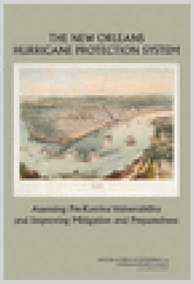

The New Orleans Hurricane Protection System: Assessing Pre-Katrina Vulnerability and Improving Mitigation and Preparedness

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THE NEW ORLEANS HURRICANE PROTECTION SYSTEM

Assessing Pre-Katrina Vulnerability and Improving Mitigation and Preparedness

Committee on New Orleans Regional Hurricane Protection Projects

Water Science and Technology Board

Division on Earth and Life Studies

Board on Infrastructure and the Constructed Environment

Division on Engineering and Physical Systems

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Preface

Hurricane Katrina struck the coast of Mississippi and Louisiana in August of 2005. New Orleans and the surrounding areas were flooded by storm surges due in large part to multiple failures of its hurricane protection system. The damage and the loss of life were catastrophic and Katrina ranks as one of the nation's most devastating natural disasters. The damages were brought home as the national media beamed scenes across the nation of New Orleans's submerged neighborhoods, people stranded on roofs, and levees torn apart by floodwaters.

In order to understand why the failures of the protection system occurred, and to aid in rebuilding of the system, the U.S. Army Corps of Engineers created the Interagency Performance Evaluation Task Force (IPET) to carry out a large-scale investigation of the issues. To provide an independent review to the IPET, Mr. John Paul Woodley, Assistant Secretary of the Army Civil Works, requested the National Academy of Engineering to convene the Committee on New Orleans Regional Hurricane Protection Projects. This is the committee's fifth and final report. It provides review comments on the IPET draft final report, and comments on lessons learned for decision makers to consider in the task of rebuilding the hurricane protection system.

This final report of our committee takes into account the findings documented in the previous four reports of the committee, the extensive IPET draft final report, and our committee's professional viewpoints on hurricane protection, risk, and mitigation. During the course of our 3.5-year project, we convened five meetings in New Orleans. At those meetings, IPET staff, those conducting alternative formal studies, and citizens of New Orleans were given opportunities to provide briefings and study materials, and to make comments as desired.

The committee wishes to express its appreciation to Mr. Woodley and his staff in the Office of the Assistant Secretary of the Army for Civil Works for excellent support of our committee's activities and consistent responsiveness to the concerns of the committee. We also wish to compliment the members of the IPET team for producing a comprehensive evaluation of the New Orleans hurricane protection system, and for their patience and thoroughness in discussing the details of their efforts with our committee. We also appreciate the willingness of parties to provide information, reports, and external review comments that helped inform our findings. Finally, the committee gives thanks to Dr. Jeff Jacobs and the staff of the National Research Council (NRC) for outstanding support and assistance in preparing the reports of the committee.

This report was reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise in accordance with the procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible, and to ensure that the report meets NRC institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process.

We thank the following for their review of this report: Rudy Bonaparte, Geosyntec Consultants; Ross Corotis, University of Colorado; Charles Cushing, C.R. Cushing and Co., Inc.; Walter Lynn (emeritus), Cornell University; Dorothy Moore, The Citadel; Doug Plasencia, Michael Baker, Jr., Inc.; Asbury Sallenger, U.S. Geological Survey; Doug Woolley (emeritus), Radford University; and Robert Whitman (emeritus), Massachusetts Institute of Technology.

Although these reviewers provided constructive comments and suggestions, they were not asked to endorse the report's conclusions and recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Robert Frosch, Harvard University, who was appointed by the NRC Report Review Committee, and by Robert Dalrymple, Johns Hopkins University, who was appointed by the NRC Division on Earth and Life Studies. Drs. Frosch and Dalrymple were responsible for ensuring that an independent examination of this report was conducted in accordance with NRC institutional procedures and that all review comments were carefully considered. Responsibility for this report's final contents rests entirely with the authoring committee and the NRC.

The post-Katrina setting poses challenges and open questions, as there is no model to follow for post-hurricane recovery for New Orleans. Although building a hurricane protection system to better standards and making wise choices about future development should help create a safer and more sustainable city, clear agreement does not exist about the basis for design or development guidelines and policies. What does seem clear is that information about the vulnerabilities to hurricanes and storm surge in New Orleans must be accorded a higher priority than in the past and be central to future development plans and decisions. The IPET has made a good faith effort to improve knowledge of these vulnerabilities. We offer our final report in the spirit of improving preparedness and public safety of the region's citizens and contributing to a more sustainable future for the city of New Orleans.

G. Wayne Clough, *Chair*

Contents

Summary

The Interagency Performance Evaluation Task Force (IPET) was established in October, 2005 by the U.S. Army Corps of Engineers to evaluate the performance of the New Orleans hurricane protection system during Hurricane Katrina. In December, 2005 the National Academy of Engineering/National Research Council (NAE/NRC) Committee on the New Orleans Hurricane Protection Projects was established to provide independent, expert advice to the IPET by reviewing a series of IPET draft reports.

This is the NAE/NRC committee's fifth and final report. It provides the committee's assessment of the IPET draft final report that was issued in June, 2008. It also summarizes the committee's views on key lessons learned from the Katrina experience and their implications for future hurricane preparedness and planning for south Louisiana (the committee's full statement of task is listed in Appendix A).

REVIEW OF THE IPET DRAFT FINAL REPORT

IPET Study Objectives and Key Contributions

The IPET conducted its evaluations in five areas:

1. design and status of the hurricane protection system pre-Katrina;
2. storm surges and waves generated by Hurricane Katrina;
3. performance of the hurricane protection system during and after the storm;
4. societal-related consequences of Katrina-related damage; and,
5. risks to New Orleans and the region posed by future tropical storms.

The IPET studies and draft final report represented important advances in characterizing and understanding the nature of Gulf hurricanes, and the storm surge response along the northern Gulf coast and the greater New Orleans area hurricane protection system. The IPET studies also have made significant contributions to simulating hurricane impacts and characterizing the collective effects of hurricane damage. The modeling procedures developed by IPET to help visualize and manage risk in communities impacted by Hurricane Katrina have improved knowledge of regional vulnerability to hurricanes and storm surge.

This NAE/NRC committee compliments the IPET on the extensive work that went into completing this study. It is crucial that the IPET work be easily accessible and understandable to the public and that the IPET makes a strong effort to present its key findings in as clear and organized a manner as possible. This is all the more important given the multi-year delay in completing this study as compared to the original study time table, and the implications this time lapse has had in removing the experience with Hurricane Katrina from the public's consciousness.

Limitations and Key Areas for Improvement

The IPET draft final of June 2008 includes eight volumes, a ninth volume of general appendices, and covers roughly 7,500 pages. The report's eight main volumes naturally are of different sizes and they were produced on different schedules. Some of these volumes were essentially completed in 2006 or 2007 and changed little or not at all since then. In many ways, the IPET report Volume VIII, entitled "Engineering and Operational Risk and Reliability Analysis," became the most important and prominent volume of the entire study. The research and development entailed in creating the June 2008 version of Volume VIII probably exceeded the IPET team's original expectations. This NAE/NRC committee's previous (fourth) report was a specific review of a draft of Volume VIII only, and much of the IPET effort in 2007-2008 was devoted to additional analyses within Volume VIII.

It thus is appropriate that this section begin with comments regarding the IPET Volume VIII. It also contains a recommendation regarding interagency cooperation, and concludes with recommendations regarding organization and presentation of the entire IPET draft final report.

Volume VIII

Among the important findings from Volume VIII is a set of inundation maps for the New Orleans metro region. The results conveyed in these maps are of great importance and interest to citizens, businesses, and government agencies that are making plans for resettlement and redevelopment in this region. Volume VIII presents these important inundation maps, but there is only limited discussion of their implications.

Volume VIII would be strengthened by adding an explicit, detailed discussion of the inundation maps and their implications for the spatial distribution of risk across the city and the region.

Volume VIII also would be strengthened by adding an objective, candid discussion of the main limitations of the risk and reliability models used therein, and areas for future improvement.

More thorough discussion of all of Volume VIII's main findings about future vulnerability to the New Orleans region—especially in layman's terms that are understandable to most decision makers, citizens, and business owners who wish to read the document—is necessary to help them better understand future vulnerabilities and to assist them in their relocation and reconstruction decisions.

Interagency Coordination on Flood Inundation Maps

In addition to flood inundation maps contained in IPET Volume VIII, the Federal Emergency Management Agency (FEMA) and the National Oceanic and Atmospheric Administration's (NOAA) National Hurricane Center also produce flood inundation maps for U.S. coastal regions. Although IPET, FEMA, and NOAA have different objectives and product needs, these agencies should engage in ongoing communication and coordinate to ensure consistency among their methods and the resulting products.

Full Draft Final Report

Volume I of the IPET report, entitled Executive Summary and Overview, contains much interesting and useful information, and readers will turn to it expecting to see primary findings and recommendations. The Volume I Executive Summary is well written, interesting, and informative. There are, however, many disconnections between the Executive Summary in Volume I, and the organization and contents of the rest of the report (Vols. II-VIII). This affects the clarity of key findings and conclusions and diminishes the value of the IPET project.

The IPET and the Department of the Army should enlist the services of a firm that specializes in technical writing of scientific and engineering reports to produce a final, summary document of the entire IPET report. The summary should be written in layman's terminology in order to communicate clearly the IPET study results to decision makers and citizens.

LESSONS LEARNED FROM THE KATRINA EXPERIENCE

Many of the "lessons learned" in the Hurricane Katrina experience, and presented in this report, represent knowledge widely recognized and recommended for years by experts and practitioners in the fields of natural hazards, emergency preparedness, civil defense, and other related fields. Unfortunately, much of this information had not been adequately implemented as part of comprehensive hurricane planning and preparedness for the greater New Orleans metro region.

This section presents this NAE/NRC committee's views on the primary lessons learned during the Hurricane Katrina experience, as well as advice on how they might be acted upon and responded to. It reflects the committee's review of the IPET report and the committee's collective experience in geotechnical engineering, hurricane wave and storm studies and modeling, water resources planning, and natural hazards mitigation and preparedness. This section is presented in the spirit that in the future, these lessons will be more widely appreciated and understood and that hurricane mitigation and preparedness in this region might be enhanced.

Hydrologic Realities and the Limits of Protective Structures

There are many inherent hydrologic vulnerabilities of living in the greater New Orleans metropolitan region, especially in areas below sea level. Post-Katrina repairs and strengthening have reduced some of these vulnerabilities. Nevertheless, because of the possibility of levee/floodwall overtopping—or more importantly, levee/floodwall failure—the risks of inundation and flooding never can be fully eliminated by protective structures no matter how large or sturdy those structures may be.

Future Footprint of the Hurricane Protection System

The pre-Katrina footprint of the New Orleans HPS consisted of roughly 350 miles of protective structures including levees, I-walls, and T-walls. There was undue optimism about the ability of this extensive network of protective structures to provide reliable flood protection. Future construction of protective structures for the region should proceed with this point firmly in mind and in the context of a more comprehensive and resilient hurricane protection plan.

Nonstructural Aspects and Options

Comprehensive flood planning and risk management for the New Orleans metro region will be based on a combination of structural and nonstructural measures, the latter including relocation options, floodproofing and elevation of structures, and evacuation studies and plans. Better risk communication also must be part of more effective mitigation and an improved state of preparedness. Structural measures such as levees and floodwalls should not be viewed as substitutes or replacements for nonstructural measures, but rather as complementary parts to a multi-tiered hurricane protection solution.

Relocation

The planning and design for upgrading the current hurricane protection system should discourage settlement in areas that are most vulnerable to flooding due to hurricane storm surge. The voluntary relocation of people and neighborhoods out of particularly vulnerable areas—with adequate resources designed to improve their safety in less vulnerable areas—should be considered as a viable public policy option.

Floodproofing Measures

When voluntary relocations are not viable, floodproofing measures will be an essential complement to protective structures—such as levees and floodwalls—in improving public safety in the New Orleans region from hurricanes and induced storm surge. This committee especially endorses the practice of elevating the first floor of buildings to at least the 100-year flood level, and preferably to a more conservative elevation. The more conservative elevation reflects a subsequent finding in this report regarding the inadequacy of the 100-year flood as a flood protection standard for a large urban center such as New Orleans.

Critical public and private infrastructure—electric power, water, gas, telecommunications, and flood water collection and pumping facilities—should be strengthened through reliable construction, and ensuring reliable interdependencies among critical infrastructure systems.

Evacuation

The disaster response plan for New Orleans, although extensive and instrumental in successfully evacuating a very large portion of the New Orleans metropolitan area population, was inadequate for the Katrina event. Thus, there is a need for more extensive and systematic evacuation studies, plans, and communication of evacuation plans. A comprehensive evacuation program should include not only well designed and tested evacuation plans, protocols, and criteria for evacuation warnings, but also alternatives such as improved local and regional shelters that could make evacuations less imposing. It also should consider longer-term strategies that can enhance the efficiency of evacuations, such as locating facilities for the ill and elderly away from more vulnerable areas that may be subject to frequent evacuations.

Risk Communication

Before Katrina, there was a limited understanding and appreciation of the residual risks of living behind levees. Improvements in future hurricane preparedness and response will depend partly upon improved public understanding of these risks. In order to enhance the communication and appreciation of these risks, it will be important to extend the efforts of the IPET and to refine, simplify, and communicate consistently the risks of hurricanes and storm surge to the region's residents, including how those risks vary across the region. Effective communication of the risk-based findings from the entire IPET report will be enhanced by creating a professional summary and compilation of the entire IPET draft report with layman's terminology (see earlier recommendation in this report).

The 100-Year Level of Flood Protection

The 100-year level of flood protection is a crucial flood insurance standard. It has been applied widely across the nation and it is being used in some circumstances in reconstruction and planning activities in the New Orleans region. For areas in which catastrophic levee failure is not a major public safety concern, and where large floods would not imperil evacuation routes, the 100-year standard may be appropriate. For heavily-populated urban areas, where the failure of protective structures would be catastrophic—such as New Orleans—this standard is inadequate.

Independent Review for Engineering and Design

It is important to enlist periodic external review in the design, construction and maintenance of large, complex civil engineering projects such as the New Orleans hurricane protection system. A "second opinion" allows an opportunity to ensure that calculations are reliable, methods employed are credible and appropriate, designs are adequate and safe, potential blind spots are minimized, and so on. An outside external review group also may be able to state politically sensitive findings or facts that a government agency may be reluctant to. Such a review team should be adequately independent of the authority that identified it.

Periodic Assessments and Updates of Concepts, Methods, and Data

Changing environmental conditions can affect the performance and operation of large hurricane and flood protection projects. Advances in scientific and engineering theories and methods may render assumptions on which these projects were based partly or fully obsolete. Because of these changes and the important implications they may have for expected performance of protective structures, a process should be implemented to ensure periodic review of underlying environmental, scientific, and engineering factors that affect New Orleans hurricane protection system performance.

The process for incorporating new scientific information into large flood protection projects, like the New Orleans hurricane protection system, can be affected by congressional reauthorization requirements. Changes or clarifications to congressional policies and reauthorizations as they relate to large construction projects may be necessary to effectively implement findings of periodic scientific reviews.

The Future of Hurricane Risk Analysis for New Orleans and the Gulf Coast Region

The IPET has conducted a landmark assessment of the New Orleans HPS that could serve as a platform for future and ongoing assessments of vulnerability, levels of protection, subsidence rates, geological studies, risk assessments, and so on. As the IPET investigations come to an end, many of the external experts that participated in the studies will return to their respective careers outside the Corps of Engineers. Much of the IPET "institutional memory" therefore may not be infused into Corps of Engineers New Orleans District office, the State of Louisiana, or the City of New Orleans.

It is essential that these analyses be extended and subsequently built upon by the Corps of Engineers and others, including the FEMA, NOAA, the State of Louisiana, New Orleans regional municipalities, and the region's universities, engineers, and scientists. To facilitate future work that builds on the IPET studies, a publicly accessible archive of all data, models, model results, and model products from the IPET project should be created.

1
Introduction

In the aftermath of Hurricane Katrina, the U.S. Army Corps of Engineers established the Interagency Performance Evaluation Task Force (IPET) to evaluate the performance of the New Orleans hurricane protection system (Figure 1) and to study the vulnerabilities posed to the city and the region by hurricanes. More specifically, the IPET defined the objectives of its study as:

1. the design and status of the hurricane protection system pre-Katrina;
2. storm surges and waves generated by Hurricane Katrina;
3. performance of the hurricane protection system during and after Katrina;
4. societal-related consequences of Katrina-related damage; and
5. risks to New Orleans and the region posed by future tropical storms.

The IPET was established in August 2005 and over the next three years issued several technical reports. To provide independent review and advice to the IPET, the Assistant Secretary of the Army of Civil Works (ASA(CW)), Mr. John Paul Woodley, requested the National Academy of Engineering (NAE) to convene a committee of experts to review the IPET technical reports as they were being released. In late 2005, the NAE and the National Research Council (NRC) appointed a committee—the Committee on New Orleans Regional Hurricane Protection Projects—to review the IPET reports and issue independent, expert advice through a series of its own reports.

The original plans for the IPET and its evaluations—which included plans to issue a final report in June 2006—changed course and evolved in many creative, useful, and challenging ways. Similarly, the original plans for this NAE/NRC committee—to issue three reports—followed these changes in the IPET schedule and evolved accordingly. During the course of this 3.5-year project, the committee convened seven meetings, five of which were held in New Orleans and two that were held in Washington, D.C. All meetings included presentations from IPET staff, the Corps of Engineers, and other invited experts; public comment sessions; and, closed sessions in which the committee discussed the IPET reports and its own draft reports. The IPET and Corps of Engineers provided an extensive amount of information to this committee in those meetings, which was essential to the committee's education and to allowing it to provide informed feedback to the IPET. The professionalism and preparedness

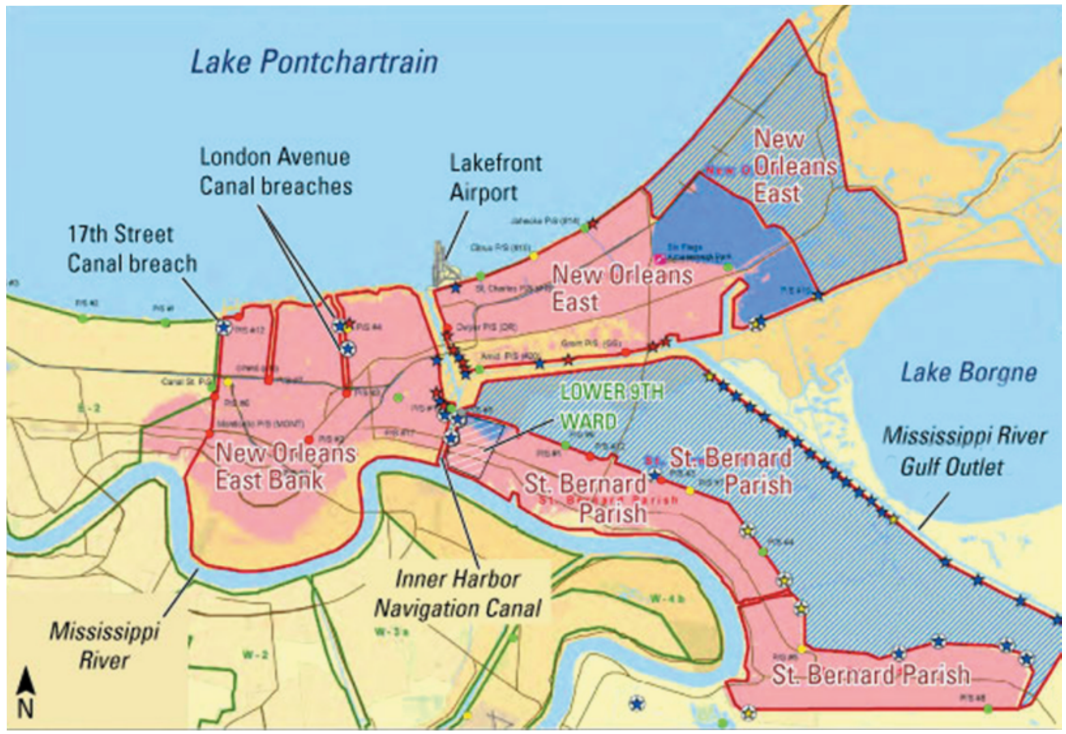

FIGURE 1 The New Orleans hurricane protection system. Map shows the features of storm surge damage in the New Orleans during and following Hurricane Katrina. Pink and blue shading indicates areas that flooded; blue-striped areas are wetlands. Starts indicate levee breaches or distressed levee areas; circles indicate pumping stations.
SOURCE: USGS. Available online at: *http://soundwaves.usgs.gov/2006/01/NewOrleansMapLG*.jpg

of the IPET and Corps of Engineers was of a high order and greatly facilitated the meeting discussions. Invited speakers provided informative presentations and perspectives that were invaluable to the committee's work. The many citizens and representatives from New Orleans neighborhoods and businesses, and various city- and state-level groups, provided unique insights on technical issues and the context in which these issues were being applied.

This NAE/NRC committee issued four reports from 2006-2008, which are summarized in Box 1-1. This following report is the committee's fifth and final report. As directed in the committee's statement of task (Appendix A), it represents a review of the IPET draft final report (dated June 1, 2008), and the committee's reflections on the lessons learned from the Hurricane Katrina experience and ways in which the hurricane protection system performance might be improved. Over the course of the IPET project, many of the committee's recommendations led to constructive improvements in the IPET reports.

BOX 1-1
Previous Four Reports from the NAE/NRC Committee on New Orleans Regional Hurricane Protection Projects

First report—February 2006

This report (NRC, 2006a) reviewed the IPET first report, which was issued in January 2006. It recommended that the IPET place a stronger emphasis on systems-level evaluation and presentation in many aspects of studies. It recommended that the IPET use more maps in its evaluations and findings, and that the IPET should make greater use of geographic information system (GIS) technology. The report included multiple recommendations for more thorough data gathering and testing of soil properties across the system. It also recommended that the IPET adopt an ensemble approach—reflecting a range of possible storms and storm surges—in its hurricane modeling exercises. The report also recommended that the IPET better characterize levels of confidence in the accuracy of the data that were being gathered and used in its various analyses.

Second report—June 2006

This report (NRC, 2006b) reviewed the IPET second report, which was issued in March 2006. The report noted that although Task Force Guardian—the group responsible for repairs to the hurricane protection system—was making progress in repairing damaged structures, that the second report did not reflect well the remaining hydrologic risks to the system. It recommended that the concepts of authorized level of protection and standard project hurricane be better

continued

BOX 1-1 Continued

explained and integrated into the report, especially with regard to levee design. The report discussed the issues of potential failure mechanisms at levee breach sites, concluding that the explanation of the failure mechanism for the 17th Street Canal breach, while plausible, was not fully convincing, and that alternative failure mechanisms should be assessed. It recommended that special emphasis be given to gathering data at areas of the protection system that were loaded to near capacity by storm surges, but did not fail. It also was noted that the IPET faced a challenge in developing a robust and defensible assessment of the risk and reliability of the hurricane protection system, and it was recommended that IPET provide a thorough and understandable explanation for the method being used in its assessment of risk and reliability of the hurricane protection system.

Third report—October 2006

This report (NRC, 2006c) reviewed the IPET draft final report, which was issued in June 2006. The report noted the prominence of risk and uncertainty within the IPET evaluations and reports, and recommended a stronger emphasis on explaining key uncertainties and implications for decision making. It recommended there be more substantial documentation to support the hypothesis that breaches along the Inner Harbor Navigation Canal (IHNC) were caused by overtopping and erosion, or foundation failure. It also recommended that the report examine other possible failure modes. Further advice on soils sampling and testing measures was included: it recommended that the IPET present site plans and soil profiles at breach sites, that clay and marsh deposit strengths be estimated at locations other than the 17th Street Canal, and that IPET provide additional guidance for identifying erodible soils, quantifying the degree of soil resistance to erosion, and selecting and placing soils to resist erosion. The report noted that although the IPET risk analysis approach was coherent and logical, that the levels of uncertainty in estimates of risks in flooding were expected to be large. It also recommended that as a complement to its joint probability methods results, that the IPET create a set of hurricane scenarios that simulate a variety of possible, future storm conditions for the New Orleans region.

Fourth report—February 2008

This report (NRC, 2008a) reviewed a single volume of the IPET report—Draft Volume VIII on Engineering and Operational Risk and Reliability Analysis. That volume was released in October 2007. A key finding from this report was that the overall risk assessment method used by the IPET seemed appropriate for evaluating risks associated with the New Orleans hurricane protection system, but that the interim draft Volume VIII “does not provide sufficient presentation and explanation of the methods employed or results obtained to allow this to be clearly determined.” The report concluded that further information was necessary in order to fully explain and validate the method used and results that were obtained. The report recommended that the IPET more carefully document the data, assumptions, and models being used in its risk analysis, and that it present intermediate results and note that component models being used would evolve and improve over

continued

BOX 1-1 Continued

time. The report recommended that the IPET team/ discuss how the fragility curves of levee vulnerability could be improved through the use of more reliable shear strength measurements in either laboratory or field tests. It also recommended that the IPET issue a set of inundation maps that displays best estimates of inundation depths for 50-year, 100-year, and 500-year event recurrence intervals. The report further recommended that the modified joint probability model employed in Volume VIII be fully and clearly explained in a single place within the report, as opposed to partial explanations that were listed in multiple, separate sections.

These reports are available at the National Academies Press website at: *www.nap.edu/*

2
The IPET Draft Final Report

The collective IPET evaluation entailed large, important human resources and institutional efforts and investments. Numerous individuals and organizations devoted extensive amounts of time and energy into this multi-year, multi-agency project. In addition to the IPET studies and reports, the Corps of Engineers and the Department of the Army sponsored two multi-year external reviews of the IPET study process and its reports, which were conducted by the American Society of Civil Engineers (ASCE, sponsored by the Corps) and by this NAE/NRC committee (sponsored by the Department of the Army). The analytical, computational, presentation, public communication and relations, logistical, and other related challenges to the IPET were substantial.

Adequate assessment of the five IPET study objectives required an ambitious and extensive research program, which is described in eight volumes of over 7,500 pages of report chapters and appendices. In addition to its evaluations of the design and performance of the New Orleans HPS during Hurricane Katrina, and its evaluations of Katrina's waves, surges, and impacts, 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 protection measures in the future (IPET, 2008, p. I-1).

The IPET represented an unusual study for the Corps of Engineers (and others) in that they brought some of the best scientists and engineers in the world to work together with Corps engineers and scientists toward a set of goals. The IPET project has improved greatly the understanding and management of the New Orleans regional hurricane protection system (HPS). The IPET draft final report of 2008, however, cannot be regarded as fully conclusive or as "the final word" with respect to all study objectives. That is, the size and the complexity of the natural and human systems involved in hurricane protection, preparedness, and forecasting for New Orleans is such that many parts of the IPET studies never could be "final." Hurricane protection is an ongoing, work in progress to which the IPET has made noteworthy contributions that serve as a platform for future inquiry and for the development of research priorities.

The remainder of this chapter presents the committee's observations and comments about the IPET draft final report and is organized according to the five IPET study objectives.

CHARACTERIZATION OF THE PRE-KATRINA HURRICANE PROTECTION SYSTEM

The IPET evaluations and reports in this area advanced greatly the understanding of the pre-Katrina state of system and its vulnerabilities. Volume I explains, for instance, that the hurricane protection system "…did not perform as a system" (IPET, 2008). In discussing the administrative and organizational history of the HPS, the IPET draft final report makes it clear that the "system" was constructed in a piecemeal fashion, "in many separate steps over a long period of time" and represented a history of "continuous incompleteness" (Ibid., p. 31). Details on this region's geologic setting also explain widespread subsidence and how this affected levee heights, stability, and reliability. The IPET report also explains how the system was incomplete in some areas, that there were different vulnerabilities across the region, and that parts of the system were unreliable and had been inadequately designed. These types of evaluations were overdue for this region; unfortunately, it took a disaster on the scale of Hurricane Katrina to provide the impetus for this kind of study. This explanation of the pre-existing condition of the HPS marks one of the important contributions of the IPET studies and will be essential information for future hurricane planning and construction activities in the region.

EVALUATION OF HURRICANE KATRINA STORM SURGE AND WAVES

The IPET work in this area represents an important advance of scientific understanding of Gulf of Mexico hurricane storm surge and waves. The IPET did a good job of explaining the storm surge generated by Hurricane Katrina, how waters from the surge entered into the New Orleans metro region from the east and from the north (across Lake Borgne, into Lake Pontchartrain, and ultimately into the city's outfall canals and the Inner Harbor Navigation Canal), the role of the Mississippi River Gulf Outlet in exacerbating storm surge (minor, if any), and inundation depths across the city. The IPET work also importantly identified the significance that the areal extent of Katrina played in determining storm surge; it was primarily Katrina's large size that contributed to the highest storm surge ever measured in North America. The IPET also implemented and calibrated state-of-the-art models for coastal wave and storm surge response.

PERFORMANCE OF THE HURRICANE PROTECTION SYSTEM DURING AND AFTER KATRINA

The IPET conducted a detailed evaluation in this area and provided explanations of the HPS performance during Hurricane Katrina. As explained in the Executive Summary of the draft final report, IPET concluded, "With the exception of four foundation design failures, all of the major breaches were caused by overtopping and subsequent erosion" (IPET, 2008, p. I-2). The report further states that "The levee-floodwall designs for the 17th Street Canal and London Avenue Outfall Canals and the IHNC were inadequate for the complex and challenging environment." In a September 3, 2008, letter to Corps of Engineers Chief Robert van Antwerp, the American Society of Civil Engineers (ASCE) External Review Panel complimented the Corps for its acknowledgement that designs were inadequate for extreme hurricane conditions, but also noted that "engineers routinely are expected to design for such conditions" (ASCE, 2008). This report concurs with the ASCE team on this issue.

The nature of the performance of the hurricane protection system during Hurricane Katrina was an important area of investigation in the IPET studies, especially the geotechnical assessments of the four sites of foundation failures in the HPS. Special explorations were conducted in the field, which were complemented by laboratory centrifuge studies and analytical investigations using numerical modeling and limit analysis. The IPET team concluded that a singular driving mechanism was a key factor affecting each of the failures; however, alternative factors contributing to failure were proposed by others, notably by a research team that was working through a grant from the National Science Foundation (NSF). An earlier report from this NAE/NRC committee drew attention to the complex soil conditions and the number of unknowns still associated with these sites despite the extensive work conducted (NRC, 2006b). In the end, that report advised the IPET to "be aware of alternative failure mechanism and assess the potential for instability at other locations along the levee system" and that "The explanation of the failure mechanism for the 17th Canal Street breach, while plausible, is not fully convincing, and alternative failure mechanisms should be more rigorously assessed" (NRC, 2006b). These issues likely will continue to be debated, with a gradual professional consensus developing about appropriate means to incorporate these findings into future design. For the time being, all reasonable possible failure modes in designs for levees and floodwalls should be considered and examined, and attention should be given to ongoing professional discussion about the issues in order to facilitate design improvements.

SOCIETAL-RELATED CONSEQUENCES OF KATRINA-RELATED DAMAGE

This section—Volume VII—of the IPET report assesses the consequences of Hurricane Katrina in a broad range of categories, including: direct economic consequences; indirect economic consequences; human health and safety; social, cultural, and historical; and, environmental. Volume VII contains extensive discussion and data on these five topic areas (the volume and its technical appendices are nearly 900 pages long).

Volume VII employs both traditional Corps of Engineers methods and approaches (e.g., use of depth-damage and stage-damage relationships to estimate flood damages) and draws upon methods and reports from other sources (e.g., the FEMA "HAZUS" damage assessment model; McCarthy et al., 2006). The methods employed and results obtained generally are well explained throughout the volume. Volume VII also contains good discussion of uncertainties and how they affected estimates of, for example, flooding depths, depth-damage relationships, and property damage estimates. The accounting of these uncertainties enhances the presentation of results obtained in Volume VII. Volume VII also usefully points out priority areas for future research.

The Executive Summary of Volume VII exhibits a trait seen in other sections of the entire report, in that it emphasizes methods and approaches employed, but does not present a clear, succinct summary of primary findings and conclusions. The Executive Summary, however, is followed by a more detailed Summary section that includes a succinct list of the primary economic, environmental, and other consequences of Hurricane Katrina, along with useful discussion of the implications of Katrina's extensive impacts.

RISKS TO NEW ORLEANS AND THE REGION POSED BY FUTURE TROPICAL STORMS

The IPET volume on risks to the region posed by future tropical storms is Volume VIII of the report and is entitled "Engineering and Operational Risk and Reliability Analysis." Volume VIII was the principal focus of the final two years of the IPET study. During its review of the IPET draft reports, the NAE/NRC committee adjusted its course to provide a full report (its fourth report, issued in February 2008; see Box 1-1) that reviewed specifically the IPET Volume VIII.

The assessment of the risks to New Orleans and the region posed by future tropical storms (IPET study objective 5 and the topic of Volume VIII) represent important methodological advances, and the June 2008 draft represents an improvement over the 2007 draft that this committee reviewed and reported on (see NRC, 2008a). The IPET developed a sophisticated way to project results from single events into a risk-based framework and this has improved the understanding of vulnerabilities to future storms across the region.

A key shortcoming of the Volume VIII risk assessment is that it lacks a succinct and clear presentation of its key findings. A previous report from this NAE/NRC committee (NRC, 2008a) noted problems related to a lack of discussion of results—particularly those regarding the report's inundation maps. The IPET draft final includes some discussion of varying vulnerabilities in different sections of the city and region, and it does include the inundation maps; this crucial information, though, is scattered and still is not well discussed. Volume VIII contains extensive discussions on the details of technical issues including crest elevations, reach descriptions, overflowing rate models, wave exceedance curves, breach elevation and volume models, and event tree branch probabilities. This extensive technical information overwhelms the discussion of key results and, where those discussions of key results can be found, they tend to be very short with little explanation of their implications.

For example, the Risk Analysis Results section in Volume I states that "New Orleans is widely vulnerable to some flooding at the 50-year or 2% frequency of occurrence level if significant pumping capacity is not available" (IPET, 2008, I-134; the same language appears in Volume VIII, as well). It goes on to state that with good pumping capacity, that flood elevations can be lowered and that "There is a small benefit in NOE and a significant benefit in OM, portions of JE, JW, and PL" (IPET, 2008, VIII-134). These are examples of the brevity and lack of elaboration in this important section on results, and they stand in contrast to extensive discussions on technical details in Volume VIII and elsewhere in the report. This contrast is especially important when considering the importance of risk communication. Details on the calculations of exceedance frequencies are important to the technical foundation of the IPET project, and all parties want to be assured that fundamental analyses are sound. Citizens, business leaders, and public officials in New Orleans, however, are likely to be more immediately concerned with IPET study results and their implications for future settlement, rebuilding, and construction activities.

Additional examples of this limited discussion of results can be found elsewhere. For example, in the section of Volume VIII on the "100-year Flood Event," it is stated that, "Without pumping, the majority of the New Orleans area remains vulnerable to moderate to deep flooding (greater than 4 ft.) at the 100-year or 1% frequency of occurrence. The area with the least vulnerability is Jefferson Parish and St. Charles Parish, where flood threats are moderate" (IPET, 2008, VIII-134). These types of statements carry a great deal of important information, but without cross-referencing these findings with maps, or without further elaboration to ensure that non-technical experts clearly understand these terms, the prospects for clear risk communication from the IPET report are diminished considerably.

This committee would like to reiterate its opinion that there should be more thorough discussion of these types of results from the IPET report, and that some of this discussion should contain less technical terminology. The public and elected officials will be especially interested in place-specific inundation estimates and what they imply for future activities.

The IPET Volume VIII of June, 2008 provides a detailed description of the risk assessment methodology to characterize the potential for failure of HPS levees, flood walls, and related facilities. Although considerable attention is devoted to justification of the climatological and hydrodynamic methods and models, there is little treatment of the approximations and extrapolation of sparse geotechnical data that is also part of applying the risk assessment methodology. A candid discussion of the most important limitations of the risk and reliability models would improve implementation of the modeling results and provide guidance on where and when the results should be applied with caution. This discussion also could identify opportunities for improvement and help formulate a future research agenda for better simulation of the HPS performance.

Among the important findings from Volume VIII is a set of inundation maps for the New Orleans metro region. The results conveyed in these maps are of great importance and interest to citizens, businesses, and government agencies that are making plans for resettlement and redevelopment in this region. Volume VIII presents these important inundation maps, but there is only limited discussion of their implications.

Volume VIII would be strengthened by adding an explicit, detailed discussion of the inundation maps and their implications for the spatial distribution of risk across the city and the region.

Volume VIII also would be strengthened by adding an objective, candid discussion of the main limitations of the risk and reliability models used therein, and areas for future improvement.

More thorough discussion of all of Volume VIII's main findings about future vulnerability to the New Orleans region—especially in layman's terms that are understandable to most decision makers, citizens, and business owners who wish to read the document—is necessary to help them better understand future vulnerabilities and to assist them in their relocation and reconstruction decisions.

ADDITIONAL COMMENTS

Discussions of "Lessons Learned"

The IPET report includes several "Lessons Learned" sections, which generally are well written and make useful statements regarding nonstructural dimensions of hurricane preparedness, such as evacuation. The importance of evacuation planning and preparedness is emphasized in Volume I and elsewhere in report. For instance, the report notes that "At this time evacuation is the only effective means to substantially reduce loss of life for large hurricane events" (p. I-4), and, "The emergency response preparedness and efficiency of evacuation prior to a storm is a key component to reducing risk to life and human safety" (p. I-5). It also explains clearly that much of the region remains subject to hurricanes and it does a good job at explaining the concept of residual risk—"No matter how well designed an HPS may be, some level of residual risk always remains: risk is never reduced to zero" (IPET, 2008, VIII-12).

The Role of Wetlands in Storm Surge and Hurricane Protection

The potential virtue of marshes, wetlands and other vegetation in protecting inshore areas from storm surge has been a topic of considerable speculation following hurricane Katrina, particularly given the documented loss of significant areas of marshes in southern Louisiana during the past 50 years. The IPET made a reasonable effort to include the effects of these landscape features in their storm surge and wave modeling with equivocal results. Considerable uncertainty remains about how to properly represent these effects in surge and wave models and in the resulting model sensitivities. Given the major investments that are being discussed for marsh restoration projects in southern Louisiana (see USACE, 2007; State of Louisiana, 2007), and the partial justification for these projects based on their value for increased hurricane protection, it is important that additional efforts be taken to improve understanding of the effects these features have on hurricane wave and storm surge across this region.

Interagency Coordination on Flood Inundation Maps

In addition to the inundation maps generated in the IPET studies, the Federal Emergency Management Agency (FEMA) is in the process of updating its Flood Insurance Rate Maps (FIRMs) to provide delineation of the 100-year flood elevation for southern Louisiana. Also, the National Hurricane Center (part of the National Oceanic and Atmospheric Administration, or NOAA) has produced a set of maximum flood elevation maps for hurricanes of various categories, tracks, forward speeds, and other variables that are used primarily for evacuation planning.

Although IPET, FEMA, and NOAA have different objectives and product needs, these agencies should engage in ongoing communication and coordinate to ensure consistency among their methods and the resulting products.

Organization and Discussion of Main Findings

The IPET draft final report of June 2008 contains roughly 7,500 pages. A document of this size presents considerable editorial challenges in fully and clearly presenting its main findings and recommendations. The IPET report Volume I, Executive Summary and Overview, contains much interesting and useful information, and readers will turn to it expecting to see primary findings and recommendations. The Volume I Executive Summary is well written, interesting, and informative. Its readability is enhanced by the editorial-type format in which it is presented.

There are, however, many disconnections between Volume I's Executive Summary (ES), and the organization and contents of the rest of the report. For example, the ES concludes that (among other things), "The standard project hurricane (SPH) methodology … is outdated and should no longer be used" (IPET, 2008). It also concludes that "The 100-year de facto standard is far too risky for the continued vitality of our economy…" (Ibid.). These are important findings with which many experts would agree. Nonetheless, it is not clear how or from where these conclusions flow from the IPET analysis presented in the various report volumes.

The size of the IPET document makes it difficult to determine quickly where supporting discussions for these and other conclusions appear in the main body of the report. In addition, cross-referencing between Volume I and the rest of the report is confusing and inadequate. As a result, key findings and conclusions based upon the IPET analysis are not as clear as they could be.

In a previous report (NRC, 2008a), this committee recommended that, in addition to the full IPET report, that a second document should be prepared "for elected officials and the public" and that this document "could be much shorter and focus on results and implications for reconstruction and resettlement" (Ibid.). The importance of this recommendation has not diminished, and the committee wishes to reiterate this point in the following recommendation.

The IPET and the Department of the Army should enlist the services of a firm that specializes in technical writing of scientific and engineering reports to produce a final, summary document of the entire IPET report. The summary should be written in layman's terminology in order to communicate clearly the IPET study results to decision makers and citizens.

3
Lessons Learned in Hurricane Katrina and Its Aftermath

The tragedy of Hurricane Katrina and its impacts exposed the many weaknesses in the hurricane protection and preparedness systems for the greater New Orleans metropolitan region. The long history of the authorizations and appropriations, construction, and maintenance of HPS protective structures; the numerous organizations and individuals with hurricane preparedness and response duties; the respective roles of structural and nonstructural approaches in preparedness, and; the large geographic region over which the HPS extends, all complicate ex post evaluations of Hurricane Katrina impacts. Careful appraisal of the root causes of those impacts, and the identification of viable actions for improving preparedness, are essential for reducing the prospects of the recurrence of such an event in the future.

This chapter offers technical, organizational, and policy recommendations for improving hurricane preparedness for New Orleans and southeastern Louisiana and responds to the portion of this committee's statement of task to "determine lessons learned from the Katrina experience and identify ways that hurricane protection system performance can be improved in the future at the authorized level of protection." The chapter is based on this NAE/NRC committee's views on the primary lessons learned during the Hurricane Katrina experience, as well as advice on how they might be acted upon and responded to. It reflects the committee's review of the IPET report and the committee's collective experience in geotechnical engineering, hurricane wave and storm studies and modeling, water resources planning, and natural hazards mitigation and preparedness.

Many of the lessons presented below do not represent new findings that were learned for the first time during and after Hurricane Katrina. On the contrary, many have been widely recognized and recommended for years by experts and practitioners in the fields of natural hazards, emergency preparedness, civil defense, and other related fields. Unfortunately, much of this information had not been adequately implemented as part of comprehensive hurricane planning and preparedness for the greater New Orleans metro region. This section is presented in the spirit that in the future, these lessons will be more widely appreciated and understood and that hurricane mitigation and preparedness might be enhanced.

THE NEW ORLEANS HURRICANE PROTECTION SYSTEM

Hydrologic Realities and the Limits of Protective Structures

Despite its strategic and economic importance, the New Orleans region always has been vulnerable to flood and hurricane storm surge hazards. The Mississippi River delta is a low-lying region surrounded by waterbodies—namely, the Mississippi River, Lake Pontchartrain, and Lake Borgne—that rise and can overflow during hurricanes and floods. The proximity of New Orleans and southeastern Louisiana to the large, shallow continental shelf of the northern Gulf of Mexico make the area highly vulnerable to Gulf hurricanes and storm surge.

The origins of today's New Orleans hurricane protection system date back to U.S. Army Corps of Engineers' planning studies in the mid-1950s and issuance of a 1962 interim survey report for the Lake Pontchartrain and Vicinity Hurricane Protection Project (LP&VHPP; Woolley and Shabman, 2007). The major principle guiding the system's construction and maintenance, as well as post-Katrina repairs and strengthening, has been to "make the city safe." In this large region of varying topography and elevation, and as demonstrated by Hurricane Katrina and past storms in New Orleans and elsewhere, this guiding principle—although noble—is flawed.

Modern protective structures and diligent maintenance and repair efforts can help reduce the risks of hurricanes and storm surge. In fact, the ability of these structures to help protect against storm surge was demonstrated in New Orleans during Hurricane Gustav in early September 2008. The drama surrounding the storm surge of Hurricane Gustav, which nearly (but did not) overtopped a protective (T-wall) structure along New Orleans's Inner Harbor Navigation Canal was broadcast to a national viewing audience. In that instance, that protective structure clearly resulted in a reduction in flood damages in the low lying areas behind that structure.

Protective structures, however, do not provide certain protection against all storm surges. They can be overtopped in large storms and there always is the risk of future—even with well-constructed and maintained structures. Thus, even in areas behind well-built structures, some risk—referred to as "residual risk"—will exist to inhabitants and structures. Structures can reduce some hydrologic risks but all flood and hurricane storm surge risks in this region never can be fully eliminated. It therefore is critical to consider a guiding principle for these protective structures as one that seeks to reduce risks from hurricanes and storm surge—but recognizes that such risks cannot be fully eliminated and, as such, augments flood and hurricane protection by protective structures with complementary measures such as floodproofing of buildings, evacuation plans, and comprehensive land use planning. In fact, the IPET recognizes and supports this principle in its report. Again, from the IPET report: "…No matter how well designed an HPS may be, some level of residual risk always remains: risk is never reduced to zero. Therefore, even with the construction and strengthening of the New Orleans HPS, some residual risk will always remain (IPET, 2008, VIII-12).

Similarly, in a 2006 report from the Interagency Levee Policy Review Committee, that group noted that, "Levees only *reduce* the risk to individuals and structures behind them; they do not *eliminate* the risk. In fact, in many cases, they can create significant and potentially catastrophic residual risk that may increase if conditions in the region change, if levees are affected by natural events, or if the levees are not properly maintained" (Interagency Levee Policy Review Committee, 2006; italics in original).

In 2007, the Association of State Floodplain Managers issued a position paper entitled "Levees: The Double-edged Sword" (ASFPM, 2007). This paper discusses many of the pros and cons of relying too heavily upon levees for flood protection. Several conclusions and recommendations from the ASFPM are relevant to hurricane protection in New Orleans and are consistent with this NAE/NRC committee's views on lessons learned in the Hurricane Katrina experience. Key points from the ASFPM report thus are presented in Box 3-1.

BOX 3-1
Views from the Association of State Floodplain Managers on Flood Protection Provided by Levees

The Association of State Floodplain Managers (ASFPM) 2007 report, "Levees: The Double-edged Sword" is a thoughtful and succinct exposition of the pros and cons of relying on levees to provide flood protection. Many of the report's recommendations overlap and are consistent with the lessons learned section in this NAE/NRC committee report. This box does not list all of the ASFMP report findings and recommendations; rather it presents those that are most relevant to this committee's report. Elected officials, business owners, and citizens in the New Orleans region interested in another perspective on some of the limitations of relying too heavily upon levee systems will find the ASFPM document of interest.

Several key points from the ASFPM paper—and that are especially relevant to this committee's report—are contained in a paragraph in the paper's Introduction:

> Because of the nature of levee failure flooding, the ASFPM believes that levees are not a wise community choice and should never be used to protect undeveloped land so development can occur in the flood risk area behind the levee. However, many levees already exist in the nation, especially in communities that were built right on the river or coast, usually at a time when the nation was convinced it could engineer its way out of flooding. Where levees already exist, or where a levee appears to be the best option after careful analysis of all alternatives to mitigate the incidence of flooding to existing development, the ASFPM advocates that levees (1)

continued

BOX 3-1 Continued

> must be designed to a high flood protection standard; (2) must be frequently and adequately inspected, with all needed maintenance continufunded and performed (if this does not occur, the levee must be treated as nonexistent); (3) should be used only as a method of last resort for providing a LIMITED means of flood risk reduction for existing development; and (4) are inappropriate as a means of protecting undeveloped land for proposed development (ASFPM, 2007, all caps in original).

Other relevant quotes from the ASFPM paper for this committee's report and hurricane and storm surge protection in New Orleans are:

> In those cases in which a levee is found to be an appropriate measure to protect urban areas or to be credited for protection, the levee should be constructed to a high level of protection. As described in various reports, the level of the 500-year flood, plus freeboard, is considered an appropriate minimum protection standard with urban areas. . .
>
> The 500-year standard for levee design is just as arbitrary as the 100-year standard so the question becomes, "what level of risk to public safety can we accept?" When one compares the potential for fire damage to an individual home, case history would indicate that a 100-year standard falls far short of the level of protection afforded by modern fire systems . . . today's fire systems tend to significantly limit the degree to which an entire community can be affected by fire, yet we continue to use a much lower threshold in levee design that most certainly will result in community-wide inundation.
>
> An added element of risk in current design practices is the lack of designing "planned failure" into levees. When levees fail, either by structural failure or overtopping by flood waters that exceed the design event, the results are often catastrophic . . . In many instances it is useful to design levees to withstand overtopping, or to control the overtopping to a limited number of spillways designed into the system. The aim is to prevent the loss of the levee, by allowing it to be overtopped and slowly flood the area in planned locations rather than randomly, so that damage is reduced and the community can recover more quickly.
>
> There is now widespread misunderstanding of the true risks associated with levees. This in turn has helped lead to the current over-reliance on structural solutions to reduce the impact of flooding, and to the creation of a false sense of security among those living, working, or seeking to build in areas behind levees. Communication with citizens and stakeholder groups is rarely an explicit consideration when levees are permitted or built, or in the development of policy for levee design, insurance, or regulation. . . Communication of the residual risk associated with any levee is key to public understanding and acceptance of appropriate public safety and flood risk reduction policies in the nation.

A related lesson from the history and construction of the Lake Pontchartrain and Vicinity Hurricane Protection Project regards the construction of protective structures in low-lying areas, with subsequent settlement in those areas. With the construction of levees and other protective structures, settlement and development took place in the areas behind those structures, and the population of the city grew. As with many structures built to protect against riverine or coastal flooding, the Lake Pontchartrain and Vicinity Hurricane Protection Project promoted a false sense of security that areas behind the structures were absolutely safe for habitation and development. Unfortunately, there were substantial "residual" risks in these areas behind the protective structures that never were adequately communicated to the public and that were not adequately considered in the settlement of many of these areas.

LESSON: There are many inherent hydrologic vulnerabilities of living in the greater New Orleans metropolitan region, especially in areas below sea level. Post-Katrina repairs and strengthening have reduced some of these vulnerabilities. Nevertheless, because of the possibility of levee/floodwall overtopping—or more importantly, levee/floodwall failure—the risks of inundation and flooding never can be fully eliminated by protective structures no matter how large or sturdy those structures may be.

Future Footprint of the Hurricane Protection System

Given the specific areas of overtopping and the substantial damage to the pre-Katina HPS, some rethinking about the extent and configuration of the HPS structures—or its 'footprint'—would seem to be a pressing priority. The pre-Katrina HPS footprint clearly had many flaws and vulnerabilities:

> The system did not perform as a system. In some areas it was not completed, and in others, datum misinterpretation and subsidence reduced its intended protective elevation. The capacity for protection varied because of some structures that provided no reliable protection above their design elevations and others that had inadequate designs leaving them vulnerable at water levels significantly below the design intent. The designs of the levee-floodwall structures along the outfall canals were particularly inadequate (IPET, 2008, p. I-2).

It is entirely appropriate therefore that discussions of the future HPS plans would focus on how a new—and different—system footprint would be designed and implemented. For example, the creation of a smaller footprint might offer advantages in terms of cost, inspection and maintenance requirements, and the prospect to create a more manageable *system* of protective structures. At the very least, pros and cons of a smaller footprint should be a topic for discussion and debate. Nevertheless, it appears that post-Katrina rebuilding activities are taking place largely according to the pre-Katrina HPS design without discussions of how a safer and more reliable design might be configured.

The additional investments necessary to rebuild and strengthen the HPS according to the pre-Katrina footprint, which included roughly 350 miles of levees, are substantial. The required investments will be far greater if these structures are to be made higher or sturdier. They also would be greater if the levees are to receive more frequent and thorough inspection and maintenance. Furthermore, regardless of the level of investments, the residual risks of hurricane storm surge always will be significant for some areas behind these protective structures.

LESSON: The pre-Katrina footprint of the New Orleans HPS consisted of roughly 350 miles of protective structures including levees, I-walls, and T-walls. There was undue optimism about the ability of this extensive network of protective structures to provide reliable flood protection. Future construction of protective structures for the region should proceed with these lessons firmly in mind and in the context of a more comprehensive and resilient hurricane protection plan.

NONSTRUCTURAL ASPECTS AND OPTIONS

Relocation

People will continue to live in this region, but flood protection and preparedness plans should be implemented with some criteria for priority areas for protection. That is, even if vast amounts of resources were available, it likely would not be possible to provide equal degrees of storm surge protection to all areas of the greater New Orleans region. For instance, higher-elevation parts of the region—such as areas on the natural Mississippi River levees—inherently are safer than lower-lying areas—such as extensive areas below sea level in St. Bernard's, Orleans, and New Orleans East parishes.

Areas at or below sea level are especially dangerous, and protective structures never can provide certain protection against hurricane storm surge and flooding. Reconstructing all pre-Katrina protective structures, and creating settlement patterns just as they existed before Katrina, simply would position the city and its inhabitants for additional, Katrina-like disasters in future big storms. Although it can be a politically charged topic, the option of voluntarily relocating some structures and residents is one means to help improve safety and reduce flood damages. The Corps has recognized the value of voluntary buyouts and relocations in another study it is conducting in southern Louisiana.

Entitled "Louisiana Coastal Protection and Restoration" (or LACPR) the Corps is conducting a comprehensive hurricane protection analysis and is considering a broad range of flood control, coastal restoration, and hurricane protection measures (USACE, 2008). A section of its 2008 draft technical report includes discussion of nonstructural measures and alternatives. That section states that:

> For the purposes of the LACPR plan formulation, buyout/relocation of structures and elevation of structures are considered to be the most viable nonstructural measures for overall applicability across South Louisiana. . . Nonstructural measures, such as buyouts and relocations, can provide opportunities for alternate uses of the vacated flood plain, such as ecosystem restoration, recreational development, or urban green space (USACE, 2008).

A report from a National Research Council committee reviewing the Corps's LACPR study concurred with these statements from the Corps draft report, concluding that "The relocation option often provides an excellent means for improving safety and reducing potential damages" (NRC, 2008b).

LESSON: The planning and design for upgrading the current hurricane protection system should discourage settlement in areas that are most vulnerable to flooding due to hurricane storm surge. The voluntary relocation of people and neighborhoods out of particularly vulnerable areas—with adequate resources designed to improve their safety in less vulnerable areas—should be considered as a viable public policy option.

Floodproofing and Strengthening Critical Infrastructure

New Orleans presents a special and complex situation with regard to hurricane preparedness and planning. There are large numbers of structures and residents in areas across the city near or below sea level. This situation poses considerable logistical challenges to relocation efforts, and it also prompts tough questions about the future of the city. For those many structures and residents in vulnerable areas that are not amenable to relocations, major floodproofing measures are recommended in order to improve public safety from hurricane storm surge.

This committee especially endorses the practice of elevating the first floor of building to at least the 100-year flood level, and preferably to a more conservative elevation. The more conservative elevation reflects a later finding in this report regarding the inadequacy of the 100-year flood level as a flood protection standard for a large urban center such as New Orleans.

In addition, attention should be given to strengthening critical infrastructure, such as electric power transmission and distribution facilities, water supply systems, natural gas, telecommunication networks, and the system of storm water collection and pumping facilities essential for removing flood water from New Orleans. Improvements in building codes and construction practices also are essential to well-designed housing and infrastructure that are able to withstand a major levee breach.

Electric power is essential for proper functioning of infrastructure, and is especially important for the operation of flood water pumping facilities. Hurricane Katrina caused unprecedented damage to the electric power system in and surrounding New Orleans through flooding of substations in low-lying areas and wind damage to overhead transmission lines. The electric power system was slow to recover; four weeks after Hurricane Katrina—when nearly 20 percent of regional customers were without power—Hurricane Rita struck an already weakened system, causing further extensive damage. The loss of electric power interrupted the flow of critical oil and refined petroleum products by shutting down pumping stations that were otherwise functional. The restoration of power, so important for emergency response, community safety, and economic recovery, was further delayed by lack of a comprehensive plan by government agencies to integrate emergency operations with the return of electricity.

The pumping facilities for flood water are of key importance in New Orleans. The reliability of the pumping system requires an assessment of power availability, plans for restoration of electricity from utilities, and the ability to protect and support pump station operators during an extreme event.

The strengthening of critical infrastructure requires careful planning. The loss of population in New Orleans after Hurricane Katrina affects directly the sustainability of critical infrastructure, through loss of revenue from both public and private utility rate payers. The restoration and maintenance of critical infrastructure therefore requires coordination with neighborhood restoration, dealing with the uneven density of the post-Katrina population, and the development of innovative public/private partnerships.

LESSON: When voluntary relocations are not viable, floodproofing measures will be an essential complement to protective structures—such as levees and floodwalls—in improving public safety in the New Orleans region from hurricanes and induced storm surge. This committee especially endorses the practice of elevating the first floor of buildings to at least the 100-year flood level, and preferably to a more conservative elevation. The more conservative elevation reflects a subsequent finding in this report regarding the inadequacy of the 100-year flood as a flood protection standard for a large urban center such as New Orleans.

Critical public and private infrastructure—electric power, water, gas, telecommunications, and flood water collection and pumping facilities—should be strengthened through reliable construction, ensuring reliable interdependencies among critical infrastructure systems.

Evacuation

The pre-Katrina warning and evacuation plans and measures for New Orleans and southeastern Louisiana were extensive. There were ongoing media announcements for days before Katrina made landfall, weather forecasters tracked the storm carefully and their forecasts were reasonably accurate, and extensive efforts were made to warn residents of the approaching storm. There were road signs and flyovers that allowed for large volumes of traffic to move in one direction, and a very large percentage of the population was successfully evacuated out of New Orleans and to other communities. Despite the best efforts of city and state officials, police and fire departments and other public safety personnel, and many others, however, the collective plans and efforts were inadequate to safely evacuate all residents, especially the sick, poor, and elderly.

Hurricane evacuation poses special planning and decision making challenges for the city of New Orleans and southern Louisiana. On the one hand, evacuations are stressful, inconvenient, expensive, and are especially difficult for ill and elderly residents. The unpredictable nature of hurricanes as they approach land means that there will be evacuations in instances in which a hurricane does not strike a given city or region. An area may have multiple and legitimate evacuations in a single season, and concerns over public safety make evacuations a way of life in coastal areas threatened by hurricanes.

At the same time, successive evacuations in which a hurricane does not strike a given city or region will contribute to "evacuation fatigue." Even though evacuations in which a storm dissipates or veers away from a city are inevitable, evacuation fatigue is a social and a political reality. It affects decision makers and it affects the public, and can encourage a "ride the storm out" mentality, thereby reducing the efficiency of future evacuations. Finding the correct balance between public safety concerns and the issuance of evacuation orders as a storm approaches, while trying to minimize possible evacuation fatigue, is a challenging decision process for elected officials and emergency managers.

As no structure can ensure complete protection against all floods and storm surges, an efficient evacuation program will be a part of comprehensive hurricane protection. As is pointed out in its own Lessons Learned section of the Executive Summary in its draft final report, the IPET noted that, "The emergency response preparedness and efficiency of evacuation prior to a storm is a key component to reducing risk to life and human safety" (IPET, 2008, p. I-5). The IPET Volume VII also concluded that "Loss of life and evacuation planning should be an integral part of hurricane protection system planning and design as well as in local planning and operation. Especially vulnerable portions of the population warrant special consideration" (Vol. VII-14).

An improved and more efficient evacuation program for New Orleans will be based on further and more systematic studies, plans, and communication. A more efficient evacuation program and strategy will include not only public announcements and plans for re-routing traffic, but also alternatives that may make evacuations less imposing and burdensome. For example, the construction of additional and better short-term emergency shelters in nearby areas may improve efficiency and compliance with evacuation orders. Longer-term improvements may include the siting of facilities of elderly or chronically ill patients in areas less vulnerable to hurricanes and where evacuations may be less necessary and frequent.

The evacuation of a large metropolitan area such as New Orleans presents numerous logistics and related challenges. To ensure public safety, residents must be evacuated well in advance of approaching hurricanes, and considering uncertainties in storm paths, the decision heavily favors issuing an evacuation order "better safe than sorry." This means that there will be evacuations in areas and cities that ultimately are not affected by a given storm, and a city or region may have multiple, legitimate evacuations in a single season with no actual storm damage. Evacuation fatigue can result from repeated evacuation orders and will affect the decision making of public officials and the effectiveness of future evacuations. It is exceptionally difficult to strike the correct balance between ordering legitimate evacuations to ensure public safety and the reality of evacuation fatigue.

LESSON: The disaster response plan for New Orleans, although extensive and instrumental in successfully evacuating a very large portion of the New Orleans metropolitan area population, was inadequate for the Katrina event. Thus, there is a need for more extensive and systematic evacuation studies, plans, and communication of evacuation plans. A comprehensive evacuation program should include not only well designed and tested evacuation plans, protocols, and criteria for evacuation warnings, but also alternatives such as improved local and regional shelters that could make evacuations less imposing. It also should consider longer-term strategies that can enhance the efficiency of evacuations, such as locating facilities for the ill and elderly away from more vulnerable areas that may be subject to frequent evacuations.

Risk Communication

Clear and effective risk communication is a fundamental component of a reliable hurricane protection and preparedness program. Effective communication of hurricane and storm surge risks represents a substantial challenge for scientists, engineers, and public officials, in that often-sophisticated science and engineering concepts must be summarized and explained in terms that most citizens will be able to grasp.

Risk communication has for many years been a field of formal inquiry and research, and a recent volume of collected papers considered many of the broad lessons learned in the field of risk communication as a result of Hurricane Katrina (Daniels et al., 2006). The contributors to this volume wrote on topics ranging from risk and decision analysis, natural disaster insurance, and risk management. According to the editors of this volume:

> Katrina revealed a large gap between the capacity of our policies and institutions and our needs, as individuals and as a society. We need a fresh understanding of the problems and new and creative solutions to tackle them. That is the most important lesson of Katrina, and if we fail to learn it, Katrina's legacy will not be "bigger and better." It will be "bigger and worse." (Daniels et al., 2006).

Unfortunately, in the greater New Orleans metropolitan region, the residual risks associated with living behind levees either were not well understood, or not well communicated, or both. Again, the Interagency Levee Policy Review Committee: "The public at large and public officials generally do not understand the residual risk to those living behind levees" (Interagency Levee Policy Review Committee, 2006).

Effective communication of the vulnerabilities of the New Orleans region to hurricanes and storm surge will encompass many of the concepts discussed in this report and evaluated in the IPET report, such as uncertainties of storm surge inundation estimates, changes in vulnerabilities over time, effective evacuation planning, and so on. Increasing public awareness of hurricane and storm surge risks will constitute an ongoing challenge for the Corps of Engineers, the State of Louisiana, parish and city governments, and local and regional media outlets.

LESSON: Before Katrina, there was a limited understanding and appreciation of the residual risks of living behind levees. Improvements in future hurricane preparedness and response will depend partly upon improved public understanding of these risks. In order to enhance the communication and appreciation of these risks, it will be important to extend the work of the IPET and to refine, simplify, and communicate consistently the risks of hurricanes and storm surge to the region's residents, including how those risks vary across the region. Effective communication of the risk-based findings from the entire IPET report will be enhanced by creating a professional summary and compilation of the entire IPET draft report with layman's terminology (see earlier recommendation in this report).

THE 100-YEAR LEVEL OF FLOOD PROTECTION

The concept of level of protection is central to levee design and flood protection. In the United States, the use of structures designed to protect against the 100-year flood has become a standard practice. The history of this 100-year standard derives from both administrative convenience and its importance in determining rates of flood insurance under the federal National Flood Insurance Program (NFIP; see NRC, 2000, for more details on the National Flood Insurance Program, the 100-year flood, and levee certification procedures; also see ASFPM, 2007, for discussion of flood protection and levee standards for urban areas).

In repairing and strengthening of the hurricane protection system, significant attention has been given to protection at the 100-year level. IPET has focused part of its analyses on the 100-year level of protection (both Task Force Guardian and the Corps' Louisiana Coastal Protection and Restoration (LACPR) study also have used this standard in the context of their efforts). Given the inadequate protection afforded by the pre-Katrina hurricane protection system, it is understandable why one would choose to focus first on providing protection from at least a 100-year event. However, for heavily urbanized regions, the 100-year standard level of protection from flooding generally is inadequate. For example, a structure located within a special flood hazard area shown on an NFIP map has a 26 percent chance of suffering flood damage during the term of a 30-year mortgage (*http://www.fema.gov/faq/faqDetails.do?action=Inut&faqId=1014*). The IPET team also concluded that "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 100-year standard has driven levels of protection below economically optimal levels, has encouraged settlement in areas behind levees, and resulted in losses of life and vast federal expenditures following major flood and hurricane disasters.

LESSON: The 100-year level of flood protection is a crucial flood insurance standard. It has been applied widely across the nation and it is being used in some circumstances in reconstruction and planning activities in the New Orleans region. For areas in which catastrophic levee failure is not a major public safety concern, and where large floods would not imperil evacuation routes, the 100-year standard may be appropriate. For heavily-populated urban areas, where the failure of protective structures would be catastrophic—such as New Orleans—this standard is inadequate.

INDEPENDENT REVIEW FOR ENGINEERING AND DESIGN

Selection and support for external review is important to promote fresh thinking as part of large, complex, and interdisciplinary ventures such as hurricane protection system maintenance and operations, and hurricane preparedness planning. Independent review also allows an opportunity for the input of external, expert opinion on issues that may be politically sensitive and that local staff members may be reluctant to raise. This point is especially relevant with regard to the New Orleans hurricane protection system, as there was no organizational process that required continual assessments of project performance capabilities:

> The absence of a standing, agency-wide process for continuing assessment and reporting of project performance capability left the District to make its own determination as to whether the analytical foundation was adequate for requesting changes to project designs, and for satisfying higher federal authorities and local sponsors that additional project funding was warranted (Woolley and Shabman, 2007, p. ES-17).

Additional advice on structuring a peer review process within the Corps of Engineers is in NRC, 2002, which reports specifically on this topic. Relevant findings and recommendations from that NRC report (NRC, 2002) include:

- The Corps should institute external review for studies that are expensive, that are highly controversial, that will affect a large area, or that involve high levels of risk;
- A review panel should be given the freedom to comment on those topics that it deems relevant to decision makers; and
- Review panels should not be tasked to provide a final, “thumbs up/thumbs down” judgment on whether a particular alternative from a planning study should be implemented, as the Corps of Engineers is ultimately responsible for this final decision.

LESSON: It is important to enlist periodic external review in the design, construction and maintenance of large, complex civil engineering projects such as the New Orleans hurricane protection system. A “second opinion” allows an opportunity to ensure that calculations are reliable, methods employed are credible and appropriate, designs are adequate and safe, potential blind spots are minimized, and so on. An outside external review group also may be able to state politically sensitive findings or facts

that a government agency may be reluctant to. Such a review team should be adequately independent of the authority that identified it (for further discussion, see NRC, 2002).

Periodic Assessments and Updates of Concepts, Methods, and Data

A topic related to independent review is a need to ensure that hurricane protection system maintenance, inspection, and upgrades are being carried out consistent with current information of scientific and engineering concepts, methods, and data. As environmental conditions change, data sets are updated, models are improved, and new concepts are implemented, it is important to have a process that integrates this new information into decision making and ensures that the hurricane protection system continues to meet its performance objectives.

An example from the New Orleans hurricane protection system of problems that can ensue if this is not done is that of the Standard Project Hurricane, or SPH. The Lake Pontchartrain and Vicinity Hurricane Protection Project used the SPH as its performance standard (Woolley and Shabman, 2007). The original estimate of the level of protection for the Lake Pontchartrain and Vicinity Hurricane Protection Project was in excess of 200 years. This level of protection was derived from the standard project hurricane stillwater design storm surge used in 1962 (Ibid.).

By the early 1970s, and with the addition of hurricanes like Betsy and Camille to the windspeed and central pressure databases, recalculation of the level of protection or return interval of the 1962 SPH design surge would have resulted in estimates that were significantly less than 200 years. This is but one example of how changes in environmental conditions, data sets, or models and methods can impinge upon hurricane system performance. A routine process of periodic review of scientific data and concepts could help identify these types of changes, and offer recommendations for related system performance upgrades.

There are other examples of why changes in environmental conditions, and updates and improvements in scientific and engineering methods, necessitate reviews and updates. For example, subsidence affects levee elevations and levels of performance of the HPS: levee heights ideally would be surveyed periodically to determine changes in system reliability. Engineering advances in technical methods in the design of I-walls and other protective structures, or updates and changes in materials used in protective structures, ideally would be periodically infused into maintenance and improvements of the HPS.

The processes and requirements of congressional authorizations can complicate the incorporation of new scientific information. New scientific information on factors such as changing environmental conditions or design methods can affect original authorizations and may require reauthorizations. In New Orleans, the Corps of Engineers and its project cost-sharing partners were reluctant to incorporate 1979 Weather Bureau revisions to the standard project hurricane concept in 1984 when the project was reevaluated. A significant argument for not incorporating the new information was a fear that the project might have to be reauthorized. At the time, Congress had not authorized any projects since 1974 because of a prolonged debate over new cost-sharing rules that might have affected this project had it been reauthorized (Woolley and Shabman, 2007). Reauthorization would have taken several years at best, the outcome of those discussions would have been uncertain, and there could have been substantial financial implications because of significantly revised cost-sharing formula.

LESSON: Changing environmental conditions can affect the performance and operation of large hurricane and flood protection projects. Advances in scientific and engineering theories and methods may render previous assumptions on which these projects were based partly or fully obsolete. Because of these changes and the important implications they may have for expected performance of protective structures, a process should be implemented to ensure periodic review of underlying environmental, scientific, and engineering factors that affect New Orleans hurricane protection system performance.

The process for incorporating new scientific information into large flood protection projects, like the New Orleans hurricane protection system, can be affected by congressional reauthorization requirements. Changes or clarifications to congressional policies and reauthorizations as they relate to large construction projects may be necessary to effectively implement findings of periodic scientific reviews.

THE FUTURE OF HURRICANE RISK ANALYSIS FOR NEW ORLEANS AND THE GULF COAST REGION

The analyses performed by the IPET were extensive and involved the investigation of many factors crucial to effective hurricane planning and preparedness. The IPET studies were not conducted as a standard part of the work program of the Corps New Orleans District office; rather, they represented a specially commissioned set of investigations with a specially appointed team of engineers and scientists. Many of these experts were Corps of Engineers staff from outside the New Orleans District, while some were recruited from academia and the private sector. Some Corps of Engineers staff involved in the study were nearing the end of their careers, and there were some retirements during the 3+-year IPET study effort.

As the IPET investigations come to an end, many of the external experts that participated in the studies will return to their respective careers outside the Corps of Engineers. Much of the IPET "institutional memory" therefore may not be infused sufficiently into Corps of Engineers New Orleans District office, the State of Louisiana, or the City of New Orleans. There thus is the potential for much of the IPET effort to not be adequately implemented into future HPS system improvements and in hurricane planning and preparedness in south Louisiana. The majority of the responsibilities for extending and building upon the IPET studies will fall to the Corps of Engineers New Orleans District office. It will be important that the analyses and findings from the IPET be incorporated into future activities and plans of the New Orleans District, and also the State of Louisiana, the City of New Orleans, and local parishes.

LESSON: The IPET has conducted a landmark assessment of the New Orleans HPS that could serve as a platform for future and ongoing assessments of vulnerability, levels of protection, subsidence rates, geological studies, risk assessments, and so on. As the IPET investigations come to an end, many of the external experts that participated in the studies will return to their respective careers outside the Corps of Engineers. Much of the IPET "institutional memory" therefore may not be infused into Corps of Engineers New Orleans District office, the State of Louisiana, or the City of New Orleans.

It is essential that these analyses be extended and subsequently built upon by the Corps of Engineers and others, including the FEMA, NOAA, the State of Louisiana, New Orleans regional municipalities, and the region's universities, engineers, and scientists. To facilitate future work that builds on the IPET studies, a publicly accessible archive of all data, models, model results, and model products from the IPET project should be created.

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Appendix A

Statement of Task: Committee on New Orleans Regional Hurricane Protection Projects

Hurricane Katrina and the subsequent flooding of much of the New Orleans metro area prompted many questions about the geotechnical and hydraulic conditions and performance of the city's hurricane protection system. To help provide credible scientific and engineering answers regarding the performance of this system, an Interagency Performance Evaluation Task Force (IPET) has been convened. The IPET effort is being led by the U.S. Army Corps of Engineers. The IPET is also working with a review team from the American Society of Civil Engineers (ASCE). The IPET, which includes both federal and non-federal scientists and engineers, is divided into ten teams focusing on different topical areas.[1] The IPET is focusing its investigation on 3 primary topics: a) design capacity of the hurricane protection system, b) forces exerted against the system and system response, and c) factors that resulted in overtopping, breaching, or failure of levees and floodwalls. The IPET issued a draft final report on June 1, 2006. The IPET plans to issue its final report in 2008.

This NAE/NRC committee will focus its review on the following tasks:

1) review the data gathered by the IPET and the ASCE teams and provide recommendations
regarding the adequacy of those data, as well as additional data that will be important to the IPET study and should be gathered;

2) review the analyses performed by the IPET and ASCE to ensure their consistency with accepted engineering approaches and practices;

3) review and comment upon the conclusions reached by the IPET and ASCE teams, and;

4) seek to determine lessons learned from the Katrina experience and identify ways that hurricane protection system performance

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[1]The committee's review will focus on the analysis of IPET teams in the areas of: data collection and management (perishable, systems data, and information management); interior drainage systems models; numerical models of the Hurricane Katrina surge and wave environment; storm surge and wave physical modeling of hydrodynamic forces and centrifuge breaching; geodetic vertical survey assessment; and the analysis of floodwall and levee performance.

can be improved in the future at the authorized level of protection.

The NAE/NRC committee will issue five reports:

1) a preliminary, letter report that comments on the adequacy of the nature of the data being collected by the IPET and ASCE teams (due in February 2006);

2) an interim report that represents the midpoint of the committee's evaluation and project (due June 1, 2006);

3) a report that reviews the IPET June 1, 2006 draft final report (due in September 2006);

4) a report that reviews the IPET draft "Volume VIII" on Engineering and Operational Risk and Reliability Analysis; and,

5) a final, comprehensive report that summarizes the committee's evaluation of the IPET final report.

The timeline for these five NAE/NRC reports conforms with plans regarding IPET report progress. The first two NRC/NAE reports will be drafted and issued following the review and evaluation of the IPET 30% and 60% completion reports, respectively. The third NAE/NRC report will review the IPET draft report (which was issued on June 1, 2006). The fourth NAE/NRC report will review the IPET Volume VIII on Risk and Reliability Analysis. The fifth NAE/NRC report will review the IPET final report.

Appendix B

Biographical Information: Committee on New Orleans Regional Hurricane Protection Projects

Committee on New Orleans Regional Hurricane Protection Projects

G. Wayne Clough (NAE), *Chair,* is secretary of the Smithsonian Institution. Prior to joining Smithsonian in 2008, Dr. Clough was the president of the Georgia Institute of Technology. His technical interests lie primarily in geotechnical engineering, earthquake engineering, and heavy construction, particularly underground construction. Dr. Clough's research has centered on laboratory and field testing, earthquake analysis, soil behavior, and the application of numerical methods to soil-structure interaction. He has been especially interested in developing new methods that allow design of soil-structure systems using movement control concepts. With his increasing involvement in academic administration, he has taken a greater interest in higher education and technology policy. Dr. Clough's recent writings have been on the future of the research and development enterprise, and the role of technology in society. He received his B.S. and M.S. degrees in civil engineering from the Georgia Institute of Technology and his Ph.D. degree in geotechnical engineering from the University of California, Berkeley.

Rafael L. Bras (NAE) is the Dean of the Henry Samueli School of Engineering at the University of California, Irvine, and Distinguished Professor in its Department of Civil and Environmental Engineering. Dr. Bras' research interests are in the prediction of hydrologic extremes (flood and droughts), the use of forecasts to improve responses to those disasters, and improved water resources management. He is also interested in quantifying the effects of large-scale changes in land surfaces (agriculture, deforestation) on the global hydrologic cycle and energy cycles. Dr. Bras also has conducted studies in landscape evolution and fluvial geomorphology. He received his B.S. and M.S. degrees in civil engineering and his Sc.D. degree in water resources and hydrology from the Massachusetts Institute of Technology.

John T. Christian (NAE) is a consulting engineer in Waban, Massachusetts. His primary area of interest is geotechnical engineering. Much of his early work involved developing and applying numerical methods such as the finite element method. He has also worked on reliability methods for geotechnical applications, soil dynamics, and earthquake engineering on a broad range of civil engineering projects. Dr. Christian's current interests are largely focused on the use of reliability techniques in geotechnical engineering and on earthquake engineering. Much of his work in industry was associated with power generating facilities, including but not limited to nuclear power plants. Dr. Christian is also interested in the evolving procedures and standards for undergraduate education, especially as reflected in the accreditation process. He received his B.S., M.S., and Ph.D. degrees in civil engineering from the Massachusetts Institute of Technology.

Jos Dijkman is a flood management engineer with Deltares/Delft Hydraulics in Delft, The Netherlands. Mr. Dijkman has over 30 years of experience in water resources and flood management projects, both in the Netherlands and internationally. He has lived and worked for many years in Southeast Asia, where he focused on regional water management issues. He was also involved in many water management and flood mitigation projects internationally, including the United States (upper Mississippi River basin). He had played a leading role in several feasibility and public policy studies in the Netherlands related to mitigating current and expected future flooding risks. Among these was the "Room for the River" study, which set a new course for national flood risk management policy in the Netherlands. He also serves as a member of the independent Dutch National Advisory Committee on Flood Management Issues. Mr. Dijkman received his M.Sc. degree in civil engineering from the University of Technology, Delft, The Netherlands.

Robin L. Dillon-Merrill is an associate professor at Georgetown University's McDonough School of Business. Her areas of specialty include decision and risk analysis, with applications in the fields of space missions, information systems, and worker safety issues. Prior to her appointment at Georgetown, Dr. Dillon served on the faculty at Virginia Tech's Pamplin College of Business, and with Fluor Daniel, Inc., where she analyzed technologies and sites for tritium supply and recycling using decision analysis and a simulation of production assurance. She received her B.S. and M.S. degrees in systems engineering with risk analysis concentration from the University of Virginia, and her Ph.D. degree in engineering risk analysis from Stanford University.

Delon Hampton (NAE) is the chairman of the board at Delon Hampton and Associates in Washington, DC. His major interest is in the area of tunneling and underground design and construction. Dr. Hampton has been involved in the design and/or construction of tunnels in both hard and soft ground, as well as shafts and connecting and intercepting structures. He has also been involved in restoration and rehabilitation of a failed submerged tunnel system, and in tunneling research. He has also worked on design of highway and airfield pavements. This includes establishing design parameters for subgrades and base courses, as well as required pavement thicknesses for Portland cement concrete and asphaltic concrete surface courses. Dr. Hampton received his B.S. degree in civil engineering from the University of Illinois at Urbana-Champaign and his M.S. and Ph.D. degrees in civil engineering from Purdue University.

Greg J. Holland is the director of the Mesoscale and Microscale Meteorology (MMM) Division of the National Center for Atmospheric Research (NCAR) in Boulder, Colorado. Dr. Holland spent much his career with Australia's Bureau of Meteorology Research Centre. Previously he was with Aerosonde, a manufacturer of lightweight and long-range robotic aircraft. After beginning his career as a mathematician, he focused primarily on tropical meteorology and severe weather at the Bureau of Meteorology Research Centre. In 2005, he joined the staff at NCAR, where he directs the MMM unit. He also helped set up field facilities, and he established programs studying the coastal impacts of tropical cyclones. He received his B.S. degree from the University of New South Wales in mathematics and physics and his M.S. and Ph.D. degrees in atmospheric science from Colorado State University.

Richard A. Luettich, Jr. is the director of the Institute of Marine Sciences at the University of North Carolina at Chapel Hill. His research has dealt broadly with modeling and measurement of circulation and transport in coastal waters. Dr. Luettich's modeling efforts have emphasized the development and application of unstructured grid solution techniques that are optimized for geometrically complex systems such as sounds, estuaries, inlets and inundated regions. He has co-developed a circulation and storm surge model that has been applied extensively for modeling storm surge in the southern Louisiana and New Orleans areas. Dr. Luettich also has participated in the development of components of the national Coastal Ocean Observing System. He received his B.S. and M.S. degrees in civil engineering at the Georgia Institute of Technology and his Sc.D. in civil engineering from the Massachusetts Institute of Technology.

Peter Marshall is a consulting engineer. Previously he was vice-president of operations at Burns & Roe Services Corporation after a career in the Civil Engineer Corps of the U.S. Navy. Prior to joining Burns and Roe, he served as a senior vice-president with Parsons Brinckerhoff Construction Services Corporation, where he was responsible for project development and project operations. His experience in the Navy Civil Engineer Corps included positions with the Naval Facilities Engineering Command. His positions there included commanding officer of the Navy Public Works Center in San Francisco, fleet civil engineer of Naval Forces Europe, commander of the 22nd Naval Construction Regiment and Pacific Division of NAVFAC, and vice-commander of NAVFAC. Mr. Marshall is a fellow of the Society of American Military Engineers and a licensed professional engineer in Virginia and California. He received his B.S. degree in civil engineering from Tufts University and his M.S. degree in ocean engineering from the University of Rhode Island.

David H. Moreau is a professor in the Departments of City and Regional Planning and Environmental Sciences and Engineering at the University of North Carolina at Chapel Hill. Dr. Moreau teaches water resources planning and regional environmental planning. His research interests include analysis, planning, financing, and evaluation of water resource and related environmental programs. He is engaged in water resources planning at the local, state, and national levels. He has chaired or served on several NRC committees, most recently as a member of the NRC committee that issued the report, "Nutrient Control Actions for Improving Water Quality in the Mississippi River Basin and the Northern Gulf of Mexico." Dr. Moreau serves as chairman of the North Carolina Environmental Management Commission, the state's regulatory commission for water quality, air quality, and water allocation. Dr. Moreau received his B.S. degree from Mississippi State University, his M.S. degree from North Carolina State University, and his Ph.D. degree from Harvard University.

Thomas D. O'Rourke (NAE) is the Thomas R. Briggs professor of engineering at Cornell University. His areas of study and research include: 1) large ground deformation during earthquakes, with emphasis on mechanisms and characteristics of soil liquefaction and its influence on critical lifeline systems, 2) seismic performance of water supply and gas and liquid fuel distribution systems, with emphasis on earthquake protection of water supply and energy distribution systems, methods for earthquake loss estimation, and interactive modeling of utility systems, 3) deep excavation and underground construction technology, with emphasis on predicting ground movements caused by deep excavations and tunneling, improved methods for assessing stability of deep excavations, and the use of deep soil mixing and jet grouting technologies, 4) pipeline design, rehabilitation, and systems performance, and 5) performance and interaction of polymeric materials with soil and groundwater. Dr. O'Rourke received his B.S. degree in civil engineering from Cornell University in 1970 and his M.S. and Ph.D. degrees in civil engineering from the University of Illinois at Urbana-Champaign.

Kenneth W. Potter is a professor in the Department of Civil and Environmental Engineering at the University of Wisconsin. Dr. Potter's areas of research interests include hydrological modeling and design, estimation of hydrologic risk, estimation of hydrological budgets, and restoration of aquatic systems. He has been a fellow of the AAAS, a fellow of the AGU, and a Woodrow Wilson fellow. Dr. Potter received his B.S. degree in geology from Louisiana State University and his Ph.D. in geography and environmental engineering from Johns Hopkins University.

Y. Peter Sheng is a professor with the Civil and Coastal Engineering Department at the University of Florida, Gainesville. His fields of interest include coastal and estuarine circulation modeling and monitoring; turbulent transport and modeling; sediment transport and water quality dynamics and modeling; light attenuation processes; seagrass dynamics and modeling; atmospheric boundary layer dynamics; tornado dynamics; dispersion and deposition processes and modeling; storm surge and coastal flooding modeling and monitoring; and, integrated modeling for ecosystem restoration and coastal hazard mitigation. Dr. Sheng received his B.S. degree in mechanical engineering from the National Taiwan University, and his M.S. and Ph.D. degrees in engineering, fluid and thermal sciences, from Case Western Reserve University.

Robert H. Weisberg is a Distinguished University Professor and a professor of physical oceanography in the College of Marine Science at the University of South Florida. Dr. Weisberg is an experimental physical oceanographer engaged in ocean circulation and ocean-atmosphere interaction studies in the tropics, on continental shelves, and in estuaries. He is the director of the USF Ocean Circulation Group and co-director of the USF Coastal Ocean Modeling and Prediction System and Center for Prediction of Red Tide. His research presently emphasizes in-situ measurements, analyses, and models of the West Florida shelf circulation and interactions between the shelf and the estuaries and between the shelf and the deep ocean. Dr. Weisberg received his B.S. degree in materials science and engineering from Cornell University and his M.S. and Ph.D. degrees in physical oceanography from the University of Rhode Island.

Andrew J. Whittle is a professor in the Department of Civil and Environmental Engineering at the Massachusetts Institute of Technology. His area of expertise is in geotechnical engineering, constitutive models for geomaterials, analysis methods for foundations, excavations and tunnels, in situ test methods, and ground improvement. Dr. Whittle's teaching interests include introduction and advanced geotechnical engineering and theoretical soil mechanics. He received his B.Sc. degree from Imperial College of Science and Technology and his Sc.D. from the Massachusetts Institute of Technology.

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