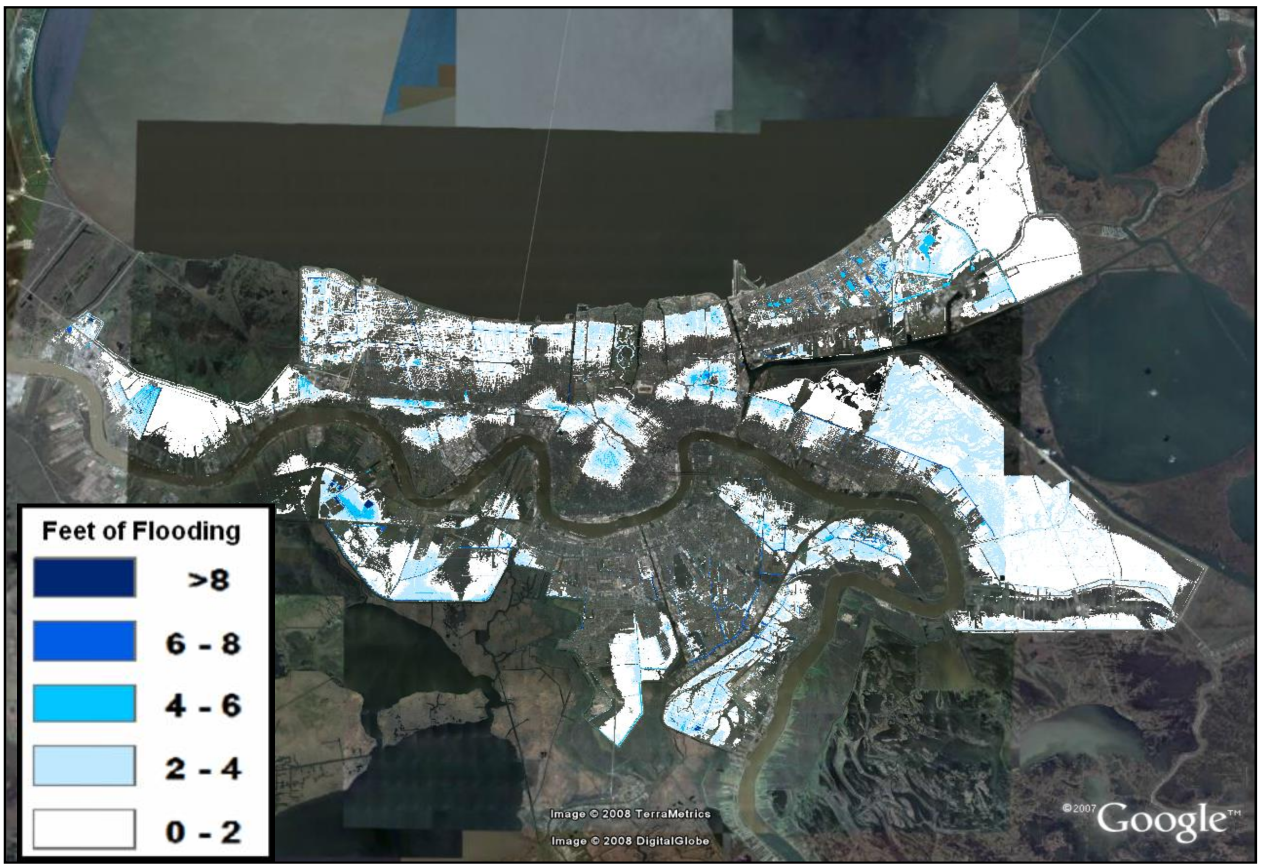

Figure 10-1. Hurricane inundation frequency map, 2% (1/50 return period) for pre-Katrina HPS and 0% pumping.

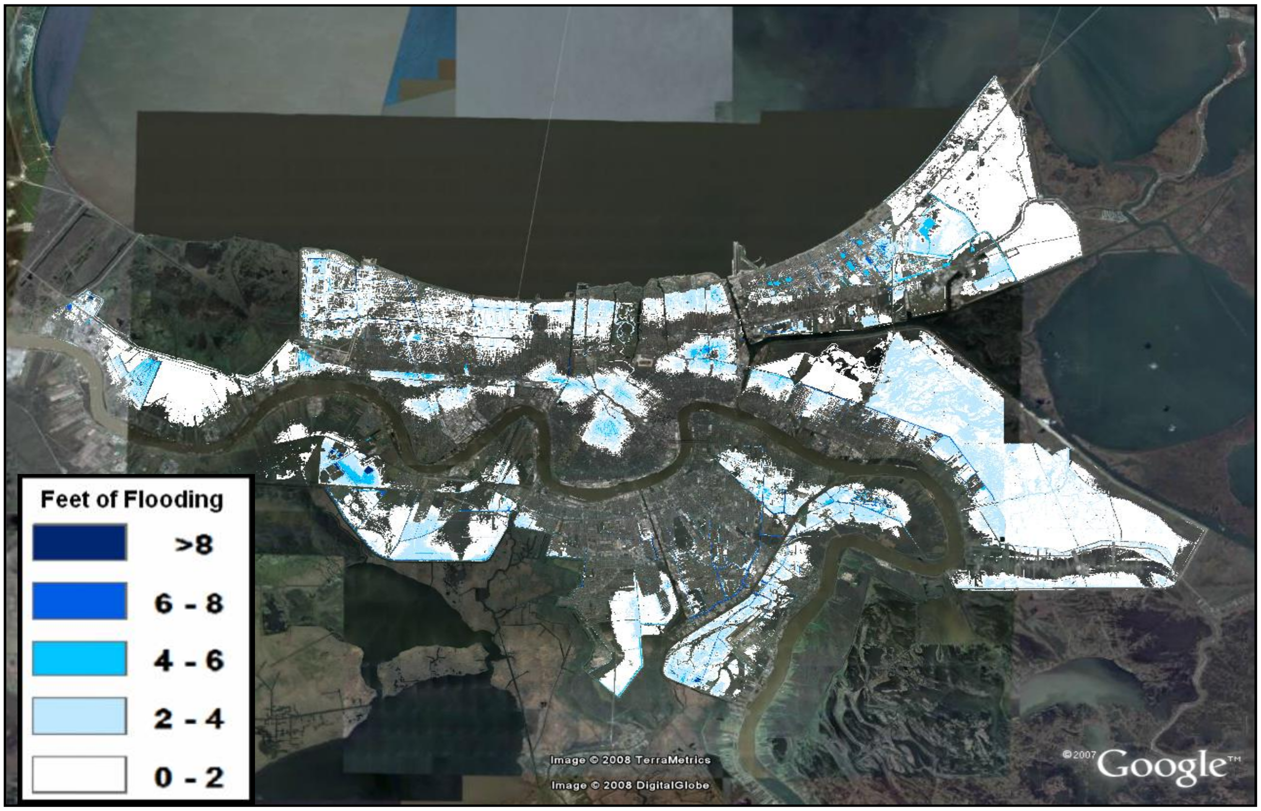

Figure 10-2. Hurricane inundation frequency map, 2% (1/50 return period) for June 2007 HPS and 0% pumping.

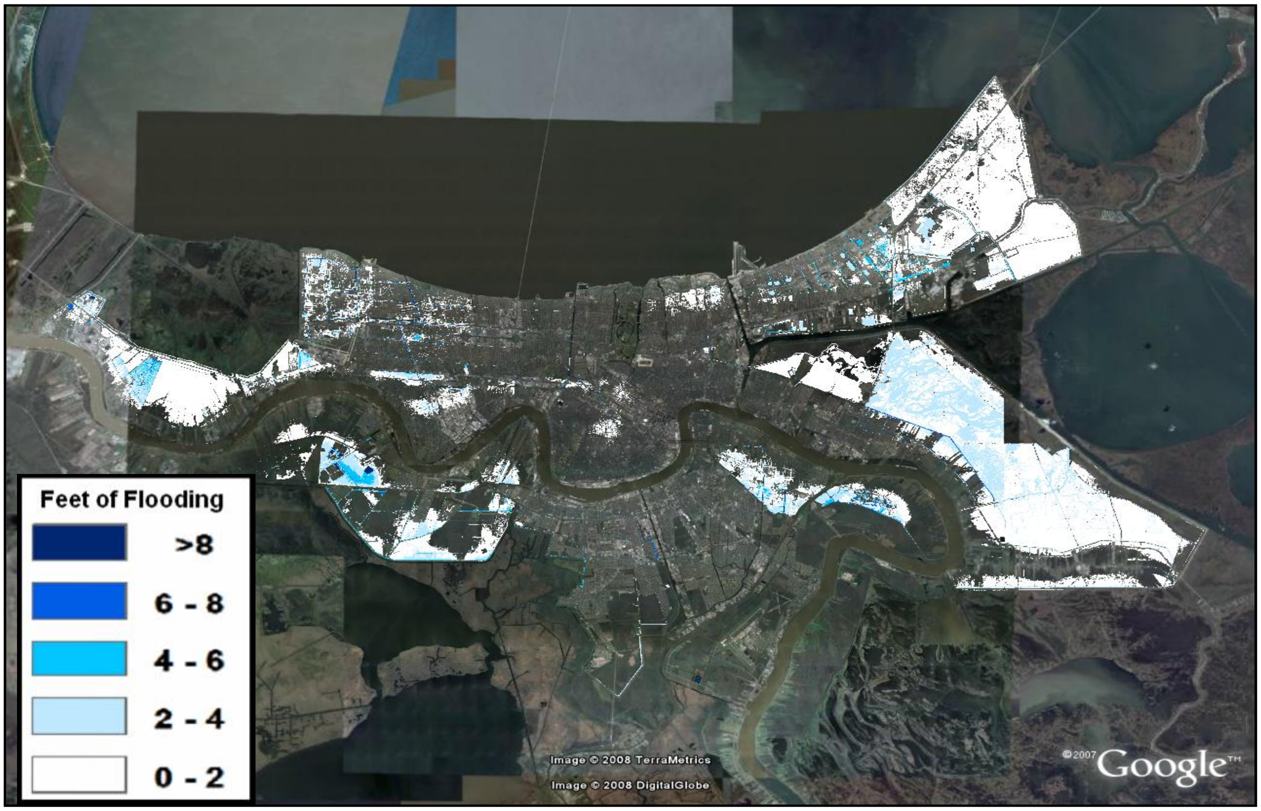

Figure 10-3. Hurricane inundation frequency map, 2% (1/50 return period) for pre-Katrina HPS and 50% pumping.

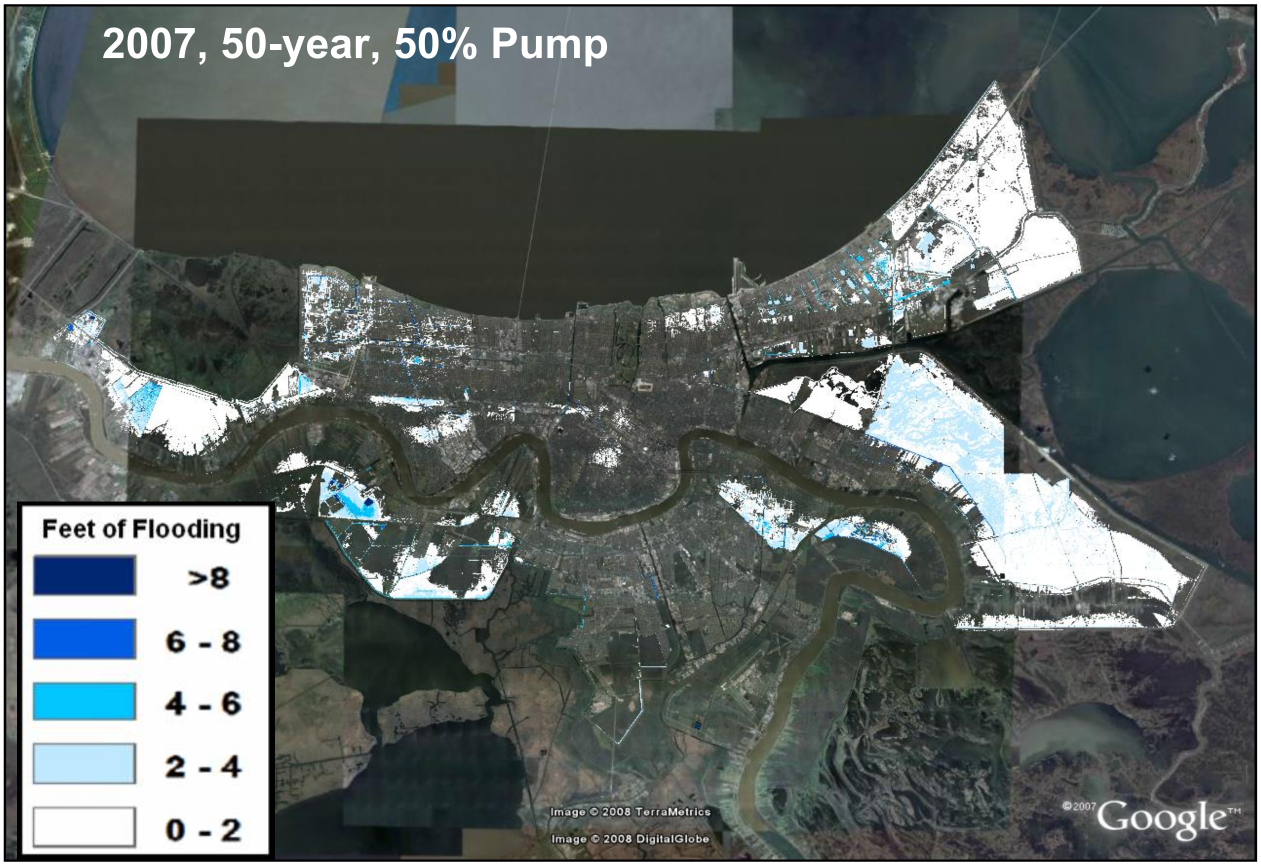

Figure 10-4. Hurricane inundation frequency map, 2% (1/50 return period) for June 2007 HPS and 50% pumping.

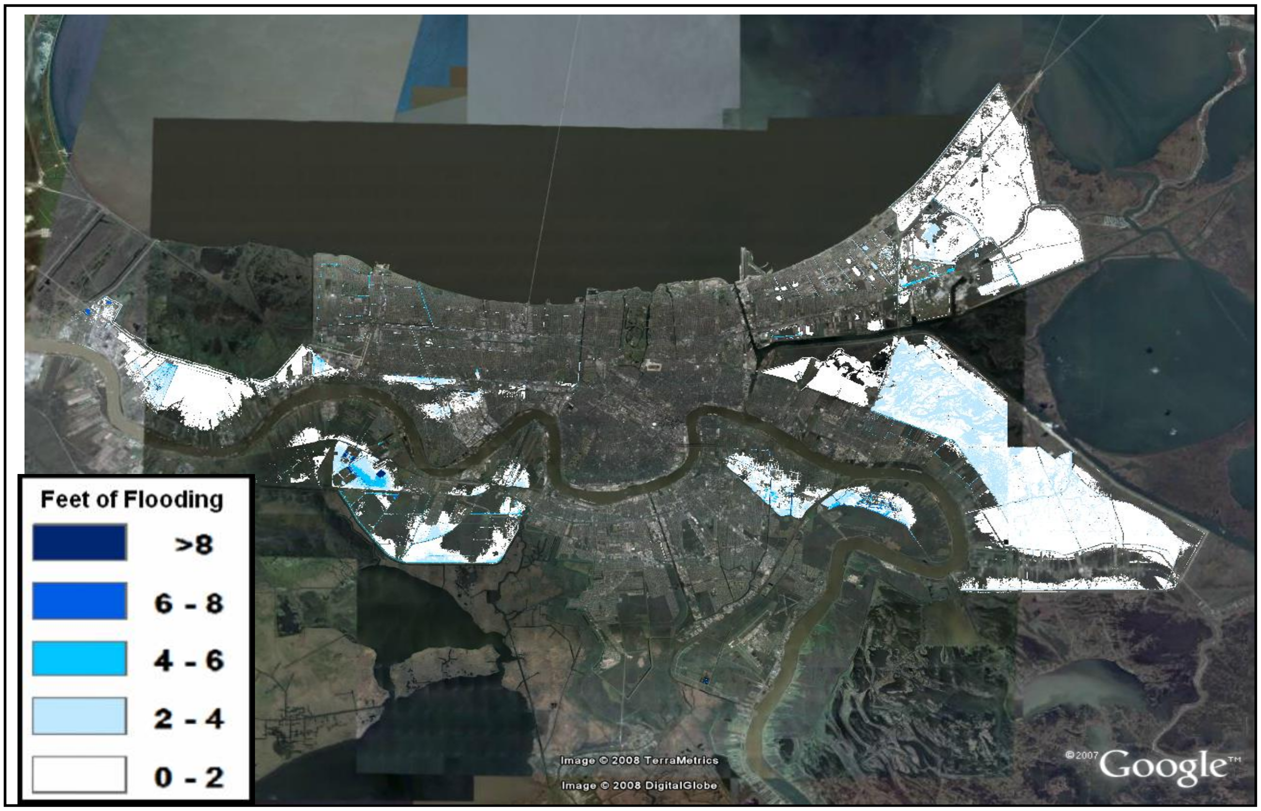

Figure 10-5. Hurricane inundation frequency map, 2% (1/50 return period) for pre-Katrina HPS and 100% pumping.

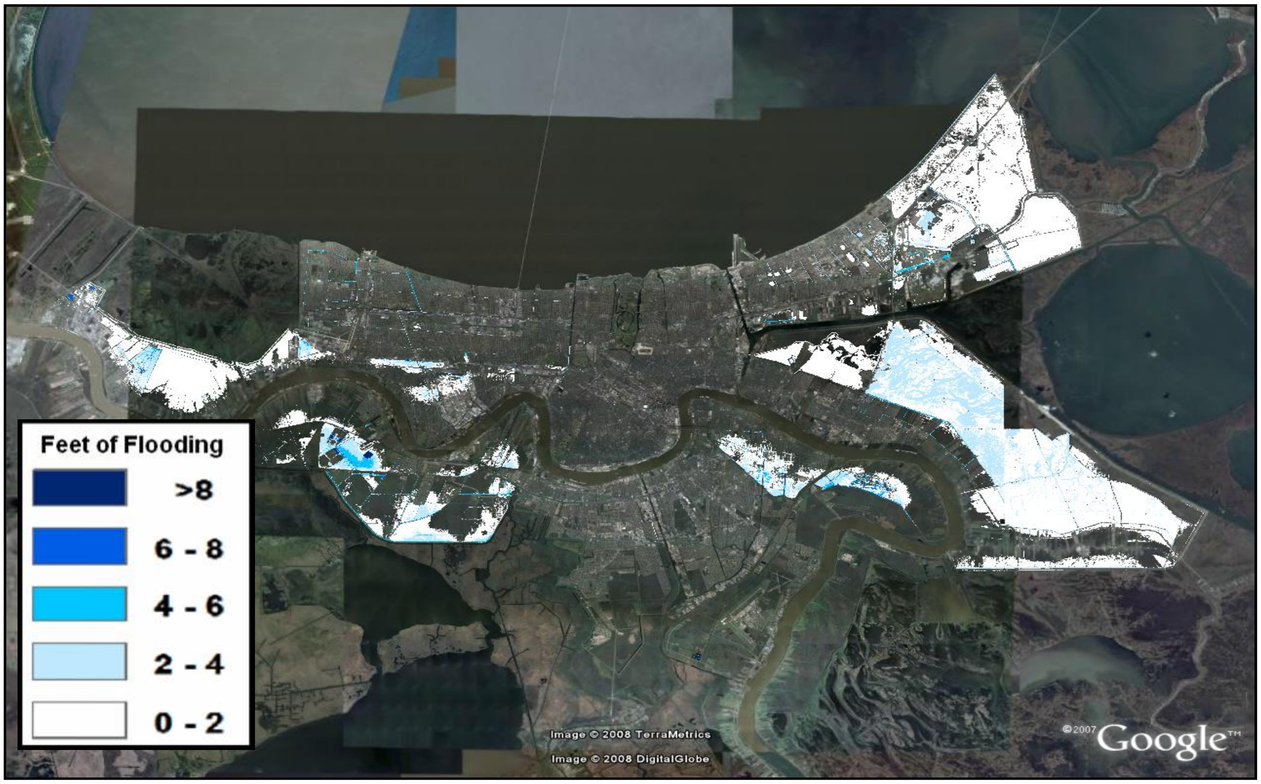

Figure 10-6. Hurricane inundation frequency map, 2% (1/50 return period) for June 2007 HPS and 100% pumping.

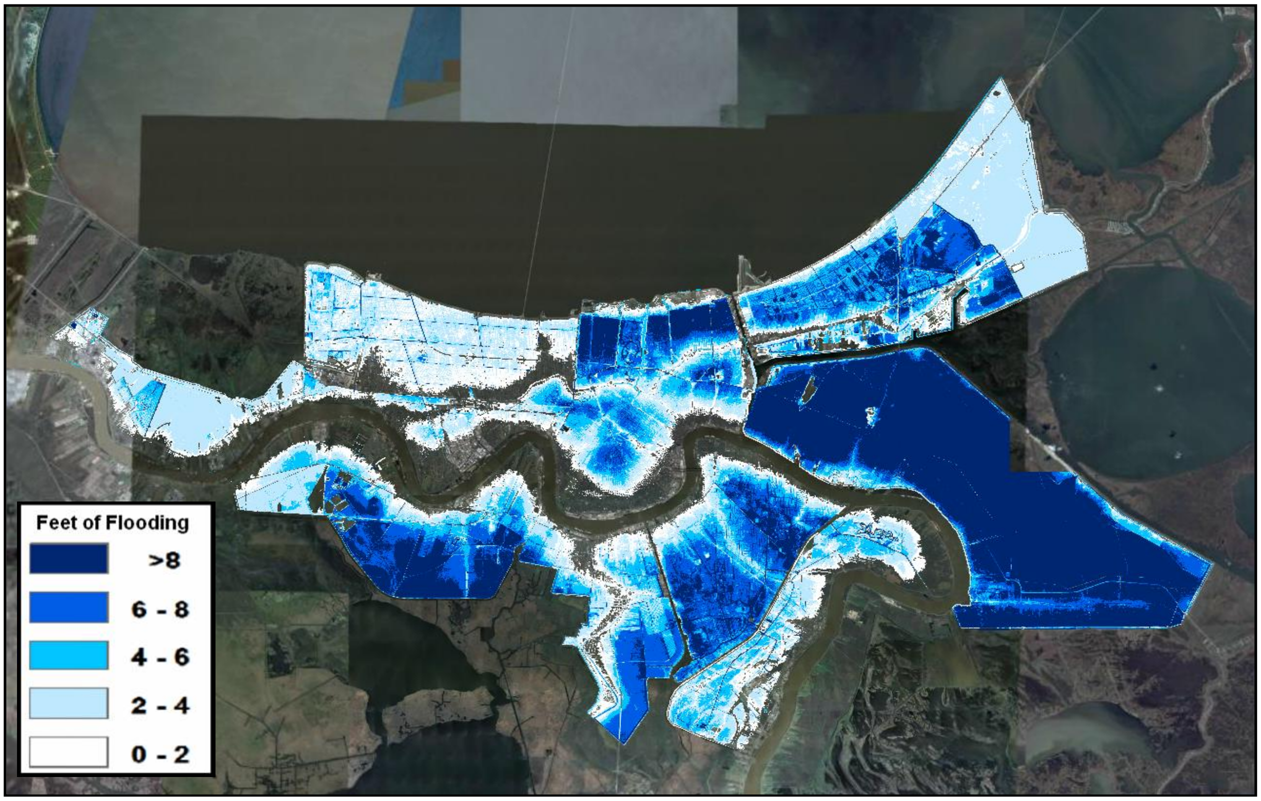

Figure 10-7. Hurricane inundation frequency map, 1% (1/100 return period) for pre-Katrina HPS and 0% pumping.

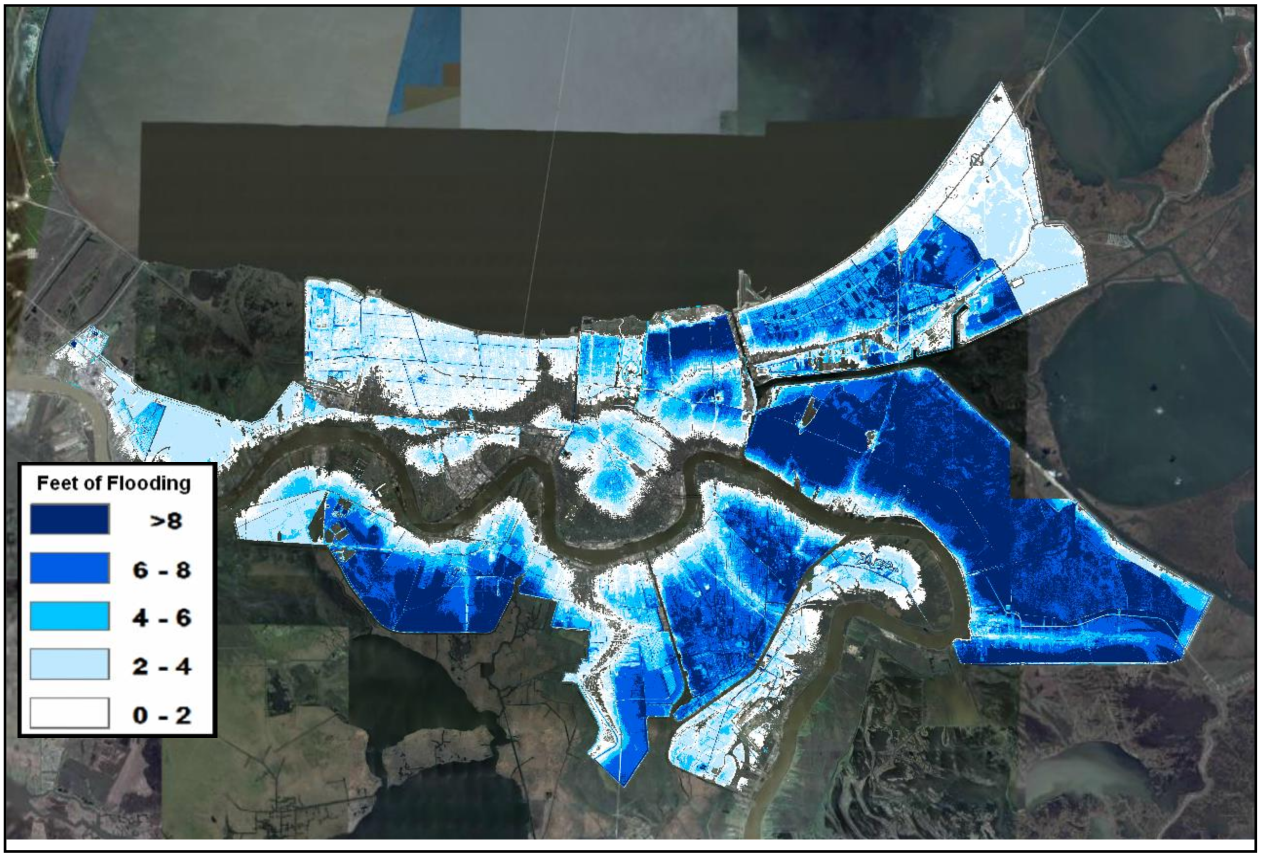

Figure 10-8. Hurricane inundation frequency map, 1% (1/100 return period) for June 2007 HPS and 0% pumping.

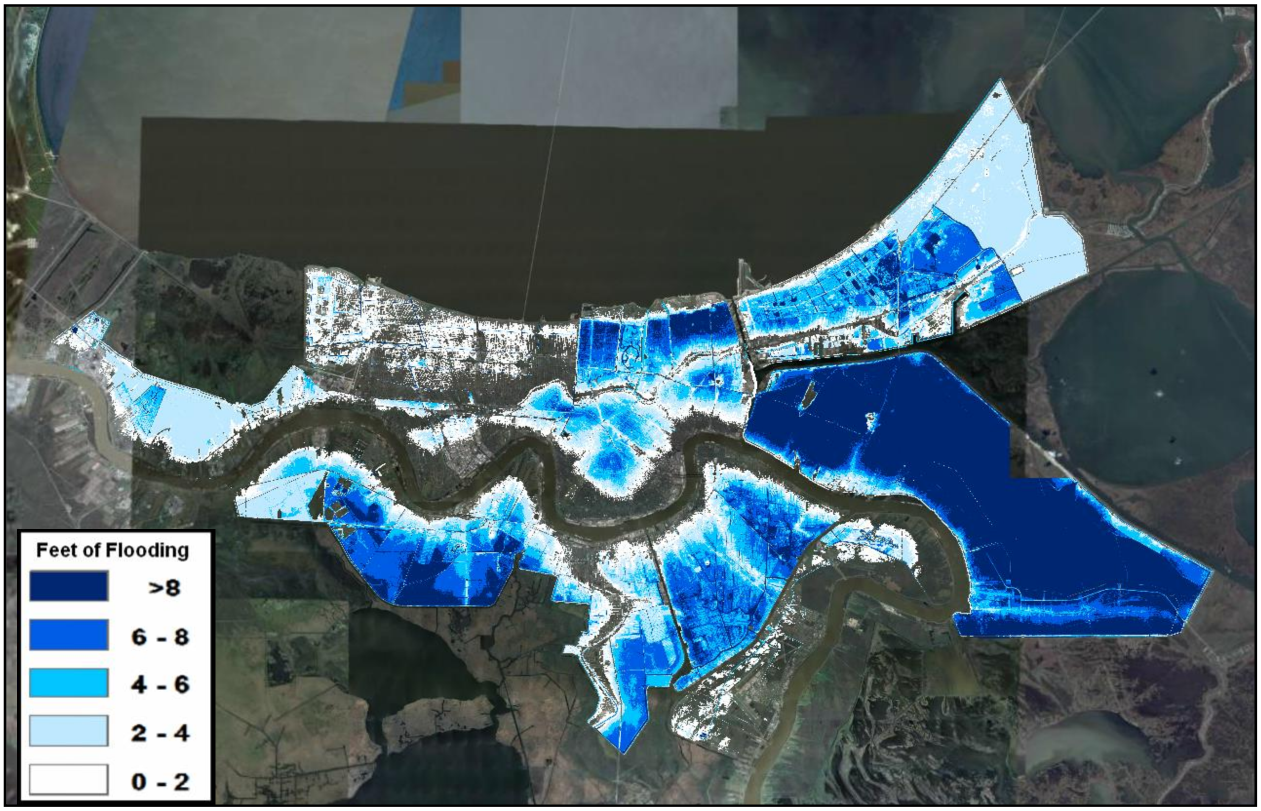

Figure 10-9. Hurricane inundation frequency map, 1% (1/100 return period) for pre-Katrina HPS and 50% of ideal pumping.

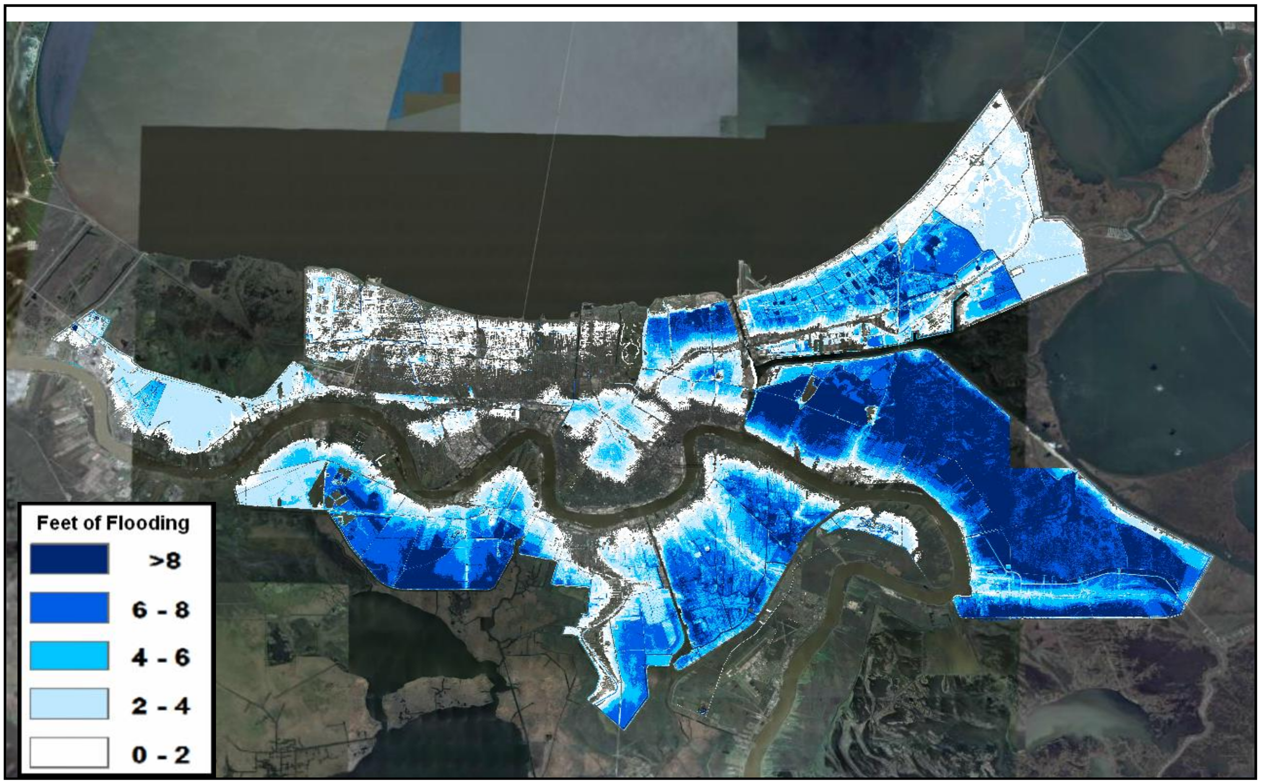

Figure 10-10. Hurricane inundation frequency map, 1% (1/100 return period) for June 2007 HPS and 50% of ideal pumping.

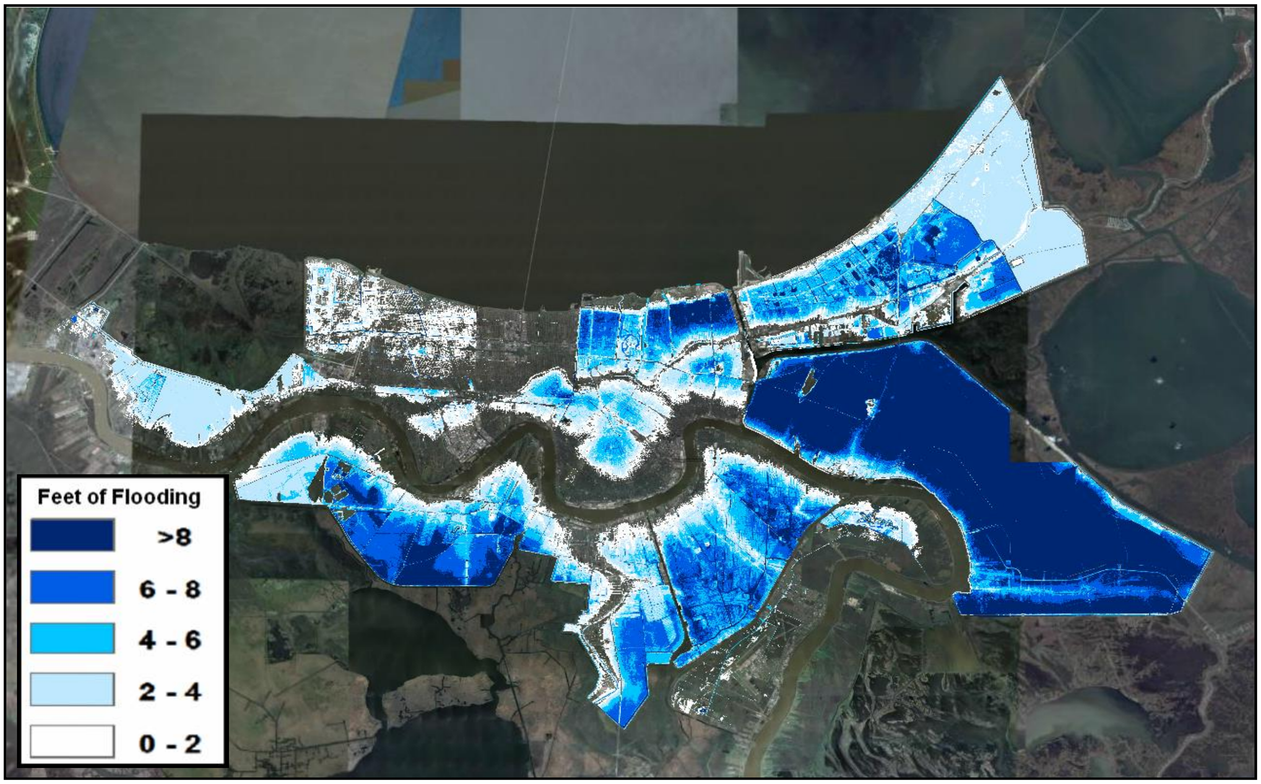

Figure 10-11. Hurricane inundation frequency map, 1% (1/100 return period) for pre-Katrina HPS and 100% of ideal pumping.

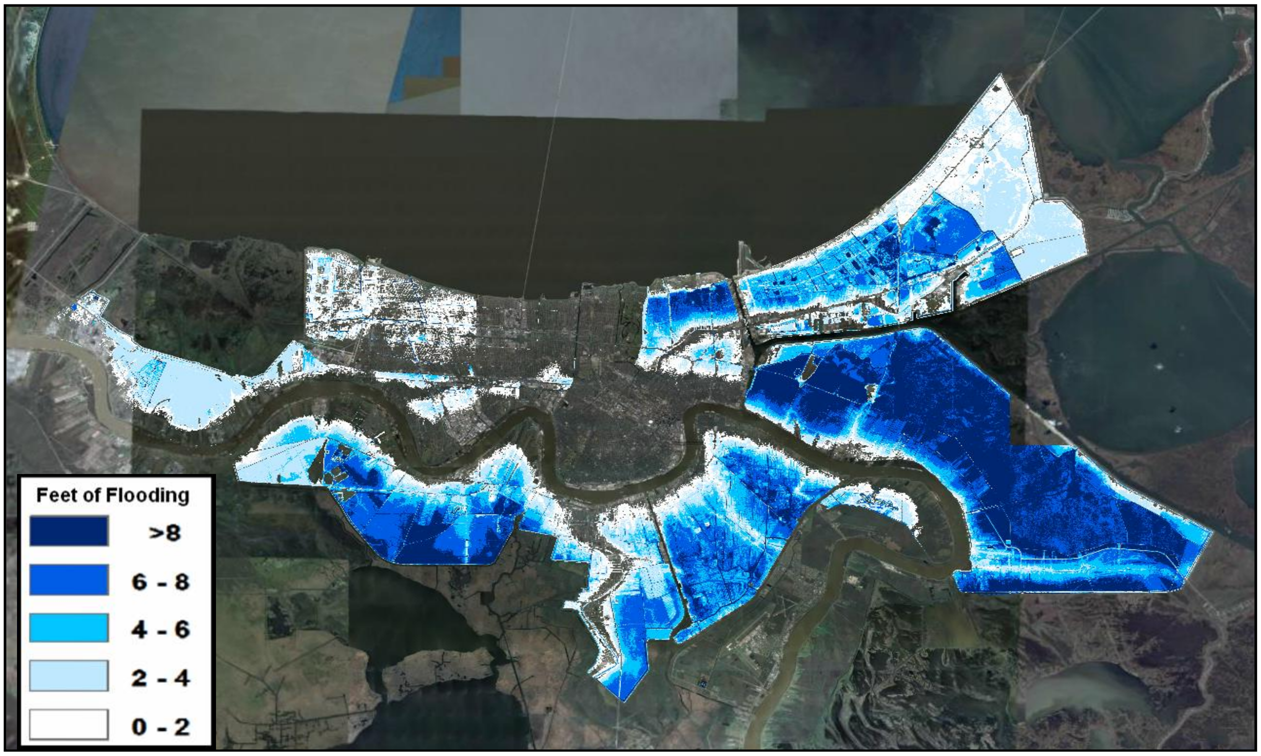

Figure 10-12. Hurricane inundation frequency map, 1% (1/100 return period) for June 2007 HPS and 100% of ideal pumping.

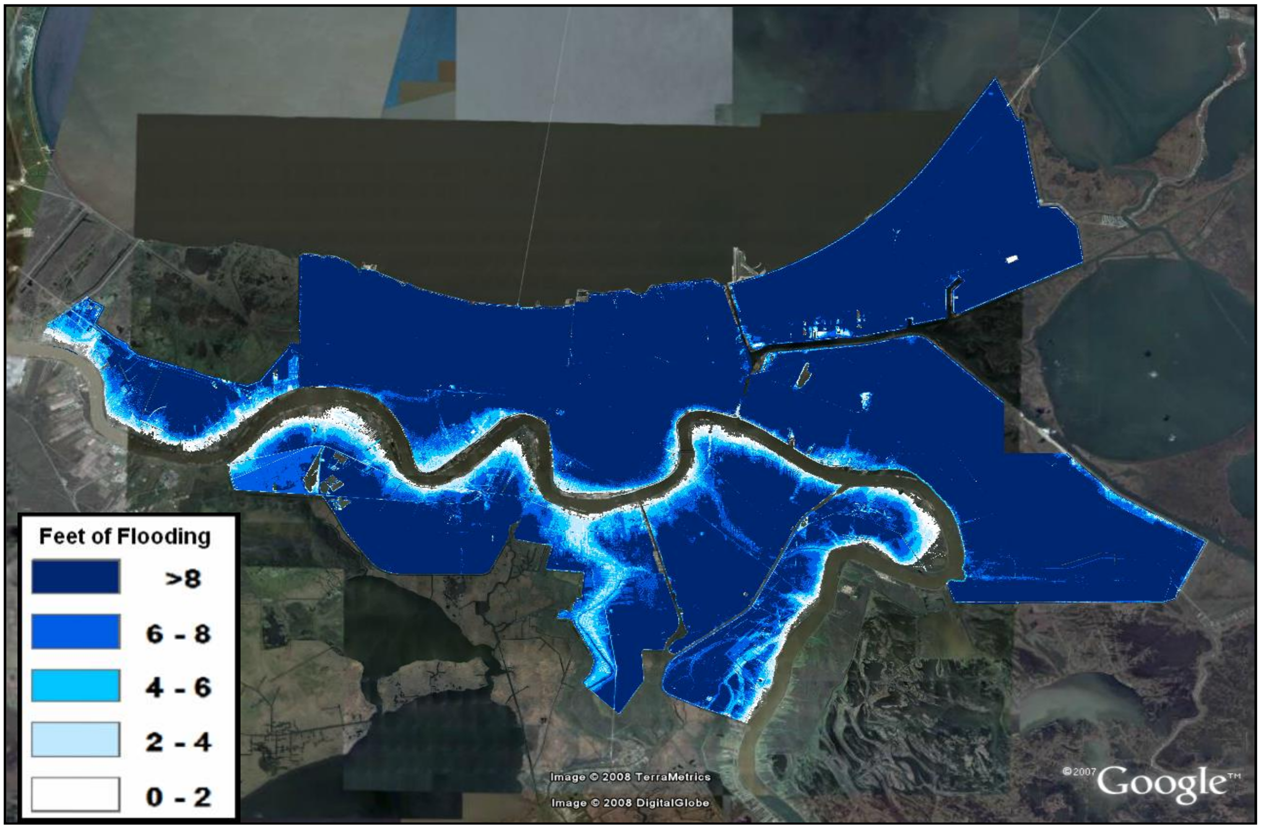

Figure 10-13. Hurricane inundation frequency map, 0.2% (1/500 return period) for pre-Katrina HPS and 0% of ideal pumping.

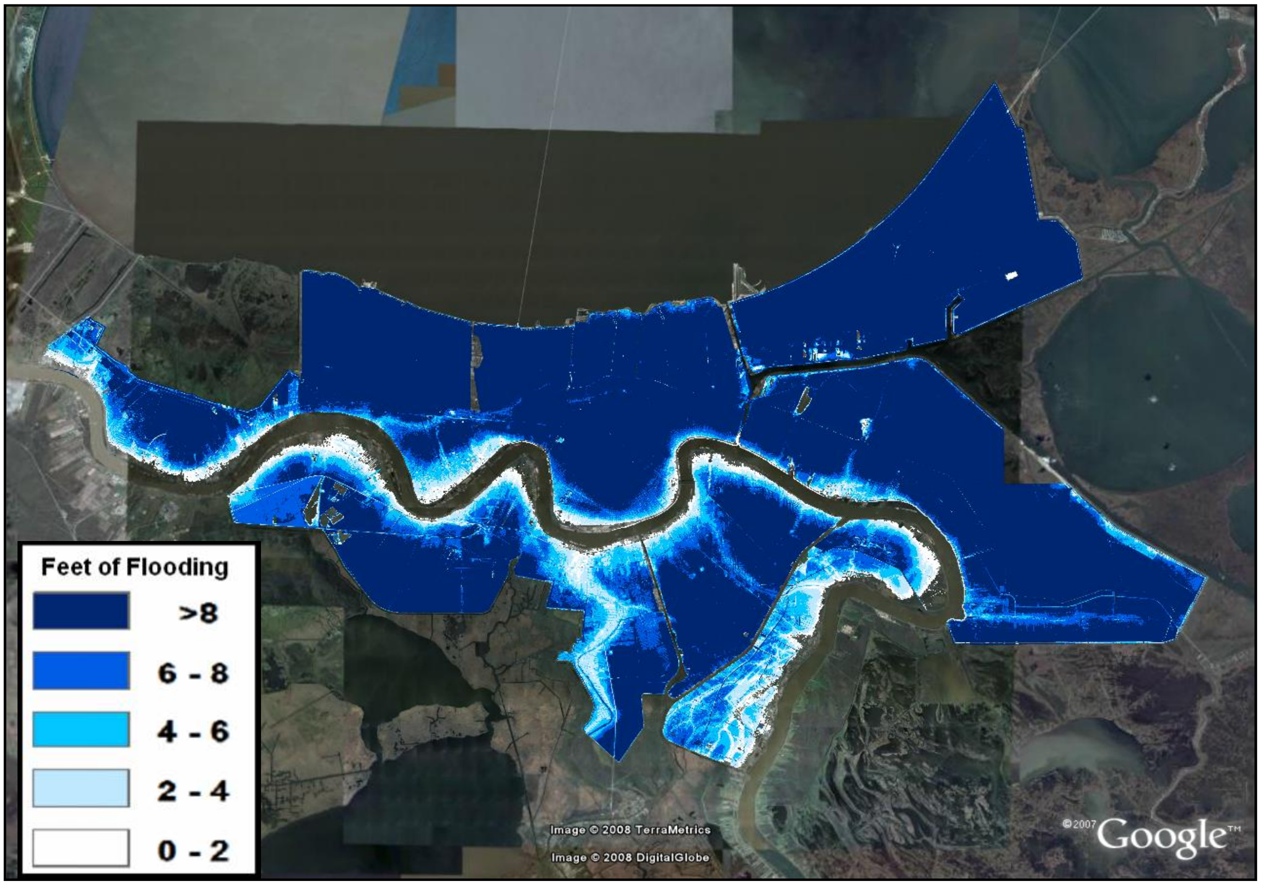

Figure 10-14. Hurricane inundation frequency map, 0.2% (1/500 return period) for June 2007 HPS and 0% of ideal pumping.

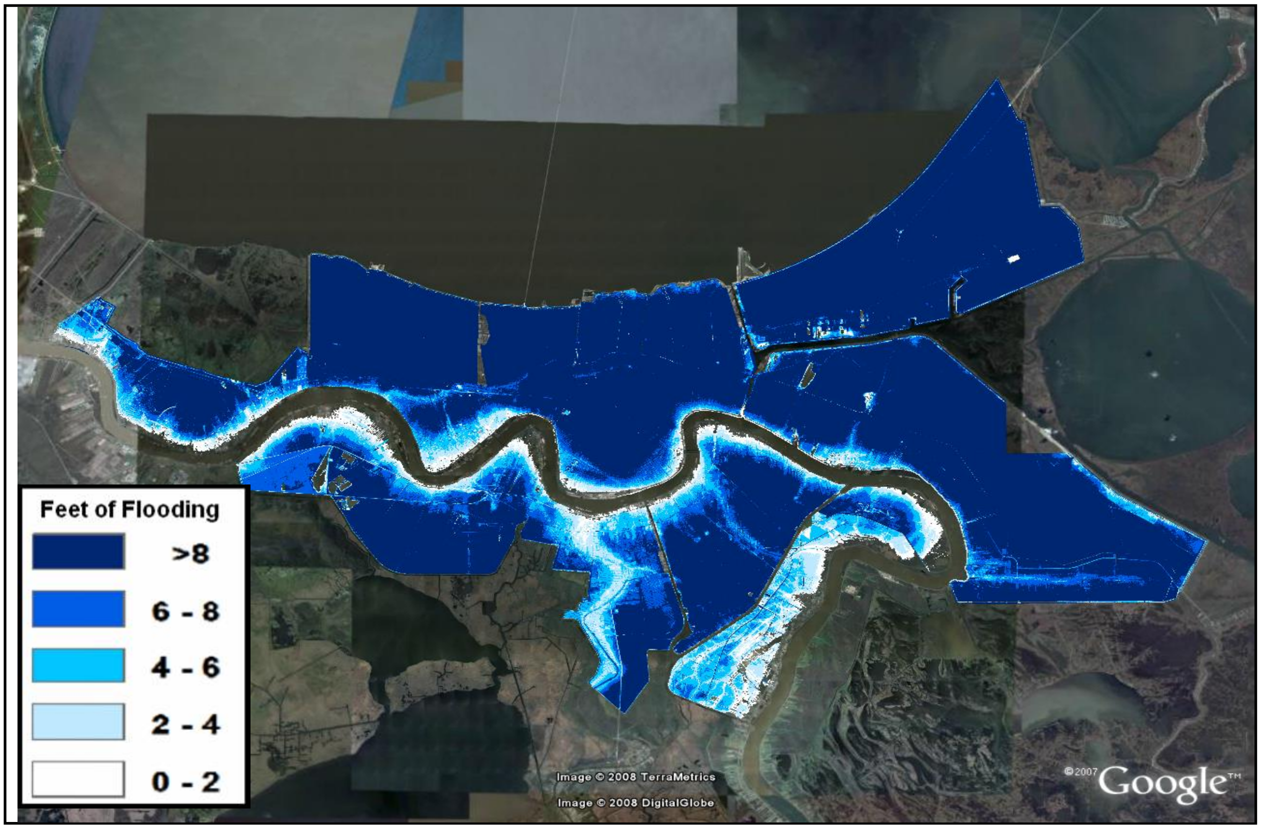

Figure 10-15. Hurricane inundation frequency map, 0.2% (1/500 return period) for pre-Katrina HPS and 50% of ideal pumping.

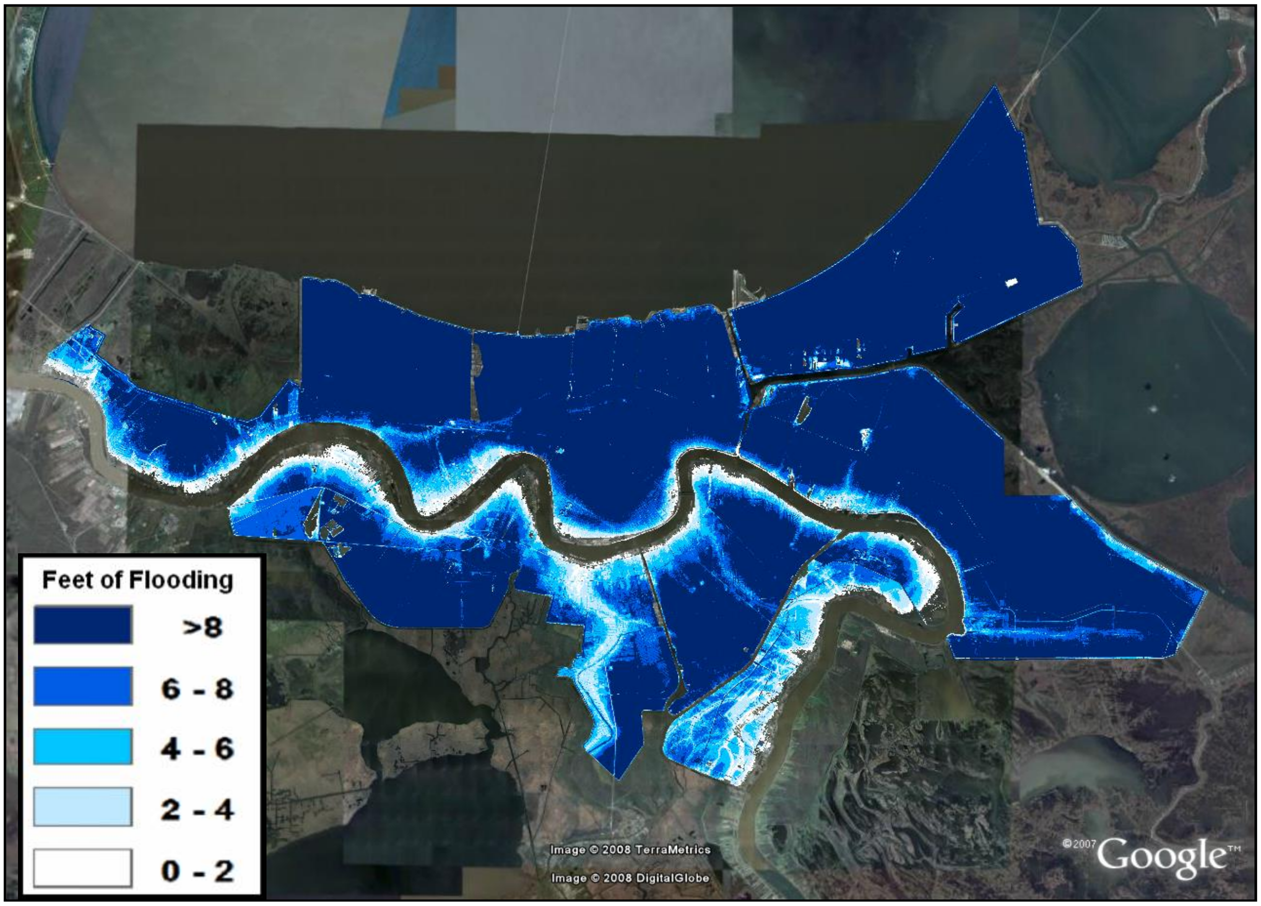

Figure 10-16. Hurricane inundation frequency map, 0.2% (1/500 return period) for June 2007 HPS and 50% of ideal pumping.

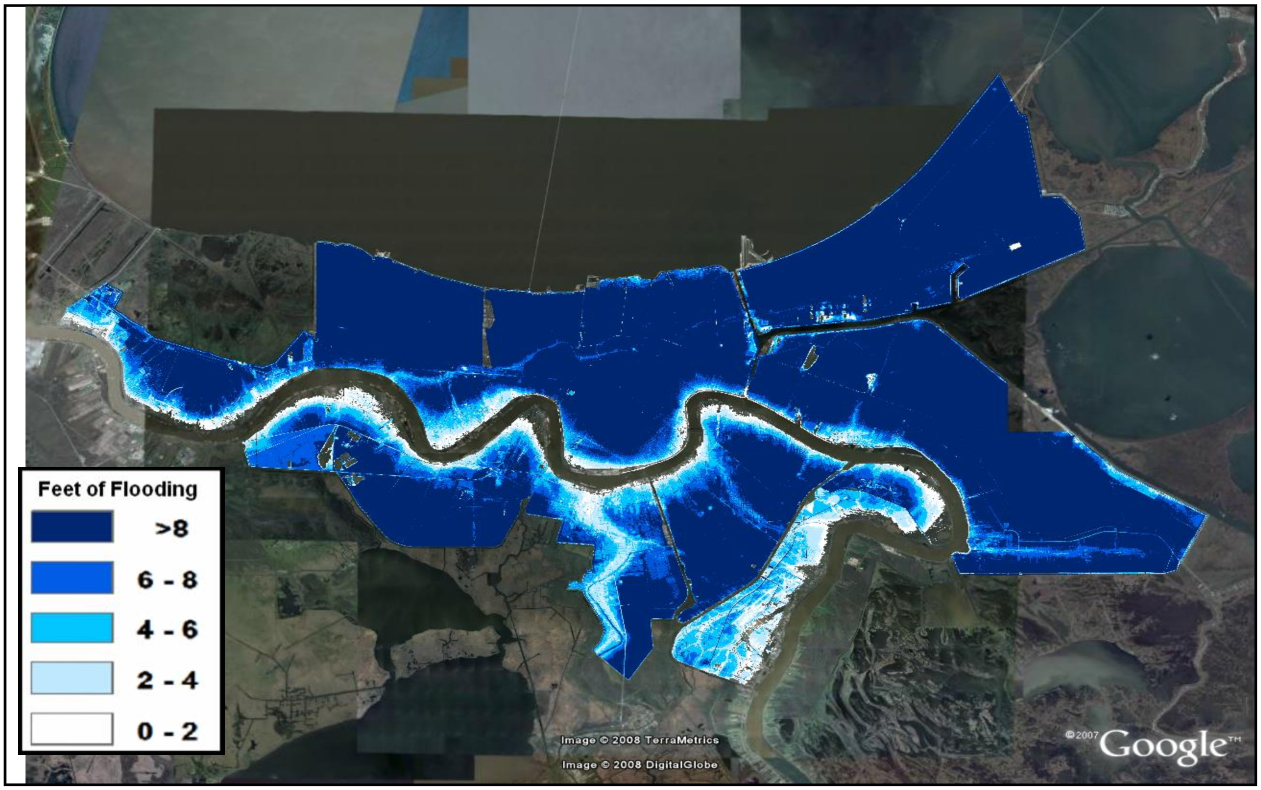

Figure 10-17. Hurricane inundation frequency map, 0.2% (1/500 return period) for pre-Katrina HPS and 100% of ideal pumping.

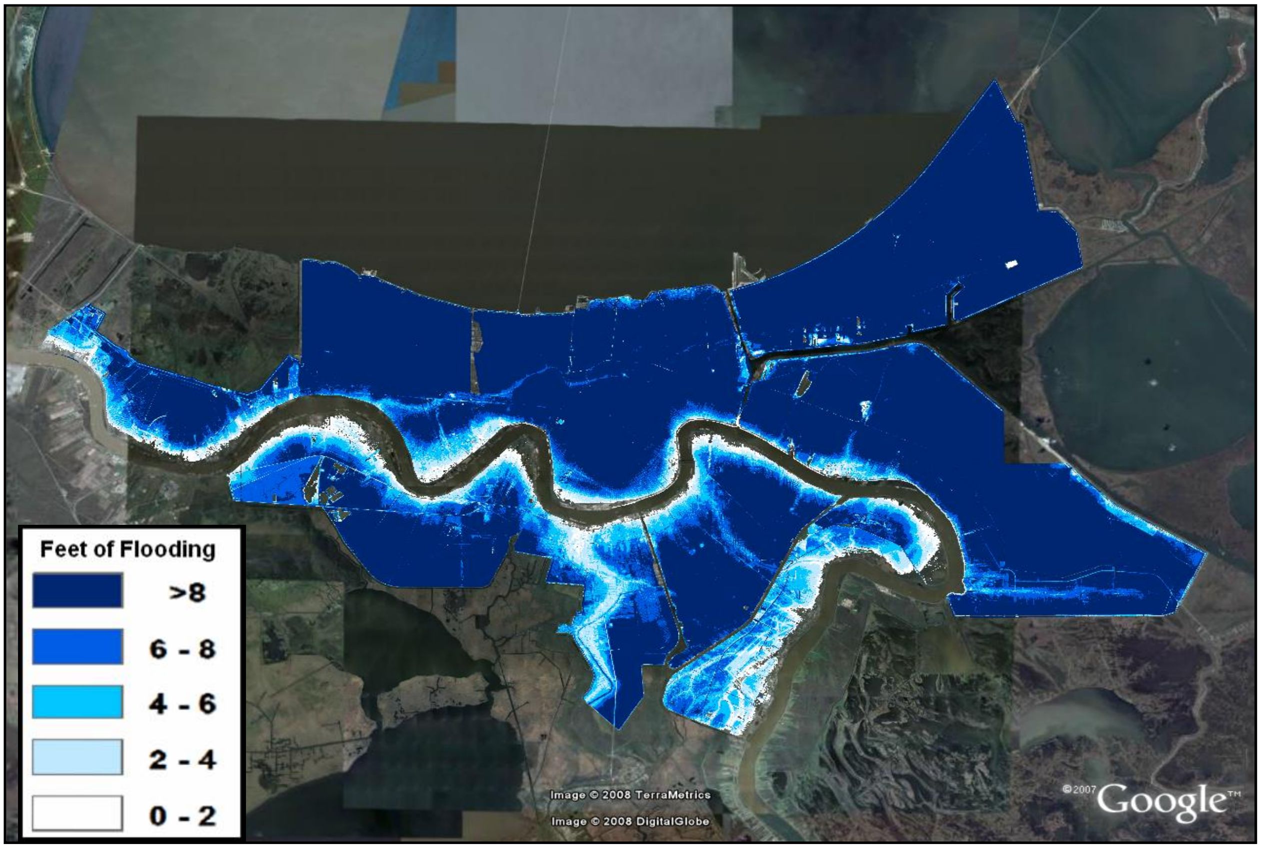

Figure 10-18. Hurricane inundation frequency map, 0.2% (1/500 return period) for June 2007 HPS and 100% of ideal pumping.

Appendix 11
Loss of Life Risk Maps

This appendix provides the individual loss of life risk maps prepared as a part of the IPET Risk and Reliability Assessment for New Orleans. Maps for the pre-Katrina and 2007 HPS are presented for the entire region modeled with the exception of the lower portions of Plaquemines Parish. Maps are provided for the 2% (1/50), 1% (1/100), and 0.2% (1/500) return periods and for 0%, 50%, and 100% of ideal pumping capacity. Lower Plaquemines was not included because of insufficient data to allow a full risk assessment. Details on the preparation of these maps are provided in IPET Final Report, Volume VIII, *Engineering and Operational Risk and Reliability Analysis*.

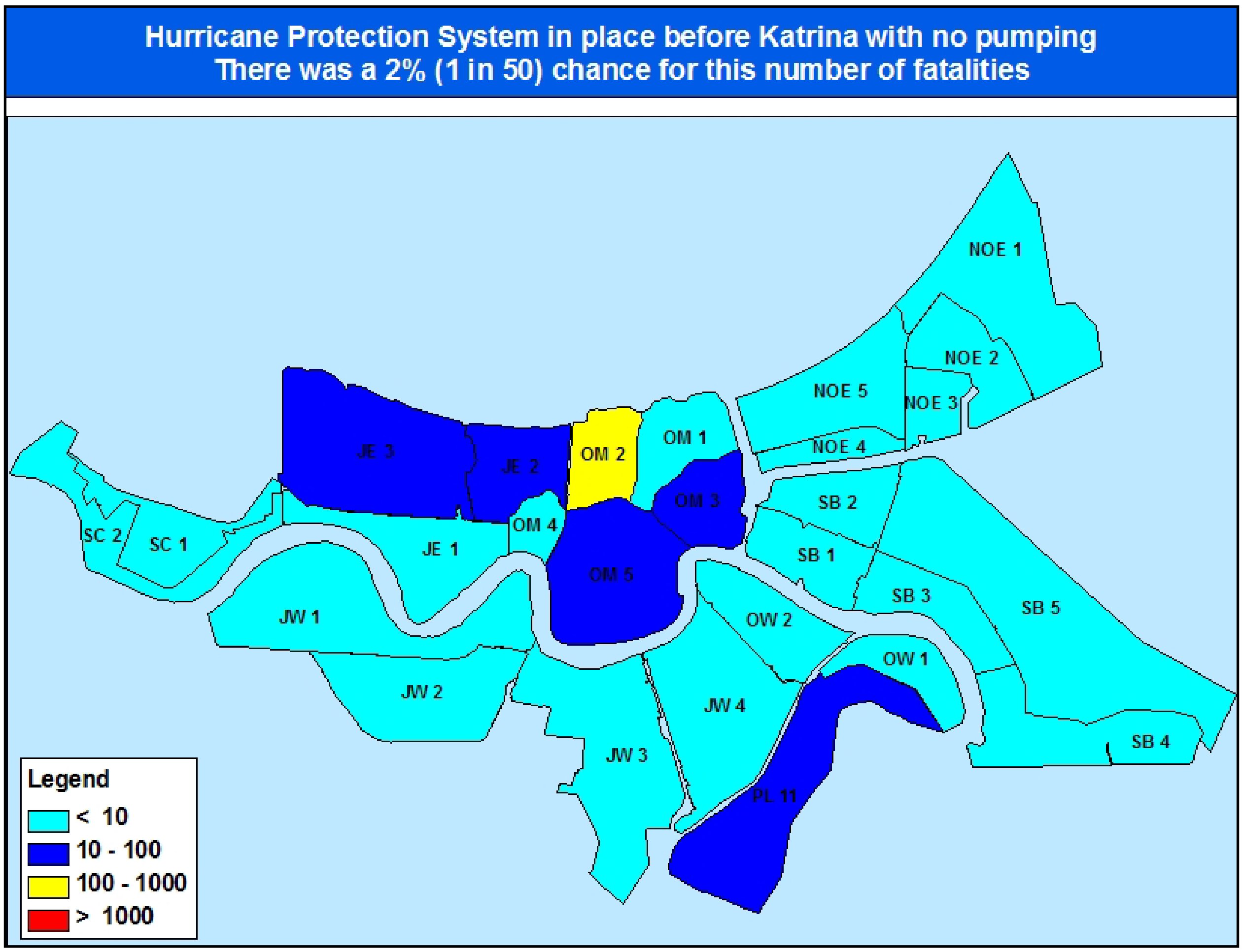

Figure 11-1. Loss of life risk map, 2% (1/50 return period) for pre-Katrina HPS and 0% pumping.

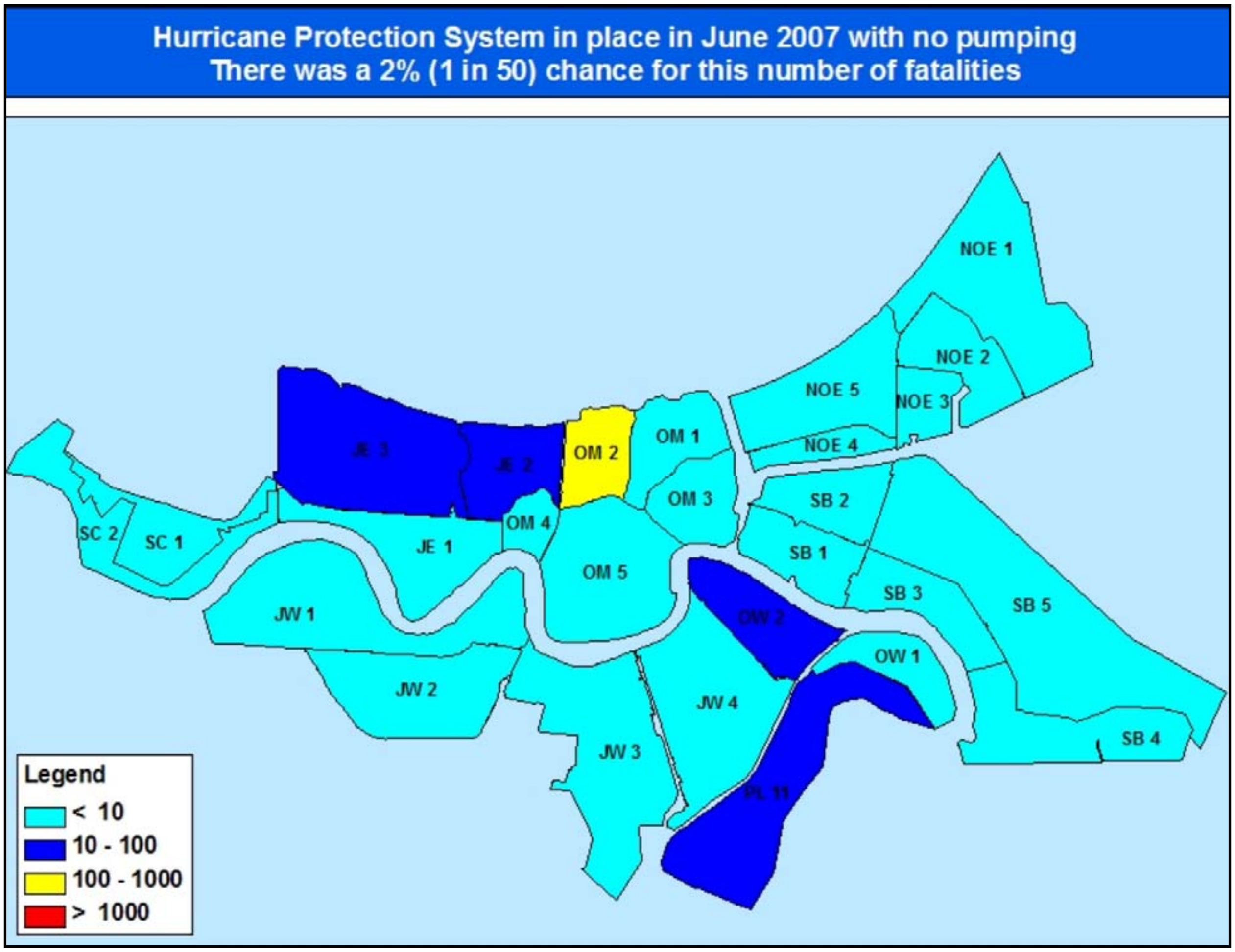

Figure 11-2. Loss of life risk map, 2% (1/50 return period) for June 2007 HPS and 0% pumping.

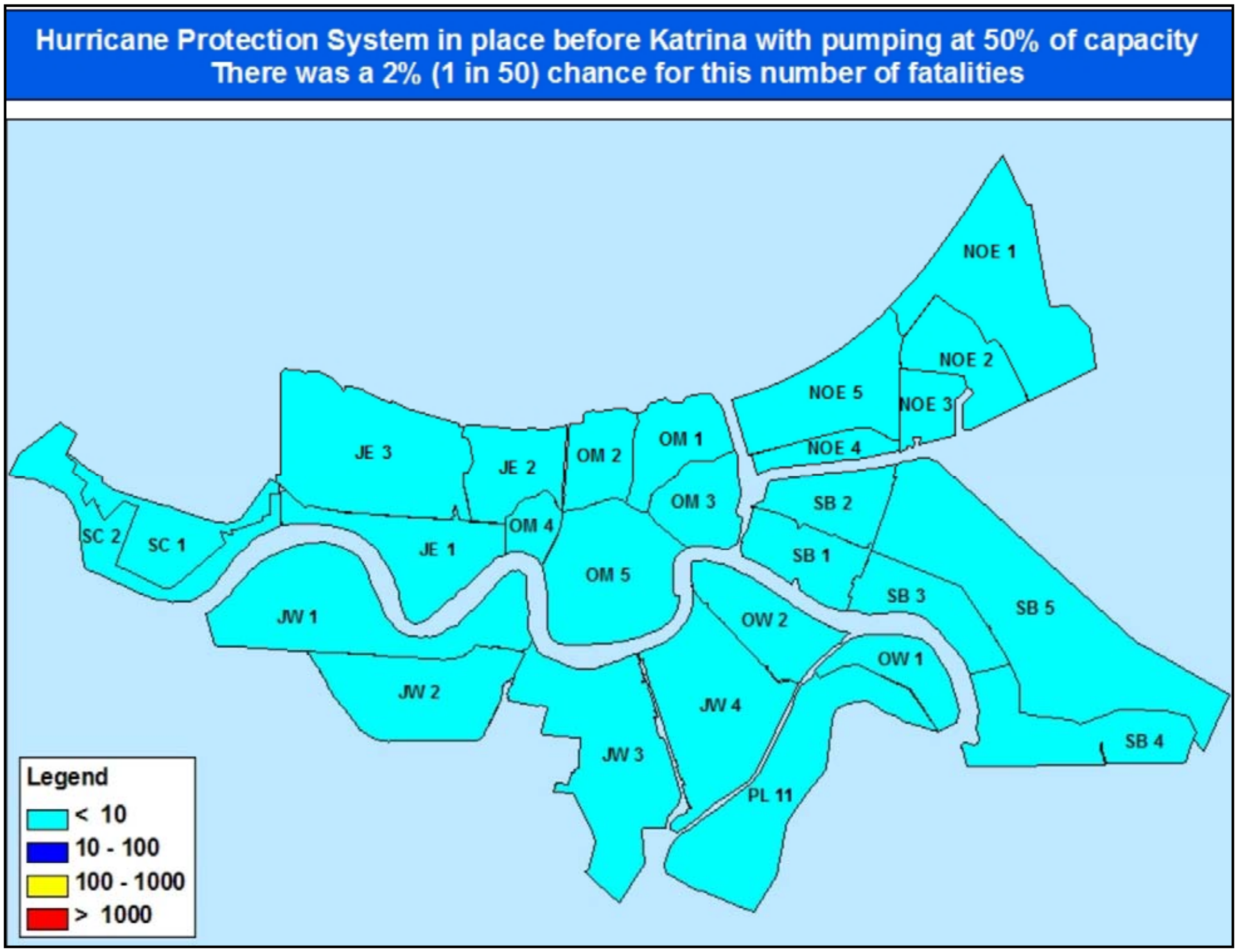

Figure 11-3. Loss of life risk map, 2% (1/50 return period) for pre-Katrina HPS and 50% pumping.

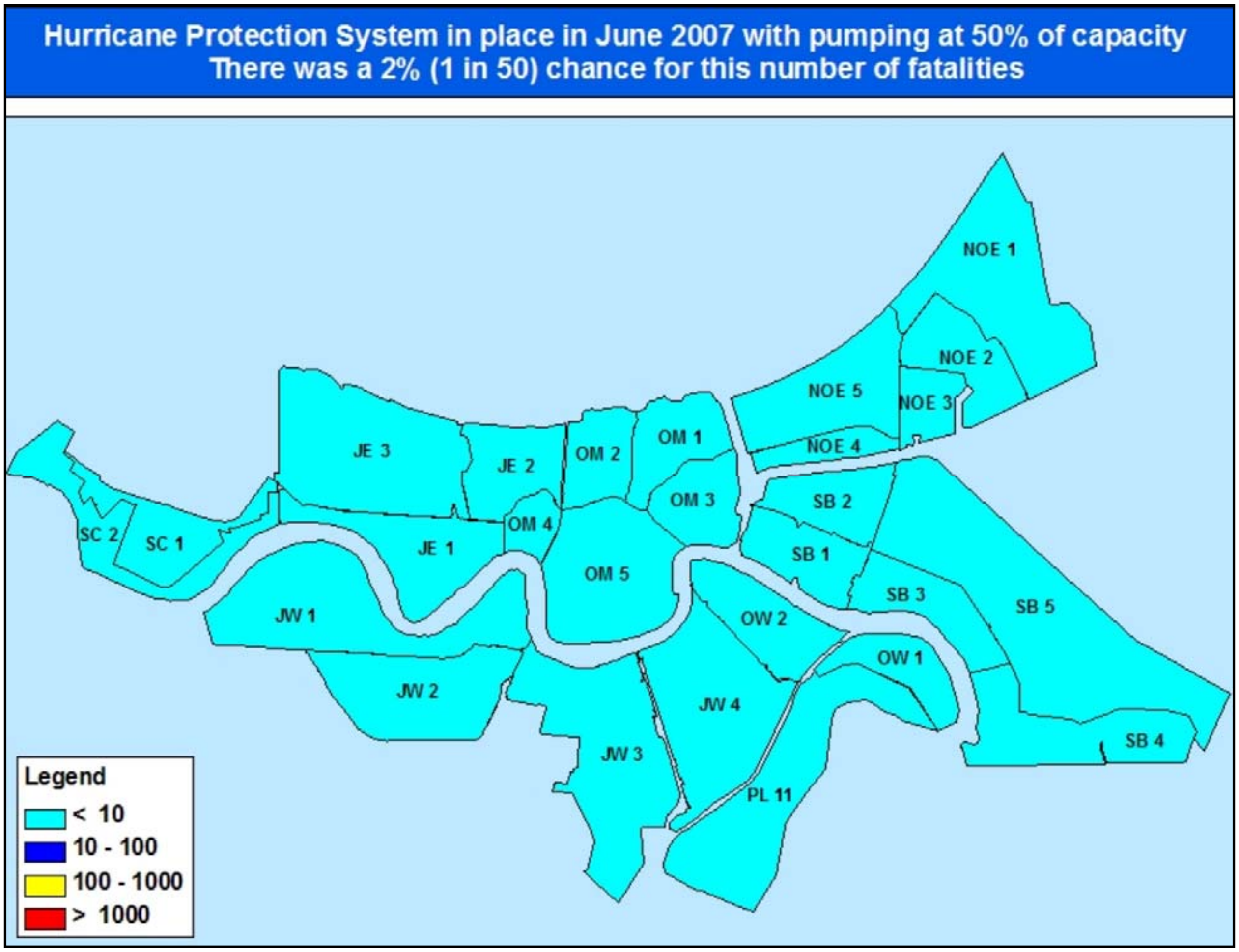

Figure 11-4. Loss of life risk map, 2% (1/50 return period) for June 2007 HPS and 50% pumping.

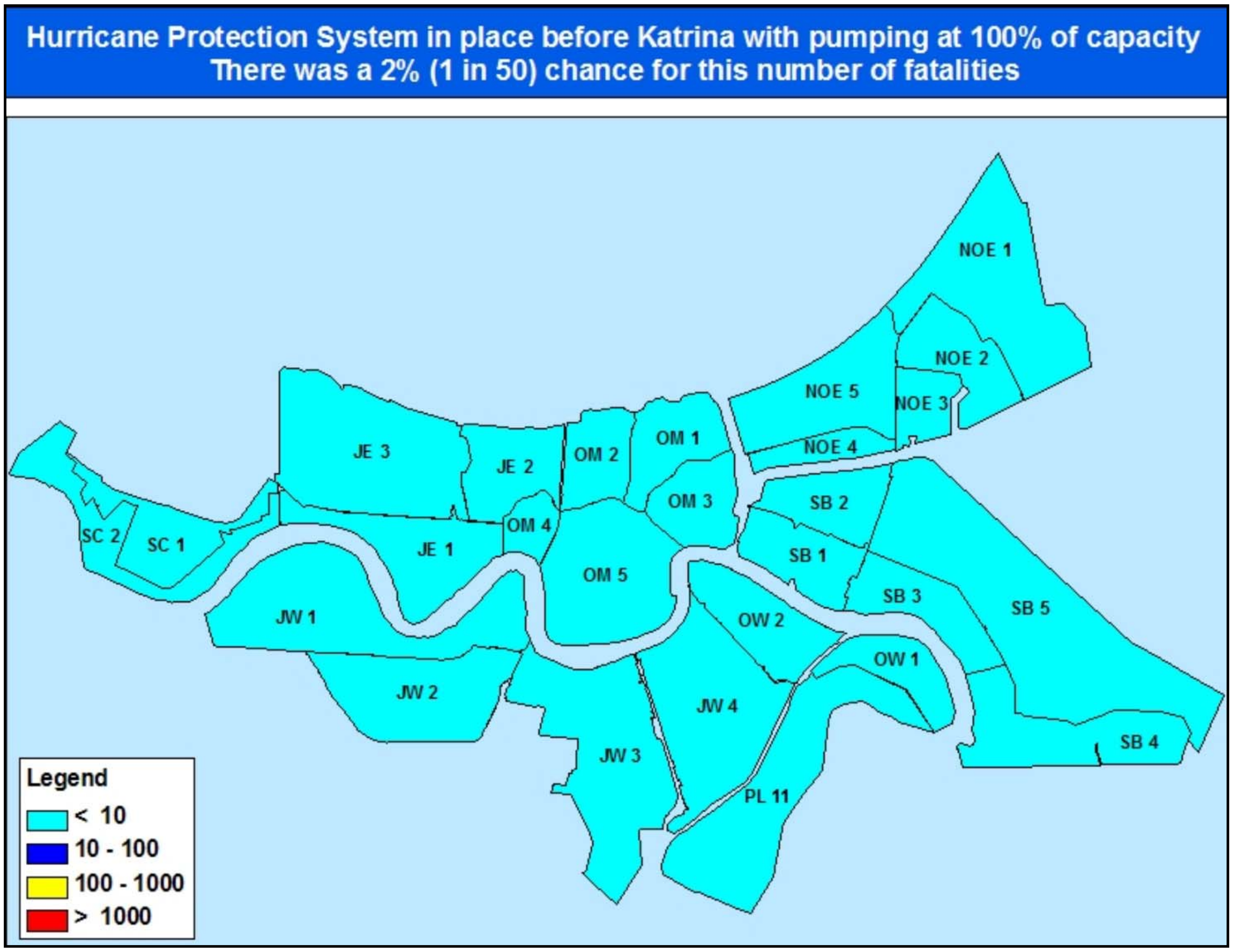

Figure 11-5. Loss of life risk map, 2% (1/50 return period) for pre-Katrina HPS and 100% pumping.

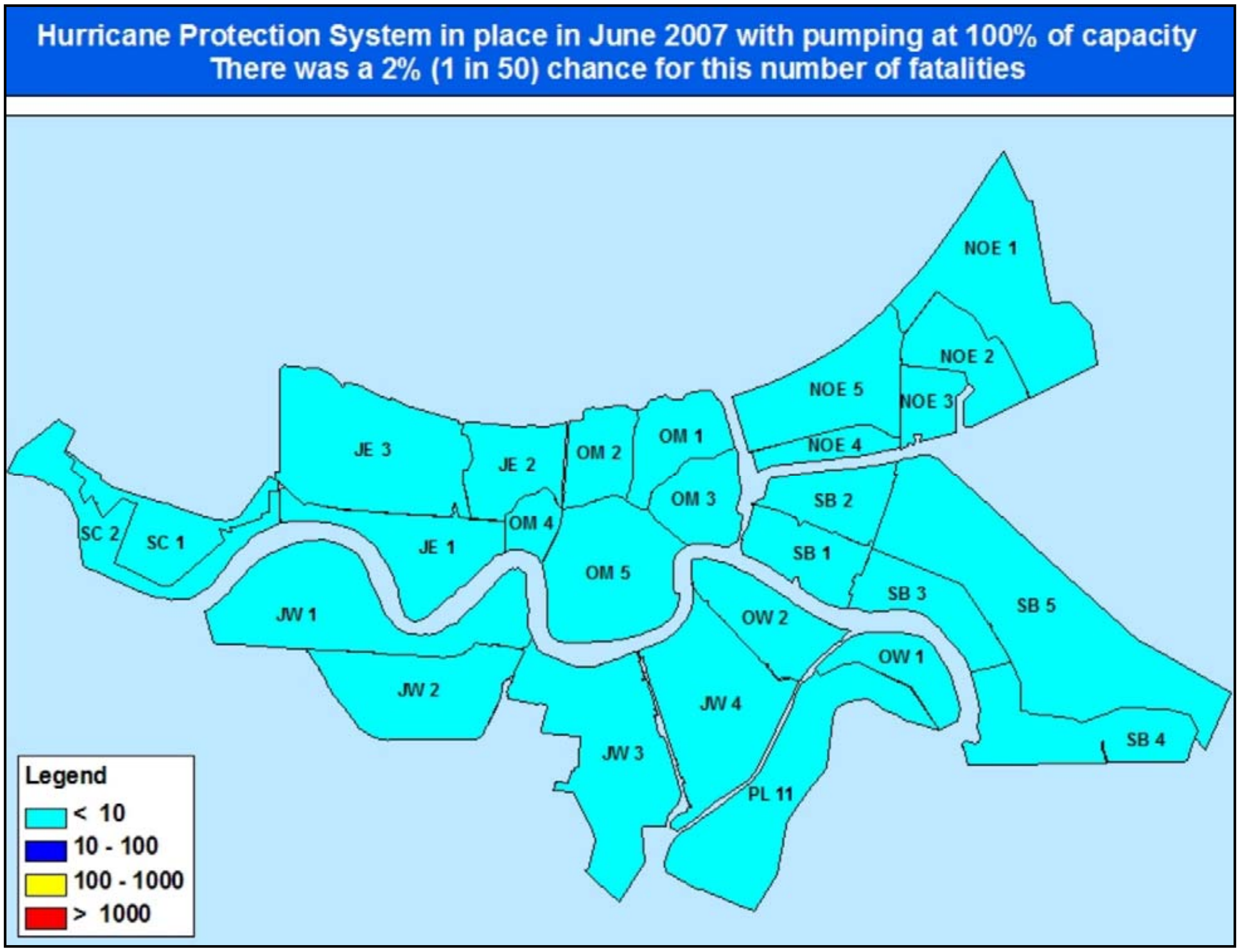

Figure 11-6. Loss of life risk map, 2% (1/50 return period) for June 2007 HPS and 100% pumping.

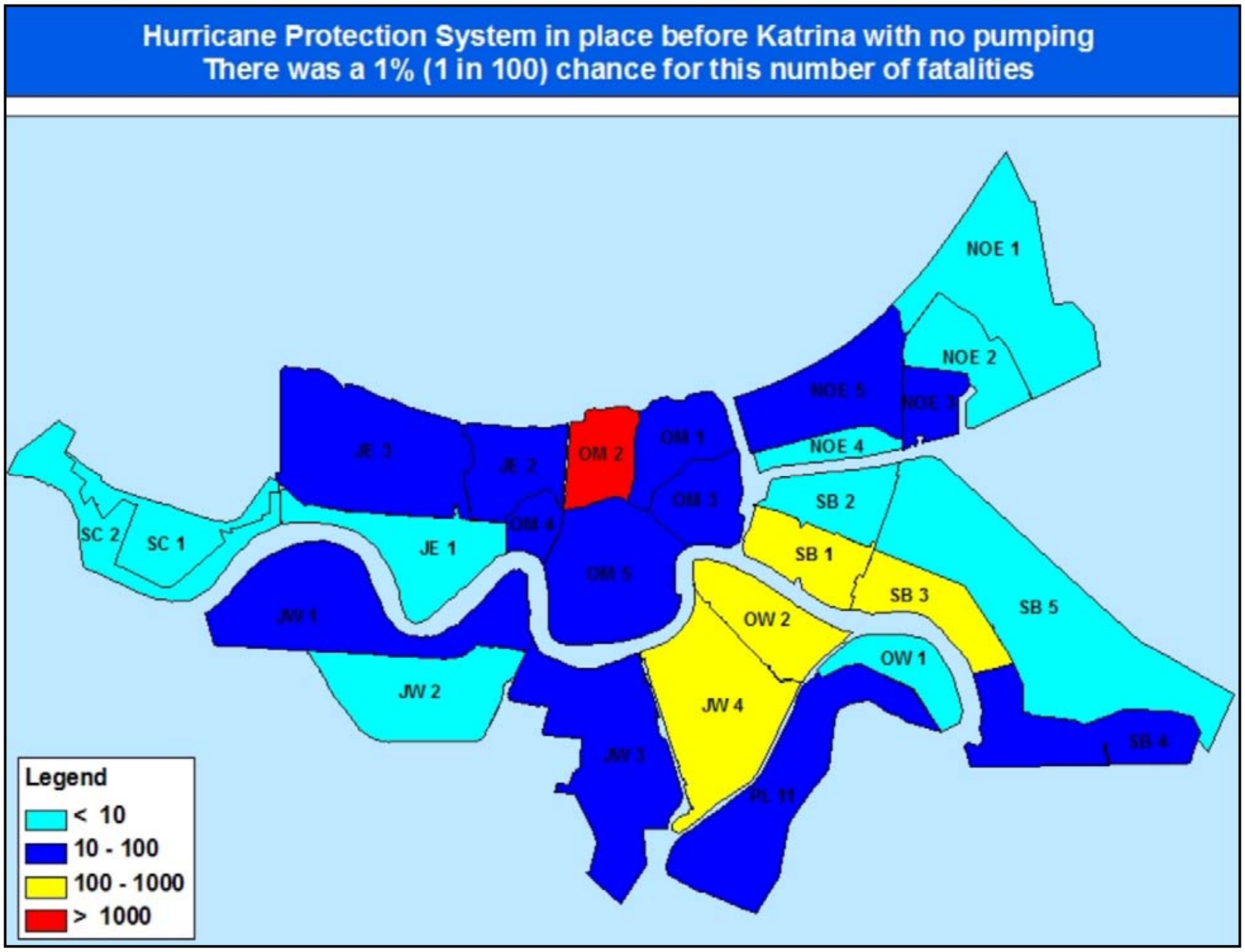

Figure 11-7. Loss of life risk map, 1% (1/100 return period) for pre-Katrina HPS and 0% pumping.

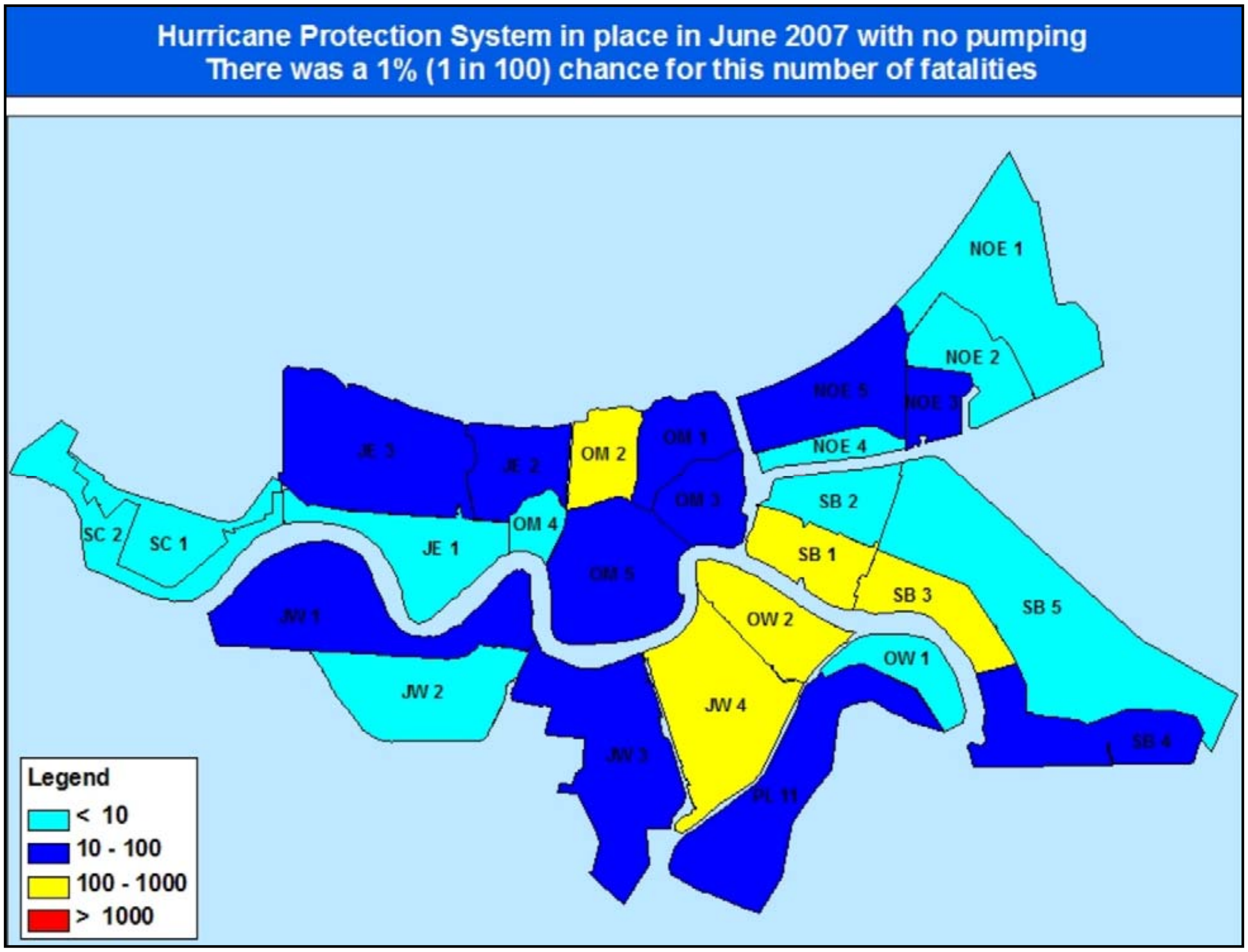

Figure 11-8. Loss of life risk map, 1% (1/100 return period) for June 2007 HPS and 0% pumping.

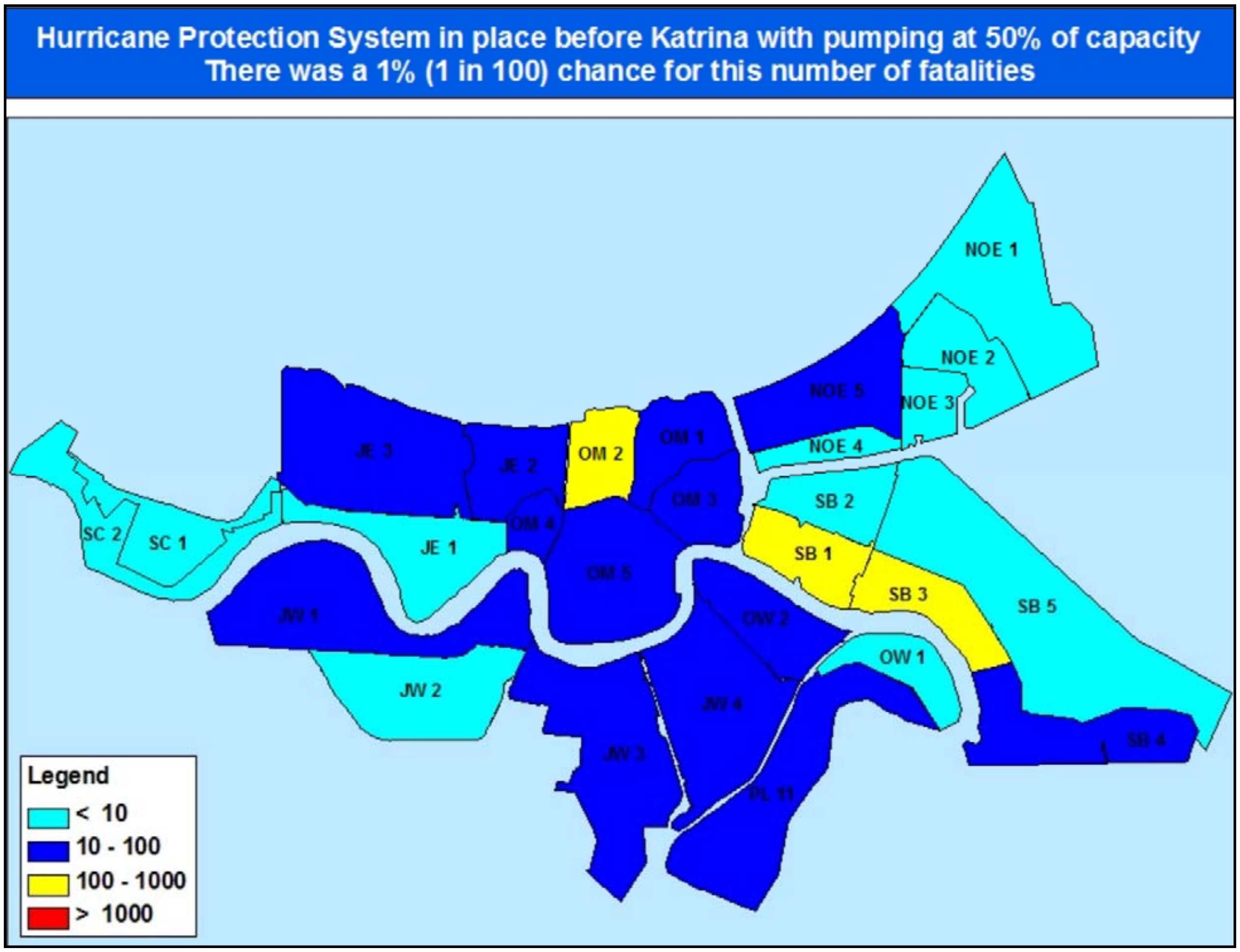

Figure 11-9. Loss of life risk map, 1% (1/100 return period) for pre-Katrina HPS and 50% pumping.

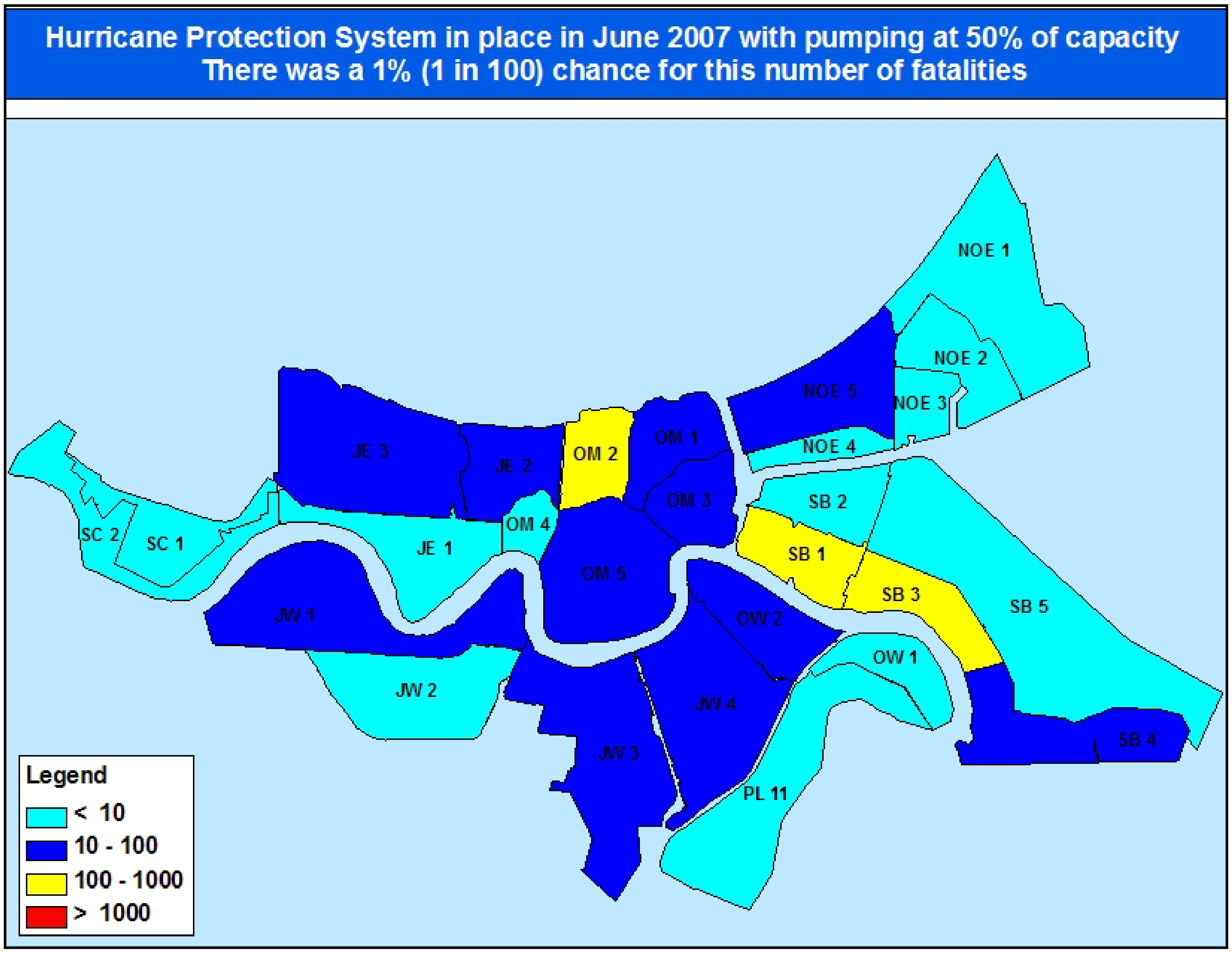

Figure 11-10. Loss of life risk map, 1% (1/100 return period) for June 2007 HPS and 50% pumping.

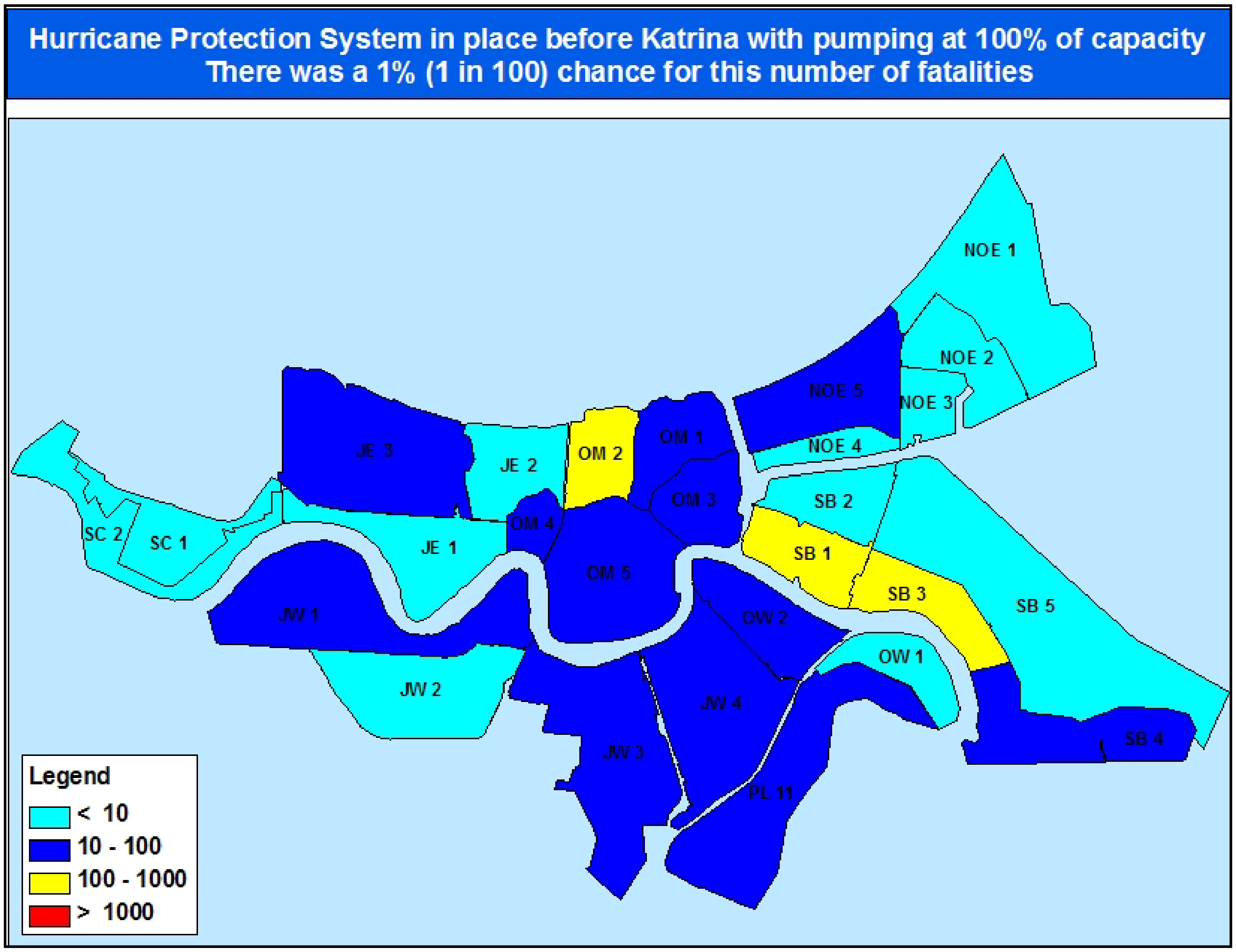

Figure 11-11. Loss of life risk map, 1% (1/100 return period) for pre-Katrina HPS and 100% pumping.

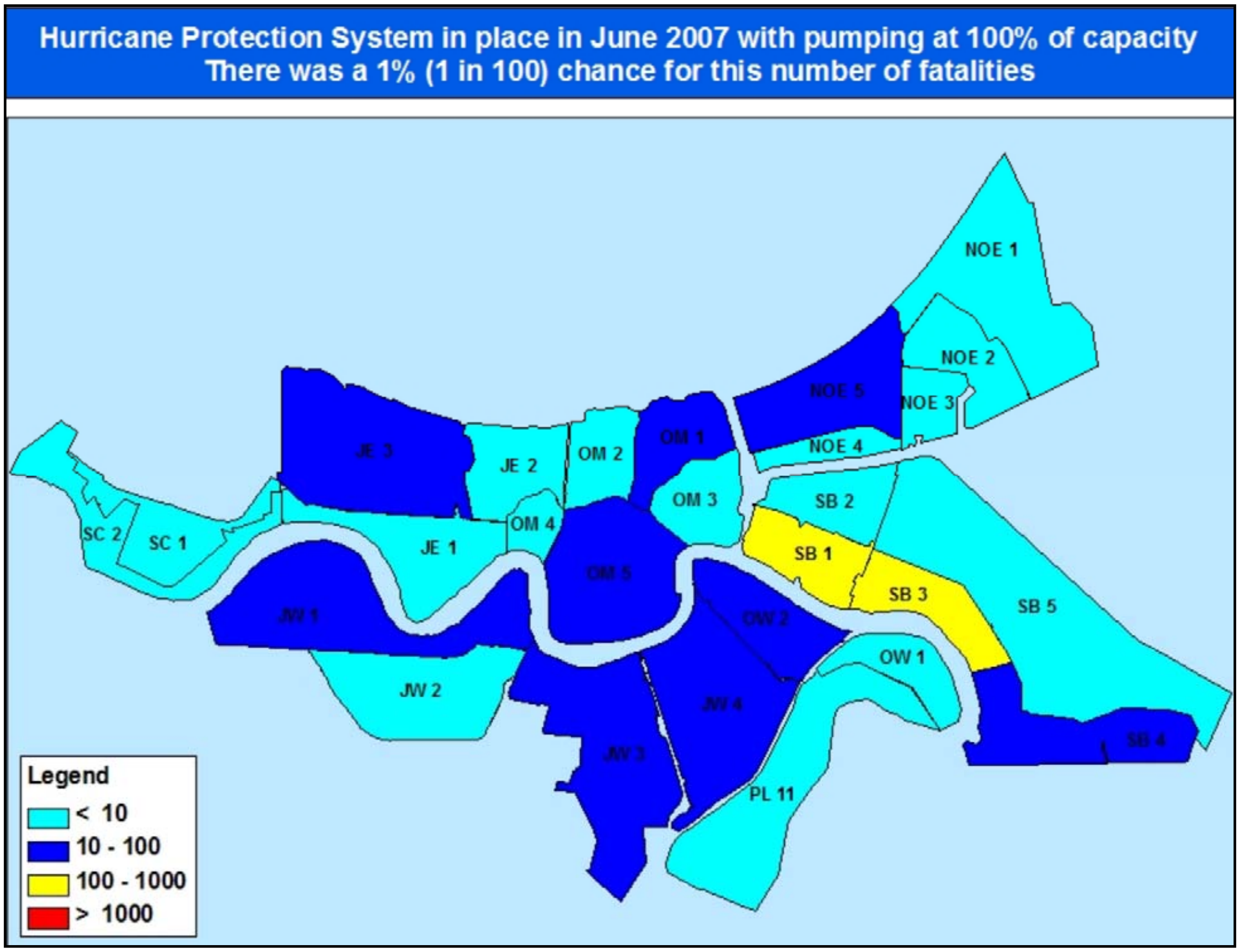

Figure 11-12. Loss of life risk map, 1% (1/100 return period) for June 2007 HPS and 100% pumping.

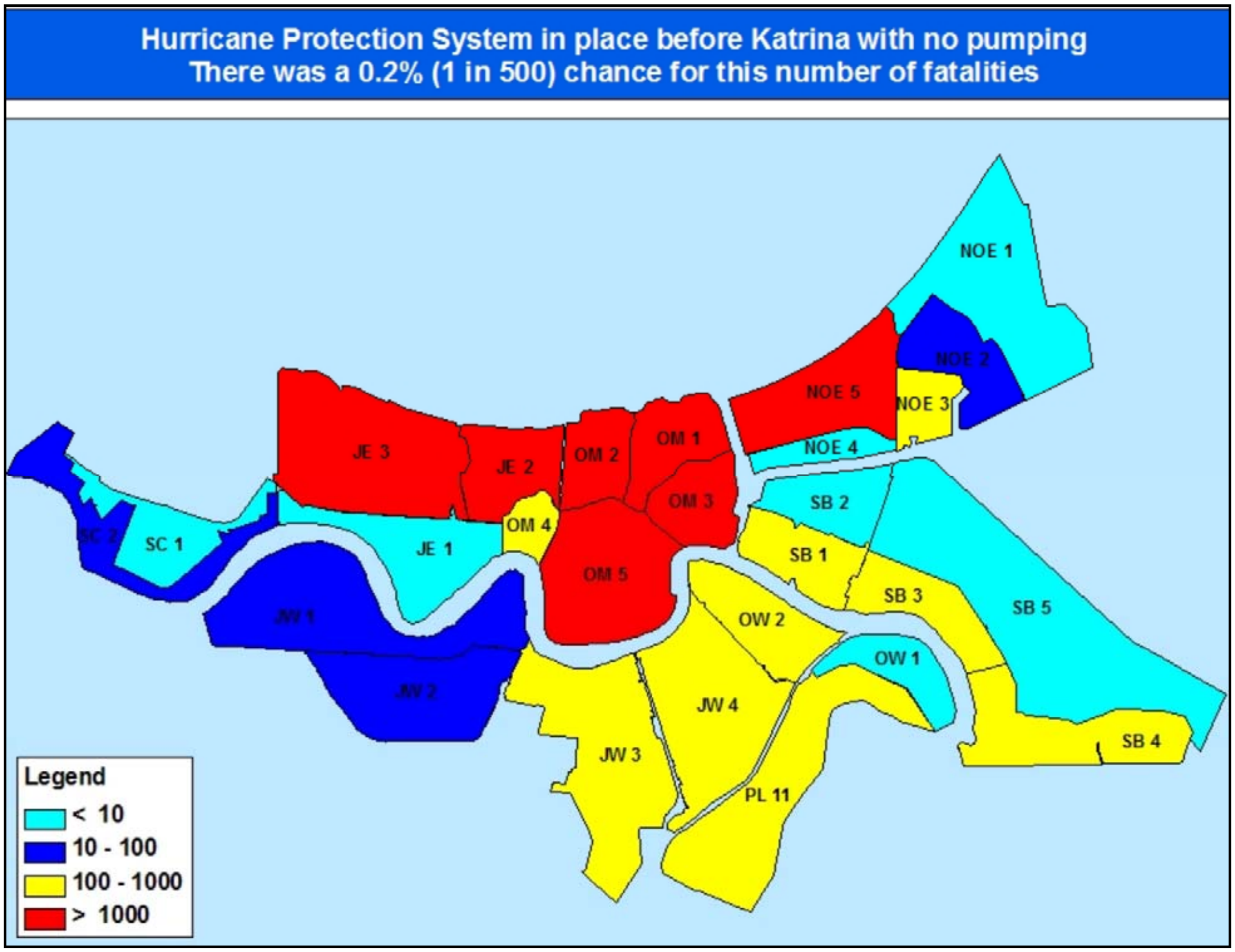

Figure 11-13. Loss of life risk map, 0.2% (1/500 return period) for pre-Katrina HPS and 0% pumping.

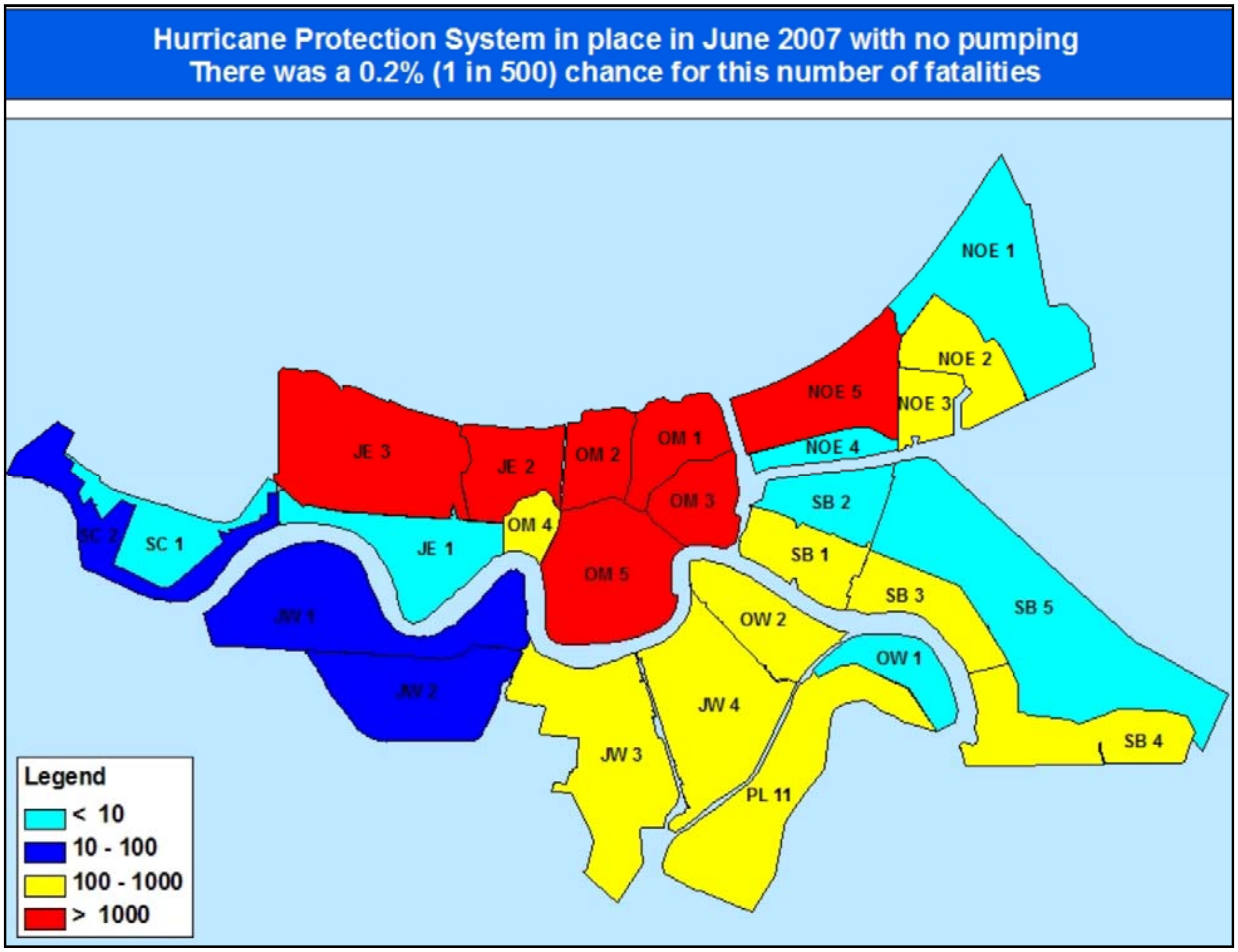

Figure 11-14. Loss of life risk map, 0.2% (1/500 return period) for June 2007 HPS and 0% pumping.

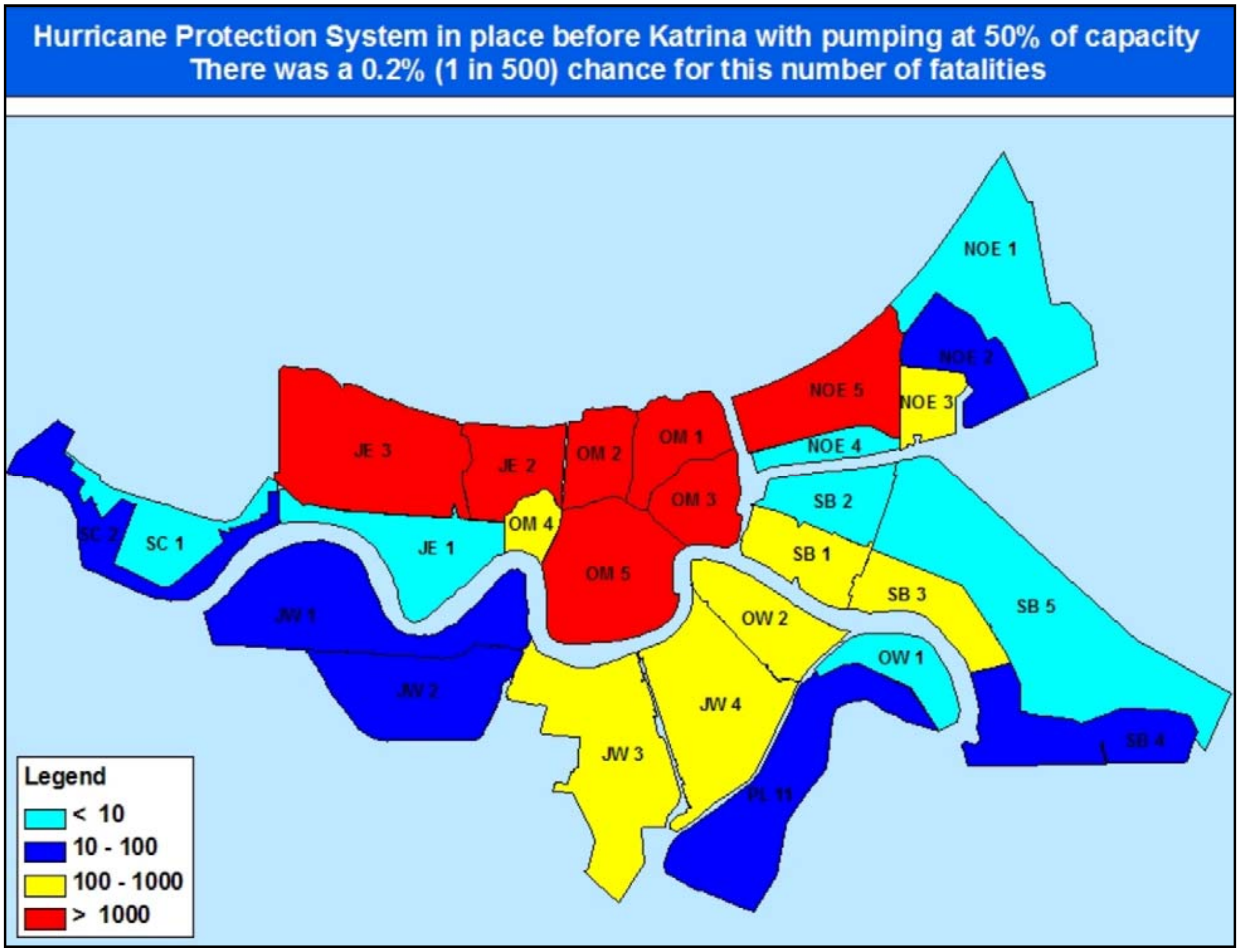

Figure 11-15. Loss of life risk map, 0.2% (1/500 return period) for pre-Katrina HPS and 50% pumping.

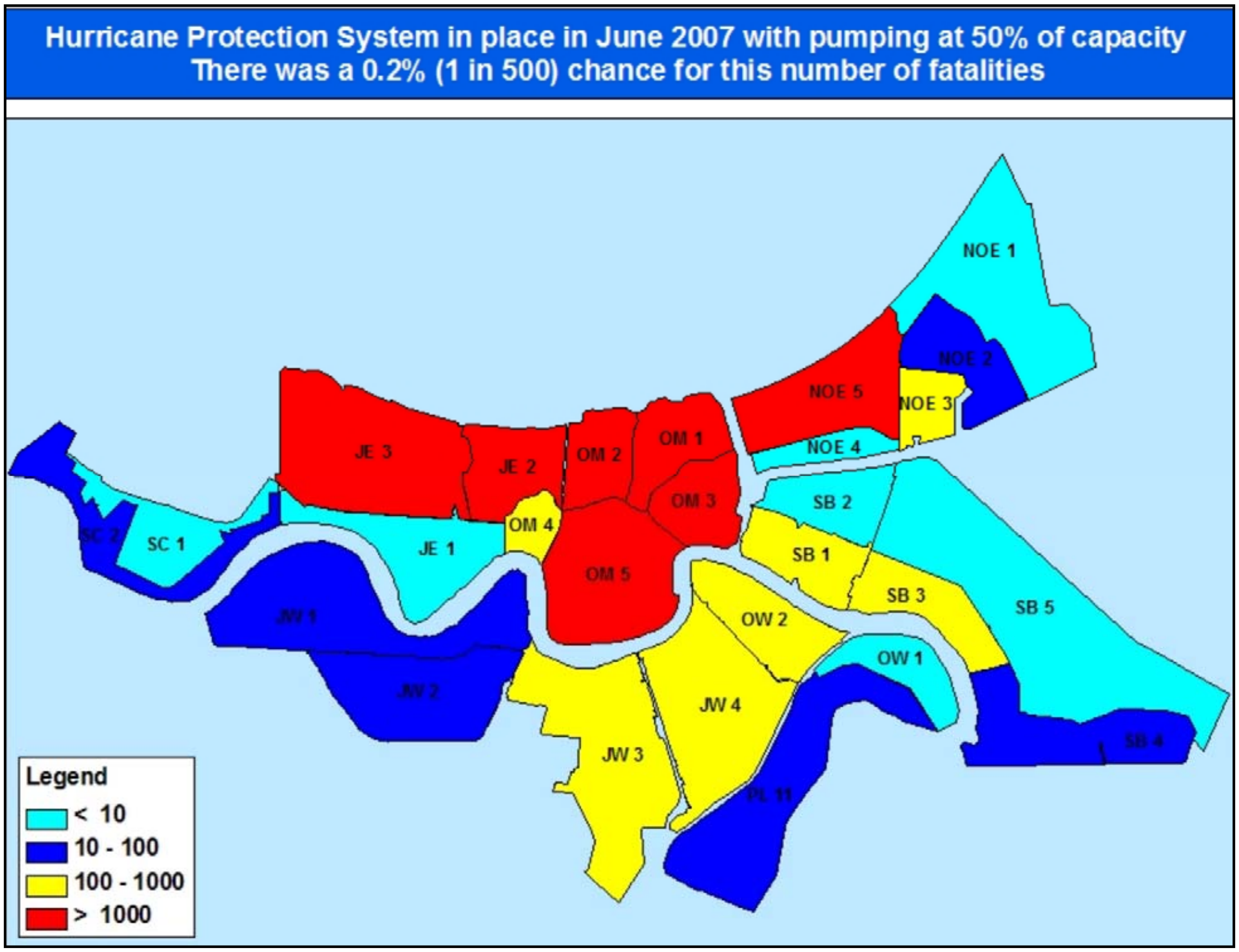

Figure 11-16. Loss of life risk map, 0.2% (1/500 return period) for June 2007 HPS and 50% pumping.

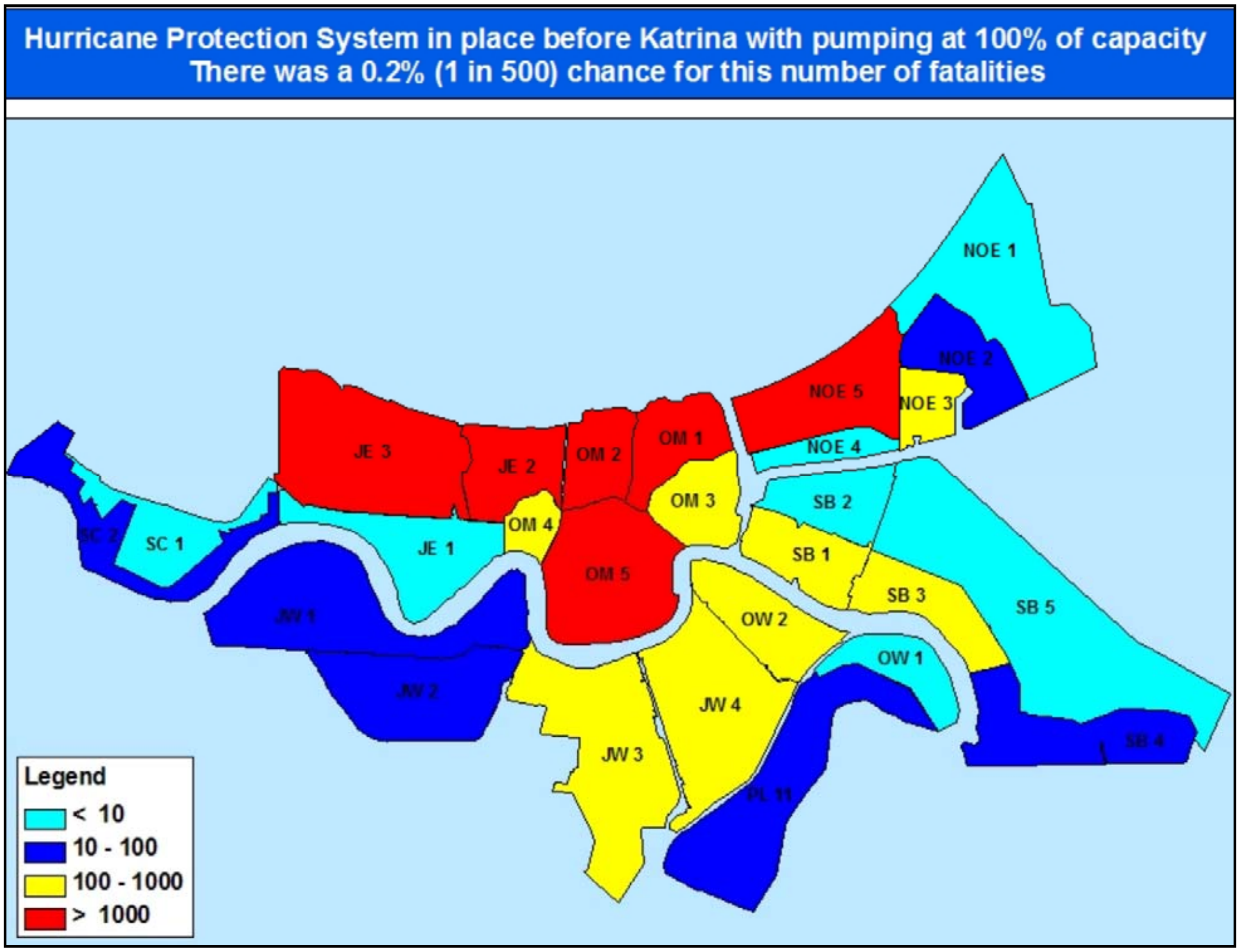

Figure 11-17. Loss of life risk map, 0.2% (1/500 return period) for pre-Katrina HPS and 100% pumping.

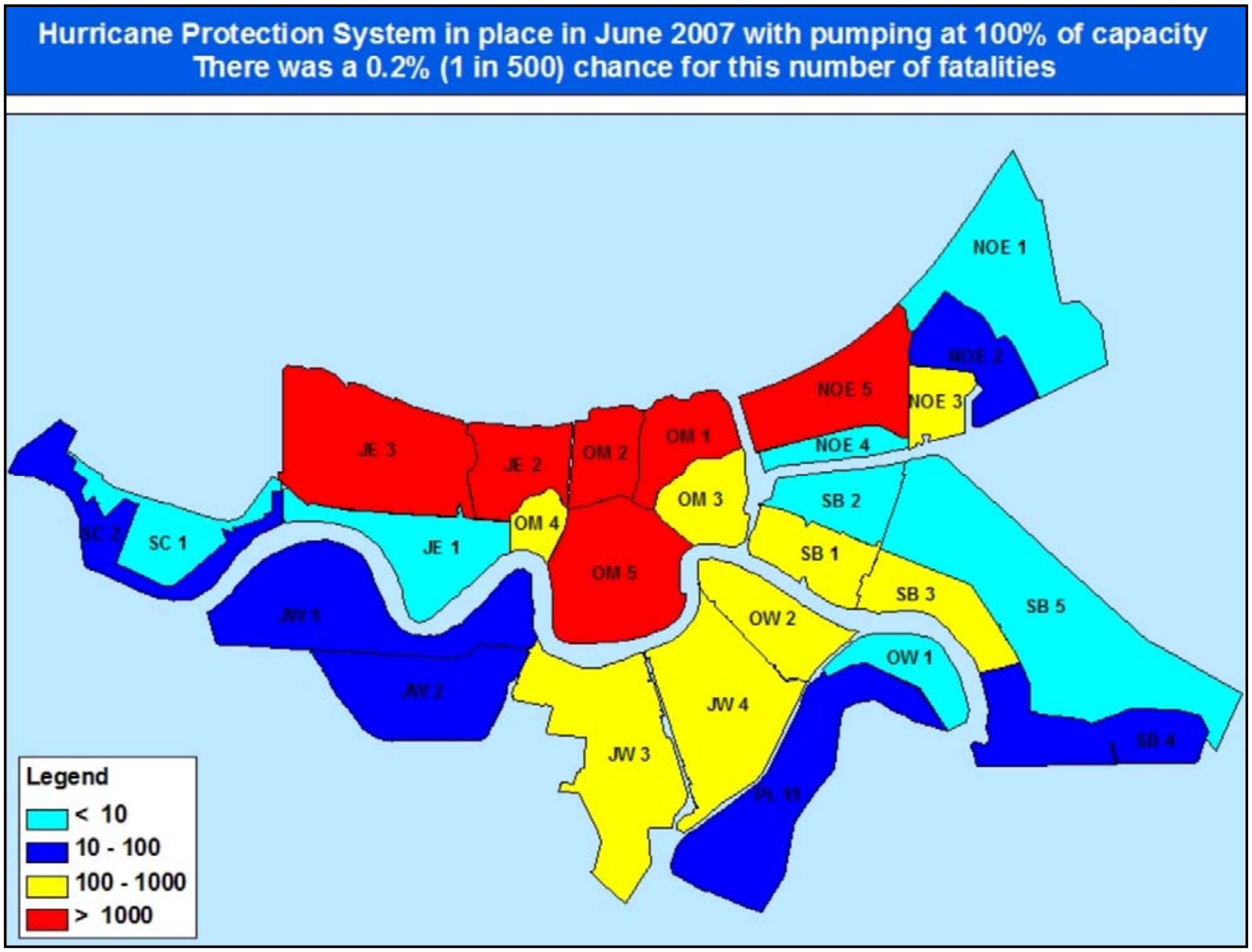

Figure 11-18. Loss of life risk map, 0.2% (1/500 return period) for June 2007 HPS and 100% pumping.

Appendix 12
Property Loss (Percentage of Total Value) Risk Maps

This appendix provides the individual property loss risk maps prepared as a part of the IPET Risk and Reliability Assessment for New Orleans. Property losses are based on estimates of direct damages to property from flooding and do not consider wind damage or associated indirect economic losses that may also occur with flooding, Maps for the Pre-Katrina and 2007 HPS are presented as percentage of total value lost for the entire region modeled with the exception of the lower portions of Plaquemines Parish. Maps are provided for the 2% (1/50), 1% (1/100), and 0.2% (1/500) return periods and for 0%, 50%, and 100% of ideal pumping capacity. Lower Plaquemines was not included because of insufficient data to allow a full risk assessment. Details on the preparation of these maps are provided in IPET Final Report, Volume VIII, *Engineering and Operational Risk and Reliability Analysis*.

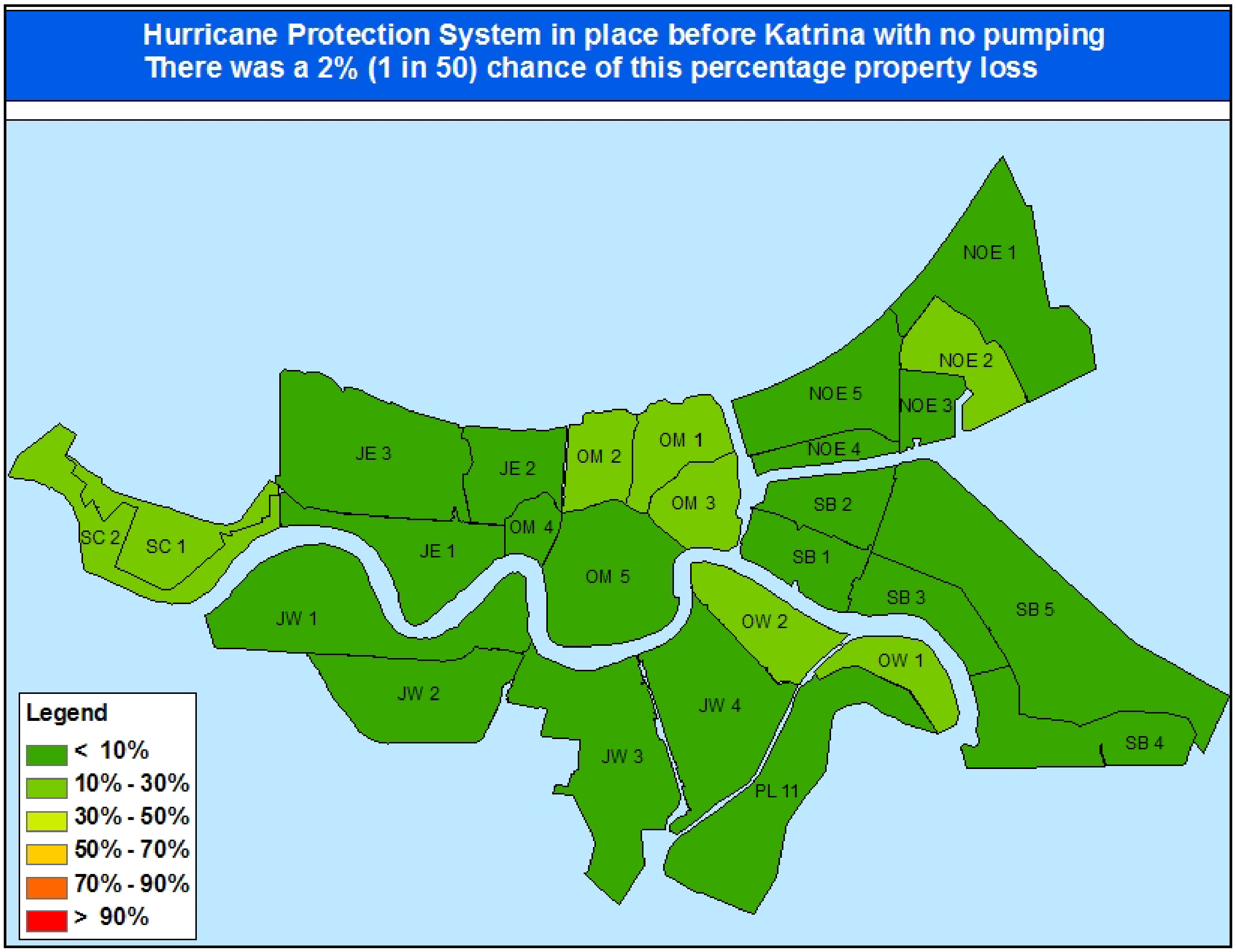

Figure 12-1. Property loss (percentage of total value) risk map, 2% (1/50 return period) for pre-Katrina HPS and 0% pumping.

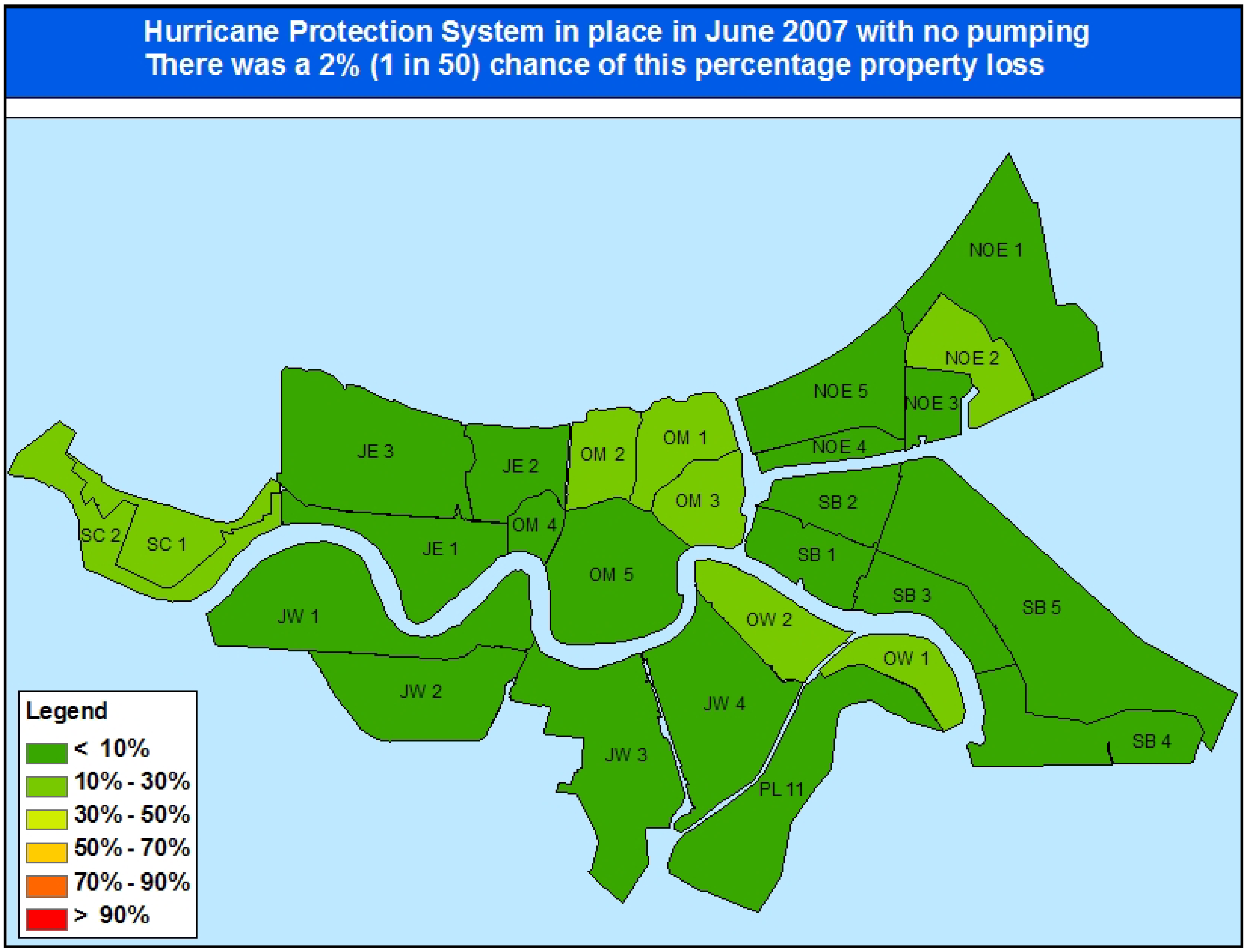

Figure 12-2. Property loss (percentage of total value) risk map, 2% (1/50 return period) for June 2007 HPS and 0% pumping.

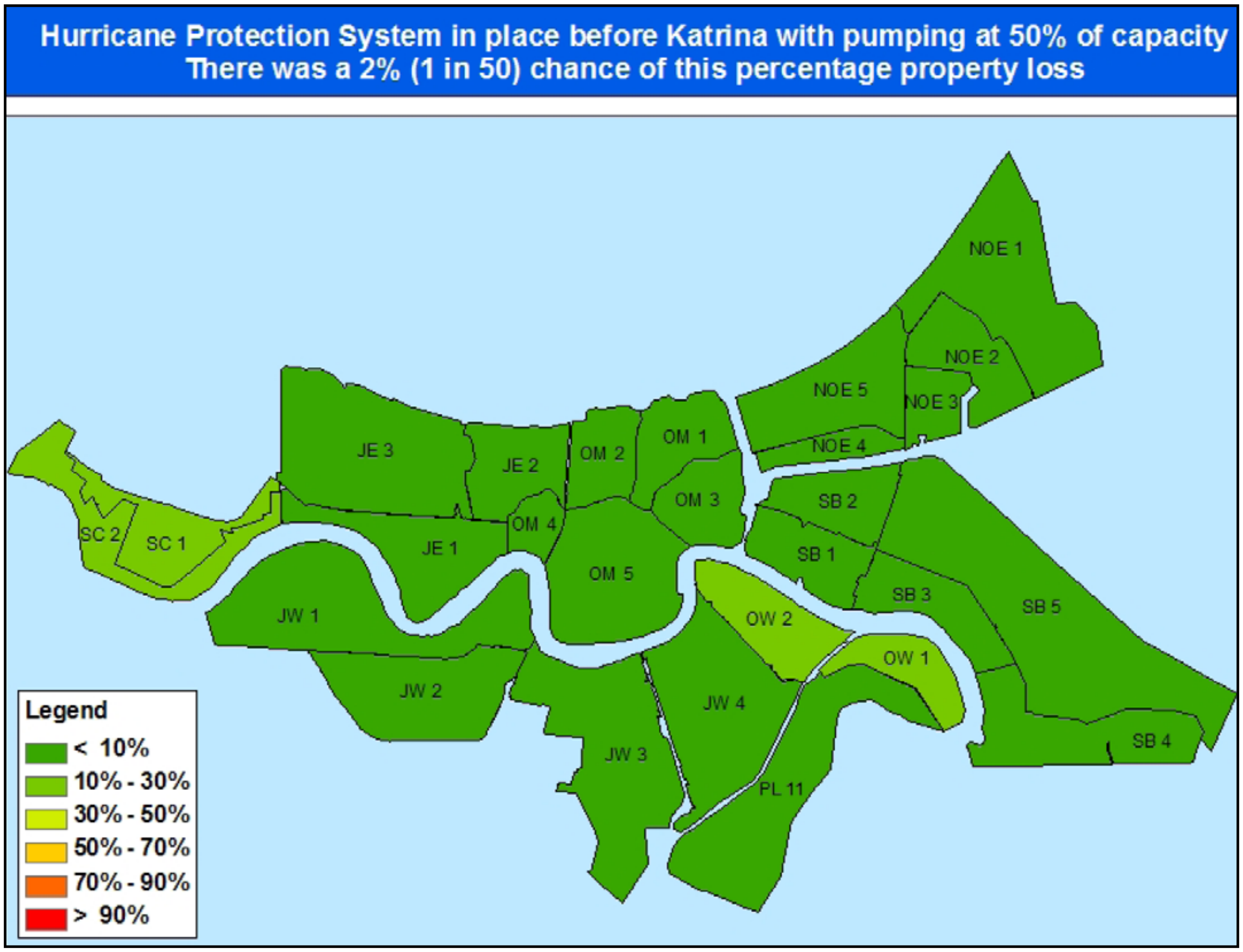

Figure 12-3. Property loss (percentage of total value) risk map, 2% (1/50 return period) for pre-Katrina HPS and 50% pumping.

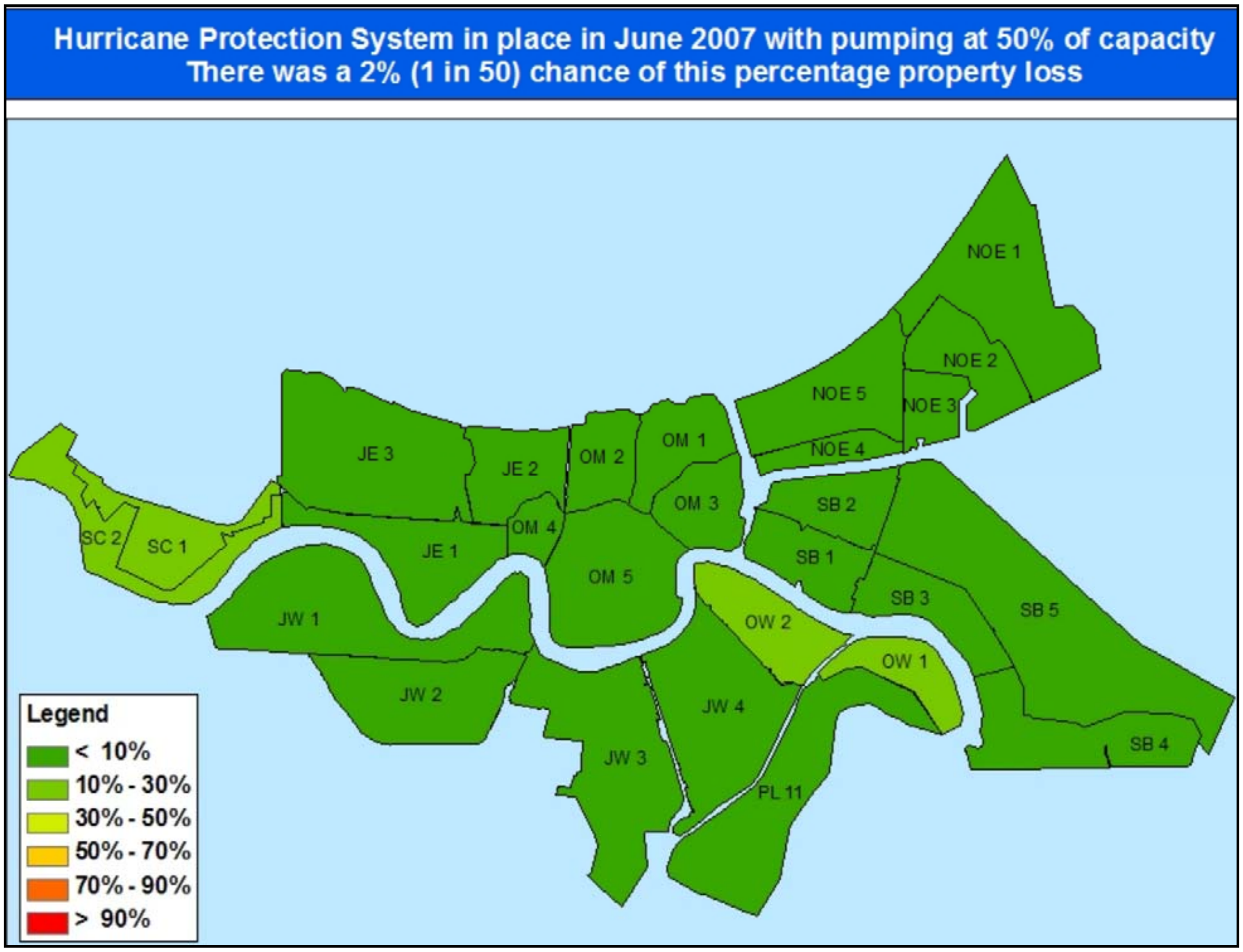

Figure 12-4. Property loss (percentage of total value) risk map, 2% (1/50 return period) for June 2007 HPS and 50% pumping.

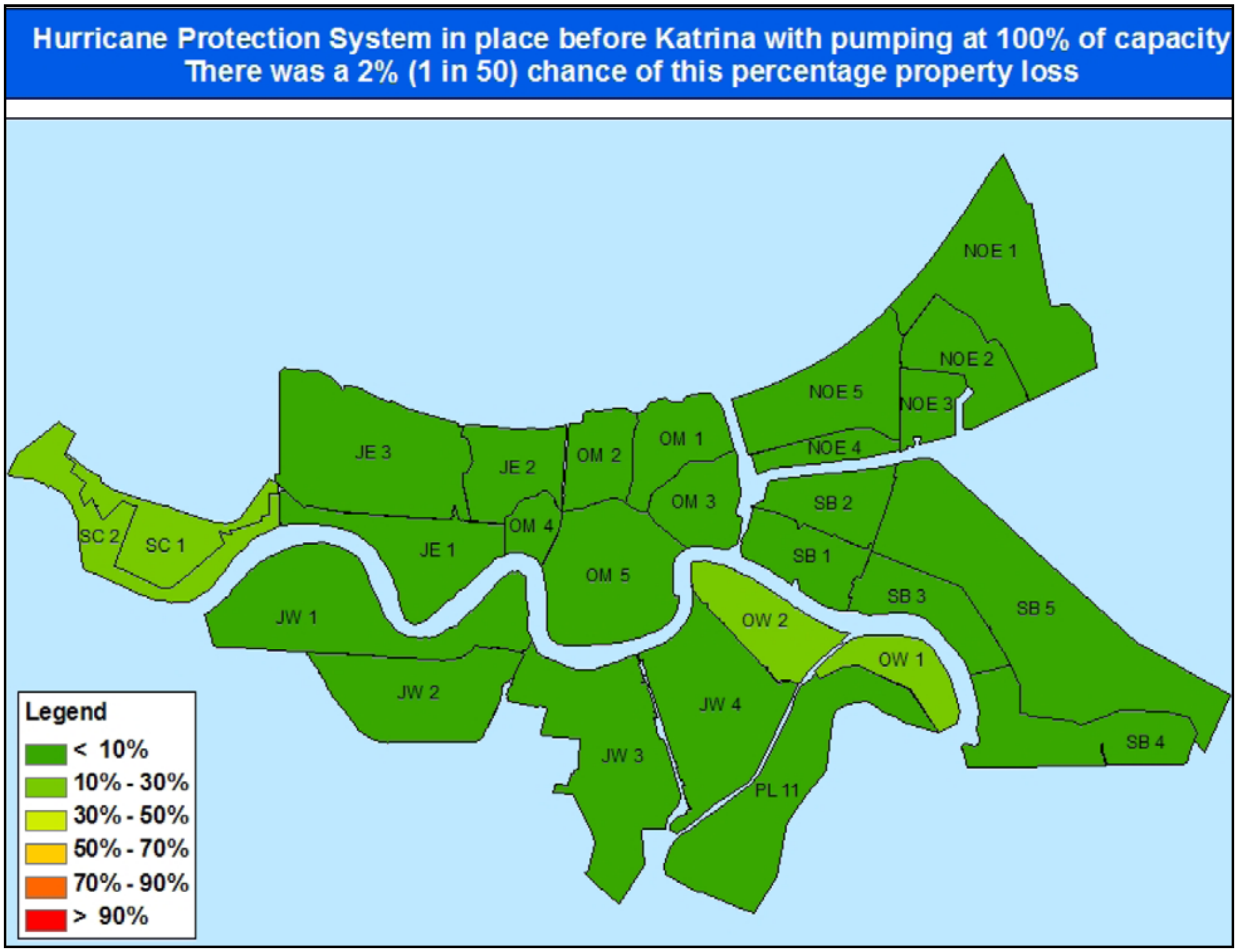

Figure 12-5. Property loss (percentage of total value) risk map, 2% (1/50 return period) for pre-Katrina HPS and 100% pumping.

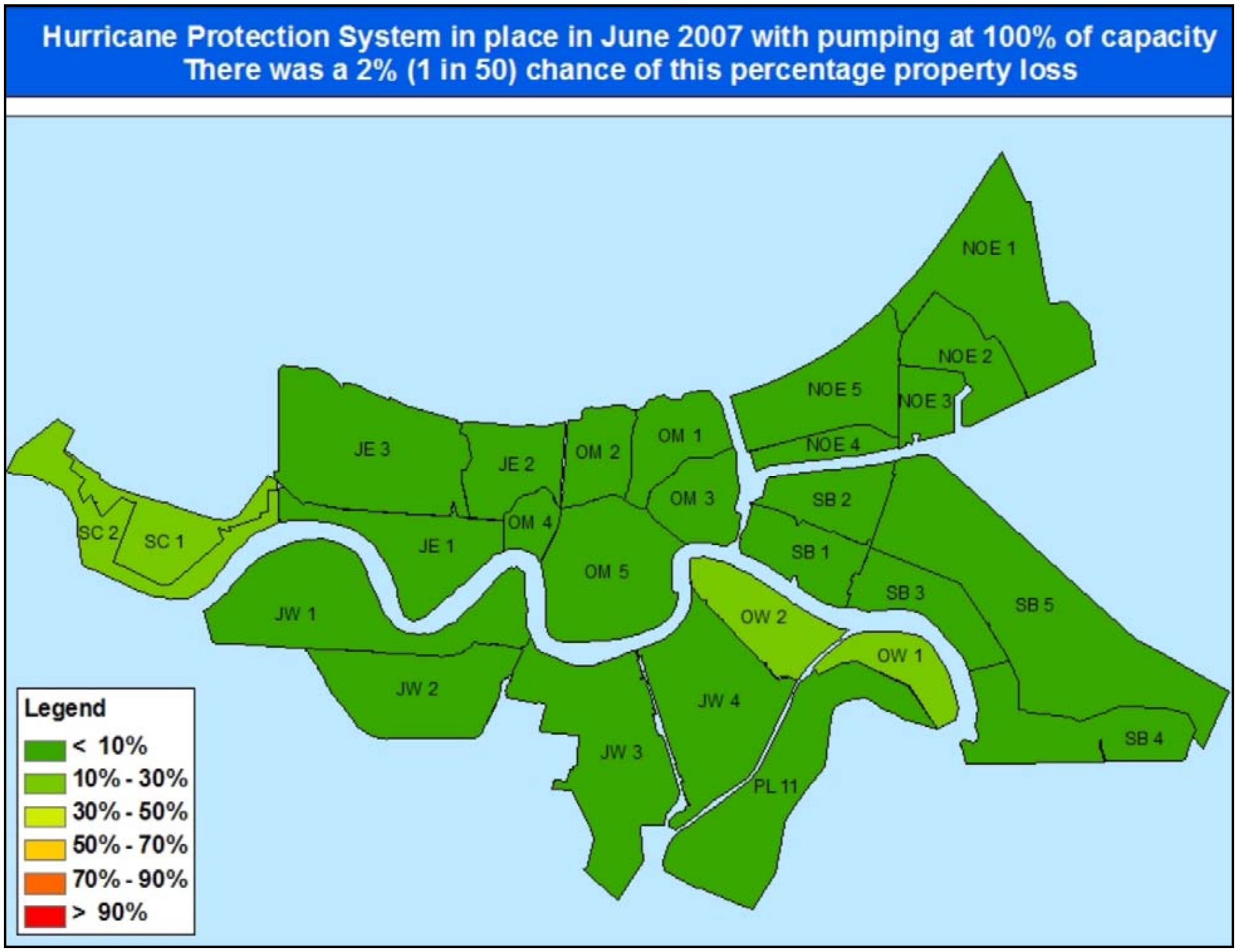

Figure 12-6. Property loss (percentage of total value) risk map, 2% (1/50 return period) for June 2007 HPS and 100% pumping.

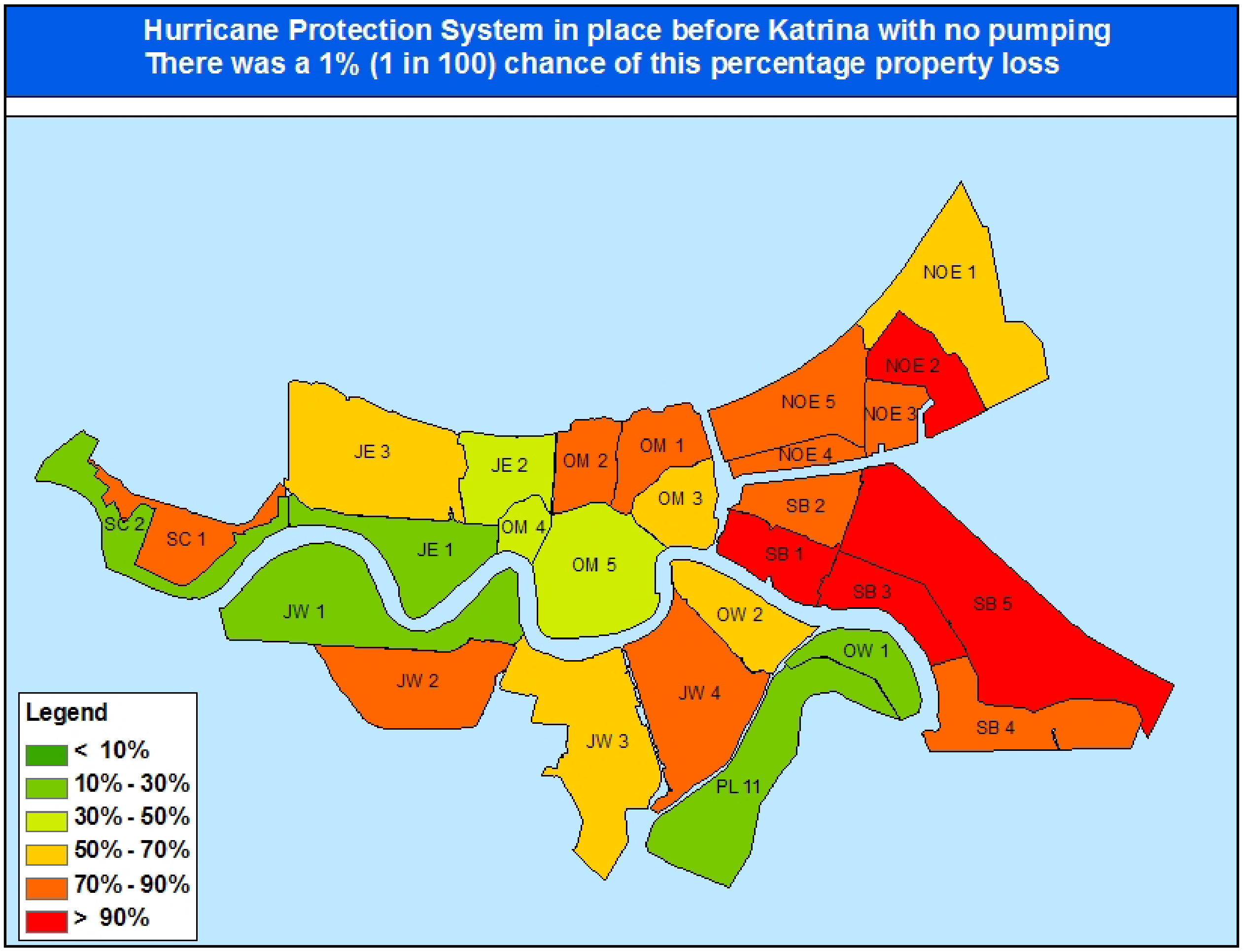

Figure 12-7. Property loss (percentage of total value) risk map, 1% (1/100 return period) for pre-Katrina HPS and 0% pumping.

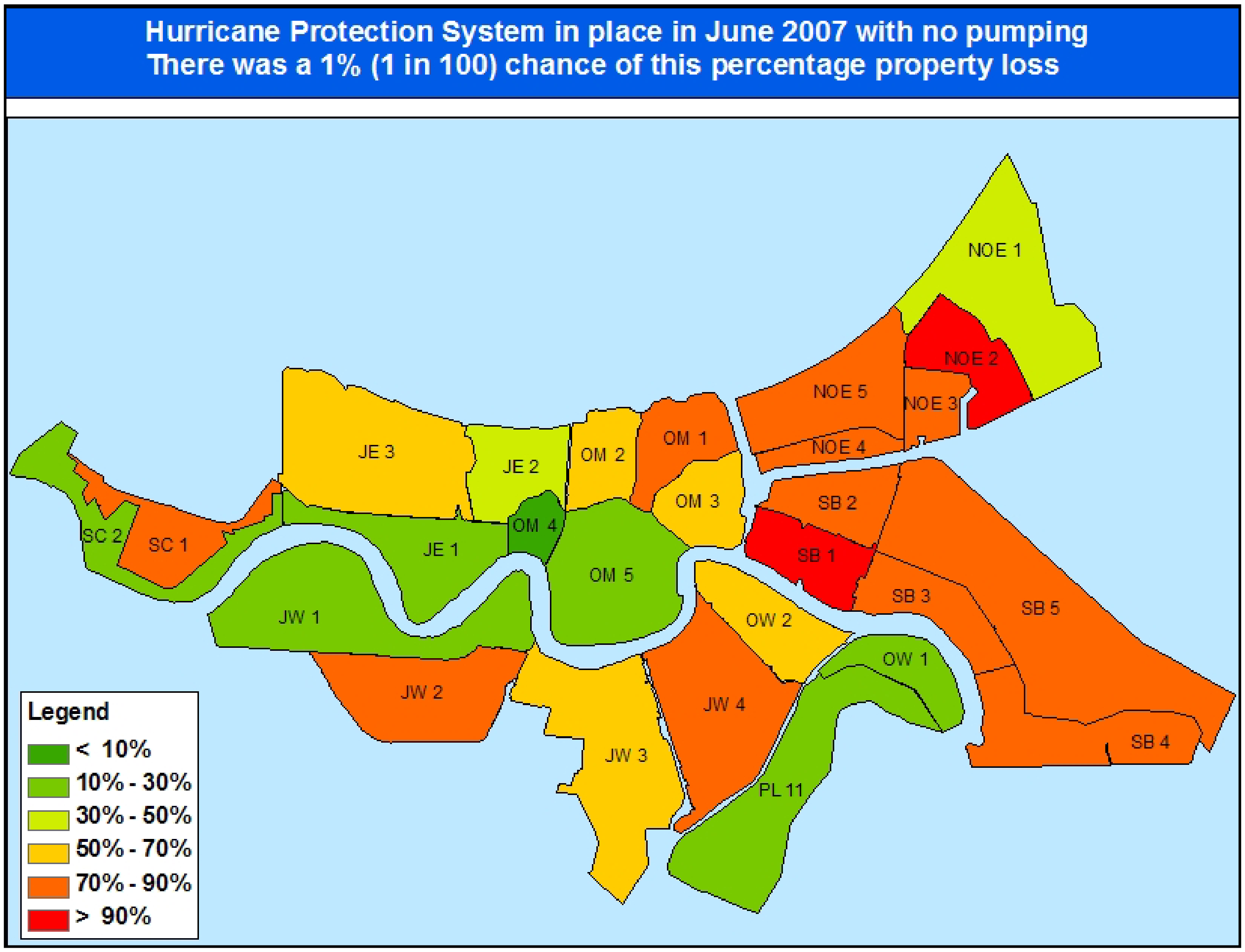

Figure 12-8. Property loss (percentage of total value) risk map, 1% (1/100 return period) for June 2007 HPS and 0% pumping.

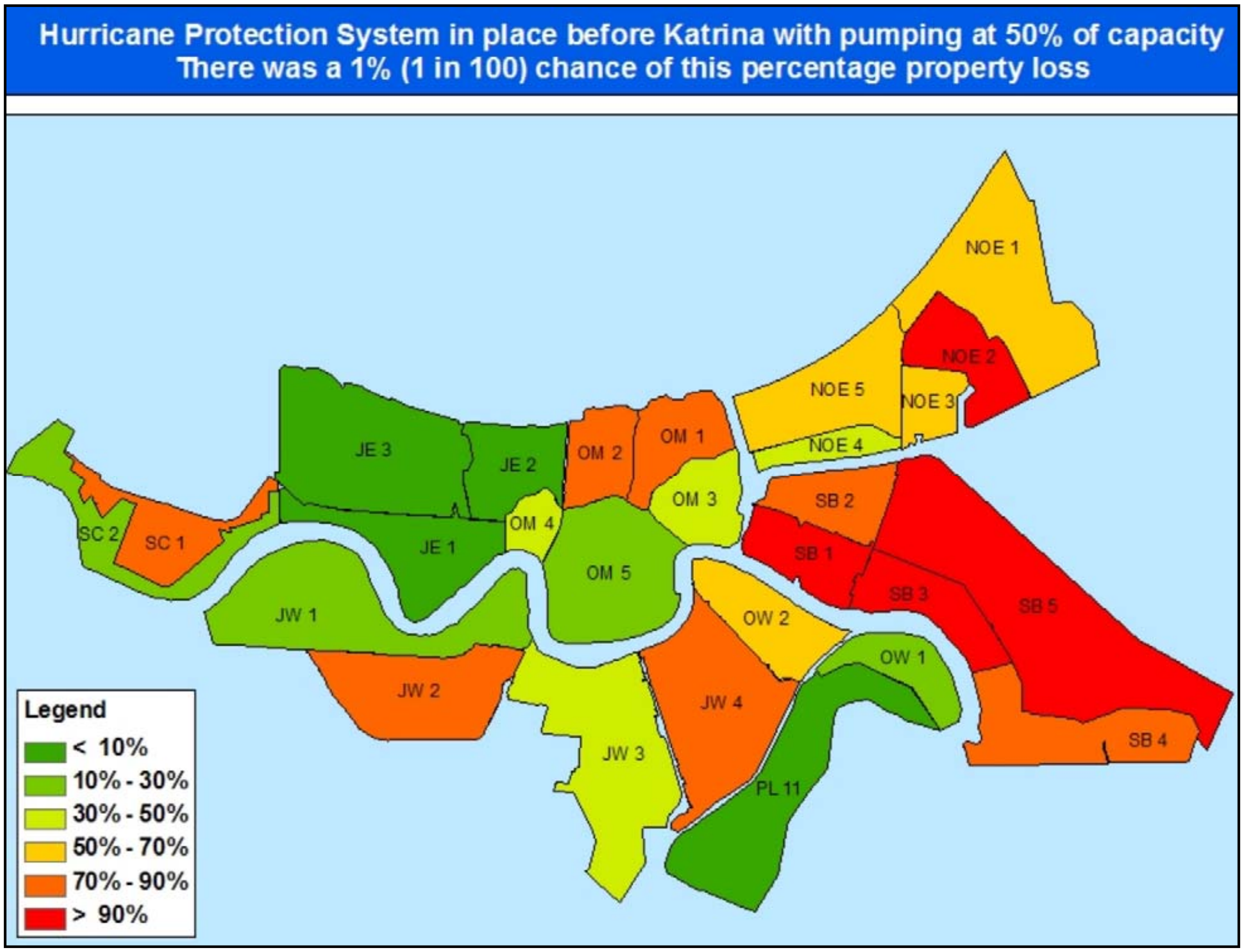

Figure 12-9. Property loss (percentage of total value) risk map, 1% (1/100 return period) for pre-Katrina HPS and 50% pumping.

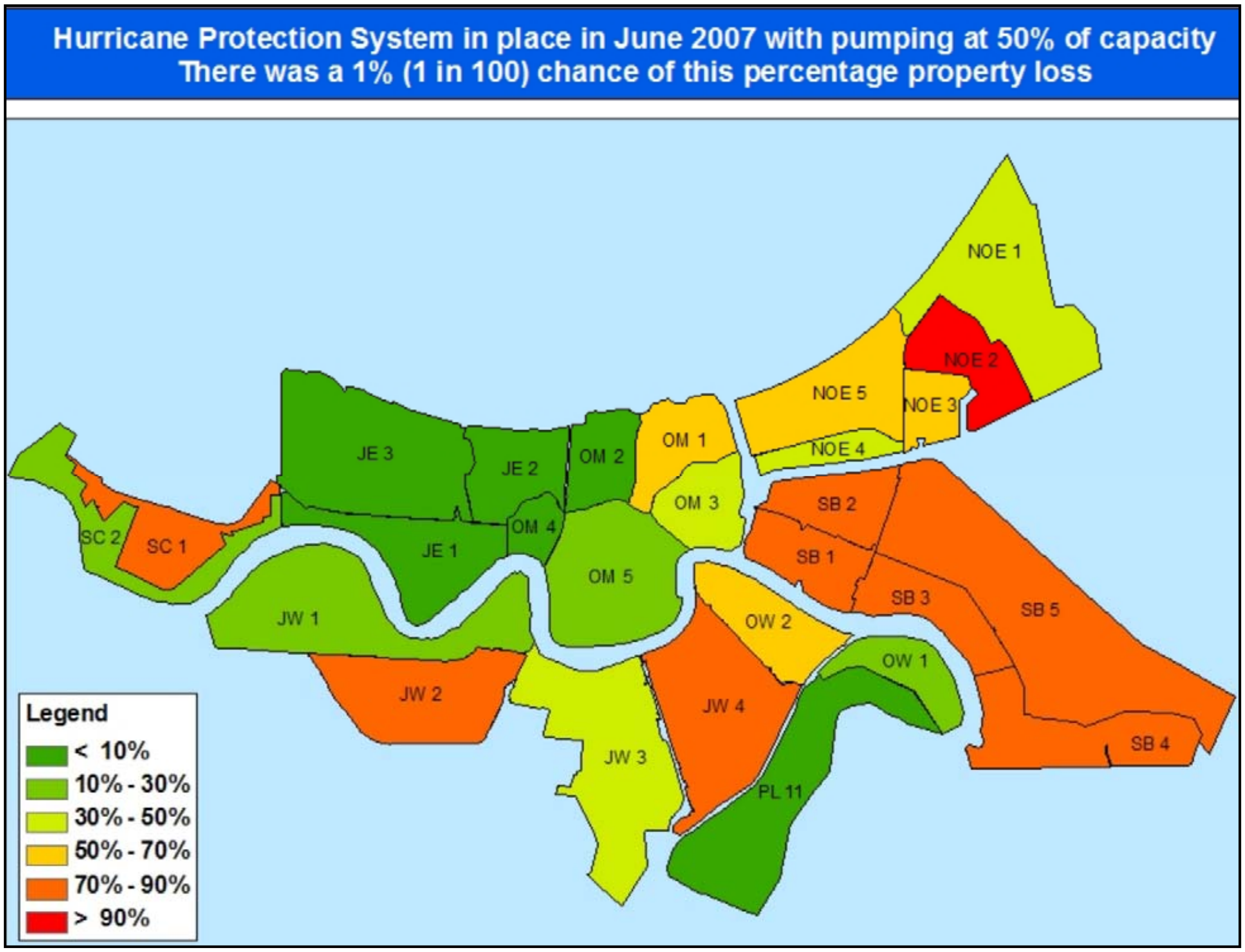

Figure 12-10. Property loss (percentage of total value) risk map, 1% (1/100 return period) for June 2007 HPS and 50% pumping.

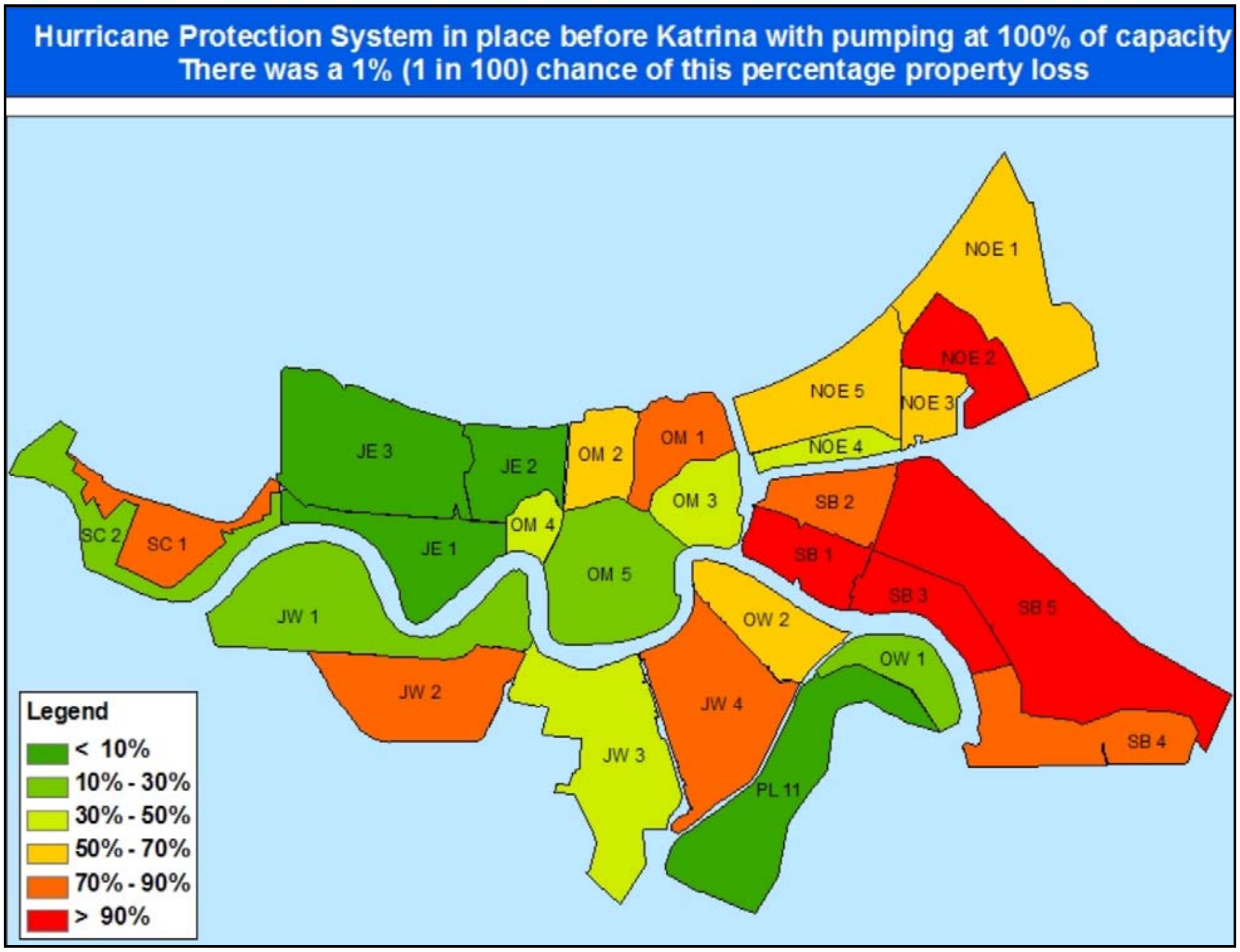

Figure 12-11. Property loss (percentage of total value) risk map, 1% (1/100 return period) for pre-Katrina HPS and 100% pumping.

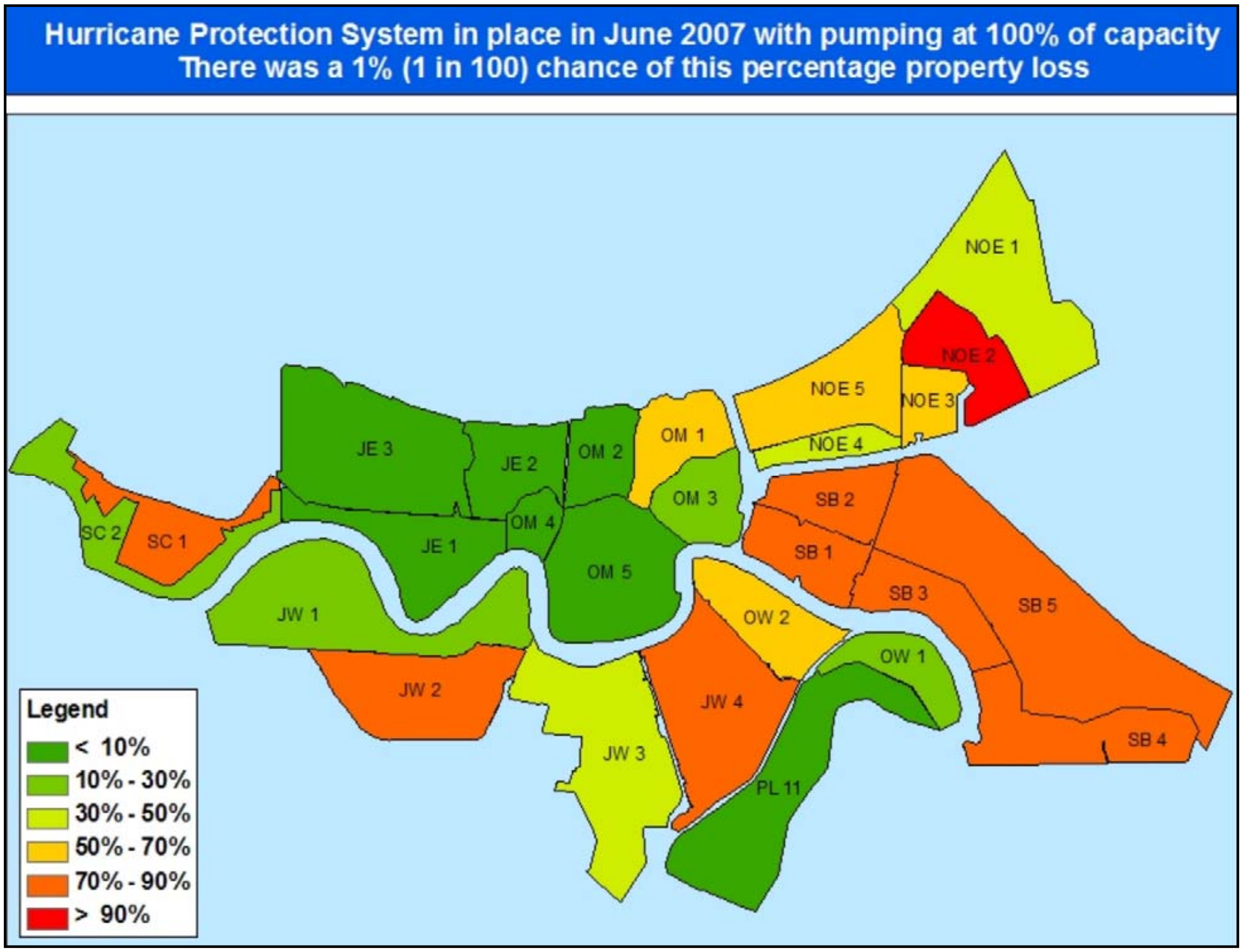

Figure 12-12. Property loss (percentage of total value) risk map, 1% (1/100 return period) for June 2007 HPS and 100% pumping.

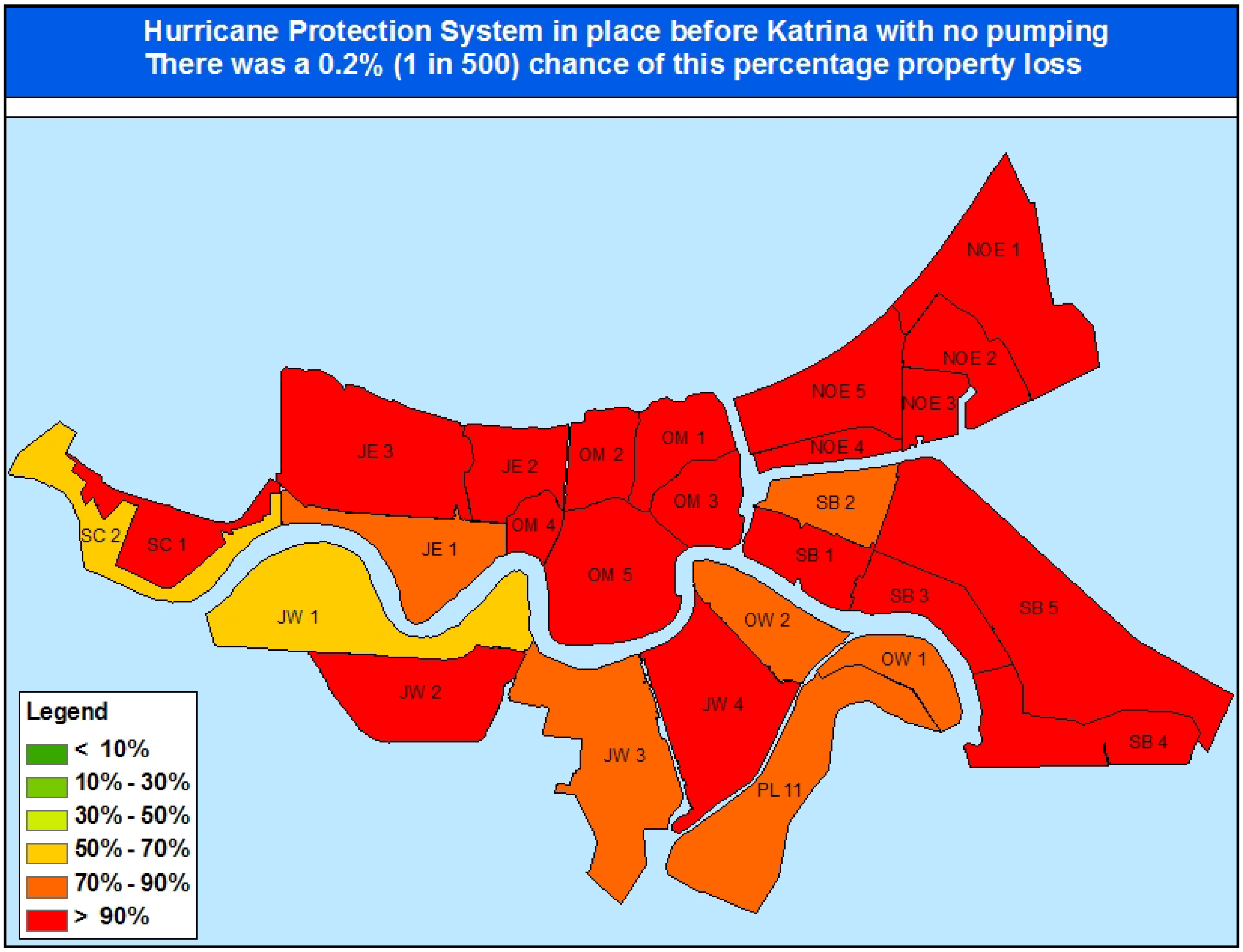

Figure 12-13. Property loss (percentage of total value) risk map, 0.2% (1/500 return period) for pre-Katrina HPS and 0% pumping.

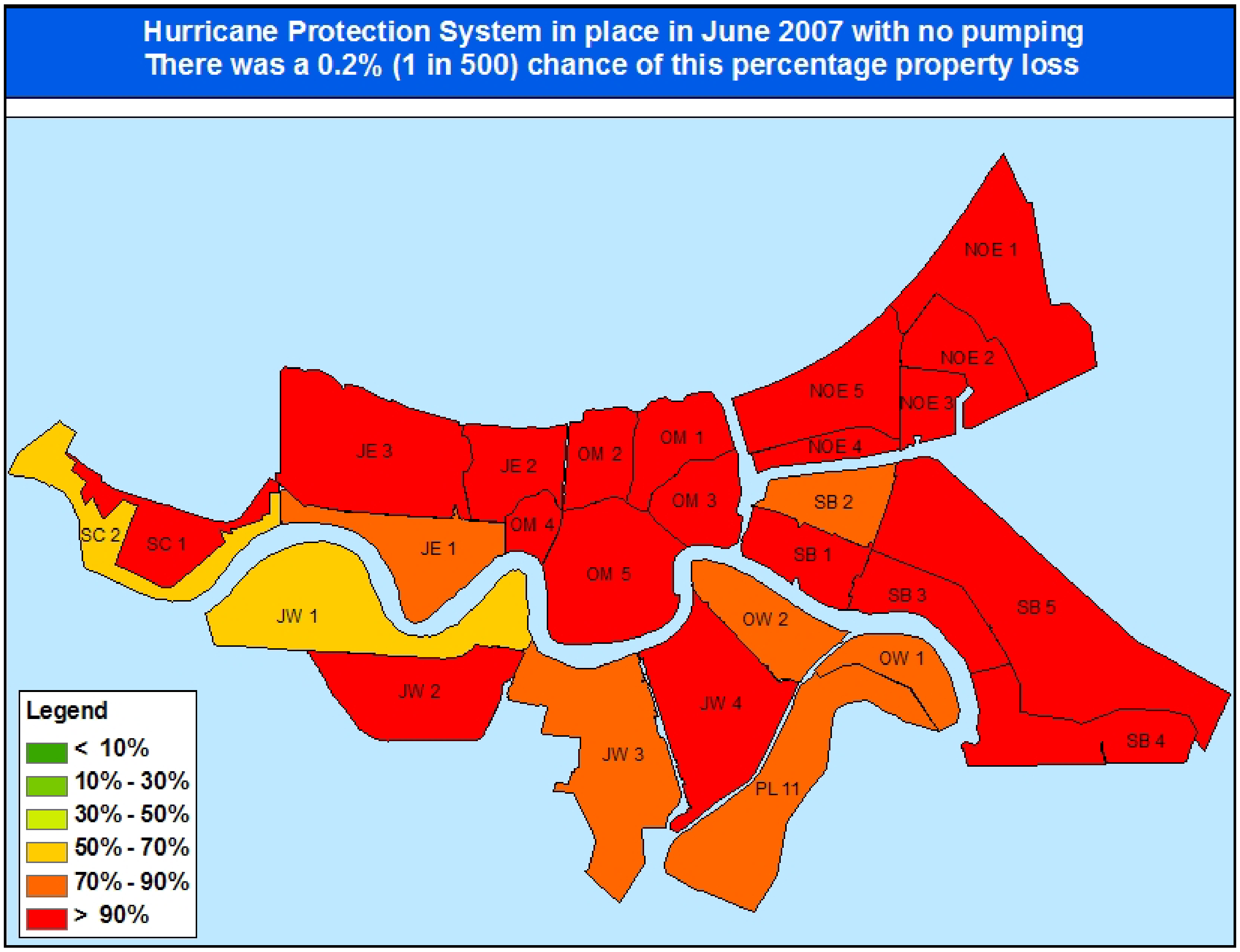

Figure 12-14. Property loss (percentage of total value) risk map, 0.2% (1/500 return period) for June 2007 HPS and 0% pumping.

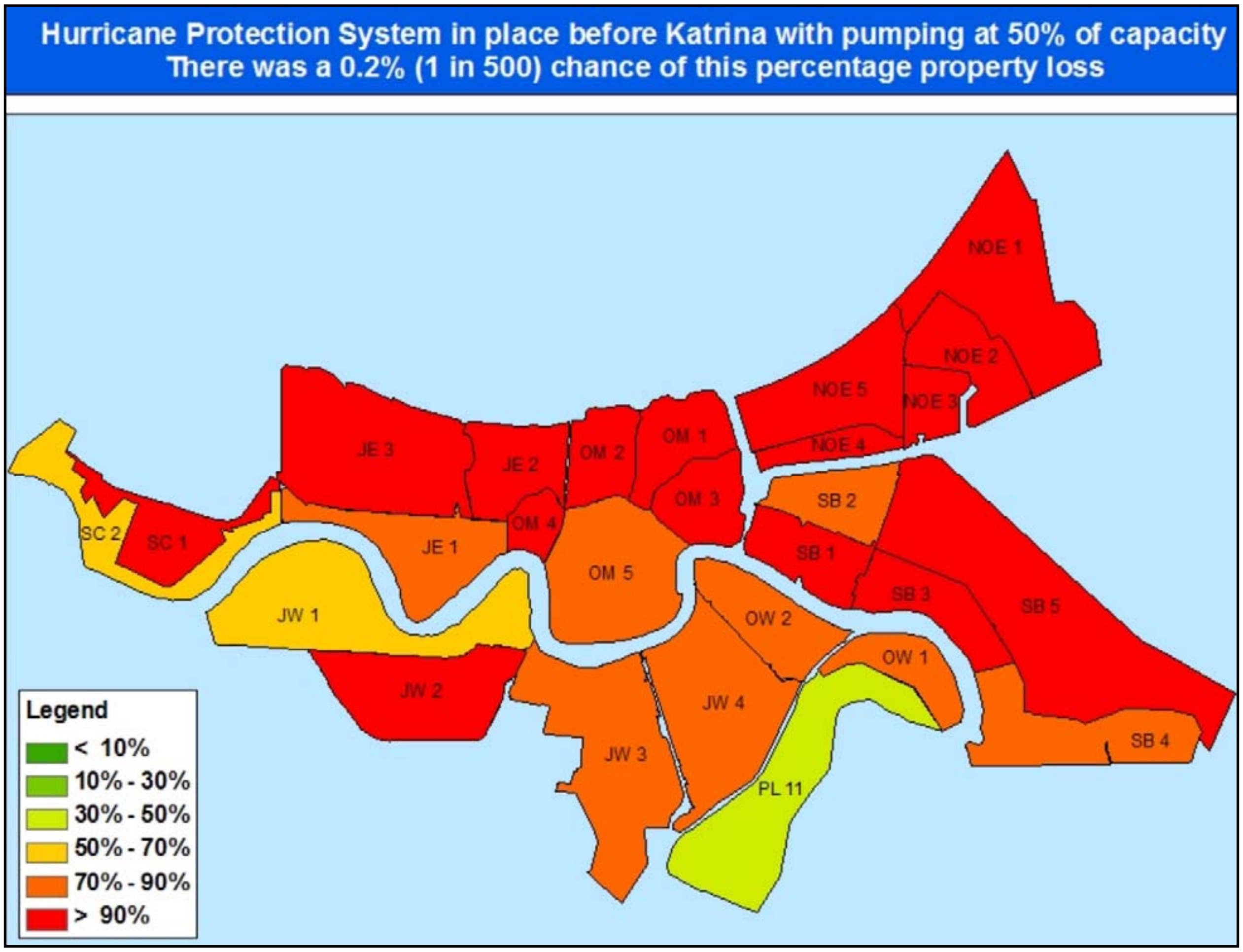

Figure 12-15. Property loss (percentage of total value) risk map, 0.2% (1/500 return period) for pre-Katrina HPS and 50% pumping.

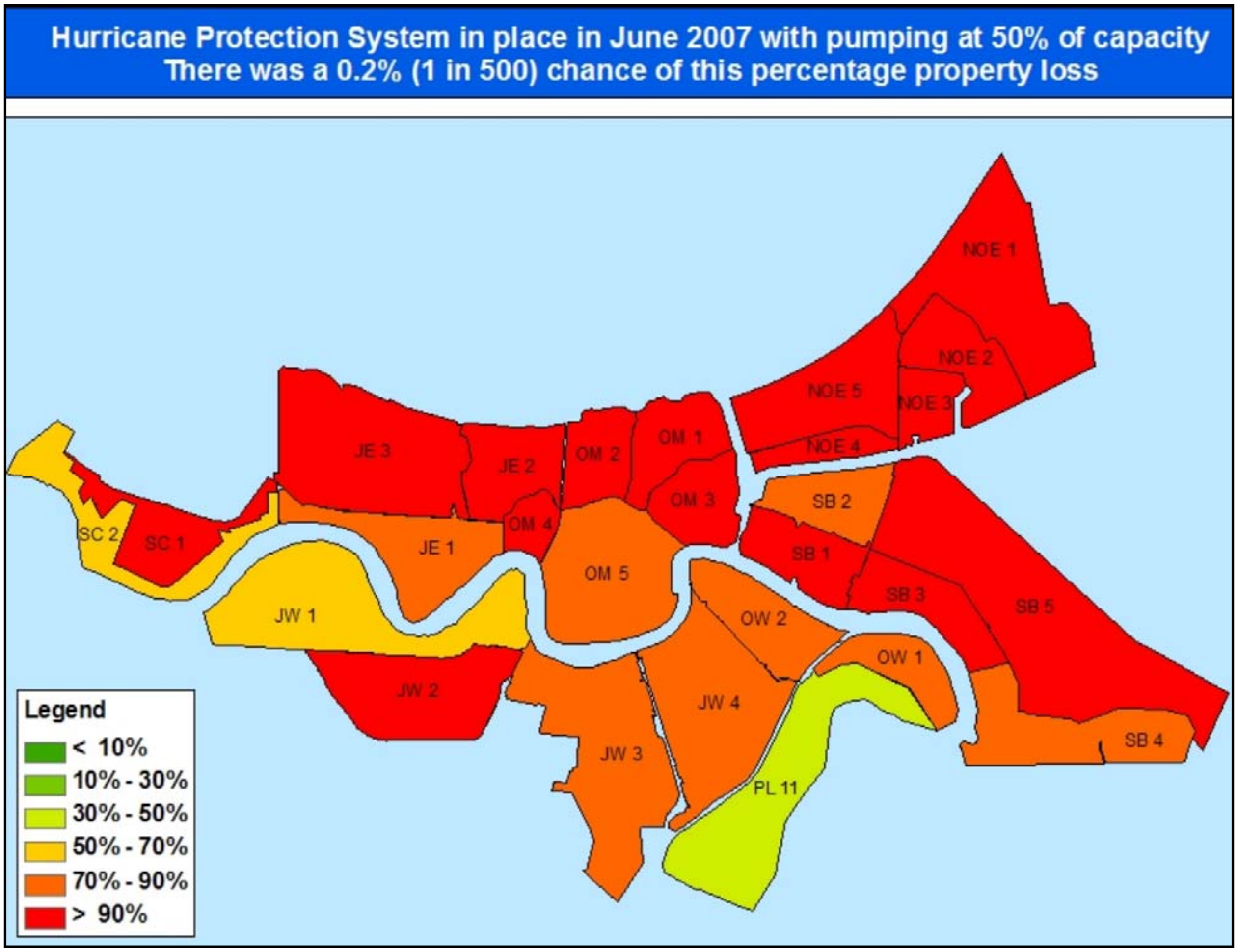

Figure 12-16. Property loss (percentage of total value) risk map, 0.2% (1/500 return period) for June 2007 HPS and 50% pumping.

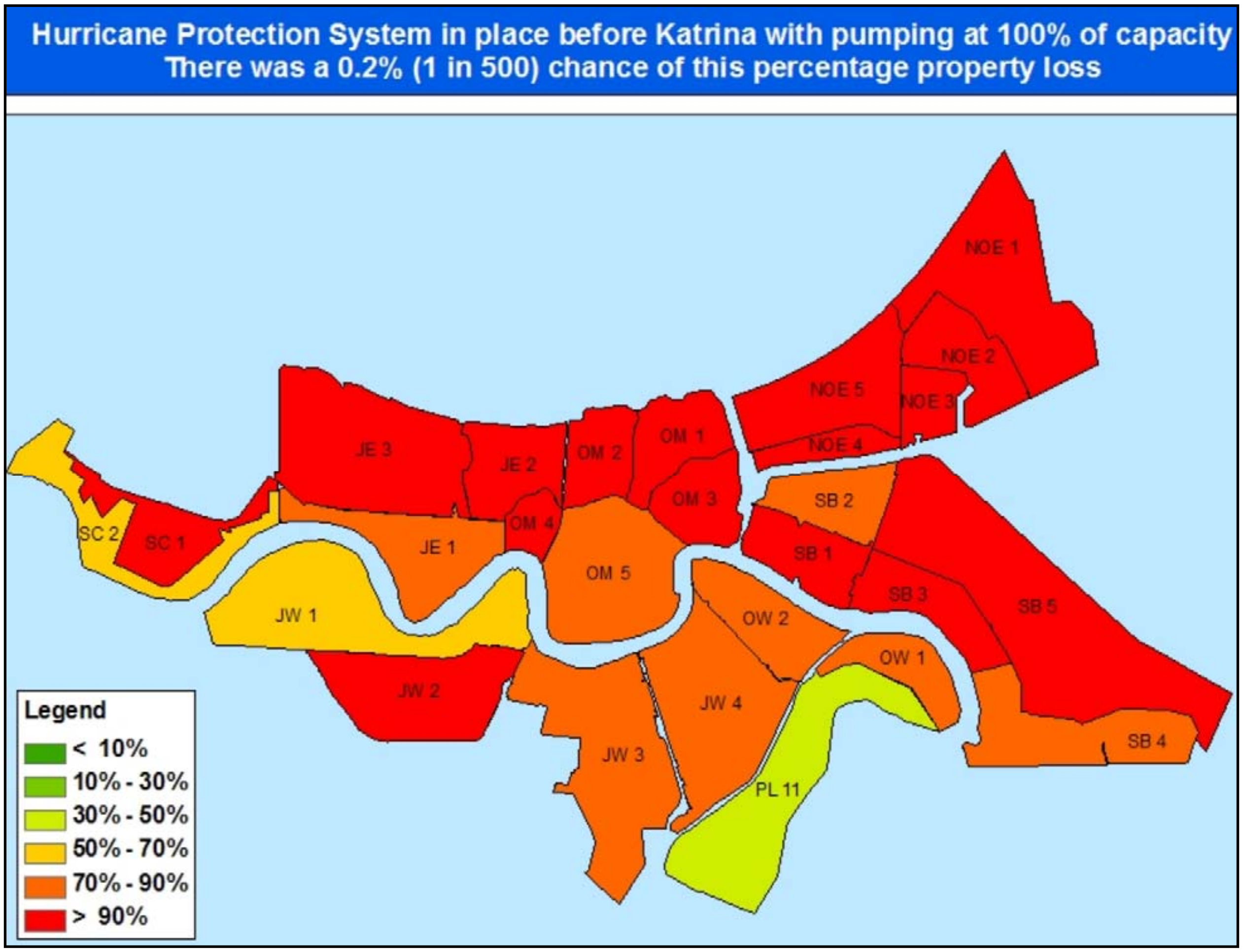

Figure 12-17. Property loss (percentage of total value) risk map, 0.2% (1/500 return period) for pre-Katrina HPS and 100% pumping.

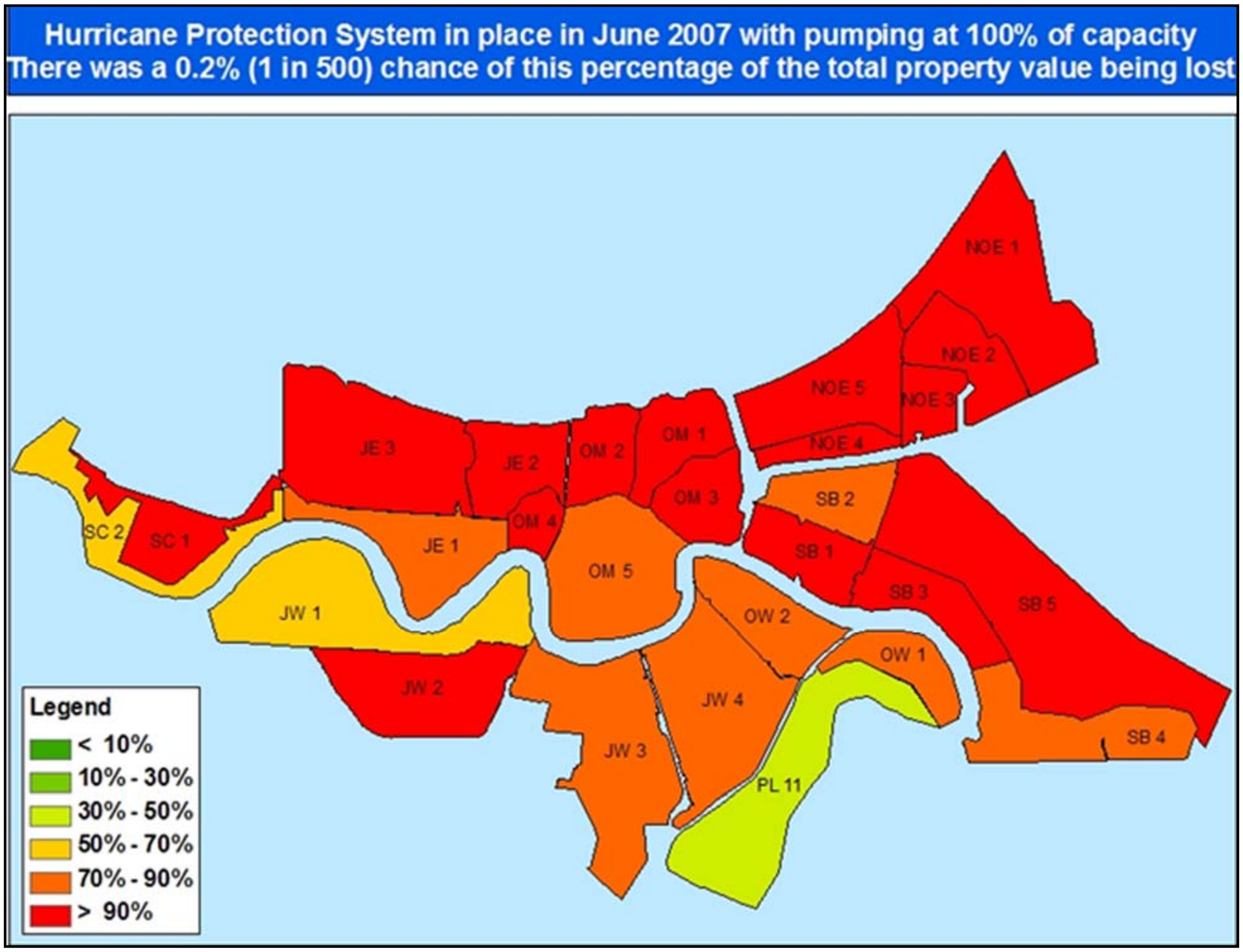

Figure 12-18. Property loss (percentage of total value) risk map, 0.2% (1/500 return period) for June 2007 HPS and 100% pumping.