TEAM LOUISIANA

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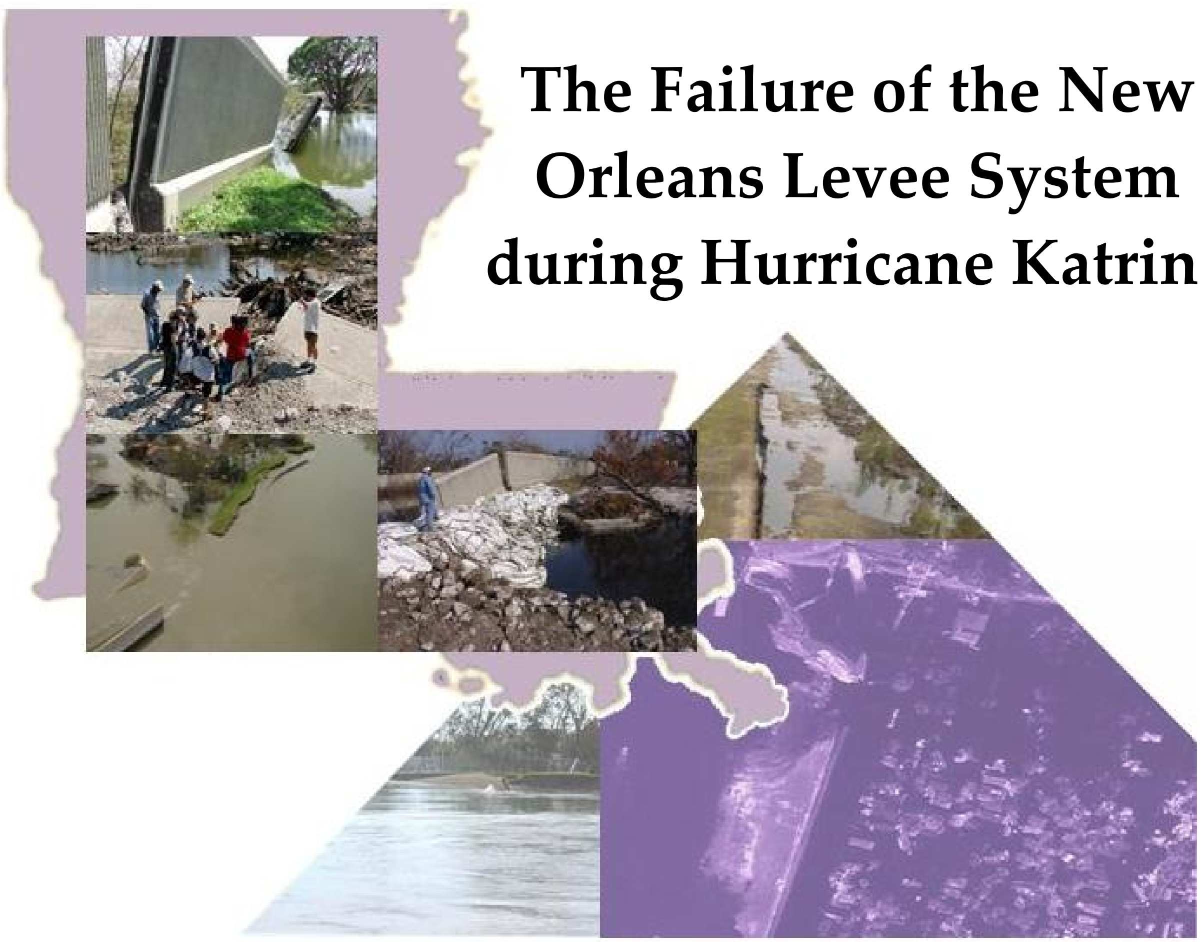
The Failure of the New Orleans Levee System during Hurricane Katrina



A Report prepared for Secretary Johnny Bradberry
Louisiana Department of Transportation and Development, Baton Rouge, Louisiana
State Project No. 704-92-0022, 20 --- December 18, 2006

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Executive Summary

Louisiana State University (LSU) was commissioned in October, 2005 by the Louisiana Department of Transportation and Development (LDOTD) to assemble a team of Louisiana-based academic and private sector experts to "collect forensic data related to the failure of the levee systems around greater New Orleans" that occurred during passage of Hurricane Katrina on the morning of 29 August 2005. This group, later known as 'Team Louisiana,' was to focus on the hurricane protection system (HPS) designed and constructed over a 40-year period by the U.S. Army Corps of Engineers (USACE) for the East Bank of the Greater New Orleans area (GNO), including New Orleans East and St. Bernard Parish.

One way to look at the Katrina event is as a catastrophic natural disaster, and, with respect to the magnitude of the storm surge, it was. This approach tends, however, to minimize the engineering contribution to the direct or indirect loss of as many as 1,500 Louisiana residents (including the over 130 still missing as of December 2006, most considered swept away and drowned). Over 100,000 families were rendered homeless, making the destruction of New Orleans the worst from that perspective since the record Mississippi River flood of 1927. The response of the Nation to that natural disaster, even though it cost far fewer human lives, came in the form of an unprecedented engineering program to ensure that the flooding of the Lower Mississippi Valley would never happen again. The federal HPS that was authorized in 1965 to protect New Orleans following Hurricane Betsy had the same goal, but was clearly ineffective. It is important to understand why.

From an engineering perspective, forensics science is the study of materials, products, structures or components that do not operate as intended. In the context of the flooding of New Orleans, the purpose is to understand, first, what performance was expected from the GNO HPS and, second, to identify causes of failure as part of an effort to improve future performance.

Team Louisiana was asked, more specifically, to develop a time-history of surge and wave elevations for levee and floodwall reaches that failed, to compare this information to the designed and actual levee crown and floodwall crest elevations, and to assemble and examine all relevant design memoranda, construction plans and as-built surveys. In addition, Team Louisiana was asked to participate in debriefing of eye-witnesses, assembling stopped clock data, collecting aerial and ground level photographic evidence, and conducting non-destructive testing to determine soil foundation conditions and sheetpile depths in the vicinity of floodwall breaches.

At the time that Team Louisiana was commissioned, researchers from the LSU Hurricane Center had already fielded a reconnaissance effort that had uncovered apparent discrepancies between what was observed and early USACE statements about the causes of levee and floodwall failures. Following public discussion of these findings, three other investigations were organized by external groups as diverse as the University of California, Berkeley and the American Society of Civil Engineers, as well as by the USACE itself. These investigative teams included few scientists or engineers from Louisiana. Secretary Johnny Bradberry of the LDOTD saw a need for an official state-sponsored initiative to ensure that state and local perspectives were not ignored as the investigations proceeded.

The external study teams, particularly the Independent Levee Investigation Team (ILIT) that grew out of the UC Berkeley initiative, and the Interagency Performance Evaluation Team (IPET) sponsored by the USACE, concluded their work and issued final reports earlier this summer. The findings of these investigations differ with respect to some details, but generally concur on the specific mechanisms of most of the foundation-related floodwall failures. It is not surprising, however, that from a local perspective, these external probes appeared to miss some of the context in which the design and construction of the still incomplete federal HPS – originally planned to take 13 years at a total cost of less than $90 million – stretched out over 40 years.

The GNO HPS project employed two generations of USACE employees at an estimated total cost more than $700 million, while consuming nearly $200 million in locally generated funds. Over this time, the USACE provided local sponsors with many conflicting claims, but few reliable assurances, of the actual level of protection being provided. The cost to repair the GNO HPS to pre-storm condition has cost as much in the year since Katrina as was spent in the previous 40 years. The repaired HPS still provides a substantially lower level of protection than was originally authorized in 1965. Given this history, the multi-generational tension between the USACE and those being protected in the GNO is complex and easily misunderstood. It is hoped that this report will enrich the historical record and provide additional local perspective.

Dr. Ivor van Heerden, Director of the Center for the Study of Public Health Impacts of Hurricanes and Deputy Director of the LSU Hurricane Center, was selected to lead these efforts. Dr. van Heerden recruited three other LSU scientists including an oceanographer, a hydraulic engineer, and a geotechnical engineer. This group of academic researchers was significantly augmented by the addition of three senior engineers from the private sector. These members included two geotechnical engineers and a water resources engineer who had each participated in the design of numerous flood control works in the GNO area across the entire 40 year evolution of the Lake Pontchartrain and Vicinity Hurricane Protection Project.

The surge generated by Hurricane Katrina, a Saffir-Simpson Category 3 storm on landfall, is unprecedented in U.S. history. There is a potential for any forensics investigation to convey an apparent omniscience derived from 20:20 hindsight, and to lose sight of key points like this one. We have tried to avoid this trap by focusing on what was known at the time the GNO HPS was designed, the analytical tools that were available then, and what tools were used.

On the other hand, engineers – then or now – all work with uncertainty and follow accepted practice to account for unknowns that increase the risk of failure. As one of our senior engineers pointed out, it is the anomalous stratum, rather than the average soils condition, that generally causes foundation failure. Engineers address these uncertainties in levee and floodwall design by adding freeboard to raise crown elevation beyond the minimum specified, by inflating the stress to be resisted by a "factor of safety" sufficient to account for unknowns, and by incorporating redundant measures to limit the effect of the failure of a single component. These are some of the key features that distinguish a safe system from one that is unsafe. Such elements are the focus of this investigation.

This report is organized in two parts. The first part provides background information critical to understanding the physical and historical setting relevant to flood protection and drainage; the magnitude and sequence of stresses placed on the HPS by Hurricane Katrina; and the nature of the flooding that directly or indirectly led to the loss of as many as fifteen hundred Louisiana residents, and the destruction of much of New Orleans. The second part addresses the forensics issues as we see them. The following key questions were formulated to guide the forensics investigation. Each is discussed briefly here, and examined in more detail in a separate section of this report.

1. Was the GNO HPS properly conceived to accomplish the 1965 Congressional mandate to protect against the "most severe combination of meteorological conditions reasonably expected?"
2. Were the levels of protection, or crown elevations, specified in designs for HPS elements sufficient to resist overtopping by surge and waves associated with the 100-year Standard Project Hurricane?

3. Did incorrect design assumptions compromise performance? Should these have been detected and corrected by engineers equipped with the tools available at the time?
4. Did the Mississippi River Gulf Outlet (MRGO), a free-flowing, deep-draft navigation canal that pierced the HPS on the eastern side, compromise system performance?
5. Was the system maintained and operated to assure the required level of protection through time? Specifically, how did the 40-year construction schedule impact system performance?

Question 1. Was the GNO HPS properly conceived to accomplish the 1965 Congressional mandate to protect against the "most severe combination of meteorological conditions reasonably expected?"

Answer 1. No. The initial meteorological and oceanographic analysis based on the 1959 U.S. Weather Bureau 1 in 100 year Standard Project Hurricane (SPH) was known to be obsolete by 1972, just as construction of initial parts of the GNO HPS was getting underway. The primary deficiency of the 1959 SPH was in the specification of maximum sustained wind speed, which the National Weather Service (NWS) had increased by 20 percent, from 107 to 129 mph. The steady-state analytical approach used by the USACE to develop surge estimates was as sensitive to the effect of wind velocity as later numerical modeling approaches (i.e. SLOSH or ADCIRC), and should have alerted the USACE to the danger of underestimating wind speed. This analysis provided a design basis for setting the minimum heights above mean sea level for levee and floodwall crowns to resist overtopping by combined SPH waves and surge. A 20 percent underestimate of maximum winds can lead to a 40 percent reduction in the predicted surge elevation. In 1979 the NWS raised the maximum sustained winds to 140 MPH, a category 4 hurricane!

The New Orleans District USACE was aware of this deficiency in the original analysis, as is indicted by testimony in 1976 and 1982 General Accounting Office (GAO) reports, but never revised the original SPH-based analysis to reflect the new understanding of the threats, even after being ordered to do so by the Chief of Engineers in 1981 (ER 1110-2-1453). New Orleans residents were not advised that the GNO HPS required significant improvements to meet 1 in 100 year SPH requirements, but, instead, the New Orleans District claimed at times that the GNO HPS would protect against a 1 in 200 to 1 in 300 year hurricane. No basis for this claim has been established, while numerous storms that have affected the GNO area – before and after the 1965 initiation of the HPS -- were more severe than the 1959 SPH.

The New Orleans District (NOD) USACE missed opportunities to revise the original SPH-based analysis after the NWS revised the SPH in 1972 and 1979, and when the SLOSH storm surge model came into use in 1979. SLOSH showed clearly that the GNO HPS, as it was constructed at the time, was vulnerable to overtopping by many possible Category 3 storms. This result was confirmed later by the ADCIRC model, as recently as during the 2004 FEMA Hurricane Pam exercise (http://hurricane.lsu.edu/floodprediction/PAM_Exercise04/). The USACE supported development of both surge models and was aware of GNO HPS vulnerabilities, but appeared to accept the inadequacy of the system with a complacency that undercut efforts to sound alarms and begin pressing for improvement.

Question 2. Were the levees and floodwalls at or above the crown elevations specified in designs for HPS elements necessary to resist overtopping by surge and waves associated with the Standard Project Hurricane?

Answer 2. No. Floodwall and levee crown elevations were built 1 to 2 ft low because of an erroneous assumption at USACE New Orleans District (NOD) that an elevation of zero referenced to the National Geodetic Vertical Datum of 1929 (NGVD29) was equal to -- and interchangeable with -- local mean sea level (LMSL). LMSL was the relevant datum for superimposition of hurricane surge and wave height from a 1950's era oceanographic analysis. In 1965, zero NGVD29 was between 1.3 and 1.6 feet below LMSL at different parts of the system, and floodwalls and levee crowns were constructed lower by this margin. This mistake was locked in for continuing HPS construction when the NOD adopted a policy in 1985, with the approval of the USACE Lower Mississippi Valley Division (LMVD), to explicitly use the outdated 1965 NGVD29 adjustment for elevation control. As a result, no provision was made to account for the 3 to 4 ft/century subsidence rates characteristic of the GNO area even though this rate was known at the time of authorization. Crown elevation deficiencies ranging up to 5 feet at the time Katrina struck resulted in prolonged overtopping of floodwalls and levees along the Inner Harbor Navigation Canal (IHNC) and to the east in the Lake Borgne funnel that otherwise would have been overtopped only briefly. Prolonged overtopping led to catastrophic breaches into the Lower 9th Ward on the east and into Orleans Metro on the west, and contributed to the early failures of levees along the Gulf Intracoastal Waterway (GIWW) and MRGO. Early failure of the MRGO levee allowed the 32,000 acre wetland buffer between MRGO and 40 Arpent back levee to fill and overtop the 40 Arpent back levee while the surge was still rising, and resulted in catastrophic flooding in St. Bernard to an elevation of 11 ft (NAVD88).

Question 3. Did the USACE follow existing engineering practice and USACE guidance for construction of levees and floodwalls? Should issues about levee materials and floodwall designs have been detected and corrected by engineers equipped with the tools available at the time of construction?

Answer 3. No to the first question, and yes to the second. Weak soil strengths or potential for underseepage were evident in strata tested for the USACE during the early 1980s under Orleans Metro drainage canal floodwall levees that failed. The potential consequences of these layers on levee stability were known to practicing engineers at the time but were missed or ignored because of inappropriate averaging of soil strengths on long levee reaches and across layers. Design engineers assumed that consolidation of soils beneath the I-wall levees on the 17th Street Canal would have increased soil strengths over time, but borings and soundings conducted since Katrina show that very soft clays in the failure zone have strengths less than values assigned in 1981. Where Division-level reviewers identified potential problems, they were rebuffed by District personnel citing "professional judgment."

The New Orleans District USACE failed to conduct appropriate analyses of the potential for seepage to compromise levee and floodwall stability where shallow sand deposits occurred beneath the levee, such as at the London Avenue Canal. Design memoranda indicate reliance upon the Lane's Weighted Average Creep method for underseepage analysis. This method was recognized in the profession at the time to be inappropriate for final design in a critical life-support structure. The presence of layered sands and clays should have led to analysis using more rigorous flow net and finite-element techniques in widespread use at the time, and specified in the governing USACE engineering manual for Design and Construction of Levees (EM 1110-2-1913, 1978 ed.). Sheetpile supported I-walls that were installed on levees with cross-sections too small to prevent underseepage also did not provide sufficient resistance when fully loaded, no matter what the sheetpile length. There is no evidence that rigorous analysis of uplift pressures was undertaken.

Idealized design templates were applied to long levee and floodwall reaches without adjustment for variable subsoil conditions or for variations in elevation on the protected side. IPET believes that such a mistake caused the levee supporting the I-wall levee to be constructed improperly in the vicinity of the north breach into the Lower 9th Ward, where the ground elevation on the protected side was lower. The foundation may have failed early in the storm sequence at a water elevation well below the design level of protection because of inadequate resistance.

The New Orleans District USACE did not follow standard engineering practice or Corps guidance when evaluating whether to protect (armor) earthen sea dikes from erosion caused by waves in the funnel area east of the city. Such evaluations should have followed the 1954 TR-4 Shore Protection Planning and Design (Beach Erosion Board) or its successor, the Shore Protection Manual, first published in 1973. Instead of the required analysis, Design Memoranda for the New Orleans East and Chalmette Levees substitute the following disclaimer.

> "Due to the short duration of hurricane flood stages and the resistant nature of clayey soils, no erosion protection is considered necessary on the levee slopes."

These levees were not designed to withstand general overtopping, as was amply demonstrated in Katrina, but were expected to experience overtopping by waves greater than the significant wave provided in the oceanographic analysis. Many miles of the Chalmette and New Orleans East Levees were constructed of shell-rich sands with poor erosion resistance derived from the hydraulic excavation of the adjacent GIWW and MRGO channels, rather than the hauled clay soils specified for levees protecting urban areas (EM 1110-2-1913, 1978 ed.).

Question 4. Did the free-flowing, deep-draft navigation canal that pierces the HPS on its eastern side compromise system performance?

Answer 4. Yes. The MRGO and GIWW channels provide efficient conduits to funnel surge into the heart of New Orleans. As a result, surge elevations peaked in Lake Borgne and the IHNC almost simultaneously at higher levels relative to levee and floodwall crowns, and earlier, than would have been true if the MRGO had not been built, and if the wetland loss it caused had not occurred. The effect of these federally constructed and operated channels on surge and waves has consistently been underestimated by the USACE from before Hurricane Betsy, right through to the recent IPET report, as has the effect of accelerated wetland loss in the funnel area. One consequence of this institutional "blind spot" was that a hurricane barrier of the type proposed in the original pre-1980s HPS for the other two main passes into Lake Pontchartrain was never included for the MRGO.

The ILIT and IPET have indicated that the original "barrier" approach was a better design than the "high-level," levees-only HPS ultimately adopted twenty years after authorization. But our work indicates that disastrous flooding during Katrina from the Lake Borgne funnel and the IHNC would have been exacerbated by the barrier proposed at the Lake Pontchartrain terminus of the IHNC (Seabrook). On the other hand, the Lake Pontchartrain surge along the south shore might have been reduced by up to 3 ft, and by a greater margin on the north shore, by the barriers that were proposed for the two other Lake Pontchartrain passes. This might have been enough to prevent one or more of the failures of the defective Orleans Metro drainage canal floodwalls built in the 1990s, and this would have greatly reduced the severity of prolonged flooding in Orleans Metro. Such trade-offs were never rigorously assessed when the decision was made to change the HPS design in such a major way in 1985 at a time when surge modeling techniques using SLOSH were available. Again, the level of protection was reduced without informing the population at risk.

Question 5. Was the system maintained and operated to assure the required level of protection through time? Specifically, how did the 40-year construction schedule impact system performance?

Answer 5. No. The GNO HPS was managed like a circa 1965 flood control museum. Design assumptions and policy made in 1965 continue to diminish the HPS today. Local sea level has risen 0.4 ft since the 1960s and much of New Orleans has sunk over 1.5 ft in the same period for a combined change of nearly 2 ft relative to sea level, but as IPET (II-78) noted,

> "It was not clear how projected subsidence rates were applied in structural elevation design, if at all. Subsidence was apparently not factored into the design freeboard allowance."

Prudent engineers operating in coastal Louisiana have made allowances for subsidence for a century. The New Orleans District was one of the first agencies to directly map coastal wetland loss in Louisiana, but this ever continuing diminishment of surge protection was never incorporated into design philosophies. An analysis of all factors affecting levee elevation is required as part of FEMA Levee Elevation and Certification Requirements (44CFR65.10). It is inexcusable that this was not done for what was the most critical urban coastal protection project in the country.

Most public works structures would be scheduled for replacement or rehabilitation after 40 years, but planning for a more modern system was put off while the original project fell farther and farther behind. Because the USACE never completed the 1965 project, it could not legally pass responsibility for major maintenance or upgrades to the local sponsors, or initiate a new project to bring protection to a higher standard. Local sponsors kept levees and rights of way mowed, operated drainage structures, commented on USACE design memoranda, and participated in inspections. They were not, however, consulted on design or construction decisions. On the other hand, they were required to pay 30 percent of all costs incurred for a level of protection that appeared on some reaches to diminish over time. When Katrina struck, the crown height on most levee and floodwall reaches was between 1 and 3 ft low relative to current mean sea level, the only datum that is relevant to the oceanography of hurricane waves and surge. On the IHNC and MRGO, every foot of crown deficiency when the surge was above 11 ft meant that overtopping and levee erosion started a half hour earlier. A half-hour in the lifetime of a moving hurricane can mean the difference between success and failure.

Lessons of Forensics Findings

The design assumptions for the GNO HPS remained static despite growing scientific evidence that the threat posed by surge was actually far greater than originally estimated. Design histories for individual HPS elements showed a pervasive trend over time toward substitution of less reliable structures for more conservative designs. On a regional perspective, management of the Lake Pontchartrain and Vicinity project led, over time, to ever greater departures from the overall objective of the original authorization, to protect against the ***"the most severe meteorological conditions considered reasonably characteristic for that region."*** This Congressional objective could be read as a mandate for continual reevaluation and adjustment.

In fact, the project did evolve in a different way, as it grew to incorporate greater undeveloped areas to the east and west of the City and as the original barrier plan was abandoned in favor of the "high-level" levees-only alternative. So, the original project was changed in fundamental ways without rigorous analysis of the trade-offs in level of protection afforded and reliability. The 1984 Reevaluation, inspired by court decisions questioning whether the environmental impacts of the proposed Lake Pontchartrain barriers had been adequately assessed, could have been seen as an opportunity to critically examine the overall integrity and reliability of the system, and to improve the design (USACE 1984). Instead, the USACE concluded that it would cost more to leave out undeveloped wetlands than to continue the construction already started on the longer routes initially chosen to aid private drainage and development efforts.

In contrast to this history of expansion and modification, other decisions were made within the USACE organization presumably to control costs that were rationalized as a meticulous adherence to the largely discarded 1965 authorization. Contractors were required to use outdated benchmark elevations during construction, for example, while the erroneous substitution of the NGVD29 datum for the mean sea level datum specified in the original SPH oceanographic analysis – like that analysis itself -- never got a second look.

Role of Local Governments, Levee Boards and the State

Interactions between the USACE and local cooperating or sponsoring agencies affected the design of protective structures like the parallel floodwalls along the banks of the

Orleans Metro drainage canals. Although the federal government had overall responsibility for the GNO HPS, the slow pace at which federal funds were made available ($3 to 5 million per year) led local agencies and their contractors to take a lead in many cases to get work started with local funds. As has been discussed, the USACE escalated the protection claimed for a completed Lake Pontchartrain and Vicinity Project from the 100-year to the 300-year storm level without changing any proposed structures. This claim led local engineers to believe that designs originally proposed for some HPS elements were excessively conservative, and that an adequate system could be constructed more quickly and at lower cost without significantly sacrificing performance or reliability. In contrast, most investigators who have reviewed the designs after Katrina have concluded that factors of safety applied by the USACE were anything but conservative given the criticality of subsurface soils and the consequences of failure.

Levee districts are state commissioned entities advised on engineering issues by the LDOTD. LDOTD assumed this function after a reorganization in which it absorbed the duties of the earlier Louisiana Department of Public Works in 1978. The levee districts have the authority to raise funds within their boundaries for flood protection projects. They have typically been the cost-sharing sponsors for development of jointly funded federal hurricane protection systems. They also assumed limited responsibilities for maintenance of portions of the federal system that the USACE decided were "substantially" complete, if not actually finished.

Another important factor came into play, however, after the National Flood Insurance Program (FIP) was established in 1968. Local governments sought to enhance economic growth by encouraging residential and commercial construction in new areas, often former wetlands, which were ringed by relatively low levees and subject to pumped drainage. With the advent of the FIP, development in these newly drained areas could proceed only if those who purchased properties there could also protect that investment with federal flood insurance. The Federal Emergency Management Agency (FEMA) would permit new areas to enter the FIP only if the levees and drainage system could be certified as providing protection against both the 100-year storm surge and 100-year rainfall event.

In the GNO, FEMA relied upon the USACE to provide engineering evaluations of flood risk in areas protected by both federal and non-federal levee systems. So local governments, rather than the levee districts, entered into discussions with the USACE to find out what minimal levee heights were necessary for certification against the 100-year surge event. If the USACE found that the perimeter levee system was high enough to prevent overtopping, then FEMA generally accepted this finding without requiring geotechnical or construction information normally called for to meet FEMA levee standards (44CFR65.10).

Once the USACE determined that the levees were adequate, or, quite often, slated to become adequate sometime in the future, the "protected" areas were then analyzed only for the capacity of the internal drainage system to remove rainfall. The probability that the perimeter levee would be breached or overtopped was not considered. The internal drainage capacity was then used to determine the Base Flood Elevation (BFE) that governed how high buildings had to be elevated, and the location of flood zones on the Flood Insurance Rate Maps (FIRMs). Development accelerated once BFEs and FIRMs were issued. Thousands of people moved into suburban areas on the outskirts of the GNO in some cases before levee and drainage systems were complete or fully functional.

The IPET found that the GNO HPS failed to function as a system, but from a local perspective the HPS was successful for decades as a multi-purpose economic development tool that had an important role in facilitating drainage. Extreme rainfall events were far more frequent than hurricane surges, and apparently could be addressed, at least in the short-term, without a complete SPH-level hurricane protection system in place. Local officials were all too ready to believe glib assurances from the Nation's premier civil engineering organization that they were well protected against 100-year hurricane flooding.

Where Things Stand Today

The Lake Pontchartrain and Vicinity project employed generations of USACE employees and contractors at an estimated total cost of more than $500 million, while consuming nearly $200 million in state and locally generated funds. Prior to Katrina, it was estimated to be about 85 percent constructed, but was not expected to reach completion until 2015. A similar West Bank and Vicinity project had been initiated on the other side of the river in 1986 after serious flooding associated with Hurricane Juan. The West Bank HPS was expected to cost $330 million, again with a 35 percent local cost share, and was only 38 percent built prior to Katrina. Though it started much later, it was scheduled to be completed only a year after the east bank HPS. This much less capable system was not tested in 2005 to the same degree as the east bank HPS.

The pre-Katrina combined estimate of cost to complete the east and west bank GNO hurricane protection systems, a total of about $1 billion, can be compared with costs recently compiled by the USACE for emergency repairs to the two projects since Katrina, and with estimates of additional expenditures necessary to achieve a more realistic 100-year level of protection. Emergency repairs carried out by USACE contractors in the year since Katrina to return the GNO levees and floodwalls to the pre-storm condition have cost between $400 and $600 million, if the interim lakeshore drainage canal closures are included.

The repaired HPS still provides a substantially lower level of protection than that originally authorized in 1965. Dr. Bob Bea, Co-Director of the University of California, Berkeley, Center for Catastrophic Risk Management, and an ILIT member, recently pointed out that "the repaired sections of the hurricane protection system are the strongest parts," but that "strong pieces embedded within weak pieces do not translate to a reliable system" (Bea 2006). Currently authorized projects to construct permanent lakeshore closures with pumps for Orleans Metro drainage canals will add an additional $100 to $200 million. Surge gates for the IHNC and MRGO are expected to cost at least $200 million more.

It is evidence of how pervasively under-built the system was that it has cost as much after Katrina to repair the GNO HPS to a marginally stable pre-storm condition as was spent in the previous 40 years. The USACE now estimates that between $2 and $4 billion will actually be required to achieve the minimal 100-year level of protection generally required for participation in the Federal Emergency Management Agency (FEMA) flood insurance program. The level of protection that this will achieve should not be confused with the much higher Category 5 hurricane protection now being studied by the State and USACE. That will cost much, much more.

The Barrier Plan Revisited

One of the flaws of the Lake Pontchartrain and Vicinity Project authorized in 1965 is inherent in its name. The primary threat to New Orleans at the time the oceanographic analysis was being conducted in the 1950s -- prior to the construction of the MRGO and before most of the suburban development in New Orleans East and St. Bernard -- was always seen as coming from the Lake. This is apparent in the planned Seabrook structure, which, had it been in place during Katrina, would have been as useful as the French Maginot Line in World War II, addressing a threat coming from the wrong direction. The highest storm surges that have caused flooding in the GNO since Hurricane Betsy have always come from Lake Borgne rather than Lake Pontchartrain, and this is likely to remain the most probable scenario going forward.

Today, the USACE seeks funds to rebuild flood defenses for a ruined city that will offer a level of protection originally conceived in the late 1950s. The evolution of the Standard Project Hurricane shows that this level of protection was known to be inadequate by at least the early 1970s. Since Katrina, elements of the 1950s era plan that were not built , notably the tidal pass closure structures, have been retrieved from mothballs, and are now being included in virtually all restoration plans. Given this impetus, Team Louisiana used the ADCIRC model to see how these closures would have affected performance during Katrina.

Results do not show the large reductions in surge in Lake Pontchartrain that some have suggested, except along the north shore, where they would certainly have helped. Elsewhere around Lake Pontchartrain, the more important effect would have been to reduce the cumulative volume of flooding through the drainage canal breaches over the next two days. Lake elevation along the south shore with the barriers in place would have dropped to its normal level within hours, instead of taking more than two days.

The lake closure at Seabrook, on the other hand, would have prevented drainage to Lake Pontchartrain of the surge coming in from Lake Borgne and caused more damage due to overtopping and breaching of levees along the IHNC. The model predicts that the greatest increase, over 3 feet, would have been observed just south of the Seabrook structure, but an increase in the surge maximum of a foot or more would be spread over a very large part of the MRGO funnel as water that actually drained to Lake Pontchartrain during Katrina was trapped.

Looking Ahead

The integrated levees and barrier structures now being proposed to provide "Category 5" protection to the GNO by state and federal agencies are similar in many ways to the barrier plan proposed in the late 1950s and authorized after Hurricane Betsy. Clearly, redundant flood protection features can be built to improve reliability. The same can be said about multiple levee lines separated by restored wetland areas designed for short-term storage of surge waters. It appears, however, that most of the proposals being presented continue to rely on legacy levees, which, though they may be built higher, are likely to suffer from legacy flaws. Katrina has taught that the long-term reliability of such structures cannot be assured, given the exposure to surge and wave that must now be assumed.

The experience with the Chalmette levee along the south bank of the MRGO is instructive. The reasons that it failed as early as it did can be debated, whether due to design or construction, but the result is indisputable. Ultimately, the USACE found that it could not retain this earthen structure at the design grade despite two major augmentations in the late 1970s and mid-1980s, and a less extensive rebuilding in the early 1990s. Efforts to improve reliability by armoring the recently rebuilt MRGO levee have been hampered by awareness that the new embankment will require additional lifts at relatively short intervals to counteract erosion and settlement, before it reaches a less dynamic condition. This remediation would be complicated by the need to repeatedly remove and replace armor installed on the levee slopes and crown.

The only structures that survived on the Chalmette levee run were the water control structures at Bayous Bienvenue and Dupre. They were left by the storm as islands of solidity in a sea of destruction. One of the most important lessons of Katrina was that pile-supported structures like these, as well as T-walls used sparingly elsewhere in the GNO HPS, were capable of surviving the worst that Katrina could deliver.

Team Louisiana members have been excluded from the planning for Category 5 protection now in progress. Some USACE-IPET investigators have apparently been engaged for this work, however, so it is hoped that information derived from study of Katrina levee failures will, one way or another, have an impact on what is built in the future. Our study tells us that failure is not inevitable, but must be actively guarded against. Proposals for more reliably protecting the eastern side of New Orleans can be derived both from study of the GNO HPS failures during Katrina, and from inspection of more reliable structures that have been built elsewhere. Dutch engineers would undoubtedly propose a modular, pile-supported structure like the Oostershelde closure across the 'funnel,' for example, to reduce the threat of surges originating in both of the lakes that flank New Orleans. The Oostershelde closure is an elevated causeway supported by concrete piers providing guides for vertically sliding closure gates that would be lowered only when a storm approaches. It is surely time for this type of creativity, and not just in New Orleans, if we are to honor the 1,500 who lost their lives during Katrina, and avoid more costly mistakes in the future.

Introduction

Louisiana is more vulnerable to hurricanes and major flooding than any other state. Prior to Katrina, 70 percent of the population lived on 36 percent of the land, much of which is at or below sea level. This includes portions of cities such as New Orleans, Houma and Morgan City. It has been known for at least a decade that the bulge of water, or "surge," pushed ashore by a Saffir-Simpson Category 3 hurricane, approaching at a range of speeds from a number of directions, could overtop New Orleans flood defenses on both the east and west banks of the Mississippi (van Heerden 1999, *Times-Picayune* 2002, IEM Inc. 2004, Brouwer 2003).

Hurricane Katrina made landfall in Louisiana as a relatively fast-moving Category 3 hurricane at 6:10 am on Monday, 29 August 2005 (Figure 1).

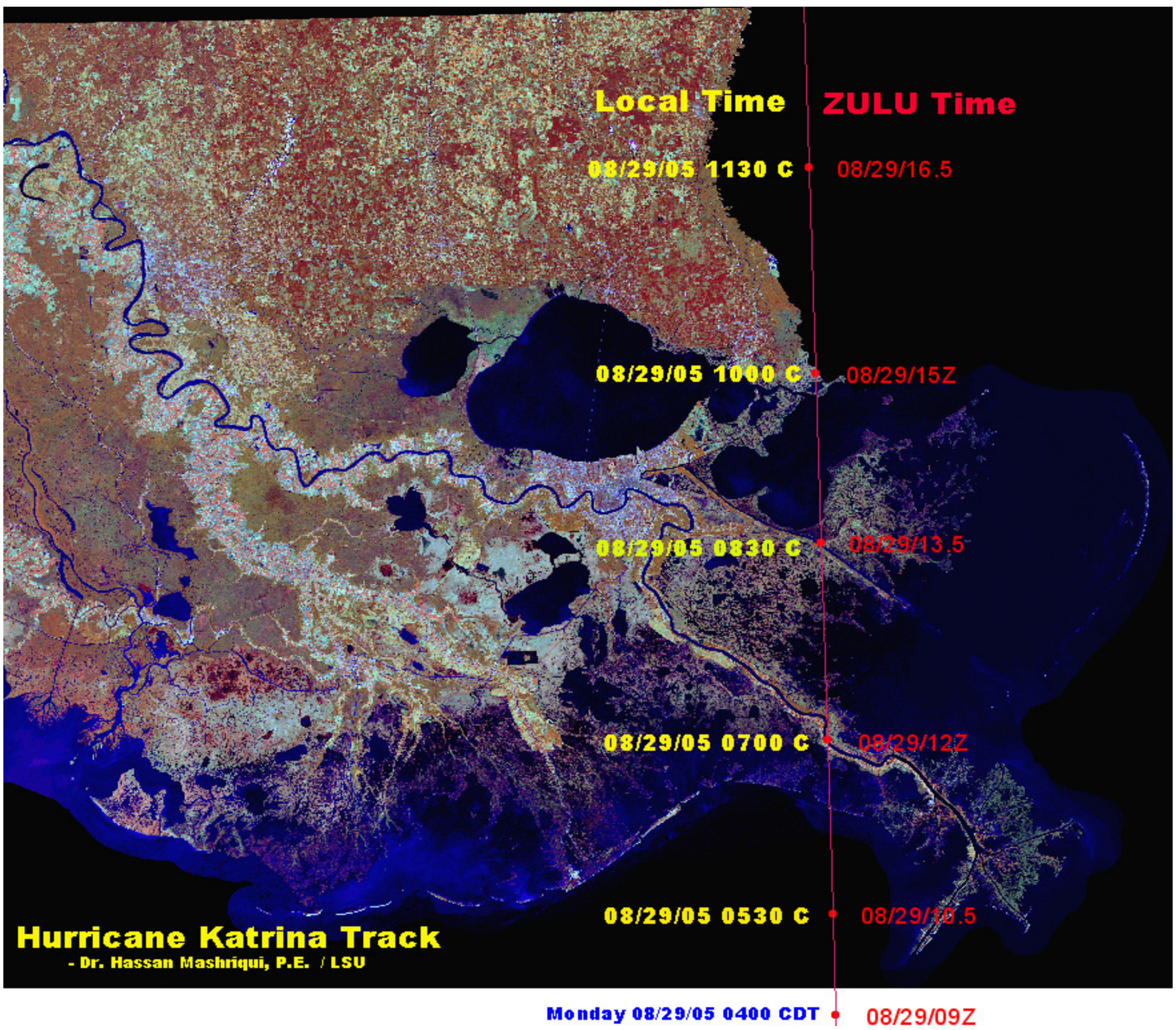

Figure 1. Advance of Hurricane Katrina from first landfall in coastal Louisiana through second landfall in Mississippi (LSU Hurricane Center).

As the storm bore down on Louisiana, LSU Hurricane Center (HC) researchers issued computer generated ADvanced CIRCulation model (ADCIRC) storm surge forecasts, predicting levee overtopping on the east and west sides of the city, to the Louisiana Office of Homeland Security and Emergency Preparedness (LOHSEP) Emergency Operations Center (EOC); a large email list serve; and the media. The Times-Picayune newspaper, in New Orleans, carried a graphic on Sunday morning that showed these forecast results, but also depicted the possibility of overtopping of lakefront levees (Figure 2). It is believed that this information encouraged compliance with evacuation orders.

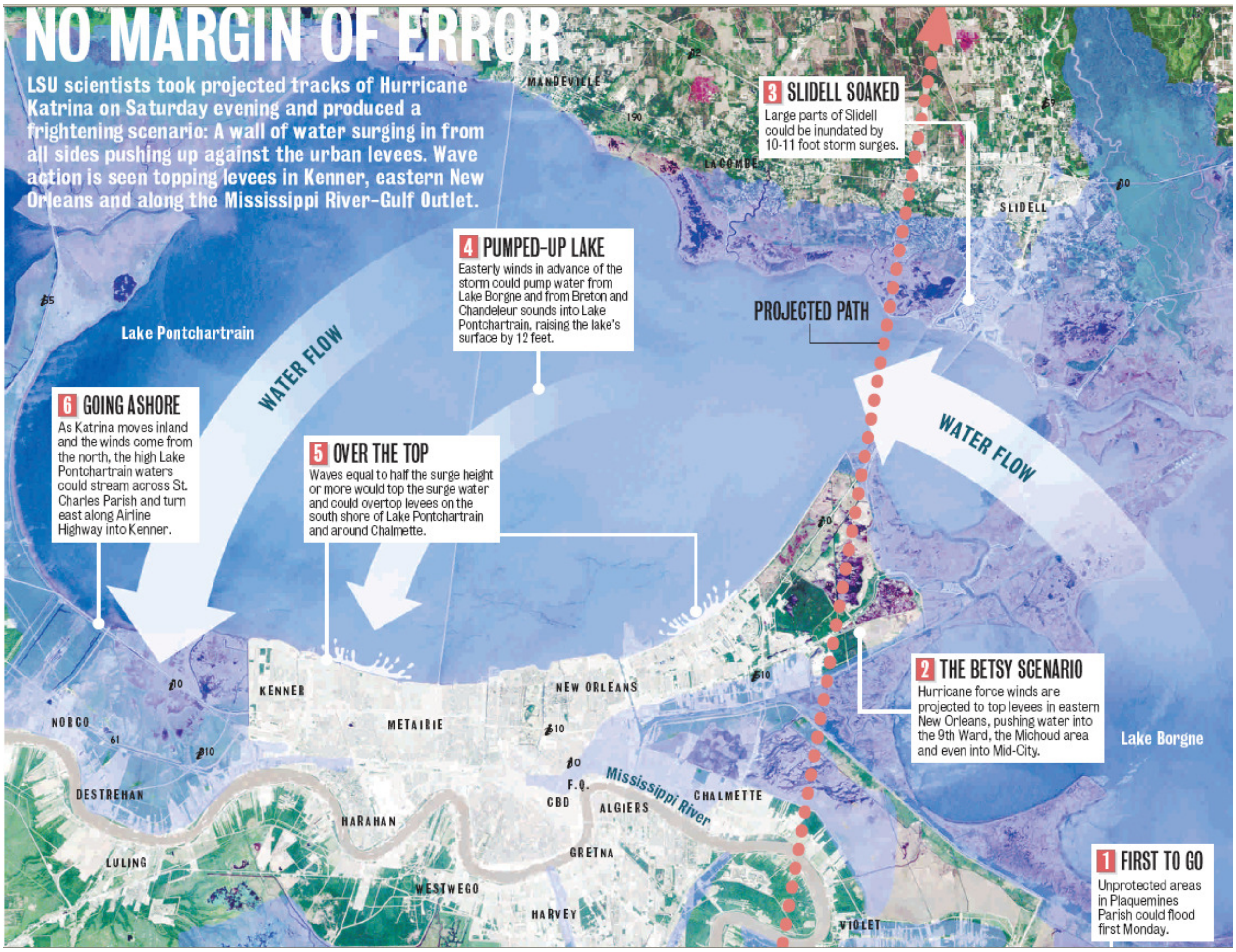

Figure 2. Graphic that appeared in the Sunday morning (August 28, 2005) edition of the New Orleans Times-Picayune newspaper, showing LSU predictions of overtopping (courtesy of the Times-Picayune).

Of the populated areas that constitute Greater New Orleans (GNO), 80 percent of Orleans Parish, 99 percent of St. Bernard Parish, and approximately 40 percent of Jefferson Parish were flooded, in some cases for weeks. This flooding may have either directly or indirectly cost the lives of as many as 1,500 Louisiana residents. However, the true loss-of-life of this disaster still remains uncertain. The Louisiana Department of Health and Hospitals (DHH) Louisiana Family Assistance Center, which closed down almost a year after the storm, found and reunited thousands but approximately 130 missing remain as of December 2006 (though most are considered drowned); while the New Orleans Fire Department and others continue to recover the remains of deceased victims from the rubble of destroyed homes.

Over 100,000 families were rendered homeless, the great majority of whom had heeded evacuation orders, making this disaster the worst since the 1927 Mississippi River flood in terms of homes destroyed. The hurricane protection system (HPS) that all residents of GNO depended upon for their security from surge floods failed catastrophically with over 50 breachings or breaks. Over 170 miles of the 350 miles of the levees that protected greater New Orleans were either destroyed or damaged (IPET 2006b).

After the storm tore through Mississippi, LSU HC scientists and engineers entered flooded New Orleans accompanied by police teams, to begin trying to reconstruct what had happened. ADCIRC model output guided these teams to specific locations where it was expected that surge conditions would have been most severe. Working initially with just laser levels and available LIDAR topography, they began to compile evidence of storm surge elevations outside the levees and flood walls of the hurricane protection system (HPS), seeking to identify high water marks (HWM) that had been relatively unaffected by wave action. It was quickly determined that the surge model output was remarkably accurate (most hindcast nodes at +/- 15% root mean square error RMSE, nearly 1:1), giving them confidence to begin to rule out some possible causes for key levee and floodwall failures including, at a number of breach sites, the assumption of overtopping-induced erosion. Insights gained in the first weeks after the storm before most other investigators arrived on the scene proved to be critical to understanding what had happened. During this critical period, evidence was observed that was quickly destroyed either in the rush to close breaches or by the natural decomposition of ephemeral features such as debris lines.

Formation of 'Team Louisiana'

The initial goal of the LSU HC field effort was to validate the ADCIRC model forecasts. It quickly became apparent that because of the extent of loss of life and the magnitude of the property damage, any discussion of surge elevations and the related causes of levee failures would not only be controversial, but also a potential basis for legal proceedings. In late September, Mr. Johnny Bradberry, Secretary of the Louisiana Department of Transportation and Development (LDOTD), initiated formation of a Louisiana forensics investigation team under the direction of Dr. Ivor van Heerden, Director of the LSU Center for Study of the Public Health Impacts of Hurricanes (also known as the Hurricane Public Health Center (HPHC)), to build on the initial LSU Hurricane Center efforts. Secretary Bradberry was joined in these efforts by Louisiana Attorney General Charles Foti.

LSU was commissioned in October 2005 by the LDOTD to assemble a team of Louisiana-based academic and private sector experts to "collect forensic data related to the failure of the levee systems around greater New Orleans" that occurred during passage of Hurricane Katrina on the morning of 29 August 2005. This group, later known as 'Team Louisiana,' was to focus on the hurricane protection system (HPS) designed and constructed over a 40 year period by the U.S. Army Corps of Engineers (USACE) for the East Bank of New Orleans, New Orleans East, and St. Bernard Parish. The LSU HC continued to provide assistance to Team Louisiana through a critical grant from the McKnight Foundation to cover additional team expenses.

By the time Team Louisiana was commissioned, the LSU HC had uncovered apparent discrepancies between their findings and early USACE statements about the causes of levee and floodwall failures (van Heerden & Bryan 2006). Following these reports, at least three other investigations were organized by groups as diverse as the University of California, Berkeley and the American Society of Civil Engineers, as well as by the USACE itself. These external investigative teams included few scientists or engineers from Louisiana. Secretary Johnny Bradberry of the LDOTD saw a need for an official state-sponsored initiative to ensure that state and local perspectives were not ignored as these external investigations proceeded.

An important secondary purpose of Team Louisiana was to energize investigations by the external teams that had greater access to necessary resources, and to encourage these teams to conduct an expeditious and comprehensive review of the causes of the disaster while the evidence of failure was still accessible for study. Team Louisiana members cooperated to varying degrees with the external teams. It is our assessment that the combined, and at times competitive, parallel efforts resulted in an unusually comprehensive treatment of a complex disaster in a relatively short period of time.

Scope of Work

From an engineering perspective, forensics science is the study of materials, products, structures or components that do not operate as intended. In the context of the flooding of New Orleans, the purpose is to understand, first, what performance was expected from the GNO HPS and, second, to identify causes of failure as part of an effort to improve future performance. Team Louisiana was asked, more specifically, to develop a time-history of surge and wave elevations for levee and floodwall reaches that failed, to compare this information to the designed and actual levee crown and floodwall crest elevations, and to assemble and examine all relevant design memoranda, construction plans and as-built surveys. In addition, Team Louisiana was asked to participate in debriefing of eye-witnesses, assembling stopped clock data, collecting aerial and ground level photographic evidence, and conducting non-destructive testing to determine soil foundation conditions and sheetpile depths in the vicinity of floodwall breaches.

Researchers from Team Louisiana have collaborated to a greater or lesser degree with all of the other investigative teams and have spent many hours in the field together with their members. Team Louisiana took a lead in ensuring that all teams agreed upon and used the same HWM survey data to eliminate any potential for confusion about how high the surge actually got. This was critical because a range of marks were originally available that were contaminated to a greater or lesser degree by wave action. As time progressed and as Hurricane Rita brought a second high water event to the scene on 24 September 2005, it was vital to get this database established before the perishable evidence disappeared. Drs. Stephen Maynord and David Biedenharn of the USACE Engineering Research and Development Center Coastal Hydraulics Laboratory (USACE-CHL) were particularly helpful in ensuring that these efforts were successful. While there has been some confusion regarding mean sea level and geodetic datums, there has been little disagreement among the teams about how high the water got either inside or outside of the HPS.

Composition of 'Team Louisiana'

Dr. Ivor van Heerden, Director of the HPHC, and Deputy Director of the LSU Hurricane Center, was selected to lead the State forensics effort. Dr. van Heerden recruited three other LSU scientists including an oceanographer, a hydraulic engineer and a geotechnical engineer. This group of academic researchers was significantly augmented by the addition of three senior engineers from the private sector, two geotechnical engineers and a water resources engineer, who each had participated in work associated with numerous flood control features in the GNO area across the 40 year evolution of the Lake Pontchartrain and Vicinity Hurricane Protection Project (Table 1).

External Study Teams

The external study teams, particularly the Independent Levee Investigation Team (ILIT) that grew out of the UC Berkeley initiative, and the Interagency Performance Evaluation Team (IPET) sponsored by the USACE, concluded their work and issued final reports earlier this summer (ILIT 2006, IPET 2005, IPET 2006a-c). The USACE also

Table 1. Members of Team Louisiana	
Ivor L. van Heerden Ph.D.	LSU Hurricane Center Department of Civil and Environmental Engineering, LSU
G. Paul Kemp Ph.D.	Natural Systems Modeling Lab, LSU
Hassan Mashriqui Ph.D., P.E.	LSU Hurricane Center Department of Civil and Environmental Engineering, LSU
Radhey Sharma, Ph.D.	Department of Civil and Environmental Engineering, LSU
Billy Prochaska P.E.	Retired professional geotechnical engineer
Lou Capozzoli Ph.D., P.E.	Retired professional geotechnical engineer
Art Theis, P.E.	Retired state construction engineer
Ahmet Binselam, M.S.	LSU Hurricane Center Department of Civil and Environmental Engineering, LSU
Kate Streva, B.S.	LSU Hurricane Center Department of Civil and Environmental Engineering, LSU
Ezra Boyd, M.A.	LSU Hurricane Center Department of Civil and Environmental Engineering, LSU

set up a review board under the auspices of the National Academy of Sciences with the assistance of the American Society of Civil Engineers (ASCE) that has issued findings (ASCE 2005, ASCE 2006a-b).

IPET had virtually unlimited funding and eventually encompassed the work of 150 government, academic and private sector scientists and engineers. The ILIT had very limited funding but grew to include more than 30 of the most capable levee scientists and engineers in the world, most contributing their time and expertise on a *pro bono* basis. The scope of the ILIT work was broader in some respects than that of any other team including ours. They carried out detailed technical investigations of the causes of failures, but also identified possible "dysfunctionalities" in the entire "Technology Delivery System," where they looked at cultural biases and apparent conflicts in and among the various governmental organizations that had responsibilities for designing, constructing and managing the HPS.

The findings of these investigations, and our informal collaboration with the investigators, have been vastly helpful to us. ILIT and IPET results differ in some details, but generally concur on the specific mechanisms of most of the foundation-related floodwall failures. **It is not surprising, however, that from a local perspective, these external probes appeared to miss some of the context in which the design and construction of the still incomplete federal HPS – originally planned to take 13 years at a total cost of less than $90 million – stretched out over 40 years. The project cost nearly $700 million, and consumed nearly $200 million in locally generated funds and services.** Over this time, the USACE provided local sponsors with many conflicting claims, but few reliable assurances of the actual level of protection being provided. **Repairing the GNO HPS to deliver the pre-Katrina level of protection has cost as much in the year since Katrina as was spent in the previous 40 years.** It is not surprising, then, that the relationship evolving over two generations between the USACE and those being protected is complex and easily misunderstood. It is hoped that this report will enrich the historical record and provide additional local perspective.

Team Louisiana Forensics Approach

The surge generated by Hurricane Katrina, at one point a Saffir-Simpson Category 5 storm which eventually came ashore in Louisiana and Mississippi at Category 3 strength, are unprecedented in U.S. history. To give one indication, Katrina generated the largest significant wave height (the average height of the top third of all recorded wave heights) ever measured by a National Data Center Buoy. The recorded wave height was 55 feet, just hours before landfall, registered at a buoy less than a hundred miles south of Dauphin Island, Alabama (Knabb et al. 2006). There is a potential for any forensics investigation to convey an apparent omniscience derived from 20:20 hindsight, and to lose sight of key points like this one. We have tried to avoid this trap by focusing on what was known at the time the GNO HPS was designed, the analytical tools that were available then, and what tools were used.

On the other hand, engineers – then or now -- must all deal with uncertainty and follow accepted practice to account for unknowns that increase the risk of failure. As one of our senior engineers pointed out, it is the anomalous stratum, rather than the average soils condition, that generally causes foundation failure. Engineers address these uncertainties in levee and floodwall design by adding freeboard to raise crown elevation beyond the minimum specified, by inflating the stress to be resisted by a "factor of safety" sufficient to account for unknowns, and by incorporating redundant measures to limit the effect of the failure of a single component. These are some of the key features that distinguish a safe system from one that is unsafe, and are the focus of this investigation.

Failure can occur when a system is stressed beyond what it was designed to resist. It is important, then, to know whether the design criteria were appropriate given the risks known at the time, and the level of performance required.

It is also important to ascertain whether any particular failure occurred before or after the design limit was attained. It is possible that a stress may occur during an event that challenges the design, but that failure or weakening took place before this critical stress was reached.

Finally, an adequate and appropriate system design may be compromised by poor construction and maintenance. The documentation of fraud or negligence can be critical in these instances, but the path to better future performance is relatively clear.

In another category are failures that take place because a system is under-designed. This situation can arise when risks and failure mechanisms that should have been known at the time are either ignored or underestimated. While an under-designed system may be rendered even less effective by poor construction or maintenance, design deficiencies can ultimately render these factors largely irrelevant. Such a flawed system cannot perform properly regardless of how well it is constructed or maintained. The path to recovery is more difficult when a design problem is discovered than when the issues arise during construction and maintenance. Design failures can occur only within a culture that tolerates them, is incurious about the risks or that does not adequately support its design professionals with training or rigorous management for quality assurance. Correction of these problems may require deep organizational retooling.

Another approach to dealing with uncertainties in engineered systems is to incorporate back-up protection, also referred to as redundancy. Team Louisiana has benefited from previous release of reports documenting findings by ILIT and the USACE IPET. These teams have focused almost exclusively on the federally designed and constructed perimeter HPS, and have described this system as similar to a series circuit in an electrical system, in that the malfunctioning of any component can lead to system failure. The IPET report has, however, described the GNO pumped drainage infrastructure as a potential back-up system that, for a variety of reasons, failed to perform as such.

In fact, the pre-Katrina GNO HPS does include some redundancy in the form of interior levees in East Orleans and St. Bernard that were constructed by state and local authorities inside the perimeter HPS. These lower levees were built to separate thousands of acres of undeveloped, tidal marsh buffers on the protected side of the federal levees from developed areas under pump (Figure 3). While these levees did not prevent catastrophic flooding during the Katrina event, they did delay the onset of flooding in a way that deserves additional attention as redesign and reconstruction of the GNO HPS proceeds.

Unlike a river flood that may last for months, the challenge presented by a hurricane surge lasts only a matter of hours at any one point. Defense in depth offers a potential to reduce the catastrophic impact of overtopping or breaching at the perimeter.

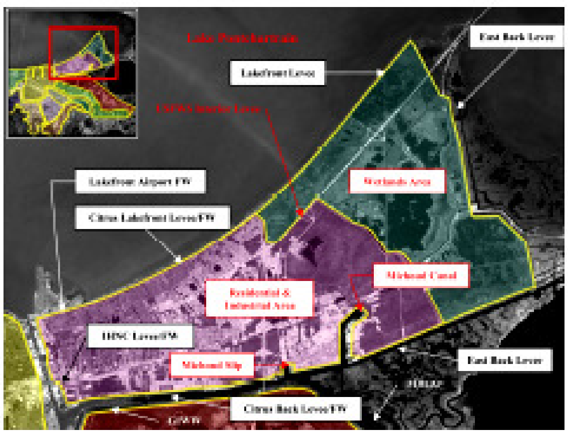

Figure 3. Wetland buffer and storage areas incorporated into the perimeter HPS in East Orleans (above) east of populated area (IPET 2006b, V-18-2) and St. Bernard (below) north of development (IPET 2006b, VII-18-23).

Organization of the Report and Key Questions

This report is organized in two parts. The first part provides background information critical to understanding the physical and historical setting relevant to flood protection and drainage; the magnitude and sequence of stresses placed on the HPS by Hurricane Katrina; and the nature of the flooding that led to the direct or indirect loss of as many as 1,500 Louisiana residents and the destruction of much of New Orleans.

The second part addresses the forensics issues as we see them. The following key questions were formulated to guide the forensics investigation. Each is discussed in further detail in the chapters that follow, with a final chapter providing specific recommendations.

1. Was the GNO HPS properly conceived to accomplish the Congressional mandate to protect against the "most severe combination of meteorological conditions reasonably expected?"

2. Were the levels of protection, or crown elevations, specified in designs for HPS elements sufficient to resist overtopping by surge and waves associated with the 100-year Standard Project Hurricane?
3. Did incorrect design assumptions compromise performance? Should these have been detected and corrected by engineers equipped with the tools available at the time? Were opportunities to install redundant or back-up protection exploited?
4. Did the Mississippi River Gulf Outlet (MRGO), a free-flowing, deep-draft navigation canal that pierced the HPS on the eastern side, compromise system performance?
5. Was the system maintained and operated to assure the required level of protection through time? Specifically, how did the 40-year construction schedule impact system performance?