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A General Description of Vulnerability to Flooding and Risk for New Orleans and Vicinity: Past, Present, and Future

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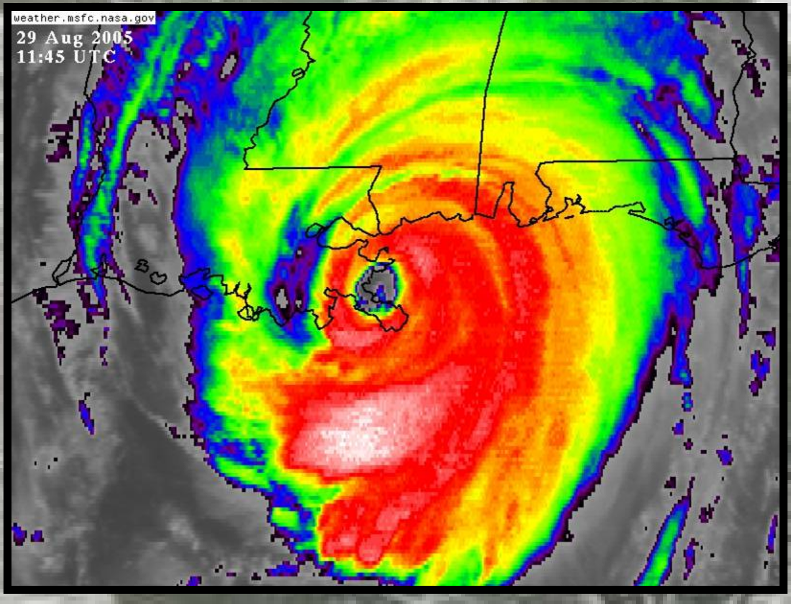

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Preface

Hurricane Katrina struck the Louisiana and Mississippi coast on August 29, 2005, with devastation never before seen. The Interagency Performance Evaluation Task Force (IPET) was established soon afterward as an engineering investigation team to understand what happened during Katrina and why. The objective was to learn from Katrina and apply those lessons immediately to the repair and rebuilding of the storm damage reduction structures in and around New Orleans. The work accomplished was reviewed by both the American Society of Civil Engineers and the National Research Council (NRC) and is reported in a nine volume report that is available through the IPET Web site or at *https://IPET.wes.army.mil*.

A part of this work included developing and applying an assessment capability to understand the risk from hurricane induced flooding faced by New Orleans prior to Katrina and following the repair and rebuilding of the levee and floodwall system (approximately June 2007). The Corps of Engineers requested that the IPET risk team also estimate risk as it would exist after the new 100-year (expected to be completed around 2011) hurricane storm damage risk reduction system (HSDRRS) is in place.

IPET released the pre-Katrina and the June 2007 risk information as a series of flood-depth maps in the summer of 2007. This was followed by the release of the initial flood depth maps for the 2011 HSDRRS by the U.S. Army Corps of Engineers' New Orleans District in the late summer of 2007. Subsequently, IPET and the New Orleans District released additional flood depth maps that included the impact of different pumping capabilities as well as expected risk of loss of life and property damage for the pre-Katrina, 2007, and 2011 conditions.

This work provides an engineering-based estimate of residual risk for New Orleans and vicinity. These data are unique and are available for no other city or region. The Pre-Katrina and 2007 risk assessments are documented in Volume I and Volume VIII of the IPET report, Performance Evaluation of the New Orleans and Southeast Louisiana Hurricane Protection System. The 2011 risk estimates have been made available to the public through the Corps' New Orleans District's Web site (*www.mvn.usace.army.mil*) but had not been documented. In their final report (released April 2009), the NRC Committee on New Orleans and Vicinity Hurricane Protection Projects, recommended that the future risk for New Orleans be described in a non-technical document that would help the public better understand the risk information and their situation. This document is intended to address at least a part of that recommendation, providing a non-technical description of the risk assessment process and the risk information for past (pre-Katrina), present (2007), and future (2011). It is only through viewing all of these scenarios that the big picture of the risk situation for New Orleans becomes evident.

This document is not intended to provide a detailed interpretation of the flood depth and risk information. Since interpretation implies application, it is not practical to interpret these complex data for the spectrum of possible users or applications. This task must be done in face-to-face communications between the responsible federal and local agencies and the public. Only through this direct discussion can the information available be appropriately used to inform the public on specific questions or issues and avoiding use of the data for applications beyond the capability of the information.

Our sincere hope is that the results of the IPET studies, especially the risk analysis and assessment tools, will be an effective platform for better policy and planning decisions dealing with hurricane risk reduction and will help such a tragedy from ever occurring again.

Lewis E. Link, Ph.D.
Director
IPET

Summary

This document provides a big-picture overview of the vulnerability to flooding and the relative risk of loss of life and property from hurricanes for New Orleans and Southeast Louisiana. The vulnerability and risk for the current situation is contrasted with that for pre-Katrina time frame and for the situation when the 100-year Hurricane and Storm Damage Risk Reduction System is completed (anticipated in 2011). The following are some important points about the analysis and the results from the analysis.

About the Analysis

- Perhaps the most critical information for any individual or organization living in a flood prone area is how often they may experience flooding and how severe the flooding may be. In essence, how often and how deep (Vulnerability). Associated with this is the expected level of loss of life or property (Risk). To provide this type of information is the fundamental objective of this effort. This has been a ubiquitous goal of many for a long time. The IPET efforts are an engineering based approach to provide an enhanced new level of this type information for large geographical areas. The application in New Orleans is a prototype. While it provides new and very valuable information concerning vulnerability to flooding and risk, it is also subject to considerable uncertainty and should be used as relative information, not absolute.

- No other coastal region in the nation has similar comprehensive risk information. The IPET risk assessment of New Orleans was a first effort of its kind, adopting a variety of models and methods used in other risk fields to evaluate the vulnerability to flooding and risk of losses of life and property from hurricane generated surge and waves for a large geographical area. This provides a unique opportunity for New Orleans to base re-development on this knowledge in concert with specific investments to mitigate risk.

- Risk information provides planners and decision makers with unique information concerning the level of vulnerability and risk in different locations and insights into their sources. This provides a more comprehensive basis for prioritizing actions and investments to reduce risk.

- The New Orleans region with 350 miles of structures, a complex coastal environment, significant areas at or below sea level and large and diverse areas of residential, commercial and industrial assets, provides a major challenge for assessing risk.

- The IPET risk process is perhaps the most sophisticated yet developed to examine vulnerability to flooding and risk of losses for a geographically distributed major metropolitan and industrial region. Yet the complexity of both the region and the risk analysis process places limitations on the results. The vulnerability to flooding and risk of losses data generated represent the best statistical estimates based on the best available models and data. But the number of sophisticated models and the limited data available to drive the models create significant uncertainty in the results. Thus, the results should be viewed as relative vulnerability and relative risk of losses. Areas with lower numbers are less vulnerable than areas with higher numbers for any given scenario or situation. Big differences in numbers represent larger difference in vulnerability or risk. The absolute values, however, should not be taken as reliable forecasts. For example, an estimate of loss of life for the 100-year flood event should **not** be used as a forecast of fatalities. Rather *it is a measure of the potential for loss of life*.

The vulnerability to flooding (flood depth or inundation maps and data) are based on the best available technical analysis and represent the best available definitions of the properties and performance capabilities of the structures and facilities that existed (for Pre-Katrina and current scenarios) or are anticipated to exist (2011 100-year system). The risk of loss of life and property are based on the pre-Katrina population and property situations and as such do not represent current or future risk. The risk estimates are highly dependent on the population and property exposed to floods. The situation now is quite different from pre-Katrina time frame and that for the future can vary even more. Thus, the changes in risk from the Pre-Katrina to current (2007) and 2011 situations represent a measure of the contribution that the changing Hurricane and Storm Damage Risk Reduction System (HSDRRS) measures are making to mitigate flood losses.

From the Analysis

- **Prior to Katrina** the New Orleans area was highly vulnerable to flooding from moderate to large hurricanes and exposed to very high risk of loss of life and property. Any event beyond the 50-year frequency of occurrence (average chance of occurring once in 50 years or a 2% chance of occurring each year) could produce significant flooding and losses. Large events such as the 100-year (1% chance each year) flood would cause extensive flooding and losses. Extreme events like the 500-year (0.2% chance each year) flood would totally devastate the entire region.

- **In 2007**, improvements and repairs made since Katrina reduced vulnerability to flooding for a number of areas, particularly those areas (largely portions of Orleans Metro and Jefferson East) that benefited by the placement of the temporary gates at the ends of the outfall canals. Many areas remain highly vulnerable to flooding from larger storms (100-year). The greatest vulnerability is in the areas surrounding the Inner Harbor Navigation Canal and on the West Bank where a number of sections had no protective structures. Extreme events would still totally devastate the area.

- **The 2011** 100-year system being constructed (scheduled for 2011) dramatically reduces vulnerability to flooding for a majority of the region. In this system status, a 100-year flood event is largely the result of heavy rainfall, not overtopping or breaching from hurricane surge. This system would also significantly reduce vulnerability of flooding for extreme events up to the 500-year event; however, some areas could experience significant flooding and losses. This represents the best structural risk mitigation New Orleans has ever had, *but it should be considered a baseline, not an endpoint*. Given similar evacuation conditions as in Katrina, the 2011 system (with significant online pumping capability during the storm) could reduce potential loss of life by as much as 97% for the 100-year flood event. The 100-year HSDRRS also dramatically reduces potential for loss of life from a 500-year flood event. Given the same property distribution and value that existed prior to Katrina, the 100-year HSDRRS would reduce direct property damages by 75% for the 100-year flood event and up to 75% for the 500-year flood event. This benefit is directly attributed to the reduction of the severity of the 100-year and 500-year floods.

- **Importance of pumping:** Pumping capability during storm events is a crucial component of flood risk mitigation. For the 100-year flood event, pumping equivalent to approximately 50% of the ideal capacity of existing pumps (assumed here to represent the peak actual performance of the pumping and drainage system) can reduce potential loss of life by approximately half for the 2007 system and up to 80% for the 2011 HSDRRS. Similarly, with this level of pumping capability, direct property losses from the 100-year flood can be reduced by up to 25% for the 2007 system and when the 100-year HSDRRS is in place, up to 75%, For the 500-year flood event, pumping can reduce loss of life potential by up to 50% and property losses by about 40% when the 2011 system is in place.

- **100% risk reduction will never be achieved** no matter how large the levees or floodwalls. There will always be residual risk. It is imperative that that level of risk be quantified and made available to the public and public officials. In addition, a 100-year system such as that planned for 2011 in New Orleans, should be considered a baseline, not an end-state, for an urban area. There is still considerable risk from extreme events and those events can happen as observed with Katrina. This type of risk reduction must be coupled with additional measures, structural and non-structural, that address the principal sources of the remaining residual risk. This may be more effective evacuation or emergency response to reduce exposure of people to flooding, or flood proofing, compartmentalization or landuse zoning to reduce property damages. A 100-year flood has a 26% chance of occurring over the life of a 30-year mortgage. The key issue is: What is the depth of flooding and extent of losses that this flood would generate? If both are relatively small, the system in place is successful. If either is large, additional measures are needed.

Introduction and Background

Lt. Gen. Carl Strock, the then Commander of the U.S. Army Corps of Engineers, established the Interagency Performance Evaluation Task Force (IPET) on Oct. 10, 2005, to determine the facts concerning the performance of the Hurricane and Storm Damage Risk Reduction System (HSDRRS) in New Orleans and Southeast Louisiana during Hurricane Katrina. The IPET conducted analyses designed to answer five principal questions:

- The System: What were the pre-Katrina characteristics of the HSDRRS components; how did they compare to the original design intent?
- The Storm: What was the surge and wave environment created by Katrina and the forces incident on the levees and floodwalls?
- The Performance: How did the levees and floodwalls perform, what insights can be gained for the effective repair and improvements of the system (lessons learned), and what is the residual capability of the undamaged portions? What was the performance of the interior drainage system and pump stations and their role in flooding and un-watering of the area?
- The Consequences: What were the societal-related consequences of the flooding from Katrina to include economic, life and safety, environmental, and historical and cultural losses?
- The Risk: What risk and reliability did the system have prior to Katrina, and what will it have after the planned repairs and improvements? *(June 2007 was established as IPET's "current" system for risk analysis.)*

The first four questions were a traditional forensic "what happened" analysis and was largely used to mitigate pre-Katrina vulnerabilities. Task Force Guardian, the team established to make the emergency repairs after Hurricane Katrina, used IPET "lessons learned" in repairing the system. Both the IPET draft report on the forensic analyses and the repairs were largely completed by 1 June 2006.

The IPET risk assessment used the body of forensic analysis knowledge gained to project near term and future residual risk. They then applied a methodology based on state-of-the-art hurricane modeling and current risk analysis practice to assess risk of flood losses for the New Orleans and Southeast Louisiana region. The objective was to estimate risk prior to Katrina, estimate the near term (June 2007) risk after repairs and rebuilding and future project risk (2011) when a stronger HSDRRS is scheduled to be in place. The unique aspect of this effort was application of the current practice to a geographically large and complex distributed infrastructure.

This document presents a simple risk methodology overview and the results obtained from its initial application in New Orleans. The authors all worked on the IPET risk efforts (pre-Katrina and June 2007) and assisted the New Orleans District with the 100-year system risk analysis. Information on vulnerability to flooding was generated and provided to the public in June 2007 for the pre-Katrina and 2007 HSDRRS situations in the form of inundation frequency depth maps for the East Bank (areas to the north and east of the Mississippi River). The same information was provided for the West Bank (areas to the west and south of the Mississippi River) in July 2007. In August 2007, a complementary set of maps was provided on the vulnerability to flooding for the projected 100-year (2011) HSDRRS by the New Orleans District. All of these computations were made with the assumption that the pumping systems in and around New Orleans were not operating. In March 2008, a supplemental set of maps were released for the Pre-Katrina , 2007 and 2011 HSDRRS conditions showing the impact of pumping on flood depths representing 50% and 100% of the ideal (name plate) pumping capacities available during strong storms.

Next the team created loss of life and property risk maps for all three HSDRRS conditions using the pre-Katrina population and property distributions. Changes in the potential loss of life and property between the three structural conditions reflect the impact of the repairs, upgrades and construction of the HSDRRS. This provides two important views to measure the value of both completed and planned HSDRRS improvements as well as an analytical approach to compare alternative future actions.

The public web site, *https://IPET.wes.army.mil*, holds all of the IPET maps and documentation. The New Orleans District web site, *www.mvn.usace.army.mil*, contains risk information and maps that pertain to the 100-year HSDRRS. The American Society of Civil Engineers External Review Panel and the National Research Council Committee on New Orleans and Regional Hurricane Protection Projects peer reviewed all IPET work.

Risk Assessment: Risk 101

The Value Proposition: What do I need to know about Vulnerability and RISK?

If you live in an area that is vulnerable to flooding (and there are many), you are probably most interested in how often you might experience flooding (what is your chance of flooding each year?) and how severe the flooding might be (how deep will I flood and for how long?). This is what is commonly called "***vulnerability to flooding***."

You also probably want to know the potential consequences of flooding, such as the loss of life or property. This is the "***risk*"** for the location. Here, risk is defined as the chance or probability of flooding at different depth levels (severity) multiplied by the losses. This gives us risk in units of loss (lives, dollars, etc., per year) for some location or area. If there are no potential losses, there is no risk. Risk can be managed or reduced by changing the probability or chance of an area being flooded (to a specific depth), reducing the number of people (evacuation) or amount of property (development limitations, raising structures, etc.) that are exposed to flooding.

Vulnerability to flooding and ***risk*** are functions of three things:

- The ***hazard*** (the hurricane and its storm surge and waves).
- The ***system*** (levees, floodwalls, gates, pumps, etc.).
- The ***consequences*** (people and property).

Typically, this is approached by starting with the hazard, then looking at the system in place to deal with the hazard, and then the potential consequences based on the performance of the system. However, it is more understandable and applicable if we start from the other direction - the consequences. For flooding problems such as in New Orleans, possible consequences depend on the population and property that exist in an area that may be flooded. A database is needed that describes where people and property are located and their elevation (with respect to water or land elevation (above or below sea level)). The demographics of people, fundamentally their age and capability to evacuate, are also important to estimate the potential for loss of life. Additional information on property values and the value lost from different depths of flooding is necessary to estimate the potential property losses from flooding.

Next, we need to determine how often and how deep flooding might occur in a given area. The bottom line is – "***How much water will get into an area and how often (chance)?***" The term “100-year flood” is often used to describe an event in this realm. Many people mistakenly think this means a flood would only occur once every 100 years – WRONG! This is a flood that has a 1% chance of occurring each year (and every year). You could actually have two 100-year floods in the same year. There are also 50-year floods (2% chance each year) and 500-year floods (0.2% chance each year). For any given year, the 50-year flood is twice as likely as the 100-year flood and 10 times more likely as the 500-year flood. Typically the 500-year flood is much more severe than the 100 or 50-year floods. The 100-year flood has been widely used in the past as an engineering benchmark or standard for flooding in the U.S.; this may be one of the problems in understanding its significance and real meaning.

The 100-year flood is usually assumed to be severe and a high consequence event, but in fact it can range from being very large to very small. The 100-year flood ***is simply the flood level that has a 1% chance each year.*** In the case of an area where there is a system in place (levees, floodwalls, gates, pumps, etc.) to prevent large volumes of water from entering the area (minimal or no breaching or overtopping) for a given range of hurricane surge, the 1% chance flood could be relatively small, for example*, rainfall only.* Flooding from more extreme events such as the 500-year flood (0.2% chance), however, could be quite severe. If the system is not robust or has problems, the 1% flood can be very severe. The key point for New Orleans and the 100-year or 1% flood depends on the ***performance of the system***. The performance of the system depends on its ability to handle the storm surge and waves water levels that hurricanes (the hazard) place on the system.

A common mistake many people make is assuming a specific hazard or storm causes a specific flood event — a 100-year hurricane creates a 100-year flood. While it is possible, it is ***not likely.*** First of all, the 100-year hurricane is a meteorological event, and the real hazard to the system (levees, floodwalls, etc.) is actually the water levels (storm surge and waves) generated by a hurricane. We know that for any given hurricane, the surge and wave conditions can vary greatly depending on the character of the hurricane (its size, how fast it is moving, etc.) and its path with regard to the location of a structure. Katrina generated record surge on the east side of New Orleans, but only routine surge on the west bank. Katrina, a 400-year meteorological event (based on size and intensity), generated surge levels that were equal to over 500-year surge levels on the east side and only 50-year surge levels and less on the west side of New Orleans. ***A hurricane’s generated surge level depends on many storm factors and CAN VARY GREATLY, depending on geographic location along the system.***

Many different storms can create the same water levels in a given location. Bottom line, the chance of experiencing a specific level of surge and waves at a given system location requires a statistical analysis of the surge and wave conditions that would be generated by the range of hurricanes that are possible in the New Orleans region. The frequency of each hurricane is only ***ONE*** input to the actual chance of experiencing different surge levels. Similarly, the relationship between the surge generated by a 100-year hurricane or the 100-year surge, determined from statistics of a large number of hurricanes to the 100-year flood, is greatly influenced by the performance of the system that separates the hazard from the possible consequences. ***You have to take the whole range of possible hurricanes, the whole range of possible water levels (surge and waves) these hurricanes may generate at many different locations, and apply this to the***

system to see how it performs (its design and reliability) to estimate how much flooding could occur at different levels of chance.

The physical system (levees, floodwalls, gates, pumps, etc.) is what separates the water generated by the hazard and the people and property of New Orleans. The system is designed to cope with a hazard of a specific chance of occurrence (the physical surge/wave water level) such as the 100-year surge level. If the structures are strong and high enough, the chance of lots of water entering the area is small and flooding is less likely than if the structures are less capable. Hence the 100-year flood could be relatively small compared to the flood that would occur in an area with a less capable system. If the 100-year (or any other) flood is smaller, the risk of losses is also probably smaller. Bottom line, the 100-year (or any chance flood) flood is dependent on the combined chances of experiencing a specific surge level, the chance of overtopping or breaching due to that surge, and the volume of water entering an area.

This Paper's Scope

This document gives a general overview of the risk assessment used to determine the vulnerability of New Orleans and vicinity to flooding from hurricanes and to estimate the difference in risk, by location, for the pre-Katrina, post-Katrina (June 2007) and proposed 100-year 2011 HSDRRS conditions. The IPET web site (*https://IPET.wes.army.mil*) presents the risk assessment process, its application, and a presentation and discussion of results. IPET's Volume VIII, Engineering and Operational Risk and Reliability Analysis, contains a detailed technical description of the risk assessment process and the results of its application. The New Orleans District web site (*www.mvn.usace.army.mil*) contains risk information and maps for the 100-year system.

The risk information focuses on hurricanes as the primary hazard source with the surge and wave conditions being the main hazard. *Wind impact on infrastructure was not considered*. The reliability or performance of the many system components is being examined through the individual and collective performance of levees, walls, gates and closures, pumping stations, and transitions (where two types of structures join). The chance of flooding is estimated based on these factors and the rainfall associated with hurricanes. Losses are based on estimated depths of flooding at different frequencies of occurrence. Rainfall from other, non-cyclonic, storms (thunderstorms) is not considered, nor is flooding resulting from high flows on the Mississippi River not directly related to hurricane surge.

This effort involved developing and applying a prototype method to estimate risk for the area of New Orleans, Louisiana - a large, complex, geographically distributed system. In many respects, this is a first-of-its-kind effort. One goal was to develop a methodology that would be practical to use, technically rigorous and provide system-wide information to make informed individual and organizational decisions concerning hurricane risk reduction. This method generates reasonable and useful results; however, applying the results of a large set of sophisticated models to a complex issue such as hurricane protection will engender significant uncertainty. This team deliberately tried to quantify that uncertainty to guide realistic use of the results as well as to allow continued improvement in the risk methods.

Why Use Risk Assessment? A significant part of the IPET risk effort was developing a system-wide risk assessment of the capability of the HSDRRS to protect New Orleans against future hurricane hazards. The goal of assessing risk is to facilitate rational decision making in several areas, including:

- Policy-level decisions on best expenditure of funding and other resources to minimize the risk of flooding from hurricanes.
- Planning level decisions on relative vulnerability of different areas to focus efforts on areas of greatest risk.
- Planning level decisions on the value of different alternatives for reducing the chance of flooding and losses (limited development, buyouts, elevated structures, etc.).
- Insights for design-level decisions on where to put gates or raise walls.
- Personal decisions on how to prepare for possible flooding from hurricanes.

To put the post-Katrina level of risk in perspective, this IPET assessment examined risk for the three storm damage reduction infrastructure scenarios: the pre-Katrina system, the repaired and upgraded system as it existed in June 2007, and the proposed 2011 HSDRRS designed to deal with the 100-year frequency surge and wave environment. The 100-year HSDRRS includes the higher and stronger levees and floodwalls, major surge gates at the entrances to the Inner-Harbor Navigation Canal (IHNC) and major new structures on the West Bank.

Risk information for the three HSDRRS scenarios provides a broad picture of the relative chance of flooding in different areas of southeast Louisiana and the potential losses as a result of flooding. A risk reduction system, however, only provides protection to a degree. The remaining risk is called *residual risk* and is a key planning factor. Residual risk defines how much risk must be managed by other means such as evacuation, zoning, flood proofing, structure elevation, and emergency response.

By estimating residual risk for different locations, we know where the greatest problems are and why. Risk variations are due to the chance of high surge and wave conditions, the strength and height of protective structures, the elevations of the land subject to flooding, the number of people and structures exposed to flooding, and different emergency response capabilities. By understanding the sources of risk, action can be directed against specific weaknesses. This helps save lives, minimize property damage, and prioritize risk reduction actions. Options such as evacuation planning and improved evacuation routes can be considered alongside more traditional options which include insurance, stronger and more resilient levees, hardened pumping facilities, higher first floor elevations, better land-use zoning, compartmentalized drainage basins, and building safe harbors.

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

In addition, risk assessment in the current context is intended to support planning decisions, not to support engineering decisions. A risk assessment over a large, complex geographical area like New Orleans requires many generalizations and assumptions compared to the details of engineering design. Although risk assessment does not generate design information, it can inform design by defining hazard levels and suggesting alternative approaches to providing risk reduction.

Risk Assessment: Methodology

The methodology underlying the IPET risk assessment, shown in Figure 1, has five steps.

- **Step 1:** The **"hazard"** is the event or condition with the potential for causing undesirable consequences. The hazard here is surge and wave conditions caused by hurricanes; it is not the hurricane themselves. To assess the hazard, we must first identify the range, character, and frequency (chance) of hurricanes that may strike the southern Louisiana coast. The surge levels for any hurricane will vary greatly depending on where you are located compared to the path of the hurricane. So, a storm with a one-in-one-hundred chance of occurring (the "100-year storm"), may not generate the 100-year surge level. It is necessary to look at many storms and the surge levels they would create to gain a reasonable estimate of the surge level (at each location) with a one-in-one-hundred (100-year) chance of occurring.

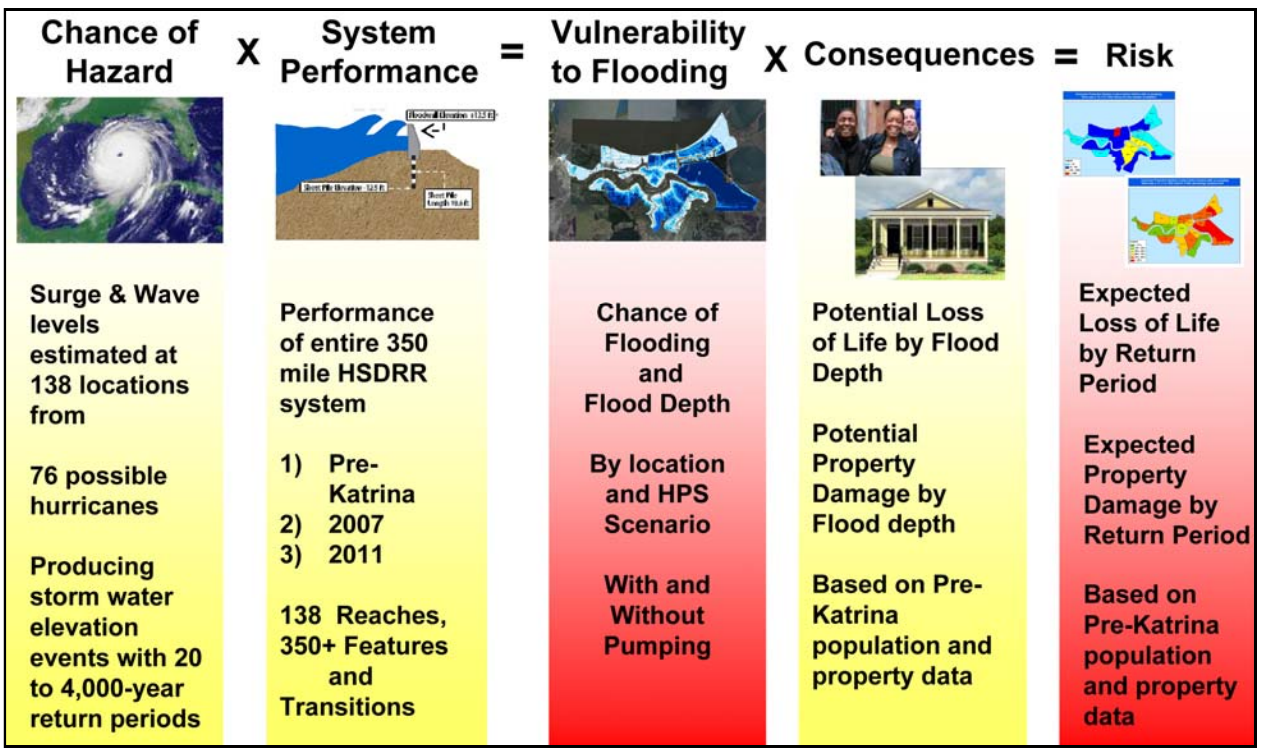


Figure 1. Risk assessment framework used in IPET analysis of New Orleans.

IPET used state-of-the-art methods, including supercomputer models, to define the surge and wave conditions that 76 different hurricanes, representing a wide variety of hurricane intensities, sizes and paths would produce around New Orleans. The analysis led to estimates of the frequency (chance) of extreme surges and waves for many locations around the HSDRRS. The surge and wave estimates are for current climatic conditions, and *do not project potential climate variations into the future*.

- **Step 2: "System Performance"** is the response of the system to the hazard, that is, to surge and wave conditions generated by the hurricanes. The system performance is assessed by modeling how each structure and component of the system (levees, floodwalls, gates, etc.) would perform under the forces generated by surge and waves. This allows you to estimate the chance of overtopping and the chance of breaching for different surge and wave levels. This "reliability" analysis starts with a detailed inventory of the engineering characteristics of every section of the HSDRRS.

- **Step 3. Vulnerability to Flooding:** Given the chance of overtopping and breaching for different surge and wave levels, you can estimate the chance of flooding within each sub-basin or drainage area across the region. This chance of flooding is sometimes called the *vulnerability*. Combining the potential for overtopping and breaching with the frequencies of the corresponding storm events leads to a vulnerability assessment of flooding from the whole range of hurricanes possible for the region. The calculation also includes the chance of water entering through open gates and the amount of rainfall associated with hurricanes. Combining the volume of water entering a basin with the geometry of the basin, allows you to estimate the depth of flooding at any location within the basin.

- **Step 4:** The **"Consequences"** of flooding, measured by potential loss of life and property damage, are estimated by defining the distribution of people and structures within each sub-basin, the elevations of all structures and the surrounding land, and the value of the properties, and then by applying actuarial information and models to approximate losses. (*The population numbers and property values used were all pre-Katrina.)*

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

- **Step 5: Risk** is calculated by combining the chance of undesirable consequences occurring with the magnitude of those consequences. This allows an estimate of risk by area, based on the character of the storm damage reduction infrastructure and other measures that may influence who and what is exposed to flooding. Risk is calculated by multiplying the chance of flooding to a certain depth by the losses expected. Losses can be expressed as potential loss of life or property.

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

Defining the HSDRRS Infrastructure

Prior to beginning the risk assessment itself, it was necessary to define the drainage areas within which flooding might occur and the structures (levees, floodwalls, gates, pumps) that are intended to prevent flooding. This divided the region into parish-level drainage basins (e.g., St. Charles, Jefferson Parish, East Bank, Orleans Main, New Orleans East, Chalmette Loop, Plaquemines, Gretna-Algiers, Harvey-Westwego, and Lake Cataouatche), and then into sub-basins within those basins. The boundaries are based on the location and character of the individual HSDRRS structural components, the topography of the protected areas, and the internal drainage system (Figure 2). Repairs and structural enhancements made following Katrina (Figure 3) have been factored into the data used to describe and model the 2007 system.

The 2011 or 100-year HSDRRS is being designed to mitigate the storm surge and wave conditions that have a 1/100 or 1% per year chance of occurring or being exceeded (Figure 4). There are two major new navigable gate structures planned for the Inner Harbor Navigation Canal, another major control structure on the West Bank (at the confluence of Harvey and Algiers canals), a number of floodwalls that will be replaced and many areas where levees will be elevated and strengthened. These designs are based on the hazard definition that will be described briefly herein. The structure elevations and reliability are based on the future 100-year frequency surge and wave levels, anticipated subsidence and settlement, sea level rise and conservative wave overtopping criteria for resilience. Potential climate change influence on the frequency of surge and wave levels was not included in the hazard definition. However, to provide a conservative design for the new HSDRRS, the 90th percentile (rather than the 50th percentile or average) surge and wave conditions were used to define the necessary HSDRRS structure elevations. *This provides an extra measure of capability to deal with unknowns such as climate change.*

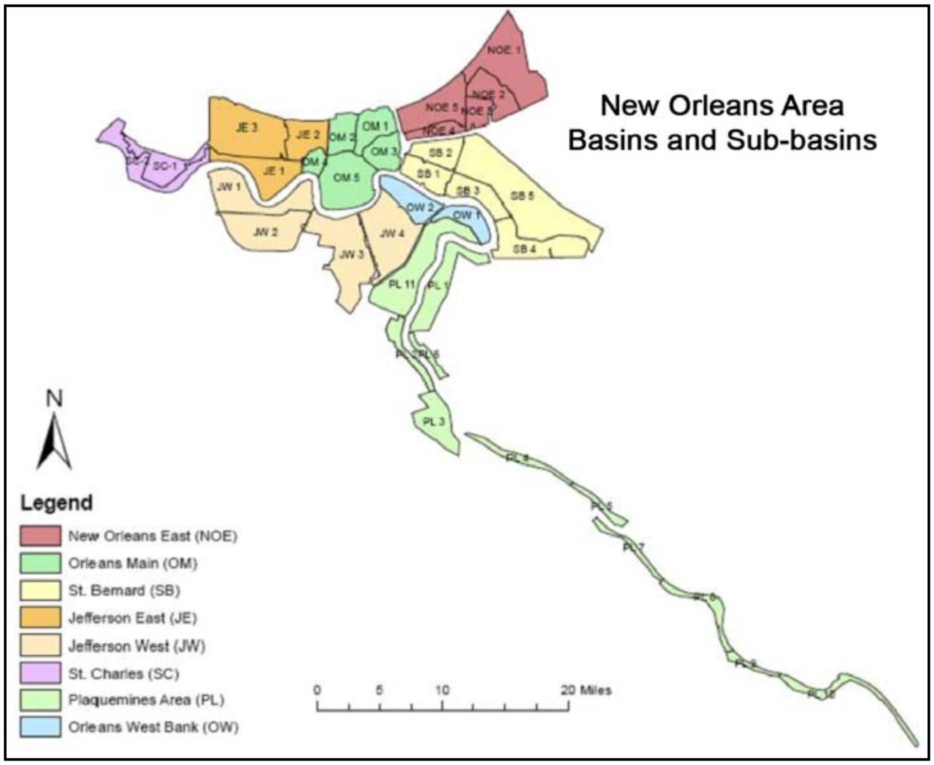


Figure 2. Definition of drainage basins and sub-basins for risk assessment.

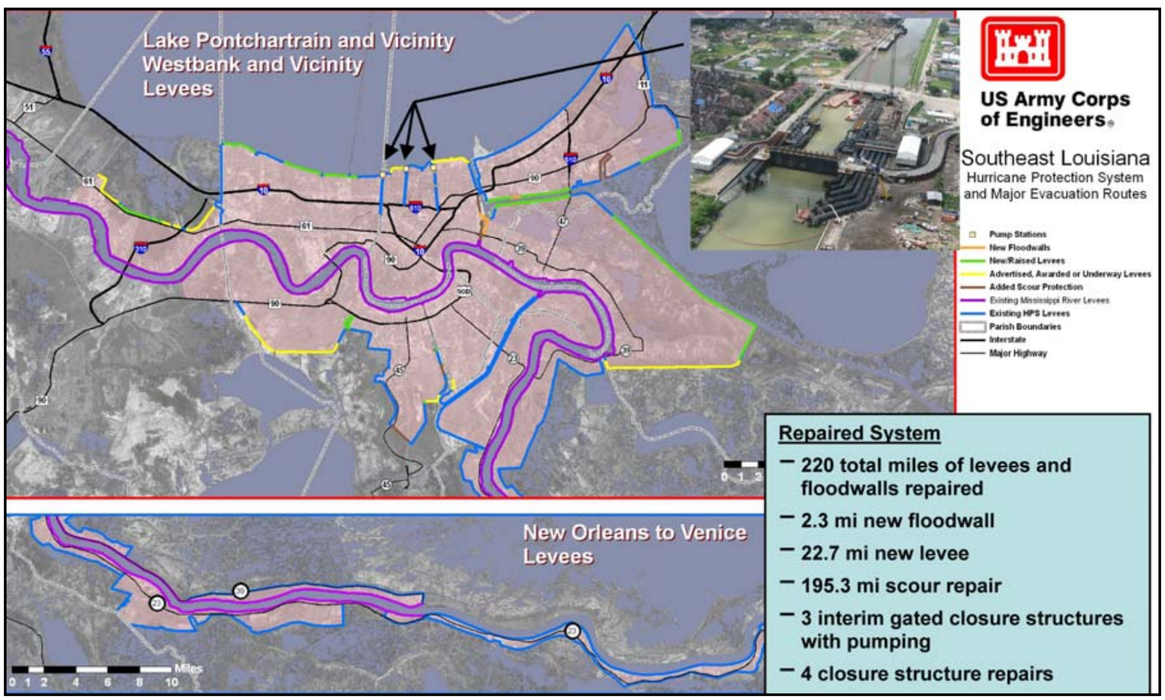


Figure 3. Map 2007 HSDRRS with listed improvements from Pre-Katrina system. Source: U.S. Army Corps of Engineers. Note: Some additional strengthening not depicted on this map has been achieved to include armoring of key transitions and structures. The modeled system was representative of the conditions of the structures and components in June 2007.

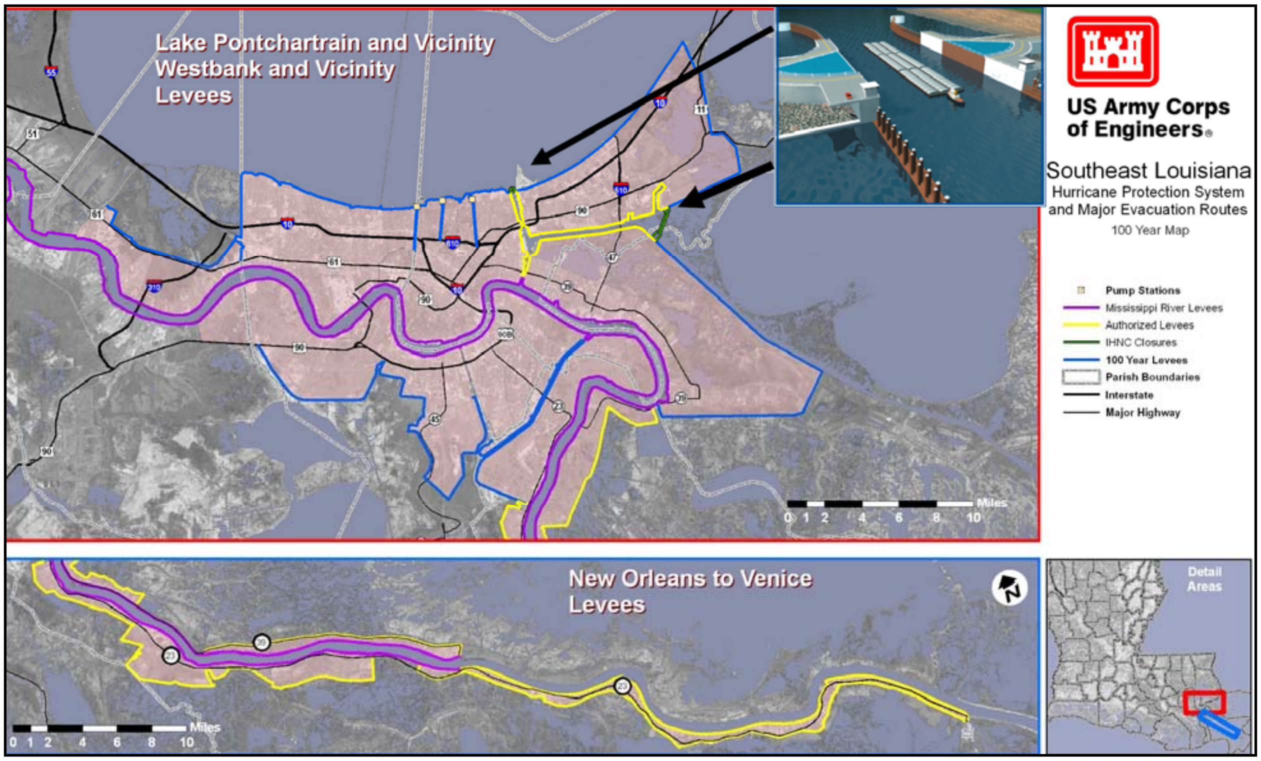


Figure 4. Map representing planned 2011 (100-year) HSDRRS. Source: U.S. Army Corps of Engineers. The 2011 HSDRRS modeled represents the best estimates of the type and character of proposed structures as planned in 2007.

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

There were 135 reaches defined for the Pre-Katrina and 138 for the 2007 system. The additional three reaches for the 2007 HSDRRS (numbers 136, 137 and 138) represent the three new temporary gate closure structures for the London Avenue, Orleans and 17th Street outfall canals. The Pre-Katrina system had 416 features and transitions compared to 375 for the 2007 HSDRRS. Fewer features and transitions were required for the 2007 system because of its increased uniformity. The 2011 HSDRRS description added an additional number of reaches for proposed gates and control structures and modified the character of the structures being upgraded. Figure 5 shows reach definitions for the Orleans Main Basin.

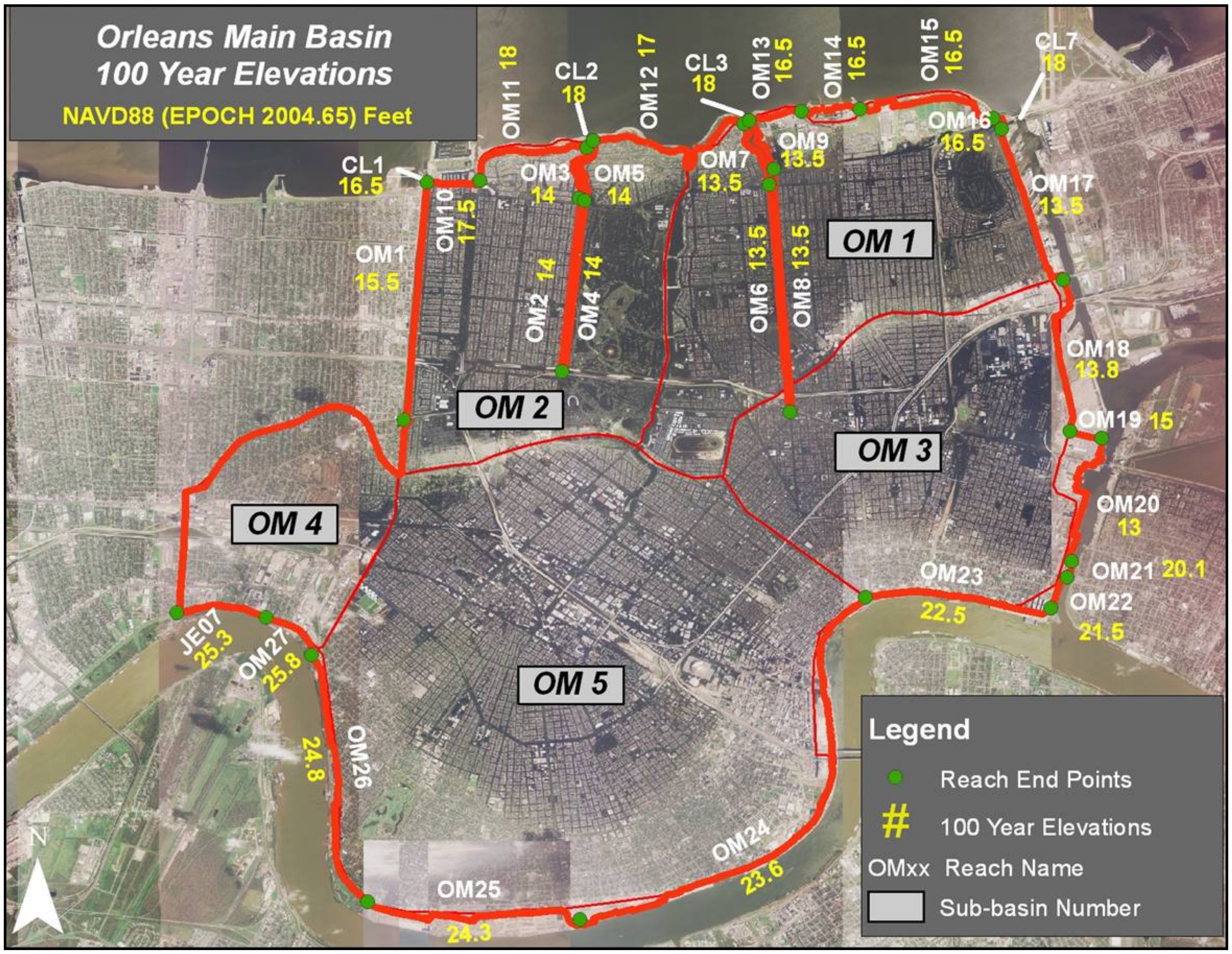


Figure 5. Definition of reaches for Orleans Main Basin HSDRRS risk assessment. Reach definitions for the Pre-Katrina and 2007 systems are given in IPET Volume VIII. The reach elevations given are the initial estimates for the 100-year HSDRRS.

Assessing the Hazard

The relationship between surge and wave levels and their frequency of occurrence differ greatly around the system. IPET, the Corps of Engineers, the Federal Emergency Management Agency (FEMA), and the National Oceanic and Atmospheric Administration (NOAA) have worked together, with the top hurricane experts (government, academia and private industry), to study the surge and wave environment of New Orleans. Collectively, these investigations have greatly advanced our understanding of hurricane forces. We know considerably more now about hurricanes and their effects than we did prior to Katrina.

The method these experts developed for IPET for evaluating surge and wave hazard involves three steps. This is called the ***Joint Probability Method—Optimal Sampling*** (JPM-OS).

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

Step 1—What Hurricanes Might Occur? The first step requires looking at potential hurricanes. In the past, this was done by analyzing and extrapolating from historical hurricanes records. In the original design of the New Orleans system in the 1960's, historical data were used to define a "Standard Project Hurricane." The Standard Project Hurricane was a hypothetical hurricane representing "the most severe storm considered reasonably characteristic of a region." The surge created by the SPH traveling along a few select tracks was used as the basis of design. In later years, the historical record was used to artificially generate a larger sample of hurricanes, to provide multiple storms for modeling surge and waves.

Experts believe these approaches are no longer the best method, especially with the recognition of trends toward more frequent and intense hurricanes. Yet, historic hurricanes are important because they are a sample of what nature can produce, and, thus, an essential part of the calibration of any modeling effort.

A major finding of the Katrina investigations was the importance of considering both the intensity (central pressure deficit) and physical size of a storm (radius to the maximum wind speed) to determine its corresponding storm surge generation. It was Katrina's combination of relatively high intensity and relatively large size that allowed it to create the highest surge ever experienced in North America. Figure 6 shows the pressure deficit-size relationship for historical storms. Hurricane Camille, a Category 5 storm on the Saffir-Simpson Scale at landfall, was a more intense storm than Katrina (Category 3 at landfall), but Katrina was twice as large in diameter (radius to maximum wind speed) and generated significantly higher surge. The Saffir-Simpson scale categorizes hurricanes primarily by ranges of maximum wind speed (*http://www.nhc.noaa.gov/aboutsshs.shtml*), and is often criticized today for being too simplistic, especially with regard to surge levels.

The JPM-OS summarizes historical hurricane information in a joint frequency distribution of the parameters used to characterize individual hurricanes (Table 1). It provides a way to consider all the major hurricane characteristics and the chance of different combinations of these characteristics occurring. It is a more comprehensive approach to understanding the chance of a particular storm occurring than the usual approach of considering the central atmospheric storm pressure.

Hurricane experts sampled a variety of these characteristics from the joint probability distribution to represent the spectrum of storms that could threaten New Orleans. The annual probability of each of these hypothetical storms is taken from the joint probability distribution. Using this approach, for example, Katrina was computed to be roughly a 400-year storm. In total, 152 hypothetical hurricanes were used to define the hazard for the risk assessment; 76 of these hurricanes were used for the actual risk analysis computations.

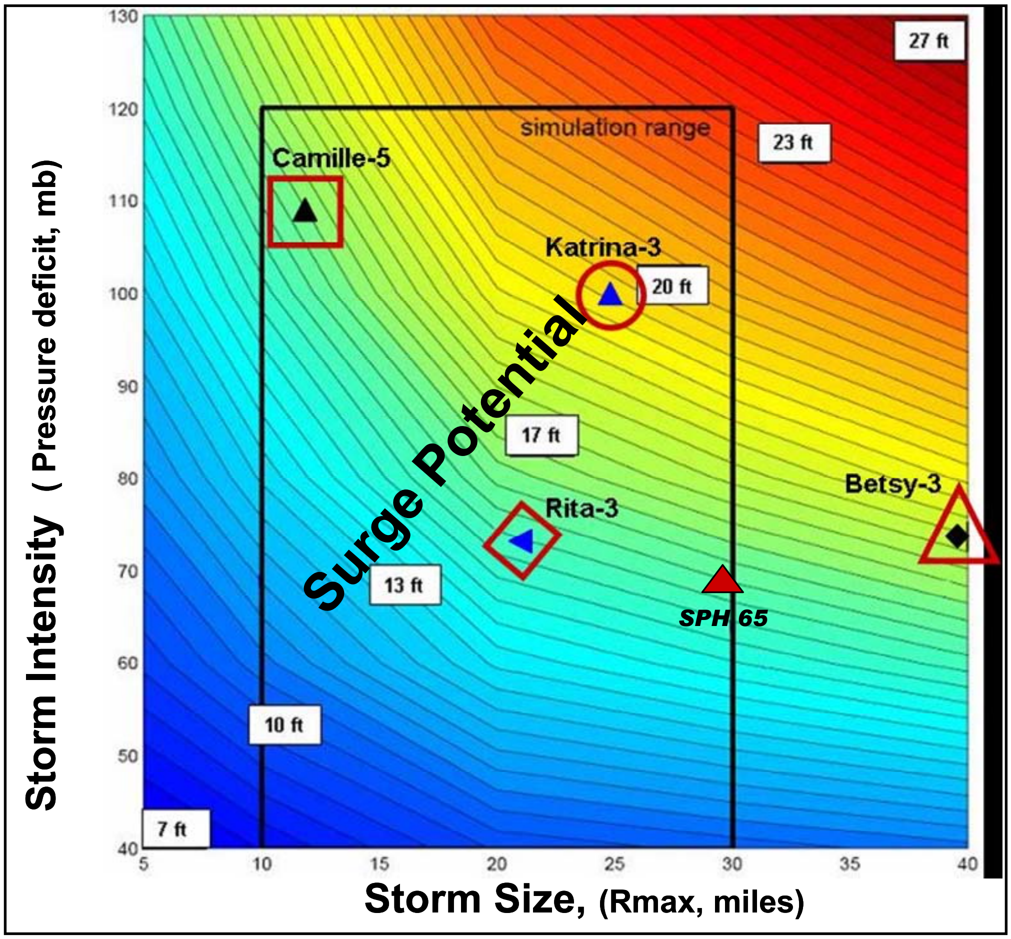


Figure 6. Relationship of intensity (central pressure deficit) to size of historical storms, including their Saffir-Simpson category at landfall. Assumes simple straight line shoreline with a uniform 1:1000 ocean bottom slope. As such, the surge values here are not necessarily those that particular storms produced for the complex shoreline and subsurface geometries of Mississippi and Louisiana. (Reference: Irish, J.L., Resio, D.T. and J. J. Ratcliff, "The Influence of Storm Size on Hurricane Surge," *J. Phys. Oceanography*, DOI: 10.1175/2008JPO3727.1)

Table 1. Major Hurricane Parameters Considered in Hazard Modeling

Parameter	Description
Intensity (Central Pressure Deficit)	Usually described by the Saffir-Simpson Scale which relates Category of Storm to the maximum wind speed and damage effects.
Size (Radius to Maximum Wind Speed)	This is a measure of the diameter or width of the storm determined by how far away from the eye that the maximum wind speed occurs. It can also be examined by the distance to which hurricane force winds exist
Speed (Rate of Forward Motion)	This is simply the speed that the hurricane is traveling along its path.
Track Angle (Angle to Shoreline Azimuth)	This measures the angle of the hurricane path with respect to the shoreline.
Landfall Location	This measures the distance between a point of interest and the location where the center of the hurricane strikes land.
Storm Shape (Holland "B")	This measures how rapidly the wind speed degrades from the point of maximum wind speed or the peakedness of the hurricane.

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

Figure 7 shows pressure and size combinations used in the JPM-OS analysis. To calibrate and test the JPM-OS approach, IPET used both Hurricane Rita and Hurricane Katrina data. No other historical storms had adequate information available. The JPM-OS data set defines a modern hurricane hazard using the latest knowledge, but it does not project potential climate change impacts on storm intensity or frequency into the future. Such projections would have involved significant speculation that was beyond the scope of the IPET effort.

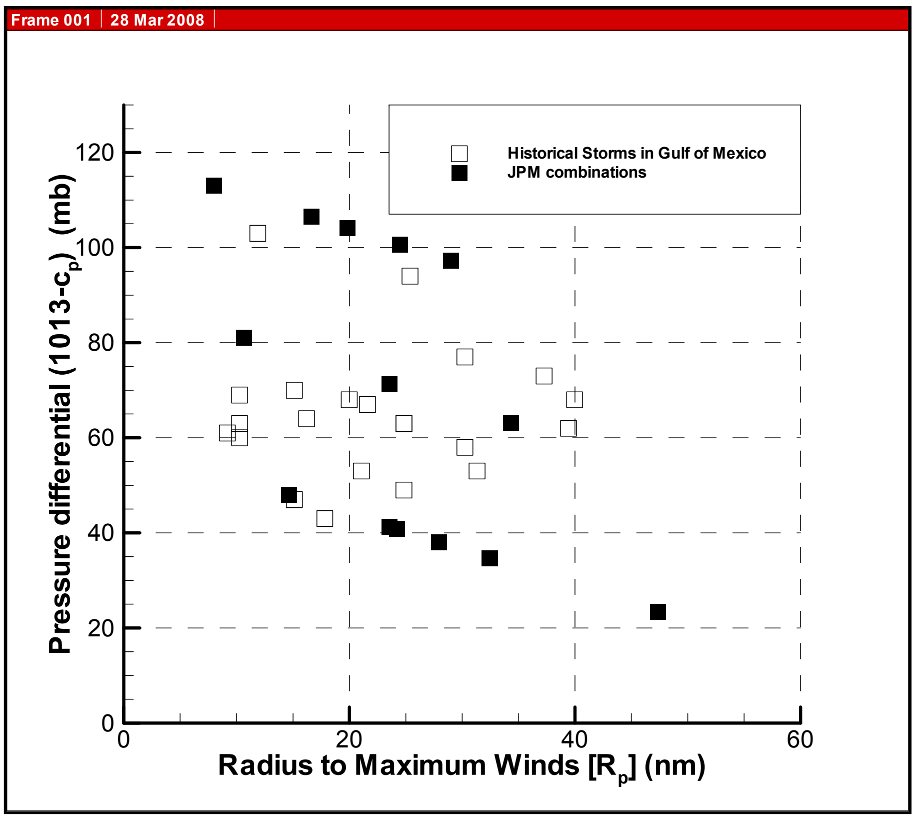


Figure 7. Plot comparing the pressure deficit-size combinations of historical and JPM-OS storms used to define the hazard for the Risk Assessment

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

Each hurricane was used to compute the surge and wave conditions that it would generate at a large number of locations around the HSDRRS, giving decision makers a more comprehensive data base to define the hazard, the likelihood of any location having water levels of different heights.

The JPM-OS was used to generate a set of 76 storms for use in the risk assessment. As meteorological events, these storms range in frequency from about 300 to 10,000-year meteorological events. As such they represent relatively large storms, some that are quite rare, providing an effective data set for evaluating risk over a wide range of conditions. Since wind, surge, and wave simulations using high resolution computer models are computationally demanding, expensive and time consuming, it was important to use as few storms as possible to define the hazard.

Step 3—What Surge and Waves Can Occur and How Often? The frequency of the surge generated by a hurricane is not necessarily directly related to the frequency of the storm (as a meteorological event). In other words, a 100-year hurricane does not necessarily generate a 100-year frequency surge. The surges generated by a storm are the result of a complex set of interactions to include the geometry of the shore line relative to the track of the storm, near-shore bottom slope, and near shore marshes and barrier islands. Surge and wave conditions also vary greatly for different locations on the ground. Katrina, for example, generated very rare (high) surge levels on the east side of New Orleans and quite benign surge levels on the west side of the city. So, a storm may generate a surge level that has a frequency of occurrence that is either significantly different (larger or smaller) than its frequency as a storm event and the surge levels (and their frequencies) can differ greatly by location. This indicates that defining hurricane hazards is a complex process, the reason the JPM-OS approach was applied.

IPET used the same surge and wave models (ADCIRC and WAM/STWAVE) for the risk analysis that were used to estimate water levels created by Hurricane Katrina. These models were verified in the IPET Katrina analysis (IPET, Volume IV) by matching computed estimates to observed high water marks. The models were coupled together to include the impact of energy transfer from waves that can increase surge levels (wave set-up).

In this process, an estimate of the total free water elevation (surge plus wave setup) was determined in a stepwise process. ADCIRC was first run to determine initial surge elevations and wind field data. STWAVE was then run to estimate distributed wave conditions. The wave information was fed back into ADCIRC as an additional forcing term to consider wave setup, which is the transfer of wave radiation stress associated with the storm that increases surge levels. The result is a time history of water elevation at each location, that is, a *hydrograph*, for each storm (Figure 8).

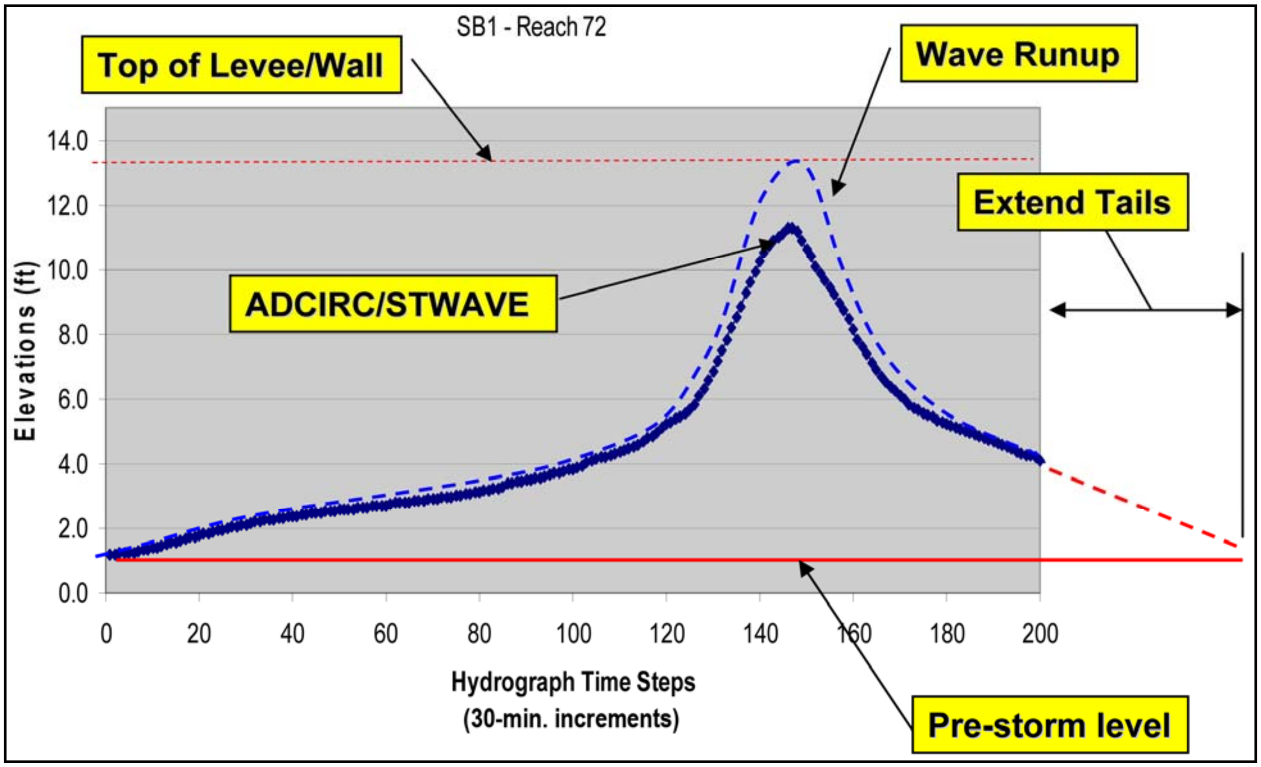


Figure 8. Illustration of hurricane hydrograph for a location. Graph shows specific process augmentation after ADCIRC/STWAVE simulation which includes wave setup.

Each storm resulted in a separate hydrograph for each section of the HSDRRS infrastructure that was evaluated in the reliability assessment (e.g., Figure 9). In a separate step, an estimate of wave run-up (additional water elevation due to the impact of waves near shore interacting with individual structures) was determined to evaluate the volume of water that could enter a sub-basin by overtopping and the effect of the additional loads generated by the waves on the reliability of the HSDRRS infrastructure. Approximately 20,000 hurricane hydrographs were generated for each HSDRRS infrastructure scenario evaluated in the risk assessment.

It was necessary to estimate the entire hydrograph of the free water elevations for the risk assessment. Since one of the key products of the assessment is an estimate of the amount of water that would enter the protected areas by overtopping or breaching, it was essential to be able to estimate the amount of water available to flow over structures or through breaches at any given time and location. Each hydrograph was divided into 30-minute time steps to estimate water level and water volumes for the risk assessment. Since the character of the HSDRRS structures (height and geometry) themselves can influence the height of the water levels, separate computations were made for the Pre-Katrina, June 2007 and the proposed 2011 HSDRRS to better capture the influence of the changes between the systems.

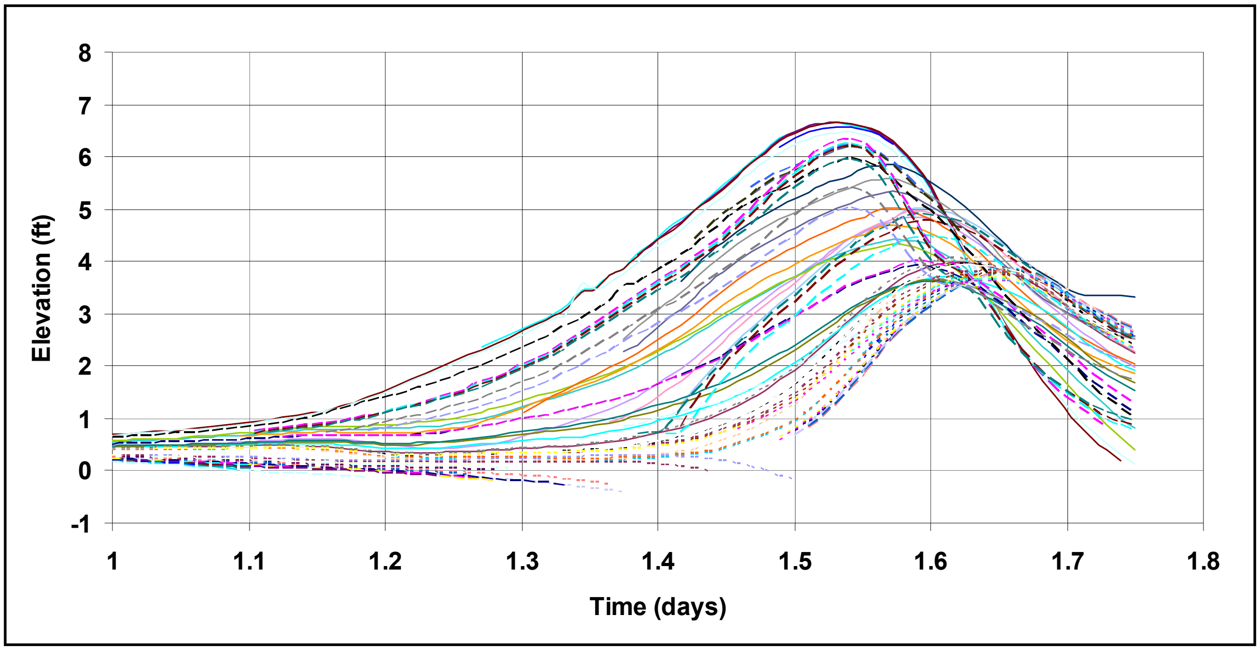


Figure 9. Example of hydrographs for a variety of locations around the HSDRRS from a single storm. This example represents a relatively moderate storm surge condition. Each hydrograph represents the surge history for a different location. Surge is defined as the rise in water level due to the wind and pressure fields of the hurricane. It is measured in reference to local mean sea level.

System Performance

The performance of the individual HSDRRS infrastructure options was analyzed in four steps. First, the performance of the individual components of the system was assessed. Then, the performances of the components were combined in a systems model to account for their interactions and dependencies. Then the contributions of rainfall associated with hurricane storms and internal pumping were evaluated. Finally, the impact of inter-basin flow (resulting from rainfall, overtopping, or possible breaches) was considered.

Component Reliability

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

The reliability of a reach or other component is summarized in a *fragility curve* (fragility is basically the inverse of reliability). A fragility curve (Figure 10) describes the probability of failure as water level increases. A value near zero means little chance of failure; a value of one means certain failure. To perform a reliability analysis of a reach, it is essential to understand subsurface geologic conditions, the design of the structures, how the structure was constructed, and how it was maintained. All of these factors influence the shape of the fragility curve.

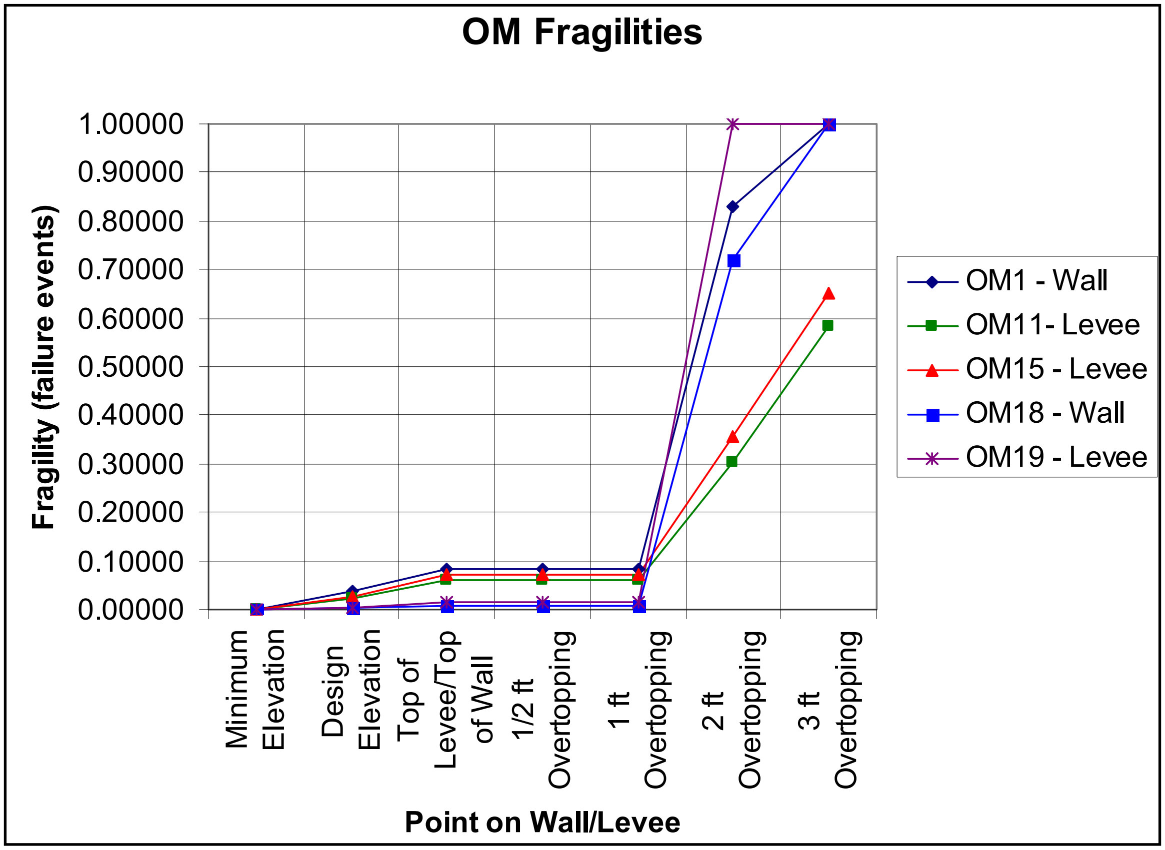


Figure 10. Fragility Curves for a sample of reaches in the Orleans Main (OM) Basin. OM1 is an I-wall along an outfall canal, OM11 and 15 are levee reaches along the south shore of Lake Pontchartrain, OM18 and OM 19 are I-wall and levee reaches, respectively, on the west side of the IHNC. Curves such as these were developed for each reach in each infrastructure option (pre-K, 2007 and 2011). See Figure 5 for graphical display of reaches.

The bottom section of the fragility curve (lower water elevations) represents the period of time when the water level is below the crest of the structure. If failure occurs at this time it is because the structure was not designed and/or constructed strong enough to resist the forces created by the water. A breach can occur because the structure cannot resist the lateral forces being applied by the water (17th Street Canal and Lower Ninth Ward north breaches) or because it loses stability from massive under-seepage (London Avenue Canal breaches). As water nears the crest, waves begin to overtop the structure and introduce the possibility of erosion on the back side of the structure. Erosion can lead to breaching of an earthen levee by washing away soils and creating a breach through which more water can flow, creating more erosion and eventual failure. For a floodwall, overtopping can cause erosion of the soils behind the wall leading to a loss of stability and eventual failure. Overtopping was the cause of all but four of the catastrophic breaches during Katrina.

System Reliability

The assessments of hazards, as manifest in hydrographs and wave loadings, and of component reliability, as manifest in fragility curves, are brought together in an event tree (Figure 11). The event tree characterizes the interactions of loads, responses, and potential inundation. The event tree charts all the possible ways the many components of the HSDRRS infrastructure might perform under a given hurricane scenario and provides a vehicle for logically calculating the corresponding probabilities of different levels of flooding. These probabilities are weighted over all of the 76 hypothetical hurricanes from the JPM-OS to arrive at annual probabilities of flooding.

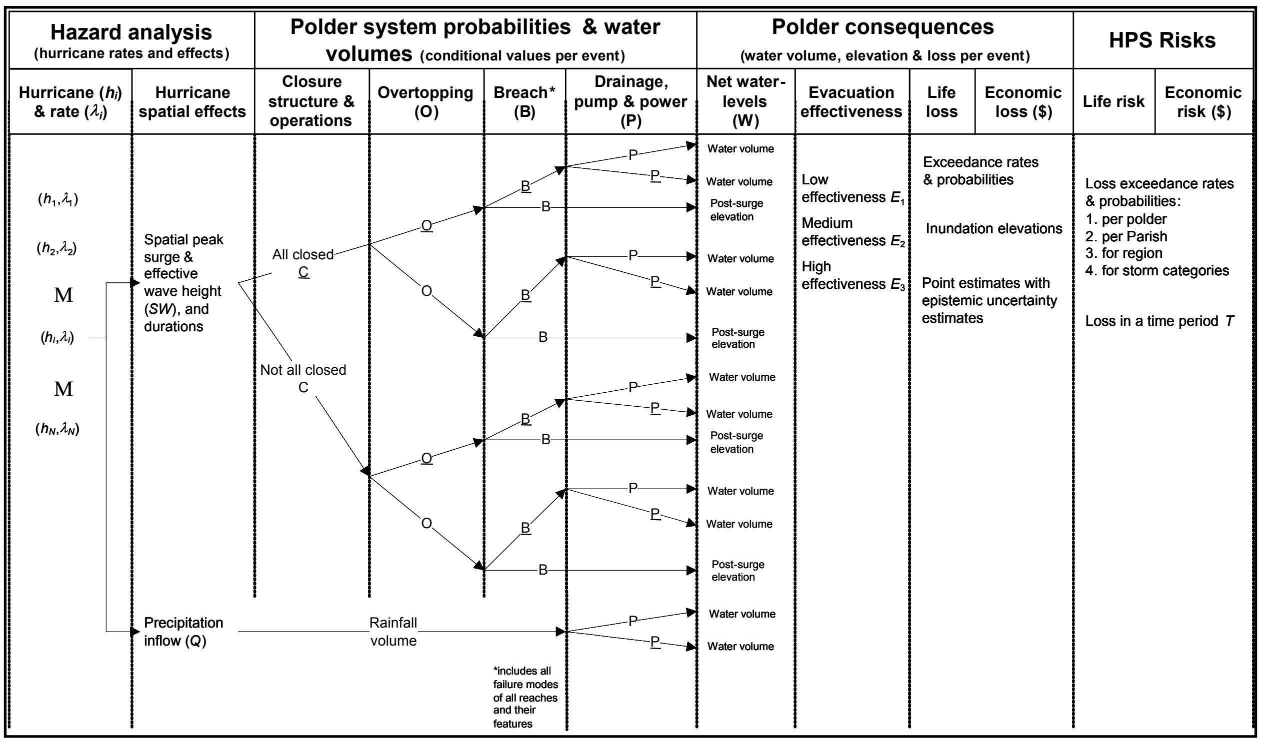


Figure 11. Example of event tree used to estimate volumes of water entering protected areas. An underlined symbol indicates non-event, for example B indicates breaching occurs while B indicates breaching does not occur.

Rainfall and Pumping

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

Pumping impact was considered using the following basic process:

- Determine total sub-basin design pumping capacity
- Determine rainfall duration per storm (generally 8 to 12 hours)
- Determine volume of rain and runoff appropriate to each sub-basin
- Assume pumps will perform at the assumed capacity (0, 50 or 100%)
- Determine volume of water that pumps could evacuate per storm at the selected capacity
- Subtract pump volume from rainfall to determine net volume
- If net volume is a negative value, pumping capacity is greater than rainfall volume.

The pumping capacities used were the ideal design ("name plate") capacities for all pumps that evacuate water from each sub-basin. These capacities are considered ideal and do not reflect the current or projected actual operational capacities, which are highly dependent on the operational reliability of the pumps, the hydraulic head they are pumping against and the condition and capability of the internal drainage system to get water to the pumping stations. *(No pump will achieve 100% capacity.)*

Sub-Basin Interflow

Once the estimates are made for the volume of water that would enter each sub-basin from a given storm, the topographic elevations of the land surfaces between adjacent sub-basins were used to estimate the amount of water that flows to or from adjacent sub-basins from simple overtopping. This did not include modeling of the intricate drainage system of canals, conduits, etc., that also provides a means for water to move between areas. That detail of modeling was not feasible for this analysis. This provided a more accurate estimate of the volume of water in each sub-basin for the subsequent flood depth analysis.

Estimates of Potential Flooding

By considering the topography of each sub-basin, it is possible to develop a curve that represents the volume of water that would be stored in the basin for different water elevations (e.g., Figure 12). Curves have been generated for each of the sub-basins. Using this relationship, the estimated volume of water entering a sub-basin from each storm can be converted to an approximate water elevation. This elevation represents an estimate of the elevation of flooding from that hurricane and is associated with a corresponding probability based on the event tree analysis.

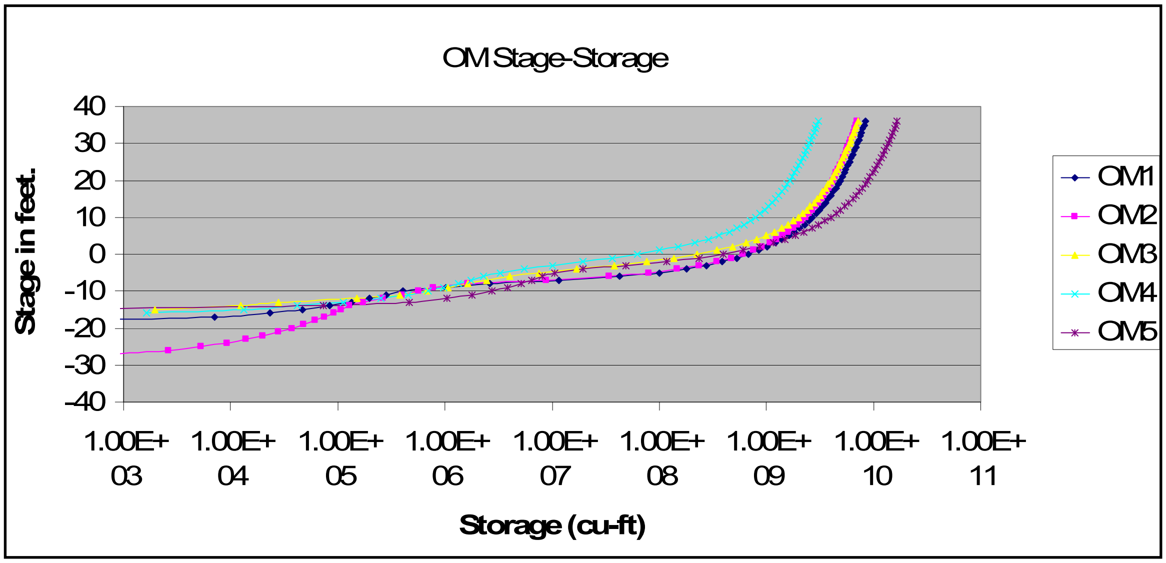


Figure 12. Example of relationship between the volume of water in a sub-basin (storage) and the resulting water elevation for OM sub-basins.

The curves typified by those in Figure 13 are the basis for generating maps showing vulnerability to flooding. For example, given the volume of water for a sub-basin that equates to a chance of occurrence of 1% in any given year, Figure 13 can be used to determine the water elevation representing the 1% or 100-year flood elevation for that sub-basin.

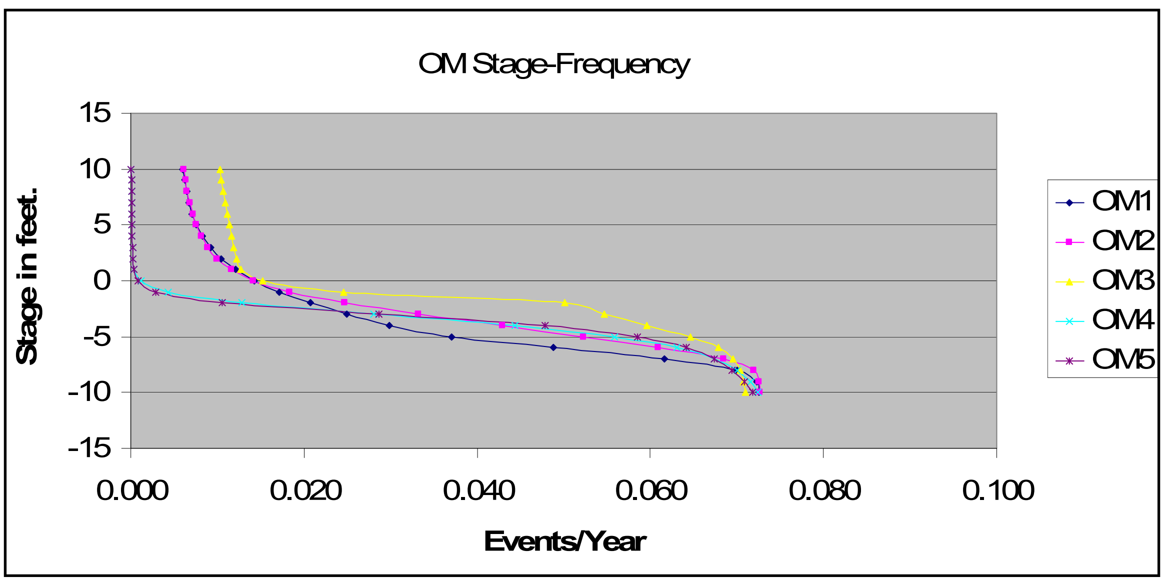


Figure 13. Example of water elevation – frequency of occurrence (Exceedence) relationships for OM sub-basins. These curves do not include the impact of flow of water between sub-basins by natural drainage, which is considered separately.

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

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

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

Consequences

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

The relationships used to determine expected losses for a given flood frequency (elevation) are shown schematically in Figure 14. Expected losses for various water elevations were determined for each sub-basin. Economic losses are based on the structure elevations, geographic distribution and property value at the census block level. Loss of life was estimated using pre-Katrina population demographics by census block through the use of two computer models.

Life loss was estimated in a series of steps using two primary models. First the LIFESim Modeling System (McClelland and Bowles, 2002[1]) was used to estimate the basic exposure of the population to flooding. LIFESim determined how people in flooded areas redistribute vertically in buildings in relation to the depth of flooding. It also considers population age to determine where people are capable of moving. This results in an estimate of the number of people in each of a number of flood lethality zones for each sub-basin. Evacuation efficiency was considered separately using a Monte Carlo Model, a standard statistical routine.

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

The Monte Carlo Uncertainty Model used research on Katrina evacuation conducted at Tulane University to estimate the proportion of the population that would evacuate. The Monte Carlo model was then used in conjunction with information from the literature (McClelland, 2000[1]) to estimate immediate loss of life. This was followed by an estimate of the delayed fatalities among those who survived the initial inundation but were not rescued. Each of these steps has considerable uncertainty and *the resulting estimates of potential loss of life should be viewed as an index of loss of life potential, not as an explicit fatality forecast.*

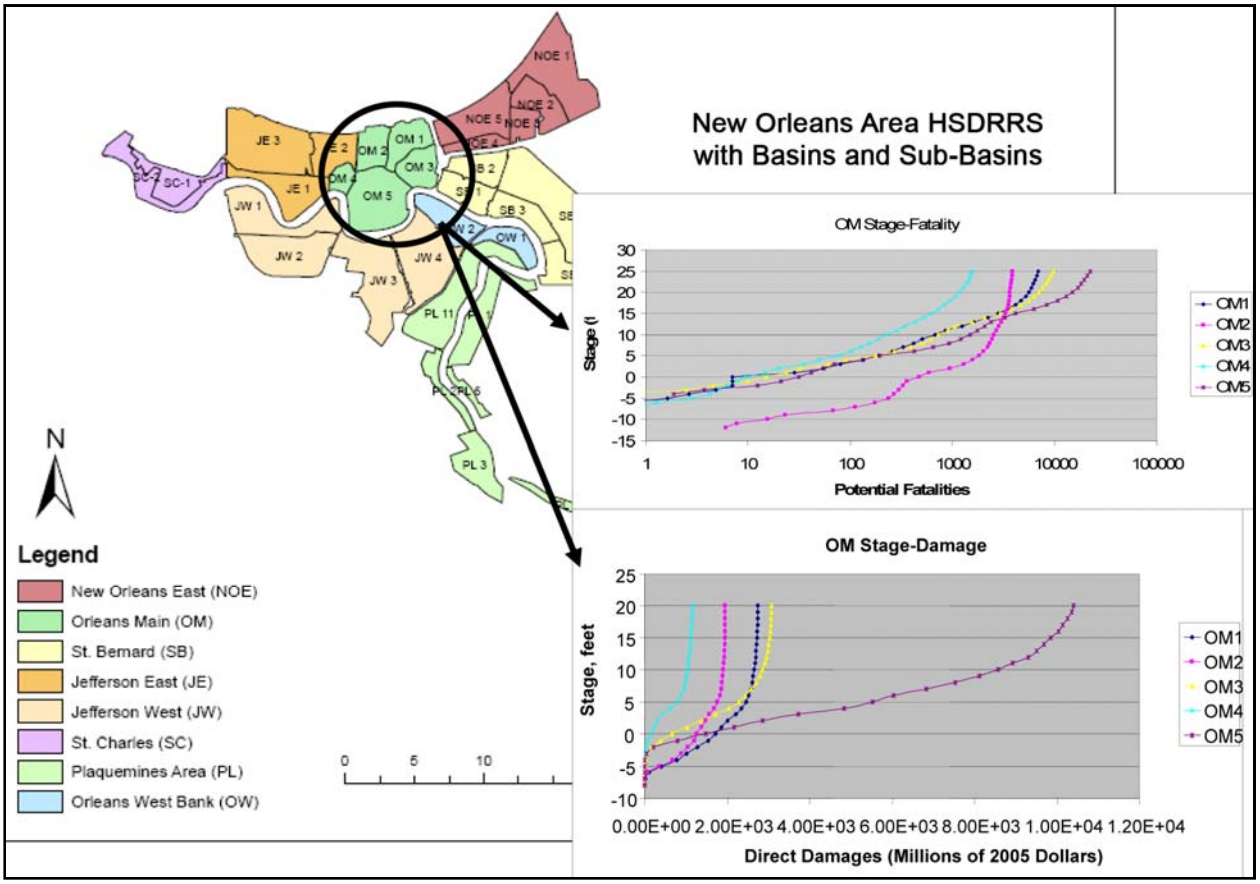


Figure 14. Example relationships for loss of life – water elevation and loss of property – water elevations for the Orleans Main sub-basins.

The LIFESim model calculated the exposure of the population to flooding for each sub-basin. The Monte Carlo Uncertainty Model first used research on Katrina evacuation conducted at Tulane University to estimate evacuation effectiveness for the risk assessment. Thus, the only population exposed to flooding was those who were not expected to evacuate. The Monte Carlo model was then used to estimate immediate loss of life. This step used information from the literature (McClelland, 2000[1]). Next an estimate was made of the delayed fatalities among those who survived the initial inundation but were not rescued. All of these steps have considerable uncertainty and the resulting estimates of potential loss of life are very approximate. This is not a

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

predictive process. The loss of life numbers should be viewed as an index of loss of life potential, not as a forecast.

For example, for the pre-Katrina no-pumping condition, significant loss of life is projected for the OM2 (Lakeview) sub-basin for the 50-year flood event. This is counter to the experience in New Orleans for historical flooding caused by large rainfall events. The fact that the majority of the sub-basins have low estimated values for loss of life at the 50-year flood levels is appropriate and meaningful. The fact that the 50-year estimates are low compared to those for the 100-year and 500-year flood levels is also appropriate as is the reduction in potential loss of life when significant pumping is considered.

Risk

Risk for loss of life and economic damages can be estimated using the flood water level associated with specific frequencies of occurrence (2%, 1% and 0.2%) and the loss-stage relationships for each sub-basin (these curves represent the Pre-Katrina population and property distributions). The information derived from this step is an average representing the most likely value. Since all the estimates have a level of uncertainty, the actual value may be higher or lower. The uncertainty of these and other parameters presented in this report was studied and is presented in IPET, Volume VIII, *Engineering and Operational Risk and Reliability Analysis.*

Risk Assessment: Results

Vulnerability to Flooding

The flood water elevations for specific events, such as the 2% (1/50), 1% (1/100) or 0.2% (1/500) year floods can be determined by aggregating the information from the hurricanes modeled. For the purposes of this analysis, only the first 76 of the 152 hurricanes were assigned frequencies of occurrence and used in the risk estimation. The smaller sample was chosen to reduce the computational burden in conduct of the risk assessment. Analysis confirmed that there is little appreciable difference between the water level estimates from this 76 storm sample and a hazard defined using up to 231 hurricanes. The flood elevations determined by this process for three pumping scenarios, (0, 50 and 100% of ideal pumping capacities) are presented in Tables 3 to 5, respectively. Note that the 2%, 1% and 0.2% elevations are represented in these charts as the 50, 100 and 500-year return period elevations, respectively.

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

Flood Depth Frequency Maps

Hurricane Flood Depth Frequency Maps are created by overlaying the water elevation representing a frequency of flood event (from Tables 3-5) on the local topography. By subtracting the land elevation from the water elevation at each point, an estimate of water depth is obtained. This does not represent flood depth with respect to the first floor elevation of local structures, but depth of water above the ground surface. It should also be considered a general estimate because of the resolution of the ground elevation data (approximately ±2 ft) and the uncertainty in the estimated flood elevations.

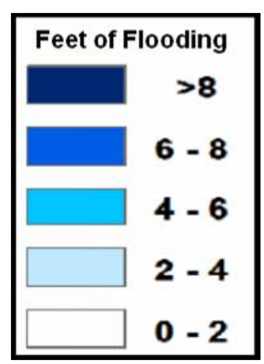
Table 3. Flood elevations in feet by sub-basin for no pumping scenario. Reference to NAVD 88 (2004.65)

Sub-basin	Analysis Results without pumping and with wave run-up								
	50-year flood elevations			100-year flood elevations			500-year flood elevations		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
OW1	-1	-1	-1	1	1	0	6	6	1
OW2	-3	-3	-3	4	4	-2	8	8	0
NOE1	0	0	0	2	1	0	12	13	3
NOE2	-4	-4	-4	2	2	-3	12	13	0
NOE3	-4	-4	-4	2	2	-3	12	13	-2
NOE4	-1	-1	-1	4	4	0	12	13	2
NOE5	-8	-8	-8	-1	-1	-7	12	13	-4
OM1	-5	-5	-5	3	3	-4	14	14	-2
OM2	-5	-5	-5	3	-2	-4	14	14	-2
OM3	-1	-1	-1	3	3	-1	14	14	1
OM4	-1	-1	-1	3	-1	-1	14	14	1
OM5	-1	-1	-1	3	1	0	14	14	1
SB1	-1	-1	-1	12	10	0	14	14	2
SB2	1	1	1	12	10	2	14	14	3
SB3	0	0	0	12	10	1	14	14	2
SB4	2	2	2	12	10	3	14	14	5
SB5	3	3	3	12	10	4	14	14	5
JE1	3	3	3	4	4	4	14	14	5
JE2	-4	-4	-4	-3	-3	-3	14	14	-2
JE3	-5	-5	-5	-3	-3	-4	14	14	-2
JW1	0	0	0	4	4	2	8	8	3
JW2	-4	-4	-4	4	4	-3	8	8	0
JW3	-2	-2	-2	4	4	0	8	8	0
JW4	-5	-5	-5	4	4	-3	8	8	-1
PL11	-2	-2	-2	0	-1	-2	6	9	1
SC1	2	2	2	4	4	3	10	10	5
SC2	4	4	4	5	5	4	10	10	6

Table 4. Flood elevations in feet by sub-basin for 50% pumping scenario. Reference to NAVD 88 (2004.65)

Sub-basin	Results with 50% pumping and with wave run-up								
	50-year flood elevations			100-year flood elevations			500–year flood elevations		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
OW1	-1	-1	-1	0	0	-1	6	6	1
OW2	-3	-3	-3	3	3	-2	8	8	0
NOE1	0	0	0	2	1	0	12	13	3
NOE2	-5	-5	-5	1	1	-4	11	12	-2
NOE3	-5	-5	-5	1	1	-4	11	12	-3
NOE4	-2	-2	-2	2	2	-1	11	12	0
NOE5	-9	-9	-9	-2	-2	-8	11	12	-6
OM1	-7	-7	-7	2	1	-5	12	12	-4
OM2	-12	-12	-12	1	-7	-12	11	11	-7
OM3	-6	-6	-6	2	1	-6	12	12	-2
OM4	-5	-5	-5	3	-2	-2	13	13	1
OM5	-4	-4	-4	2	0	-4	12	12	0
SB1	-5	-5	-5	11	8	-2	12	12	1
SB2	1	1	1	12	9	2	13	13	3
SB3	-1	-1	-1	11	8	-1	12	12	0
SB4	1	1	1	11	9	1	12	12	4
SB5	3	3	3	12	10	3	13	13	5
JE1	2	2	2	3	3	2	12	12	4
JE2	-12	-12	-12	-5	-5	-12	12	12	-3
JE3	-6	-6	-6	-5	-5	-5	12	12	-3
JW1	0	0	0	4	4	1	8	8	2
JW2	-5	-5	-5	3	3	-5	7	7	-2
JW3	-5	-5	-5	3	3	-1	7	7	0
JW4	-12	-12	-12	3	3	-4	7	7	-3
PL11	-12	-12	-12	-4	-8	-12	1	2	-4
SC1	2	2	2	4	4	3	10	10	5
SC2	4	4	4	5	5	4	10	10	5

Table 5. Flood elevations in feet by sub-basin for 100% pumping scenario. Reference to NAVD 88 (2004.65)									
Sub-basin	Results with 100% pumping and with wave run-up								
	50-year flood elevations			100–year flood elevations			500-year flood elevations		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
OW1	-1	-1	-1	0	0	-1	6	6	1
OW2	-3	-3	-3	3	3	-2	8	8	0
NOE1	0	0	0	2	1	0	12	13	3
NOE2	-5	-5	-5	1	1	-4	11	12	-2
NOE3	-5	-5	-5	1	1	-4	11	12	-3
NOE4	-3	-3	-3	2	2	-1	11	12	0
NOE5	-11	-11	-11	-2	-2	-9	11	12	-6
OM1	-12	-12	-12	2	1	-6	12	12	-5
OM2	-12	-12	-12	0	-12	-12	10	10	-12
OM3	-12	-12	-12	1	-1	-12	11	11	-12
OM4	-5	-5	-5	3	-2	-2	13	13	1
OM5	-12	-12	-12	1	-2	-12	12	12	-2
SB1	-12	-12	-12	11	8	-12	12	12	0
SB2	1	1	1	12	9	2	13	13	3
SB3	-3	-3	-3	11	8	-3	12	12	-1
SB4	1	1	1	11	9	1	12	12	4
SB5	3	3	3	12	10	3	13	13	5
JE1	2	2	2	3	3	2	12	12	4
JE2	-12	-12	-12	-12	-12	-12	11	11	-4
JE3	-10	-10	-10	-5	-5	-5	12	12	-3
JW1	0	0	0	4	4	1	8	8	2
JW2	-5	-5	-5	3	3	-5	7	7	-2
JW3	-12	-12	-12	3	3	-2	7	7	0
JW4	-12	-12	-12	3	3	-6	7	7	-4
PL11	-12	-12	-12	-5	-12	-12	1	2	-5
SC1	2	2	2	4	4	3	10	10	5
SC2	3	3	3	4	4	3	10	10	5



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

The maps in Figure 15 to 17 provide a “big picture” perspective of flooding vulnerability of greater New Orleans, for different flood frequencies, and for the three HSDRRS infrastructure options and the three pumping scenarios.

Figure 15. Flood Depth Frequency Maps for 50-Year (2%) Hurricane Floodplain, showing impact of different pumping capacities. The label on each map indicates the HSDRRS infrastructure, flood frequency and percent pumping capacity modeled.

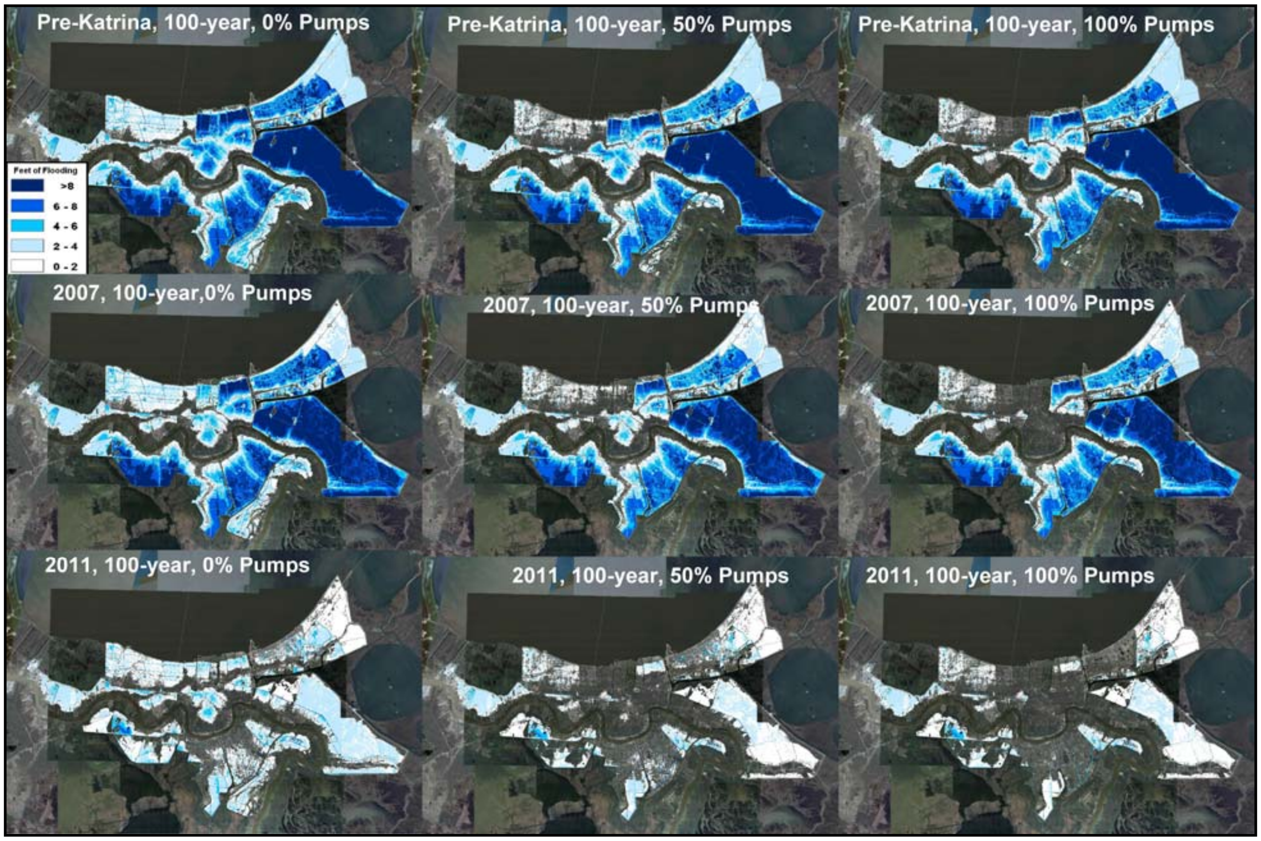


Figure 16. Flood Depth Frequency Maps for 100-Year (1%) Hurricane Floodplain. The label on each map indicates the HSDRRS infrastructure, flood frequency and percent pumping capacity modeled.

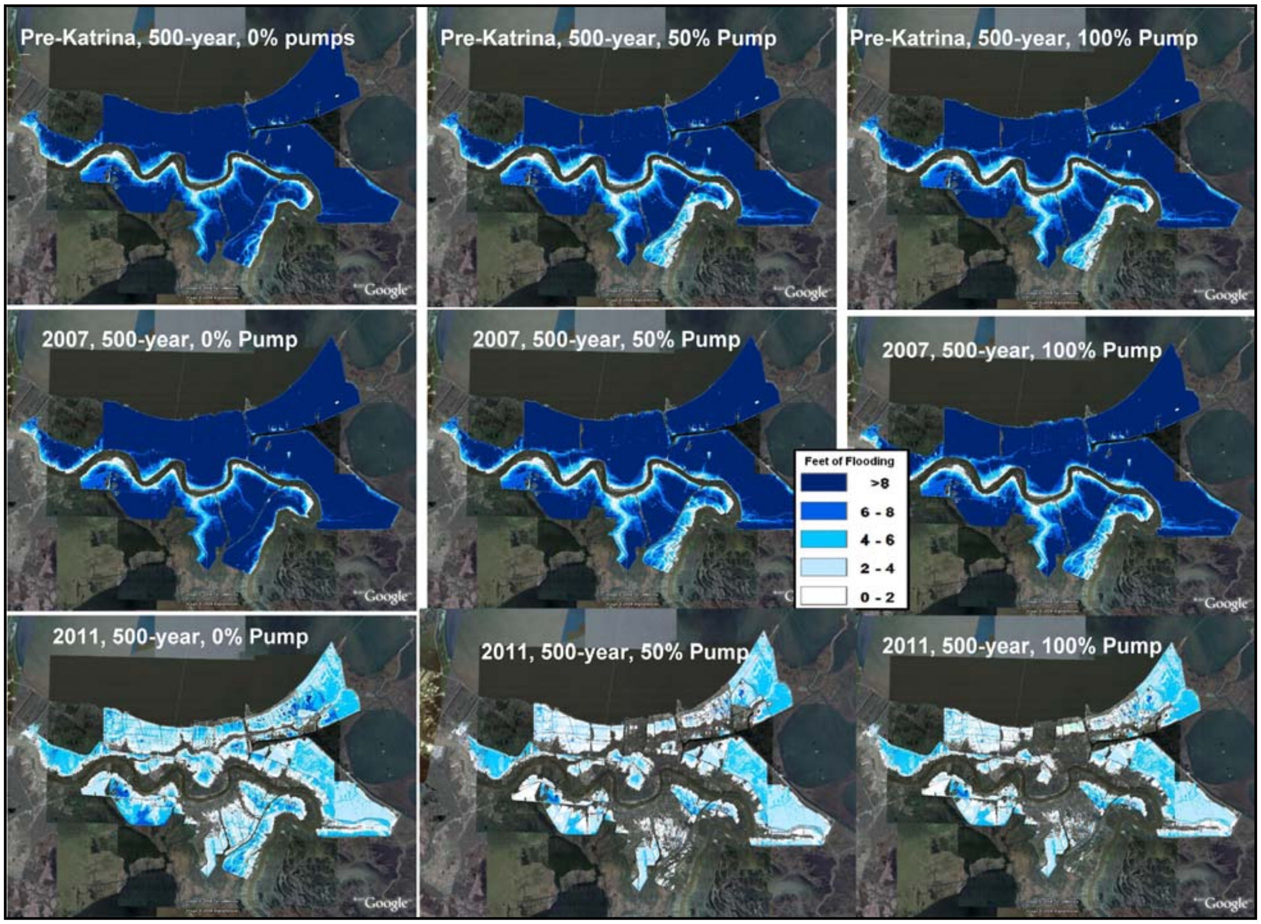


Figure 17. Flood Depth Frequency Maps for 500-Year (0.2%) Hurricane Floodplain, showing impact of different pumping capacities. The label on each map indicates the HSDRRS infrastructure option, flood frequency and percent pumping.

Vulnerability Findings

The assessments represent a "big picture" look at the information in the flood depth frequency maps presented here and in IPET Volume VIII -*Engineering and Operational Risk and Reliability Analysis*. The information is focused on a systems wide look at (1.) the vulnerability to flooding and (2.) the probable sources of flooding. A more in-depth basin by basin analysis is provided in Volume VIII. Information and future updates can also be found on the New Orleans District web site (*www.mvn.usace.army.mil*).

The primary findings are presented for the entire region modeled and the individual major basins as described in Figure 2. A full risk assessment was conducted only for the northern part of Plaquemines Parish (basin PL11, Belle Chasse). IPET did not examine the individual sub-basins in isolation because sub-basins are interconnected, especially with higher levels of water.

The following findings have been determined from analysis of the maps.

50-Year Flood Event

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

2. No significant difference exists in the flood elevations between the Pre-Katrina, 2007 or 2011 HSDRRS at the 50 Year (2%) frequency of occurrence. Rainfall likely dominates as the source of water at this level of event. If this is true, hurricanes are not the dominant threat to New Orleans at or below this return period. (Thunderstorms, tropical storms and other rainfall events dominant the threat at this level.)

3. Pumping equal to or greater than 50% of the ideal (or name plate) capacity of the sub-basins can have a dramatic impact in reducing the flood elevations at the 50-year or 2% frequency of occurrence in a number of the basins modeled.

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

100-Year Flood Event

1. Without pumping, the majority of the New Orleans area remains vulnerable to moderate to deep flooding (greater than 4 feet) at the 100-year or 1% frequency of occurrence in 2007. The areas with least vulnerability are Jefferson Parish East and Saint Charles Parish where flood threats are moderate.

2. The improvements in the system from Pre-Katrina to the 2007 have provided significantly reduced flood levels in a few areas, notably portions of Orleans Main (OM2 and OM4) and moderate reductions in the 1% flood level in St. Bernard (SB) and Plaquemines (PL11). Completion of the 2011 HSDRRS will provide dramatic improvement in all areas. With this system in place, as modeled, the dominant source of flood water for the 100-year flood is rainfall.

3. Improvements from Pre-Katrina to 2007 level in Orleans Main are largely due to the presence of the new gates and temporary pumps at the ends of the outfall canals. Continued vulnerability of the areas adjacent to the Inner Harbor Navigation Canal (IHNC) can be attributed to the remaining pre-Katrina elevations and significant fragility of the I-walls along the IHNC. Strengthening of the I-walls with stability berms and relief wells has improved the performance of the structures in the IHNC, but they remain unable to cope with surge conditions created by large storms. The 100-year HSDRRS dramatically reduces the 100-year flood depths across the area because of higher and stronger levees as well as large navigable surge gates at the entrances to the IHNC.

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

5. The West Bank area remained highly vulnerable to flooding in 2007 and pumping will likely have little impact until all of the fundamental HSDRRS structures are completed. The 2011 HSDRRS will dramatically reduce vulnerability to flooding in this area because of new floodwalls and levees and substantial closure gate structures.

500-Year Flood Event

1. Virtually all of the New Orleans region remains highly vulnerable to deep and catastrophic flooding at the 500-year or 0.2% flood frequency for the 2007 system. The vast majority of the region would experience flooding of greater than 8 feet.

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

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

4. The 2011 HSDRRS would, in comparison to 2007, dramatically reduce the 500-year catastrophic flooding across the region and, with capable pumping capacities, would further reduce flood depths.

Loss of Life Risk

The estimates of loss of life are provided in Tables 6 to 8. The losses are by sub-basin for each HSDRRS infrastructure option (Pre-Katrina, 2007 and 2011) and the three pumping capacities (0, 50, and 100% of ideal capacity) modeled. The values in these tables were derived by combining the flood elevations for each frequency of occurrence and the loss of life-water elevation relationships for each sub-basin. The values of expected loss of life presented in the tables are the mean values. The mean value is average for loss of life within the range of possible values that represent the uncertainty in the data. The level of uncertainty is discussed in IPET Volume VIII. In the case of loss of life, the uncertainties are substantial because of the complexities of the evacuation process and lack of basic information on the specific location and cause of many of the fatalities during Katrina.

Table 6. Summary of mean values of expected loss of life by sub-basin for no pumping situation. Assumes 2005 population distribution.									
Subbasin	No Pumping								
	50-year mean loss of life			100-year mean loss of life			500-year mean loss of life		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
JE1	0	0	0	0	0	0	3	3	0
JE2	37	37	37	50	50	50	5,886	5,886	63
JE3	31	31	31	93	93	53	17,136	17,136	132
JW1	4	4	4	31	31	13	63	63	20
JW2	0	0	0	6	6	0	40	40	2
JW3	1	1	1	42	42	9	195	195	9
JW4	1	1	1	132	132	5	607	607	20
NOE1	0	0	0	0	0	0	0	0	0
NOE2	0	0	0	1	1	1	91	154	1
NOE3	0	0	0	13	13	2	298	524	3
NOE4	0	0	0	0	0	0	2	2	0
NOE5	4	4	4	63	63	6	6,528	7,945	21
OM1	2	2	2	80	80	3	2,217	2,217	7
OM2	237	237	237	1,289	329	269	3,179	3,179	329
OM3	10	10	10	61	61	10	2,079	2,079	24
OM4	8	8	8	35	8	8	530	530	15
OM5	21	21	21	70	41	31	3,262	3,262	41
OW1	0	0	0	0	0	0	1	1	0
OW2	6	6	6	101	101	10	420	420	19
PL11	28	28	28	33	31	28	180	247	37
SB1	-	-	-	915	888	-	915	915	22
SB2	-	-	-	-	-	-	-	-	-
SB3	-	-	-	561	561	2	646	646	4
SB4	0	0	0	82	49	2	107	107	5
SB5	0	0	0	3	3	0	3	3	0
SC1	-	-	-	-	-	-	1	1	-
SC2	1	1	1	1	1	1	23	23	2
Totals	**391**	**391**	**391**	**3,663**	**2,585**	**501**	**44,411**	**46,184**	**776**

Table 7. Summary of mean values of expected loss of life by sub-basin for 50% pumping situation. Assumes 2005 population distribution.

Subbasin	50% Pumping								
	50-year mean loss of life			100-year mean loss of life			500-year mean loss of life		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
JE1	-	-	-	0	0	-	3	3	0
JE2	-	-	-	23	23	-	3,716	3,716	50
JE3	9	9	9	31		31	9,678	9,678	93
JW1	4	4	4	31	31	6	63	63	13
JW2	0	0	0	5	5	0	24	24	0
JW3	0	0	0	33	33	5	138	138	9
JW4	-	-	-	83	83	3	418	418	5
NOE1	0	0	0	0	0	0	0	0	0
NOE2	0	0	0	1	1	0	56	91	1
NOE3	-	-	-	9	9	0	228	298	2
NOE4	0	0	0	0	0	0	2	2	0
NOE5	2	2	2	45	45	4	5,111	6,528	10
OM1	1	1	1	54	29	2	1,241	1,241	3
OM2	6	6	6	586	113	6	2,683	2,683	113
OM3	-	-	-	32	24	-	1,055	1,055	5
OM4	3	3	3	35	6	6	438	438	15
OM5	2	2	2	56	31	2	2,075	2,075	31
OW1	0	0	0	0	0	0	1	1	0
OW2	6	6	6	52	52	10	420	420	19
PL11	1	1	1	16	1	1	37	41	16
SB1	-	-	-	901	393	-	915	915	11
SB2	-	-	-	-	-	-	-	-	-
SB3	-	-	-	561	136	-	561	561	-
SB4	0	0	0	66	34	0	82	82	4
SB5	0	0	0	3	3	0	3	3	0
SC1	-	-	-	-	-	-	1	1	-
SC2	1	1	1	1	1	1	23	23	1
Totals	33	33	33	2,625	1,054	77	28,971	30,497	398

Table 8. Summary of mean values of expected loss of life by sub-basin for 100% pumping situation. Assumes 2005 population distribution.									
Subbasin	100% Pumping								
	50-year mean loss of life			100-year mean loss of life			500-year mean loss of life		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
JE1	-	-	-	0	0	-	3	3	0
JE2	-	-	-	-	-	-	2,584	2,584	37
JE3	-	-	-	31	31	31	9,678	9,678	93
JW1	4	4	4	31	31	6	63	63	13
JW2	0	0	0	5	5	0	24	24	0
JW3	-	-	-	33	33	1	138	138	9
JW4	-	-	-	83	83	1	418	418	3
NOE1	0	0	0	0	0	0	0	0	0
NOE2	0	0	0	1	1	0	56	91	1
NOE3	-	-	-	9	9	0	228	298	2
NOE4	0	0	0	0	0	0	2	2	0
NOE5	-	-	-	45	45	2	5,111	6,528	10
OM1	-	-	-	54	29	1	1,241	1,241	2
OM2	6	6	6	472	6	6	2,560	2,560	6
OM3	-	-	-	24	10	-	888	888	0
OM4	3	3	3	35	6	6	438	438	15
OM5	-	-	-	41	12	-	2,075	2,075	12
OW1	0	0	0	0	0	0	1	1	0
OW2	6	6	6	52	52	10	420	420	19
PL11	1	1	1	10	1	1	37	41	10
SB1	-	-	-	901	393	-	915	915	0
SB2	-	-	-	-	-	-	-	-	0
SB3	-	-	-	561	136	-	561	561	0
SB4	0	0	0	66	34	0	82	82	4
SB5	0	0	0	3	3	0	3	3	0
SC1	-	-	-	-	-	-	1	1	0
SC2	0	0	0	1	1	0	23	23	1
Totals	19	19	19	2,458	921	65	27,549	29,075	235

The results presented, while calibrated to some extent by what happened in Katrina, are largely influenced by the assumptions made in the LIFESim model and the consideration of evacuation through a separate probability distribution. These estimates are conservative and should be viewed as an index of potential loss of life rather than a specific estimate of actual fatalities. For example, for the pre-Katrina no-pumping condition, significant loss of life is projected for the OM2 (Lakeview) sub-basin for the 50-year flood event. This is counter to the experience in New Orleans for historical flooding caused by large rainfall events. The fact that the majority of the sub-basins have low estimated values for loss of life at the 50-year flood levels is appropriate and meaningful. The fact that the 50-year estimates are quite low compared to those for the 100-year and 500-year flood levels is also appropriate as is the reduction in potential loss of life when significant pumping is considered. The loss-of-life risk maps derived are presented in Figures 18 to 20 for the 50, 100 and 500-year flood frequencies, respectively. The color codes on the maps represent different ranges of potential loss of life.

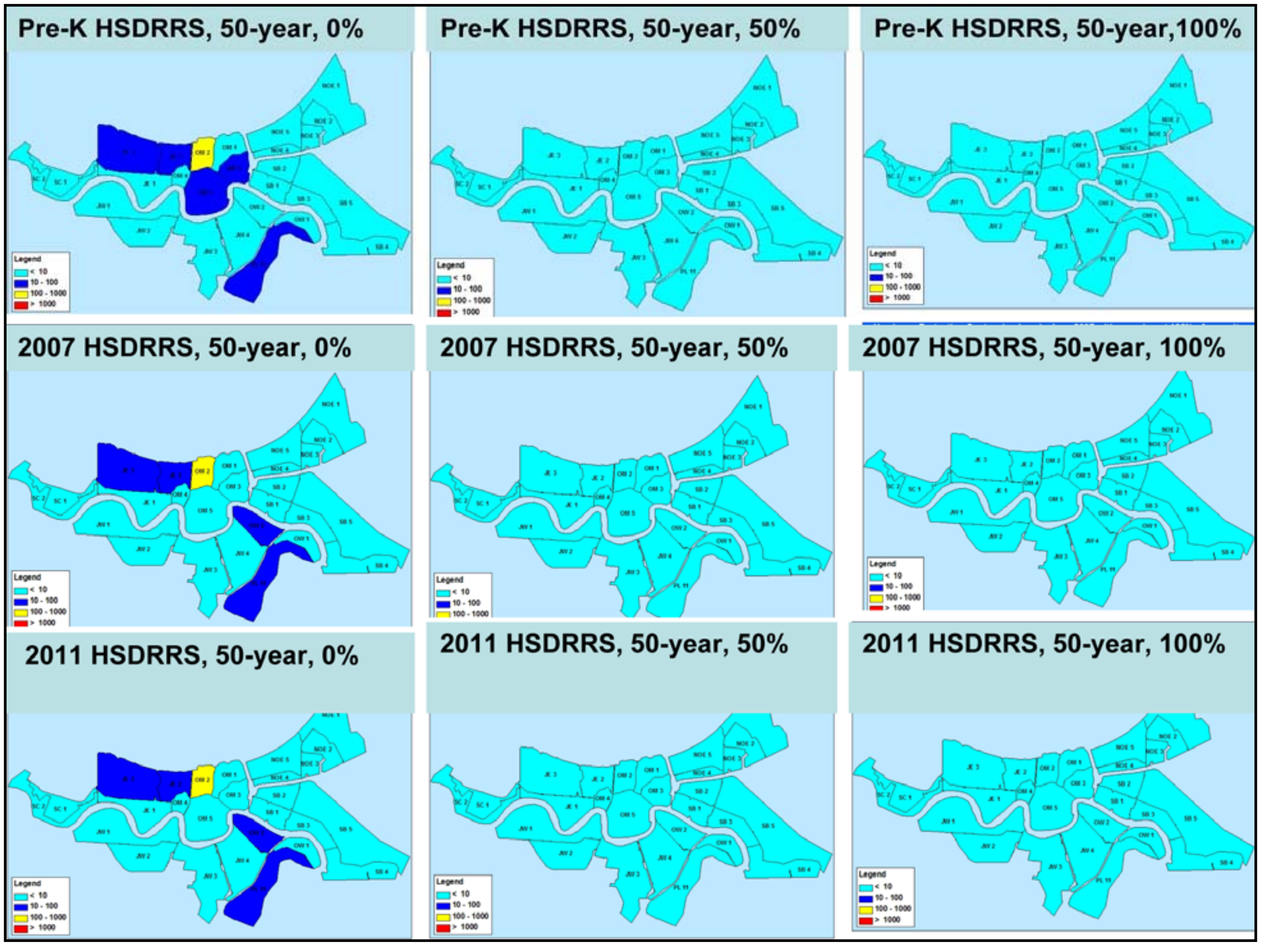


Figure 18. Loss of Life Risk Maps comparing Pre-Katrina, 2007 and 2011 HSDRRS for 50-Year (2%) flood frequency with the various pumping scenarios (0, 50, and 100%). These maps represent pre-Katrina population and property distributions. *These values should be considered an index of potential loss of life, not actual fatalities*. Evacuation assumptions were conservative, making fatality estimates relatively larger than if effective evacuation is achieved.

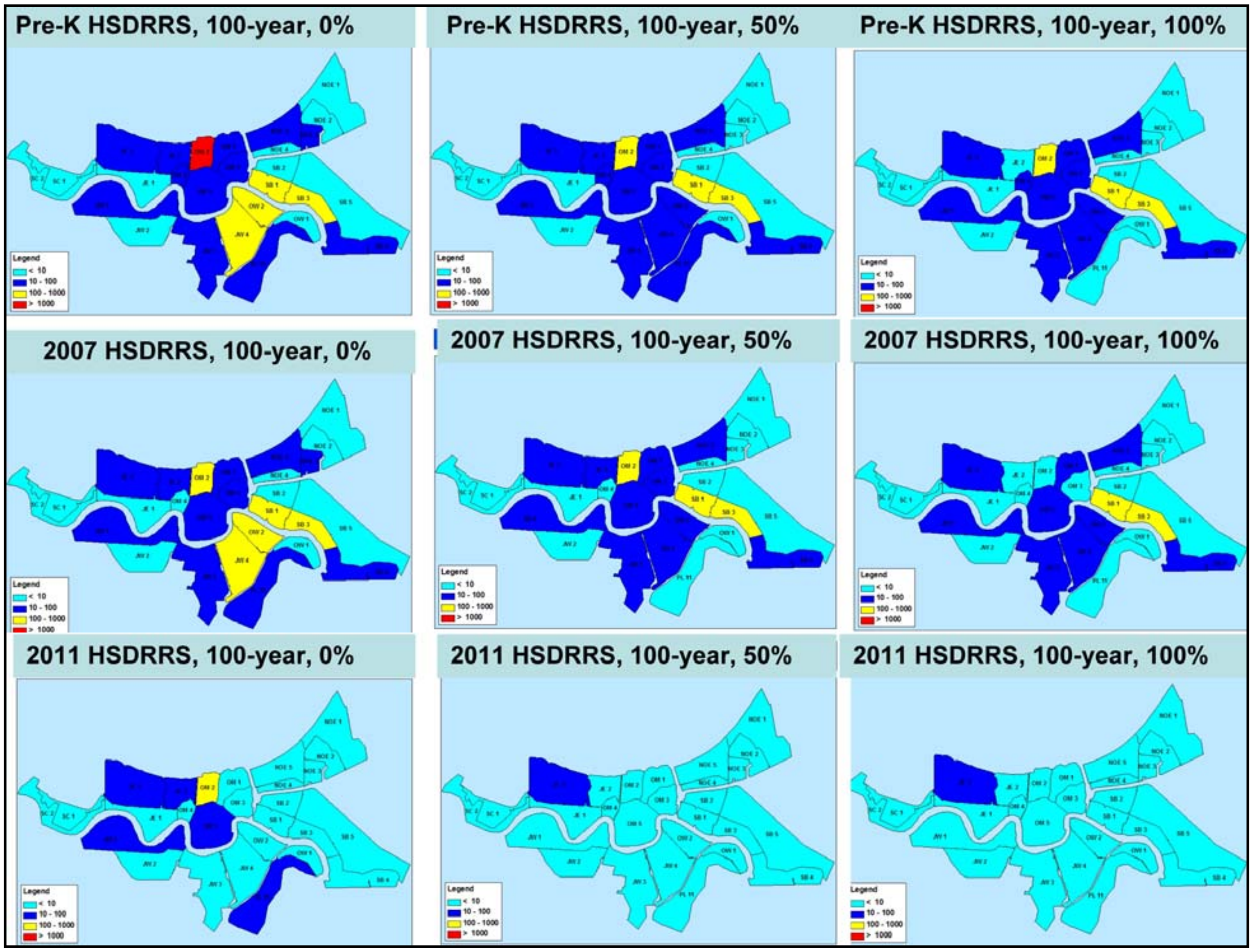


Figure 19. Loss of Life risk maps comparing Pre-Katrina, 2007 and 2011 HSDRRS for 100-year (1%) flood frequency with the various pumping scenarios (0, 50, and 100%). These maps represent pre-Katrina population and property distributions. *These values should be considered an index of potential loss of life, not actual fatalities.* Evacuation assumptions were conservative making the fatality estimates relatively larger than if effective evacuation is achieved.

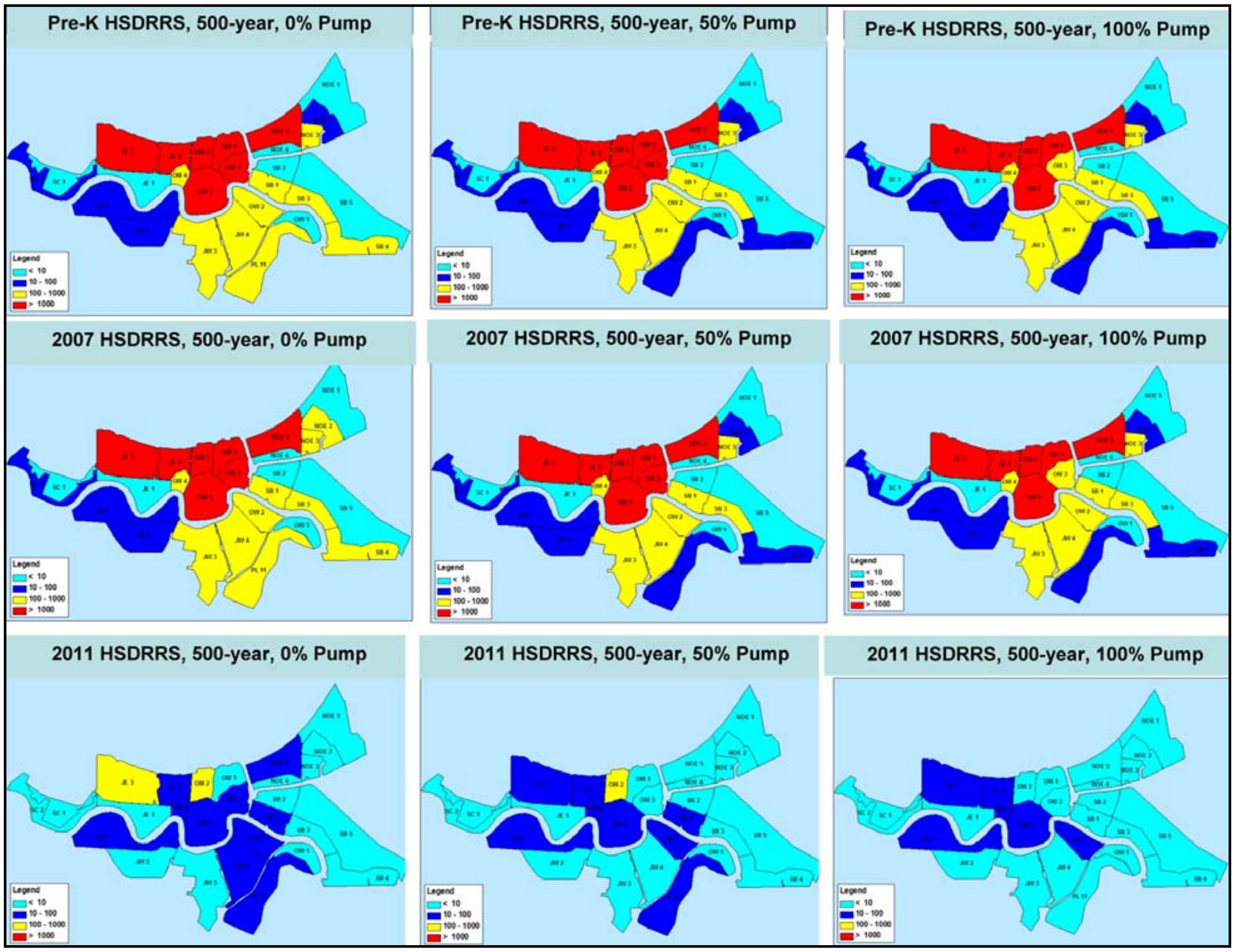


Figure 20. Loss of Life risk maps comparing Pre-Katrina, 2007 and 2011 HSDRRS for 500-year (0.2%) flood frequency with the various pumping scenarios (0, 50, and 100%). These maps represent pre-Katrina population and property distributions. *These values should be considered an index of potential loss of life, not actual fatalities.* Evacuation assumptions were conservative making the fatality estimates relatively larger than if effective evacuation is achieved.

Table 9 presents a summary of the loss of life estimates for the entire region as a function of the system and level of pumping. This shows that the potential loss of life, given the assumptions in the analysis, is somewhat improved for 2007 at the 100-year frequency of occurrence, but little different at the 50 and 500-year frequencies. There is no difference between the storm damage reduction scenarios at the 50-year level because flooding is dominantly from rainfall. For the 500-year level, there is such extensive flooding that the improvements made for the 2007 system have little impact. These numbers also show that pumping can significantly impact loss of life if an operational capability comparable to the 50% ideal capacity modeled can be achieved.

Table 9. Loss of Life mean risk summary statistics for entire region modeled (x1000). Pumping is percent of ideal capacities and does not represent current operational capabilities.								
Fatalities (1000)	**Pre-K HSDRRS 50-yr**	**2007 HSDRRS 50-yr**	**2011 HSDRRS 50-yr**	**Pre-K HSDRRS 100-yr**	**2007 HSDRRS 100-yr**	**2011 HSDRRS 100-yr**	**Pre-K & 2007 HSDRRS 500-yr**	**2011 HSDRRS 500-yr**
0% Pump	0.4	0.4	0.4	3.7	2.6	0.5	45	0.8
50% Pump	0.03	0.03	0.03	2.6	1.1	0.08	30	0.4
100% Pump	0.02	0.02	0.02	2.5	0.9	0.07	28	0.2

Loss of Life Risk Findings

50-Year Flood Event: Given the pre-Katrina population conditions

1. At this return period there is little difference in the potential loss of life risk between the three system conditions. This is primarily because the hazard largely is rainfall — not hurricanes.

2. Pre-Katrina potential for loss of life was very high in OM2 sub-basin and high in portions of JE, JW, PL and OW.

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

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

100-Year Flood Event: Given the pre-Katrina population conditions

1. At the 100-year flood frequency, Pre-Katrina potential for loss of life risk was extreme for OM2 and very high for SB and portions of OW and JW.

2. The 2007 system, without pumping, reduces loss of life risk for the entire area by 29%. With at least 50% of ideal pumping capacity, the benefit increases to 60%.

3. The 2011 HSDRRS dramatically reduces potential for loss of life by 86% without pumping and up to 97% with 50% pumping. This is a direct reflection of the fact that the 100-year flood event is quite small for this scenario.

500-Year Flood Event: Given the pre-Katrina population conditions

1. The 500-year (0.2%) flood frequency presents an extremely high potential for loss of life risk for all of OM, most of JE and a good portion of NOE, SB, OW, and JW for both Pre-Katrina HSDRRS and the 2007 HSDRRS.

2. Areas with lower loss of life risk are primarily areas with lower populations exposed to flooding.

3. While the data show pumping to have some influence in loss of life risk at the 500-year flood frequency for the Pre-Katrina and 2007 systems, the potential loss levels are so high, this result is not considered relevant.

4. The 2011 HSDRRS dramatically reduced potential for loss of life by up to 98%. Risk remains moderate in a number of sub-basins.

5. Given the 2011 HSDRRS is in place, pumping at or above the 50% of ideal capacity can significantly reduce loss of life in many basins.

Property Loss Risk

The estimates of potential direct property loss due to direct property damages are presented in Tables 10 to 12 by sub-basin for each HSDRRS infrastructure (Pre-Katrina, 2007 and 2011) and the three pumping capacities (0, 50, and 100% of ideal capacity) modeled. The values are derived by combining the flood elevations for each frequency of occurrence in the loss-water elevation relationships for each sub-basin.

Table 10. Summary of mean values of expected direct property losses by sub-basin for no pumping situation ($1000). Assumes 2005 Property distribution and values.

Sub-basin	Analysis Results without pumping and with wave run-up								
	50-year mean property loss			100-year mean property loss			500-year mean property loss		
	Pre-k	2007	2011 sys	Pre-k	2007	2011 sys	Pre-k	2007	2011 sys
OW1	23	23	23	39	39	28	170	170	39
OW2	412	412	412	2,405	2,405	784	3,105	3,105	1,465
NOE1	0	0	0	8	6	0	12	12	9
NOE2	19	19	19	123	123	29	143	143	116
NOE3	8	8	8	510	510	40	668	671	189
NOE4	0	0	0	49	49	0	61	62	33
NOE5	43	43	43	4,561	4,561	241	6,022	6,026	3,083
OM1	402	402	402	2,209	2,209	783	2,718	2,718	1,270
OM2	348	348	348	1,573	1,040	677	1,945	1,945	1,040
OM3	376	376	376	1,709	1,709	376	3,010	3,010	1,031
OM4	68	68	68	420	68	68	1,111	1,111	219
OM5	785	785	785	3,721	2,167	1,483	9,680	9,680	2,167
SB1	196	196	196	2,617	2,542	477	2,677	2,677	1,263
SB2	-	-	-	25	24	-	26	26	-
SB3	71	71	71	2,456	2,298	218	2,510	2,510	633
SB4	0	0	0	497	465	7	516	516	90
SB5	2	2	2	43	41	11	44	44	30
JE1	420	420	420	1,093	1,093	1,093	5,728	5,728	1,490
JE2	471	471	471	2,190	2,190	2,190	6,278	6,278	3,394
JE3	515	515	515	6,174	6,174	2,336	12,081	12,081	8,346
JW1	0	0	0	230	230	61	542	542	151
JW2	5	5	5	393	393	44	426	426	262
JW3	122	122	122	3,660	3,660	635	5,625	5,625	635
JW4	23	23	23	5,551	5,551	426	6,437	6,437	2,702
SC1	19	19	19	113	113	85	132	132	121
SC2	390	390	390	485	485	390	1,355	1,355	661
Totals	**4,718**	**4,718**	**4,719**	**42,856**	**40,147**	**12,481**	**73,020**	**73,028**	**30,438**

Table 11. Summary of mean values of expected direct economic property losses by sub-basin for 50% pumping situation ($1000). Assumes 2005 Property distribution and values.									
Sub-basin	**Results with 50% pumping and with wave run-up**								
	50-year mean property loss			**100-year mean property loss**			**500-year mean property loss**		
	Pre-k	**2007**	**2011**	**Pre-k**	**2007**	**2011**	**Pre-k**	**2007**	**2011**
OW1	23	23	23	28	28	23	170	170	39
OW2	412	412	412	2,205	2,205	784	3,105	3,105	1,465
NOE1	0	0	0	8	6	0	12	12	9
NOE2	1	1	1	121	121	19	143	143	98
NOE3	0	0	0	416	416	8	667	668	40
NOE4	0	0	0	33	33	0	60	61	0
NOE5	5	5	5	4,121	4,121	43	6,007	6,022	962
OM1	8	8	8	2,012	1,864	402	2,689	2,689	783
OM2	-	-	-	1,377	2	-	1,922	1,922	2
OM3	1	1	1	1,365	1,031	1	2,953	2,953	154
OM4	3	3	3	420	28	28	1,096	1,096	219
OM5	7	7	7	2,860	1,483	7	9,306	9,306	1,483
SB1	-	-	-	2,582	2,403	54	2,617	2,617	877
SB2	-	-	-	25	24	-	25	25	-
SB3	4	4	4	2,393	2,077	4	2,456	2,456	71
SB4	-	-	-	491	439	-	497	497	33
SB5	2	2	2	43	41	2	44	44	30
JE1	218	218	218	420	420	218	5,122	5,122	1,093
JE2	-	-	-	52	52	-	6,243	6,243	2,190
JE3	116	116	116	515	515	515	12,062	12,062	6,174
JW1	0	0	0	230	230	4	542	542	61
JW2	1	1	1	383	383	1	416	416	114
JW3	0	0	0	2,750	2,750	314	5,466	5,466	635
JW4	-	-	-	5,236	5,236	83	6,272	6,272	426
SC1	19	19	19	113	113	85	132	132	121
SC2	390	390	390	485	485	390	1,355	1,355	485
-	**1,209**	**1,209**	**1,209**	**30,684**	**26,506**	**2,983**	**71,379**	**71,396**	**17,563**

Table 12. Summary of mean values of expected direct economic losses property by sub-basin for 100% pumping situation ($1000). Assumes 2005 Property distribution and values.

Sub-basin	Results with 100% pumping and with wave run-up								
	50-year mean property loss			100-year mean property loss			500-year mean property loss		
	Pre-k	2007	2011	Pre-k	2007	2011	Pre-k	2007	2011
OW1	23	23	23	28	28	23	170	170	39
OW2	412	412	412	2,205	2,205	784	3,105	3,105	1,465
NOE1	0	0	0	8	6	0	12	12	9
NOE2	1	1	1	121	121	19	143	143	98
NOE3	0	0	0	416	416	8	667	668	40
NOE4	0	0	0	33	33	0	60	61	0
NOE5	0	0	0	4,121	4,121	5	6,007	6,022	962
OM1	-	-	-	2,012	1,864	103	2,689	2,689	402
OM2	-	-	-	1,261	-	-	1,910	1,910	0
OM3	-	-	-	1,031	376	-	2,910	2,910	0
OM4	3	3	3	420	28	28	1,096	1,096	219
OM5	-	-	-	2,167	200	-	9,306	9,306	200
SB1	-	-	-	2,582	2,403	-	2,617	2,617	477
SB2	-	-	-	25	24	-	25	25	0
SB3	0	0	0	2,393	2,077	0	2,456	2,456	4
SB4	-	-	-	491	439	-	497	497	33
SB5	2	2	2	43	41	2	44	44	30
JE1	218	218	218	420	420	218	5,122	5,122	1,093
JE2	-	-	-	-	-	-	6,216	6,216	471
JE3	0	0	0	515	515	515	12,062	12,062	6,174
JW1	0	0	0	230	230	4	542	542	61
JW2	1	1	1	383	383	1	416	416	114
JW3	-	-	-	2,750	2,750	122	5,466	5,466	635
JW4	-	-	-	5,236	5,236	0	6,272	6,272	83
SC1	19	19	19	113	113	85	132	132	121
SC2	290	290	290	390	390	290	1,355	1,355	485
Totals	**969**	**969**	**969**	**29,394**	**24,419**	**2,208**	**71,297**	**71,313**	**13,214**

Tables 13 and 14 provide basin-wide summaries of direct property loss risk estimates. Figures 21 to 23 are maps providing a graphical portrayal of the mean property loss risk data for the 50, 100 and 500-year flood frequencies, respectively. Each figure provides appropriate maps for the Pre-Katrina, 2007 and 2011 HSDRRS and for the three pumping scenarios. The maps show estimated economic risk in terms of expected losses as a percent of total value. Property loss risk was initially computed as actual dollar (2005) losses but is presented on the maps as the percent of total value lost. The map representations were chosen to normalize the influence of high cost structures in the risk estimates. Obviously, the maps representing actual dollar losses would look different and provide a different and valuable perspective on the risk situation. The colors on the maps represent different ranges of property loss values in terms of percent loss of total value using 2005 property values.

Table 13. Property loss mean risk for the entire region modeled ($B). Pumping is percent of ideal capacities, not current operational capabilities. These values assume pre-Katrina property values and distribution.								
$B	Pre-K HSDRRS 50-yr	2007 HSDRRS 50-yr	2011 HSDRRS 50-yr	Pre-K HSDRRS 100-yr	2007 HSDRRS 100-yr	2011 HSDRRS 100-yr	Pre-K & 2007 HSDRRS 500-yr	2011 HSDRRS 500-yr
No Pump	4.7	4.7	4.7	41	38	12.5	73	30.6
50% Pump	1	1	1	31	28	3.0	72	17.5
100% Pump	1	1	1-	30	26	2.2	72	13.2

Table 14. Property loss mean risk for the entire region modeled as percent of value. Pumping is percent of ideal capacities, not current operational capabilities. Values assume pre-Katrina property values and distribution.								
Percent of Value	Pre-K HSDRRS 50-yr	2007 HSDRRS 50-yr	2011 HSDRRS 50-yr	Pre-K HSDRRS 100-yr	2007 HSDRRS 100-yr	2011 HSDRRS 100-yr	Pre-K & 2007 HSDRRS 500-yr	2011 HSDRRS 500-yr
No Pump	6	6	6	55	51	16	94	39
50% Pump	2	2	2	39	34	4	91	22
100% Pump	1	1	1	37	31	3	91	17

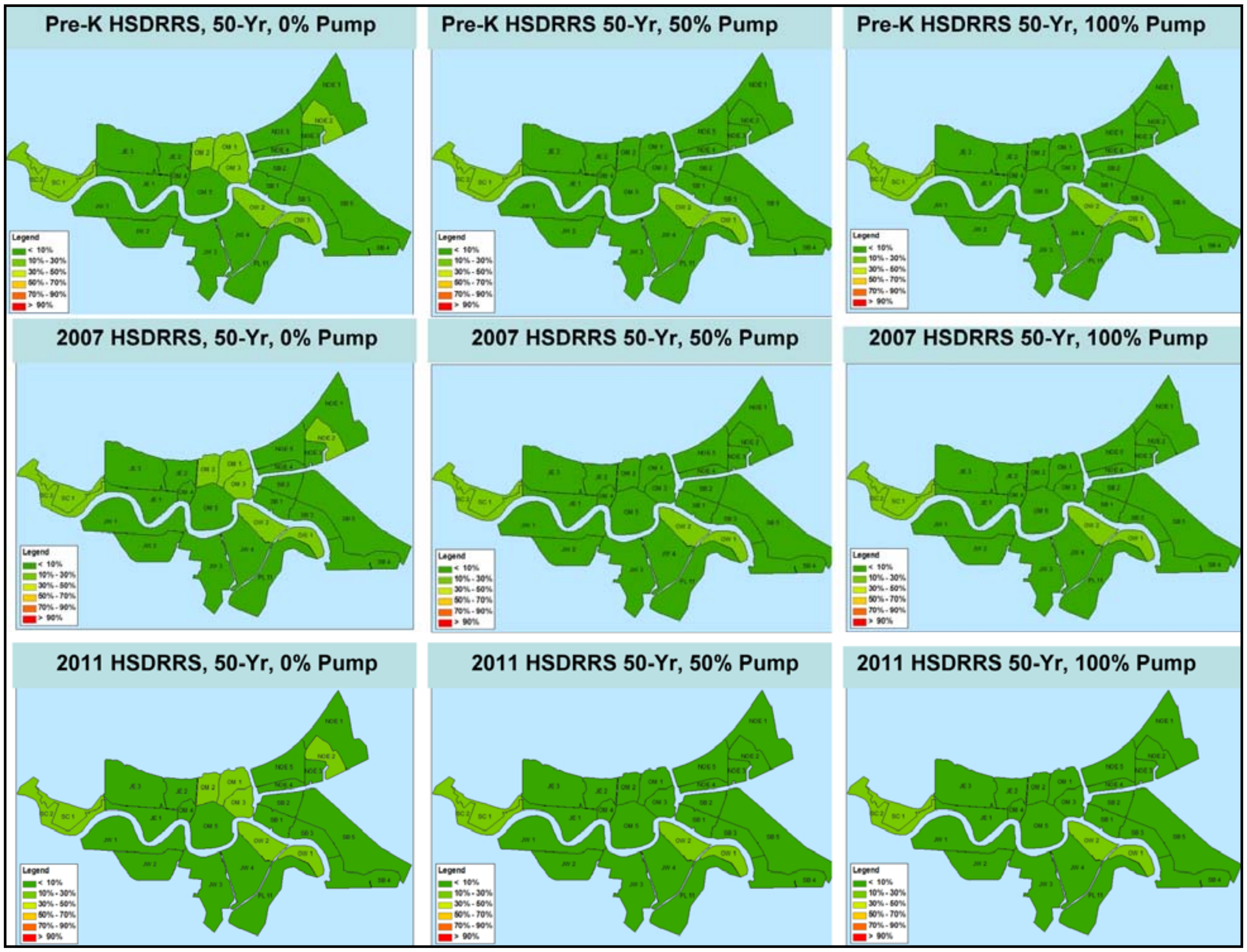


Figure 21. Property Loss risk maps comparing Pre-Katrina, 2007 and 2011 HSDRRS percent of value lost for 50-Year (2%) Flood Frequency. These maps represent pre-Katrina population and property distributions.

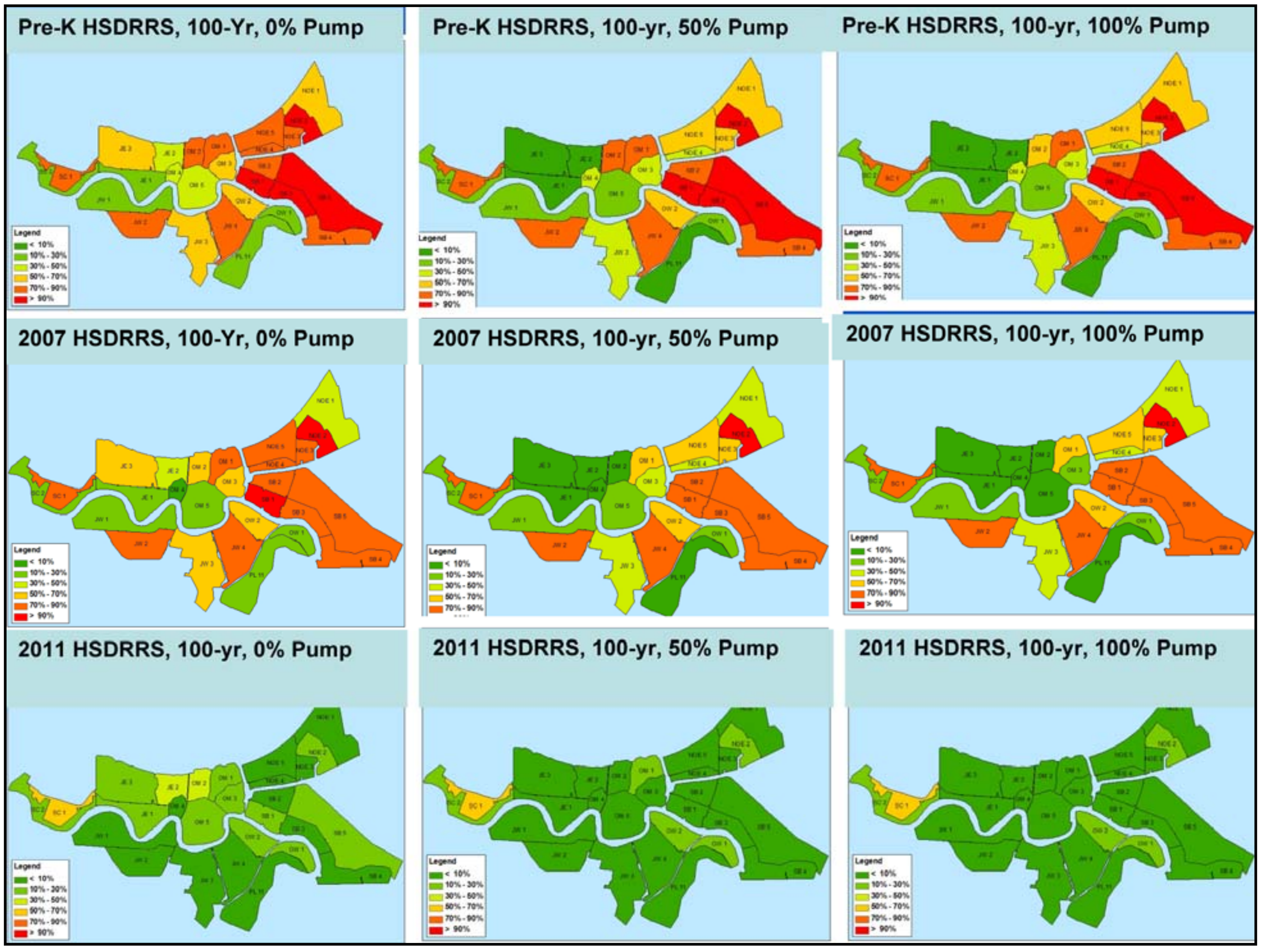


Figure 22. Property Loss risk maps comparing Pre-Katrina, 2007 and 2011 HSDRRS percent of value lost for 100-year (1%) flood frequency. These maps represent pre-Katrina population and property distributions.

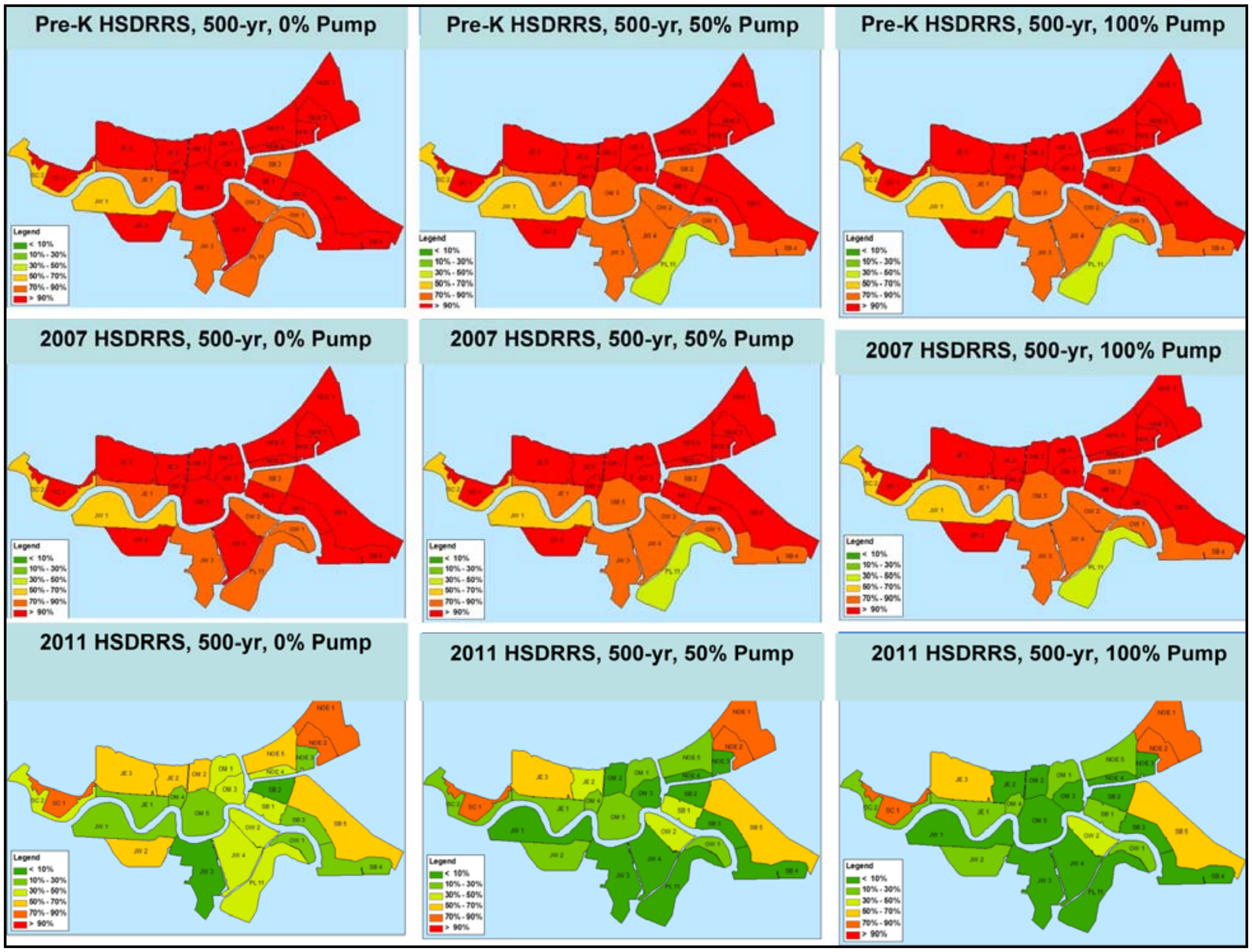


Figure 23. Property Loss risk maps comparing Pre-Katrina, 2007 and 2011 HSDRRS percent of value lost for 500-year (0.2%) flood frequency. These maps represent pre-Katrina population and property distributions.

Tables 13 and 14 provide the system-wide estimated mean property loss in dollars and percent of value lost, respectively. These numbers must be placed in the proper perspective. They represent the total potential loss or percent loss for the entire region at a given frequency of occurrence. For any given event, such as Katrina, the entire region will not be impacted equally. Some areas may be totally devastated while others receive little damage. As such, event losses should be less, sometimes very significantly less, than these totals. These values are useful to understand the benefits of changes in the capability of the HSDRRS infrastructure in place.

The property loss data in Tables 13 and 14 shows that the 2007 system provides a small reduction overall in the property loss risk in comparison to Pre-Katrina, and there is no difference in property loss risk between the two systems at 50- and 500-year frequencies. The 50-year level is dominantly flooding from rainfall, and the 500-year level has extensive and severe flooding regardless of which system is in place.

Property Loss Risk Findings

50-Year Flood Event: Given pre-Katrina property conditions

1. Property loss risk is relatively low for the 50-year (2%) flood frequency, being below 10% of total value in most areas and from 10 to 30% in areas of Orleans Main near the canals and Orleans West.

2. Property loss risk maps for Pre-Katrina, 2007 and 2011 HSDRRS are essentially the same at this return period. This is due to rainfall being the major source of floodwaters at these frequencies.

3. Pumping at operational capacities equal to or greater than the 50% ideal value modeled would reduce all sub-basins to the lowest category except OW and SC, which remain the same.

100-Year Flood Event: Given pre-Katrina property conditions

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

2. The 2007 system provides a risk reduction in 3 of the 5 sub-basins of Orleans Main; those nearest the IHNC remaining at higher risk levels. There is also some reduction in St. Bernard but none on the West Bank or in New Orleans East. The 2007 system with 50% pumping provides a 38% reduction in actual losses in comparison to the Pre-Katrina and no pumping scenario.

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

4. The 2011 HSDRRS dramatically reduces potential property losses over the pre-Katrina and 2007 system. If built as planned, it would reduce property losses by 70% without pumping and up to 93% with 50% pumping in comparison to Pre-Katrina and no pumping. The overall percent of value lost would drop from 55% (Pre-Katrina and no pumping) to 4% (2011 and 50% pumping).

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

500-Year Flood Event: Given pre-Katrina property conditions

1. The economic risk for the 500-year (0.2%) flood frequency is extremely high in all areas for both Pre-Katrina and 2007. There is essentially no change in property loss risk between the

Pre-Katrina and 2007. Over 90% of total property value would be lost in a 500-year flood event.

2. Pumping capacity has little impact on the economic risk at this level of flooding for Pre-Katrina or 2007 because of the excessively large volumes of floodwaters.

3. The 2011 HSDRRS, built and performing as modeled, provides significant reduction in property losses for the 500-year flood frequency in comparison to 2007. Given the 2011 HSDRRS with 50% pumping, the potential property losses for a 500-year flood event would be reduced by 76% in comparison to the Pre-Katrina and no pumping scenario.

Overall Lessons Learned

The findings presented herein have been examined to extract principal lessons learned. These lessons learned represent the big picture guidelines that can help shape future policy and practice with regard to understanding and reducing risk for New Orleans as well as other areas impacted by serious natural hazards. They deal with both the risk assessment process itself as well as the information and insights that the risk assessment provides.

Risk Assessment Process

The risk assessment process required a rigorous effort. It was complicated by lack of data, the large geographical area and the many components of the HSDRRS infrastructure options being assessed and the need to adapt existing risk methods, normally applied to an individual structure at a specific site, to this new application.

The definition of the hurricane hazard for the future was the most demanding and complex technical challenge. While it was clear that the historical record was insufficient, most alternatives were either simple extrapolations of historical data or too computationally intensive to be practical tools.

The JPM-OS method exploited the value of historical data in conjunction with modern high resolution, physics-based models and high performance computing to provide a more comprehensive definition of the current and future hurricane generated surge and wave hazard New Orleans faces.

The reliability assessment process was challenged to include the vast amount of geologic, structural design and condition data available on the 350 miles of HSDRRS infrastructure. This included the task of dividing the infrastructure into reaches of uniform performance potential; estimating the fragility of each reach, transition and feature; and handling the complex issue of overtopping and erosion impact on structure performance.

Consequences were limited to pre-Katrina population and property conditions, but required extrapolation of loss of life through the LIFESim model. This was essential because of both the scarcity of fatality information that allowed correlation of fatalities to the location and the situation leading to the fatalities.

The overall process used to estimate vulnerability to flooding and risk (loss of life and economic) generated reasonable results when compared to losses from historical events. Very significant uncertainties can be expected in the application of this type of method because of the large data sets, sophisticated models and many steps in the process.

Risk Assessment of New Orleans and Vicinity

Having a quantitative estimate of vulnerability and risk is important information for understanding both the current situation and the relative value of alternative risk reduction measures for the future.

Both the public at large and public officials at all levels benefit by having a common situational awareness of residual risk. The common picture provides a valuable focus for communication, for current risk reduction measures as well as those that should be examined for the future.

The 2007 system has provided measurable reductions in loss of life and economic risk that directly relate to the major differences in the character of the 2007 and Pre-Katrina systems.

In 2007, the overall residual loss of life and property loss risk levels for New Orleans remain very high for flooding events beyond the 50-year (2%) frequency of occurrence.

In 2007, the loss of life and property loss risk for New Orleans is extreme for flood events at the 500-year frequency of occurrence.

The 2011 HSDRRS, if built as modeled, will dramatically reduce depth of flooding for the 100-year frequency flood event and thereby dramatically reduce potential loss of life and property in comparison to the pre-Katrina and 2007 systems. With significant integrated pumping (having at least 50% of ideal capacity modeled operational) the 2011 system would reduce loss of life risk by well over 90% compared to pre-Katrina with no pumping, for the 100-year frequency and the 500-year frequency. The 2011 system would reduce property losses by over 90% for the 100-year frequency and 76% for the 500-year frequency.

Pumping capabilities, if operational at or above the 50% of ideal capacity modeled, can play a very important role in reducing vulnerability to flooding and managing risk. Pumping is only an effective measure when the overall volume of flood waters that has to be managed is minimized by the performance of the HSDRRS.