Risk Analysis of a Protected Hurricane-Prone Region. I: Model Development

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Abstract: A risk analysis methodology is presented in this paper for protected hurricane-prone regions. The methodology is intended to assist decision and policy makers, and has the characteristics of being analytic, transparent, quantitative, and probabilistic. The hazard is quantified using a probabilistic framework to obtain hazard profiles as elevation-exceedance rates, and the risk profiles as loss-exceedance rates that are based on a spectrum of hurricanes determined using a joint probability distribution of the parameters that define hurricane intensity. The resulting surges, waves, and precipitations are used to evaluate the performance of a hurricane protection system consisting of a series of basins and subbasins that define the interior drainage characteristics of the system. The protection against flooding is provided by levees, floodwalls, closure gates, and interior drainage system and pumping stations. Stage-storage relationships define the characteristics of subbasins and the population and property at risk. The proposed methodology will enable decision makers to evaluate alternatives for managing risk such as: providing increased hurricane protection, increasing evacuation effectiveness, changing land-use policy, enhancing hurricane protection system operations, and increasing public and governmental preparedness.

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Introduction

Hurricane Katrina was an extraordinary act of nature and the most destructive natural disaster in American history, creating a human tragedy and laying waste to 90,000 mi² (233,000 km²) of land, an area the size of the United Kingdom. In Louisiana and Mississippi, the storm surge obliterated coastal communities and left thousands destitute. New Orleans was overwhelmed by flooding leading to more than 1,500 people dead. Moreover, tens of thousands suffered without basic essentials for almost 1 week along the Gulf Coast (US Senate 2006). FEMA (2006), NFIP (2006), USACE (2006), USN (1983), and the White House (2006) provide additional information on hurricanes, hurricane Katrina, risk and insurance, and other related issues.

One of the primary contributors to the flooding of New Orleans was the failures of levees and floodwalls that make up the hurricane protection system (HPS). The utilization of engineered systems leads to risks that result from humans using technology in an attempt to gain benefits, such as control of naturally occurring conditions. For instance, the HPS in New Orleans has been designed to provide protection from storm induced surges and

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waves. An interior drainage system controls flooding within the city during normal rainfall and tropical storm events. The HPS project was designed to perform this function without imposing unacceptable risks to public safety, property and welfare; however this does not mean that the risks are nonexistent.

The term "risk" is used many ways to define hazards, losses, potential problems, etc. In the engineering community, risk is generally defined as the potential of losses for a system resulting from an uncertain exposure to a hazard or as a result of an uncertain event (Ayyub 2003). Risk should be based on identified risk events or event scenarios. Risk is quantified as the rate (measured in events per unit time, such as a year) that lives, economic, environmental, and social and cultural losses will occur due to the nonperformance of an engineered system or component. The nonperformance of the system or component can be quantified as the probability that specific loads (or demands) exceed respective strengths (or capacities) causing the system or component to fail, and losses are defined as the adverse impacts of that failure if it occurs. Risk can be viewed to be a multidimensional quantity that includes event-occurrence rate (or probability), event-occurrence consequences, consequence significance, and the population at risk; however, it is commonly measured as a pair of the rate (or probability) of occurrence of an event, and the outcomes or consequences associated with the event's occurrence that account for system weakness, i.e., vulnerabilities. Another common representation of risk is in the form of an exceedance rate (or probability) function of consequences. In a simplified notional (or Cartesian) product, risk is commonly expressed as

risk = event rate(or probability)
$$\times$$
 vulnerability \times consequences of failure (1)

This equation not only defines risk but also offers strategies to control or manage risk: by making the system more reliable or by reducing the potential losses resulting from a failure. The probability of failure part of the equation can be influenced by engi-

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neers by strengthening of existing structures or by adding additional protection; however the consequence part is highly dependent upon the actions and decisions made by residents, government, and local officials, including first-response and evacuation plans and practices. In densely populated areas, simply increasing system reliability may not reduce risks to acceptable levels and increasing consequences through continued flood plain development can offset any risk reductions.

The reliability and risk analyses relate the performance of individual elements and features (such as floodwalls, levees, pumps, levee closures, etc.) located throughout the hurricane protection system to the overall performance of the integrated HPS and the impact of that performance on public safety, and social and economic welfare. The reliability of the various elements and features also considers the varying material properties of the structures and of foundation conditions that exist throughout the HPS.

Decisions concerning investments in systems designed to control natural hazards are best made by explicitly and quantitatively considering the risks that the systems pose to public safety and property. Implementation of risk analysis to the HPS of New Orleans and Southeast Louisiana is challenging because it is a complex system of levees, floodwalls, and pumping stations that serve a large geographical region. In addition, existing capability to accurately predict and model hurricanes in regions as complex as the Mississippi delta is limited. Nonetheless, mathematical modeling of hurricanes and risk analysis methodologies have improved greatly in recent years to make them important, viable tools for supporting investment decisions as the HPS is restored and improved. In developing a risk analysis methodology in this paper, the following requirements were identified as key guiding principles:

- Analytic: the methodology must provide a systematic framework for assessing risk by decomposing risk into its basic elements;
- Transparent: all assumptions and analytical steps are clearly defined;
- Defensible: values for each parameter are supported by all available data, including knowledge from previous studies and expert opinion;
- 4. Quantitative: risk is expressed in meaningful and consistent units (e.g., dollars and fatalities) so as to provide a basis for performing trade-offs and benefit-cost analysis;
- Probabilistic: the mathematics of probability theory is used for expressing uncertainty in all model parameters and assessing the likelihood of alternative scenarios; and
- 6. Consistent: it is consistent with established and accepted practices of probabilistic risk assessment (PRA) used in many other fields.

Ayyub et al. (2007) and McGill et al. (2007) developed and demonstrated the quantitative risk methodology called the critical asset and portfolio risk analysis (CARRA) for all hazards including natural and human-caused hazards that applied these principles. Additional risk and statistical methods and studies relating to hurricanes are provided by Eijgenraam (2006), Grossi and Kunreuther (2005), Hallegatte (2006), Van Gelder (2000), Van Manen and Brinkhuis (2005), and Voortman (2003).

The quantification of risk requires the analysis and appropriate modeling of uncertainty including both aleatory and epistemic uncertainties (Ayyub and Klir 2006). For example, detailed knowledge of the engineering parameters that influence the performance of the HPS and of the hurricane characteristics of storms expected to impact New Orleans is limited, such as the

properties of foundation soils underlying the extensive levee and floodwall system, and the frequency with which hurricanes will occur in the future. As other examples, Dixon et al. (2006) provide an overview of subsidence and flooding in New Orleans; Dokka (2006) describes the tectonic subsidence in coastal Louisiana; and Muir-Wood and Bateman (2005) describe uncertainties and constraints on breaching and their implications for flood loss estimation. Hurricane models can predict winds, waves, and surges only with limited accuracy, and the reliability models used to predict levee performance when subjected to hurricane forces are similarly limited. Hence, the risk profiles of hurricane-induced flooding cannot be established with certainty. Risk analysis, therefore, must include not just a best estimate of risk, but also an estimate of the uncertainty in that best estimate. By identifying the sources of uncertainty in the analysis, measures, such as gathering additional data, can be taken to reduce the uncertainty and improve the risk estimates.

The risk model presented herein was developed in part to meet the needs of the U. S. Army Corps of Engineers Interagency Performance Evaluation Task (IPET) Force as provided in Volume VIII of its report (USACE 2006). The IPET study was performed to meet several key considerations including the following:

- Defining the physical features of the system required an accurate inventory of all components that provide protection against storm surge and waves including cross sections and strength parameters of components, transitions between elements, differences in the crest elevations along a reach of similar components, and varying foundation conditions. The characterization of the physical features of the protection system was, however, limited by the available information and the resources available to conduct field surveys, and process the information.
- The hurricane modeling and reliability analyses required an accurate depiction of the elevations of the tops of levees and walls that make up the HPS.
- 3. The pumping system is an important element that controls flooding during and after a storm, but commonly not designed to handle hurricane events.
- 4. The consequences of pre- and post-Katrina flooding are different due to changes in population and economic activity.
- 5. The effectiveness of the protection system depends on human factors as well as engineered systems (e.g., timely road and railroad closures, gate operations, and functioning of pumping stations). Lessons learned from Katrina and other natural disasters can be used in modeling the closures.

Analysis Boundaries

An important initial step in the analysis is to clearly define the bounds of the study and the physical descriptions of the various components of HPS. These bounds included defining the geographic bounds of the study region and the elements of the hurricane protection system, the resolution of information and analyses to be performed, and analysis constraints or assumptions associated with the risk and reliability analyses.

Study Region and Hurricane Protection System

The analysis examines risks to New Orleans and Southeast Louisiana associated with the performance of the HPS under the stress

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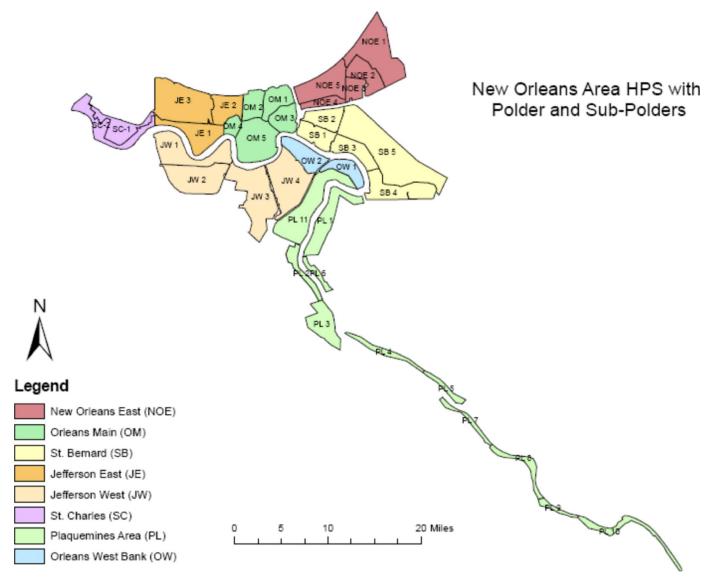


Fig. 1. Map of New Orleans and South East Louisiana area showing geographic bounds of study region considered in risk analysis

imposed on it by a wide spectrum of tropical storms and hurricanes. Fig. 1 identifies the region considered and the major features of the hurricane protection system.

Physical Description of HPS

The HPS is comprised of a variety of subsystems, structures, and components which include earthen levees, floodwalls, foundation conditions, pumping stations, canals, wall closures, power supply systems, and operations personnel. The system is a combination of low-lying tracts of land that form artificial hydrologic entities enclosed by levees, called basins, which are independently maintained and operated by local parishes and levee boards.

Detailed physical descriptions for each basin based on current conditions are provided by USACE (2006). Data collected during site inspections were used to define characteristics of the basins and their interdependence for use in the risk model. This was a critical and time consuming step in the development of the risk model that has yielded a comprehensive description of the HPS. These descriptions were developed by examining available information gathered by IPET including:

Design memorandums and supporting documents;

- Construction documents;
- Inspection reports;
- Katrina damage reports; and
- Detailed field surveys conducted by the risk team to verify the location and configurations of the HPS.

The information gathered was incorporated into detailed geographic information system (GIS) based maps of each basin that included: locations of all features (walls, levees, pumping stations, and closure gates), geotechnical information (boring logs, geologic profiles), aerial photographs, and photos of each feature.

Analysis Assumptions and Constraints

As part of the process of developing the risk analysis model, it was necessary to identify key assumptions and analysis constraints. Constraints refer to events or situations that were not modeled or considered explicitly in the analysis. The assumptions and constraints are provided at the appropriate location in subsequent sections. The analysis limitations or constraints of the risk model development are summarized by the following:

1. Modeling procedures that existed prior to Katrina were used;

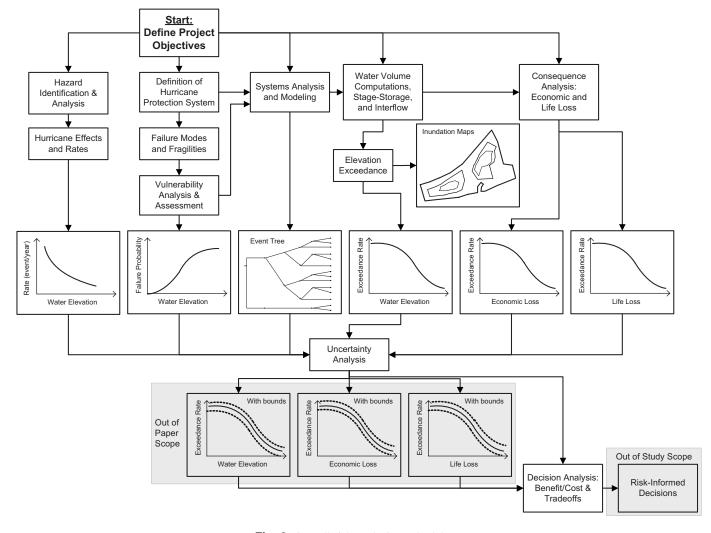


Fig. 2. Overall risk analysis methodology

- Geographic area was limited to elements of the hurricane protection system in the basins listed;
- The risk model does not produce temporal profiles, but spatial profiles accumulated over the entire durations of respective storms;
- The risk model includes assumptions in the parameters used in various major aspects of the hurricane protection system characterization, hurricane simulation, reliability analysis inundation analysis, and consequence analysis;
- Hazards, and thus consequences, not considered in the risk analysis are: wind damage to buildings, fire, civil unrest, indirect economic consequences, effect of a release of hazardous materials, and environmental consequences; and
- The performance of the evacuation plan, New Orleans was not explicitly modeled in the risk analysis. Evacuation effectiveness is, however, considered in the consequence analyses.

Risk Analysis Methodology

Overview

Probabilistic risk analysis as described by Ayyub (2003), Kumamoto and Henley (1996), and Modarres et al. (1999) was used to develop the overall risk analysis methodology of the hurricane

protection system as presented in Fig. 2. Subsequent sections describe individual parts of the methodology. A case study describing the implementation of the proposed risk methodology for a notional city is provided in a companion paper (Ayyub et al. 2009).

Contributing Factors and Their Interrelationships

The development of the risk analysis model was facilitated by the preparation of an influence diagram (for example see Ayyub 2003). The process of creating an influence diagram helped establish a basic understanding of the elements of the hurricane protection system and their relationship to the overall system performance during a hurricane event and the analysis of consequences and risks. Fig. 3 shows the influence diagram for the hurricane protection system and the analysis of consequences. There are four parts to the influence diagram as follows:

- Value nodes (rounded-corner box);
- Chance nodes (circular areas);
- Decision nodes (square-corner boxes); and
- Factors and dependencies in the form of arrows.

The influence diagram shown in Fig. 3 was used to develop an event (or probability) tree for the hurricane protection system. Fig. 4 shows an initial probability tree derived from the influence diagram in Fig. 3. The top events across the tree identify the

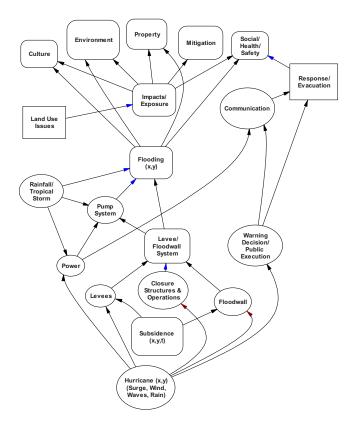


Fig. 3. Influence diagrams for risk analysis

random events whose performance during and immediately after the hurricane could contribute to flooding in a protected area. The tree begins with the initiating event, a hurricane that generates a storm surge, winds, and rainfall in the region. As the focus of this methodology is on the risks associated with the unreliability of a hurricane protection system, only flooding is considered.

Hurricane Protection System Definition

The HPS as illustrated in Fig. 1 was discretized for the reliability and risk analysis as schematically shown in Fig. 5 for illustration purposes for a portion of the system. The system consists of basins, subbasins, and reaches. The definition of these hurricane protection basins, subbasins, and reaches are based on the following considerations:

- · Local jurisdiction;
- Floodwall type and cross section;
- Levee type and cross section;
- Engineering parameters defining structural performance;
- · Soil strength parameters; and

• Foundations parameters.

Reaches (*R*) of each basin are defined of varying length as a discretization of the protection length such that each reach has about the same properties and exposure conditions, and are uniquely identified using sequential numbers as illustrated in Fig. 5. The figure also shows the approximate locations of pumping stations for the purpose of illustration. Detailed maps and descriptions of each basin are provided in the USACE IPET report (2006).

Probabilistic Risk Model

Risk associated with the HPS is quantified through a regional hurricane rate (λ) and the probability P(L>l) with which a consequence measure (L) exceeds different levels (l). The regional hurricane rate gives the average annual number of hurricanes experienced by the region irrespective of magnitude. The loss-exceedance probability per event is evaluated as

$$P(L > l) = \sum_{i} \sum_{j} P(h_{i}) P(S_{j} | h_{i}) P(L > l | h_{i}, S_{j})$$
 (2)

An annual loss-exceedance rate was estimated as follows:

$$\lambda(L > l) = \sum_{i} \sum_{j} \lambda P(h_i) P(S_j | h_i) P(L > l | h_i, S_j)$$
 (3)

where $P(h_i)$ =probability of hurricane events of type i predicated on the occurrence of a hurricane in general; $P(S_j|h_i)$ =probability that the system is left in state j from the occurrence of h_i ; and $P(L>l|h_i,S_j)$ =probability that the consequence L exceeds level l under (h_i,S_j) . The summation in Eq. (3) is over all hurricane types i and all system states j using a suitable discretization. Simulation studies of hurricanes for risk analysis require the use of representative combinations of hurricane parameters and their respective probabilities. The outcome of this process is a set of hurricane simulation cases and their respective conditional rates $\lambda P(h_i)$.

Evaluation of the regional hurricane rate λ and the probability $P(h_i)$, the conditional probabilities $P(S_j|h_i)$, and the conditional probabilities $P(L>l|h_i,S_j)$ is the main objective of the hurricane model, the system model, and the consequence model, respectively. The probability $P(S_j|h_i)$ covers the states of the components of the HPS, such as closure structure and operations, precipitation levels, electric power availability, failures modes of levees and floodwalls, and pumping station reliability. To assess the state of the HPS, given a hurricane event, requires an evaluation of the reliability of individual structures, systems, and components (e.g., levees, floodwalls, pump systems) when they are exposed to the loads and effects of the hurricane (e.g., the peak

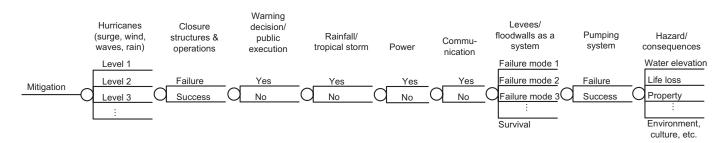


Fig. 4. Probability tree for hurricane protection system

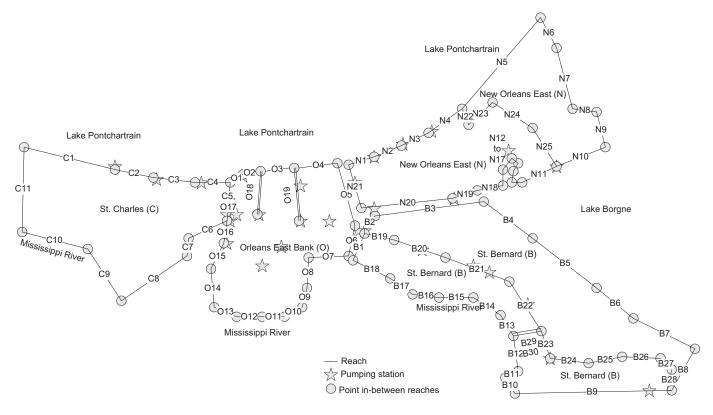


Fig. 5. Schematic representation of HPS defined by basins, subbasins, and reaches

surge, wave action) and the relationship of these elements to the overall function of the system to prevent flooding in protected areas.

Probability and Risk Tree

The probability tree of Fig. 4 was simplified to determine the rate of flooding elevations and displaying the results as inundation contours within the basins. The processes of transforming inundation to consequences is simplified by grouping communication, warning decision, and public execution into an *exposure factor* parameter applied to lives and property at risk, and grouping power and pumping availability into one event. The resulting tree appropriately branched out including consequences is shown in Fig. 6 as a probability and risk tree. The events of the tree are defined in Table 1.

Risk Quantification

Functional Modeling and Computational Considerations

The protected areas of the HPS are subdivided into basins and subbasins. This partitioning is based on the internal drainage and pumping system within each basin. Fig. 1 shows these basins and their *sub* basins. Basins and subbasins are divided into reaches that have similar cross sections, material strength parameters, and foundation conditions.

The quantification of risk associated with the HPS requires determination of the amount of water that is expected to reach the protected areas for a particular hurricane. While the primary purpose of the HPS is to prevent water from entering protected areas during hurricanes, water may also enter the system during rainfall events and from groundwater. In particular, water entering the protected the areas comes from:

- Nonbreach events producing overtopping water volume, water volume entering through closures (i.e., gates) that are left open, precipitation, and potential backflow from pumping stations; and
- 2. Breach events leading to water elevations in protected areas. The risk quantification framework was, therefore, based on obtaining estimates of water volumes and elevations entering the HPS due to one of these cases.

The event tree presented in Fig. 6 shows the two quantities of interest in the net water levels column: water volumes resulting from overtopping, precipitation and open closures, and the post-surge elevation that would result in breaching cases. Potential backflow from pumping stations in nonbreach cases was not considered. The branches of the rainfall volume are added to all the other branches for a particular hurricane. The figure shows a total of 16 branches that are constructed per hurricane. The computations needed to quantify risk are presented in a manner that correspond to the events shown in Fig. 6, and were implemented in a combination of spreadsheet tools and MATLAB scripts. The sections that follow provide the background information and bases behind the approaches used for these computations. Additional information on the computations with example is provided in the companion paper (Ayyub et al. 2009).

Definition of Basins, Subbasins, Reaches, and Features

The HPS is divided into basins, subbasins, and reaches with features, such as gates. Initially the reaches were defined using the beginning and ending stations shown in the original design memoranda. The stations were then adjusted based on examinations of the subsurface material information to form reaches that were expected to have similar performance (reliability). Table 2 illustrates the information structure used to define reaches. The table shows for each reach its unique reach number, length, el-

NATURAL HAZARDS REVIEW © ASCE / MAY 2009 / 43

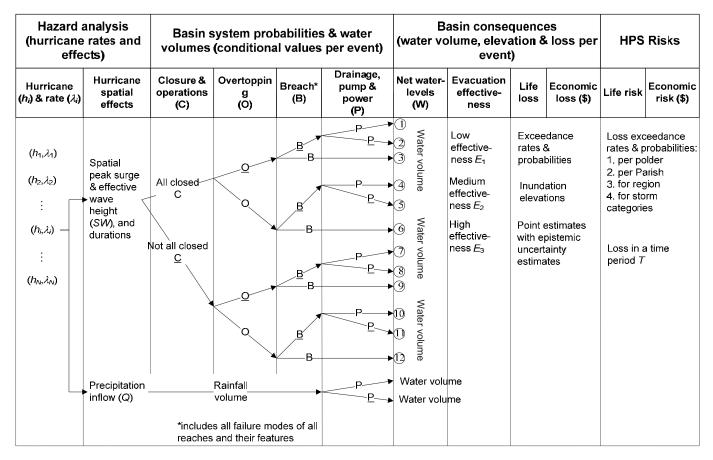


Fig. 6. Event tree for quantifying risk. Underlined events (i.e., C, P, Q, and B) are complements of respective events (i.e., C, P, O, and B).

evation, design water elevation, reach type (either a levee, wall, or transition), and applicable weir coefficient for calculating volume flow rates (Daugherty et al. 1985), and a subbasin identification. The elevations of the tops of walls and levees, adjusted to the current datum, of the entire New Orleans area HPS were developed for use in the suite of hurricane simulations and the risk assessment model calculations of water volumes from overtopping and breaching. Table 3 lists features that consist of gates and closures within each reach. For each feature, the following information is needed:

- 1. Feature number for unique identification;
- 2. Reach in which the feature is located;
- 3. A reference value for correlated features that could have different probabilities of closure, however a set of gates of the same reference value are either all closed or all open;
- 4. Length (ft) of water inflow when gates are left completely open;
- 5. Bottom elevation (ft) of gates; and
- 6. Probability of not closing gates.

Data were collected from design documents, construction drawings, and studies conducted by other IPET teams to develop detailed descriptions of the basins. Maps were assembled from aerial photos that included: latitude/longitude data, geotechnical profiles and boring logs, crest elevations, stationing used to define reaches, and the locations of critical features such as closure gates and pump stations. The information on these maps was confirmed by field surveys of the entire system. Photos, global positioning coordinates and notes were taken during these surveys to document each feature and reach used in the risk model. This process resulted in a comprehensive description of the HPS.

Hurricane Hazard Analysis

The hurricane hazard analysis method parameterizes hurricanes using their characteristics at landfall. The following parameters were considered:

- Central pressure deficit at landfall;
- · Radius to maximum winds at landfall;
- Longitudinal landfall location relative to downtown New Orleans;
- Direction of storm motion at landfall;
- · Storm translation speed at landfall; and
- Holland's radial pressure profile parameter at landfall (Holland 1980).

Using these values and historic events, the recurrence rate (λ) is estimated for hurricane events in a neighborhood of the region of interest and the joint probability density function of the hurricane parameters in that neighborhood. The possible combinations of winds, surges, and waves would be computationally demanding if every combination was run through the ADCIRC models (ADCIRC 2006). To reduce the number of runs a response surface approach was used. In this approach a relatively small number of hurricanes are selected and used to calculate the corresponding surge and wave levels at the sites of interest. Then a response surface model is fitted to each response variable (surge or wave level at a specific site). Finally, a refined discretization of the parameter space is used with the response surface as a proxy model in place of the range of possible events to represent the hurricane hazard. The outcomes of these computations are combined surge and effective wave values at particular locations of interest along the hurricane protection system, e.g., repre-

Table 1. Summary of Event Tree Top Events

Top event	Description
Hurricane initiating event	The hurricane initiating event is mapping of hydrographs of the peak flood surge with waves in the study area with a hurricane rate λ . This event was denoted, $h_i(x,y)$, and has a probability of occurrence, $P(h_i(x,y))$ and a rate of occurrence of $\lambda P(h_i(x,y))$.
Closure structure and operations (C)	This event models whether the hurricane protection system closures, i.e., gates, have been sealed prior to the hurricane. This event depends on a number of factors as illustrated in the influence diagram of Fig. 3. The closure structures are treated in groups in terms of probability of being closed in preparation for the arrival of a hurricane. This event was used to account for variations in local practices and effectiveness relating to closures and their operations.
Precipitation inflow (Q)	This event corresponds to the rainfall that occurs during a hurricane event. The precipitation inflow per subbasin is treated as a random variable.
Drainage, pumping and power (P)	This event models the availability of power (normal) power for the pump systems. This event is modeled in the event tree to represent a common mode of failure for the pump systems, and is included in developing a model for drainage and pumping efficiency or lack thereof including backflow through pumps. The event also models the availability of the pump system and its ability to handle a particular floodwater volume. This event is treated in aggregate with drainage effectiveness and power reliability including backflow through pumps.
Overtopping (O)	This event models the failure of the enclosure/protection system due to overtopping, given that failure has not occurred by some other (nonovertopping) failure mode. If failure (breach) does not occur, flooding due to overtopping could still result.
Breach (B)	This event models the failure of the enclosure/protection system (e.g., levees/floodwalls, closures) during the hurricane, exclusive of overtopping failures). This event includes all other failures and it models all 'independent' levee/floodwall sections. This event is treated using conditional probabilities as provided in Fig. 6.

sentative values at the reaches. These values are denoted as h_i in Fig. 6.

The water elevation required by the risk model as a loading is taken as a hydrograph of the surge elevation plus wave setup and runup at each reach in the system. Table 4 illustrates information and results related to hurricane simulations that include the following:

- 1. Hurricane run numeric identification;
- 2. Hurricane rates; and
- 3. Total subbasin overtopping volume over all the reaches in a subbasin as the mean value and standard deviation with computational models based on hydraulic engineering provided in subsequent sections.

Hurricane rate modeling and prediction methods are then used to compute the corresponding exceedance rates to h_i values, and are denoted as λ_i in Fig. 6. Also, the water elevation in a basin after

a breach is termed the postsurge elevation. This postsurge elevation in a basin could be higher than the applicable lake or river water level. A breach model was developed to compute this elevation as provided in subsequent sections.

The epistemic uncertainties in both the surge/wave elevation and the rates are considered. Fig. 7 illustrates surge water elevation as a function of time, i.e., hydrographs, at stations defining the HPS for one storm.

Overtopping Volume and Probability Models

The overtopping volume flow rate can be computed using the rectangular weir formula (Daugherty et al. 1985). The overtopping water flow has the elevation H and width L. If the water is assumed to be the ideal liquid, it can be shown using the energy conservation law that the flow rate $Q[L^3/T]$ is given by the following equation:

Table 2. Definition of Reaches

Reach number	Length (ft)	Elevation (ft)	Design water elevation (ft)	Reach type	Reach weir coefficient	Subbasin reference
1	5,000	14.00	8.00	Levee	2.6	Basin1-1
2	10,000	15.00	9.00	Floodwall	3.0	Basin1-2
3	22,500	16.00	11.00	Levee	2.6	Basin1-3
4	6,000	14.00	10.00	Floodwall	3.0	Basin1-4
5	9,000	18.00	13.00	Levee	2.6	Basin1-5
6	7,000	14.00	8.00	Levee	2.6	Basin2-1
7	11,000	15.00	9.00	Floodwall	3.0	Basin2-2
8	7,500	16.00	11.00	Levee	2.6	Basin2-3
9	500	11.00	8.00	Transition	3.0	Basin1-2
10	400	12.00	8.00	Transition	2.6	Basin2-2

Note: 1 ft=0.3048 m.

Table 3. Definition of Features with Respective Reaches

Feature number	Reach number	Correlated features	Length (ft)	Bottom elevation (ft)	Not-closed probability
1	1	1	500	5.00	0.10
2	1	1	500	5.00	0.15
3	2	3	400	6.00	0.10
4	2	3	400	7.00	0.20
5	2	3	400	5.00	0.10
6	3	3	600	5.00	0.15
7	4	7	600	7.00	0.20
8	4	8	600	6.00	0.10
9	5	9	500	6.00	0.10
10	5	9	500	5.00	0.01

Note: 1 ft=0.3048 m.

$$Q = \frac{2}{3}(2g)^{1/2}LH^{3/2} \tag{4}$$

where g=acceleration of gravity. The actual flow over the weir is known to be less than ideal (Daugherty et al. 1985) because the effective flow area is considerably smaller than the product LH.

The model can be enhanced further for engineering applications by replacing the term $2/3(2g)^{1/2}$ in Eq. (4) by the empirical coefficient, known as the weir coefficient C_w , so that Eq. (4) takes on the following form:

$$O = C_{\nu} L H^{3/2} \tag{5}$$

where

$$C_{w} = \begin{cases} 3.33 & \text{if } L \text{ and } H \text{ are given in English units} \\ 1.84 & \text{if } L \text{ and } H \text{ are given in SI units} \end{cases}$$
 (6)

Note that the C_w for the ideal fluid case is $2/3(2g)^{1/2}$ which is equal to 5.35 ft^{1/2}/s (2.95 m^{1/2}/s). This coefficient is assumed to have a coefficient of variation (COV) of 0.2. The weir coefficient takes a value of 3.0, 2.6, and 2.0 for floodwalls, levees, and gates, respectively, with an assumed COV of 0.2 in English units (L and H in feet).

For the application considered, the mean volume of the over-topping (O) water μ_V for a given reach can be calculated as

$$\mu_V = C_w L \int \left[\max(X_s h_s(t) - H_r, 0) \right]^{3/2} dt \tag{7}$$

where a surge hydrograph is represented by $h_s(t)$ as illustrated in Fig. 7; H_r =reach height; L=reach length; C_w =weir coefficient with a COV of 0.2, and a mean of 3.0, 2.6, and 2.0 for floodwalls, levees, and gates, respectively; and X_s =aleatory uncertainty random factor with a lognormal distribution that accounts for variability in surge height.

The variance of the overtopping water volume for each case is computed based on the coefficient of variation (δ) of the weir coefficient as follows:

$$\sigma_{Vi}^2 = (\mu_{Vi} \delta_{Cw})^2 \tag{8}$$

where μ_{Vi} is provided by Eq. (7), and the coefficient of variation (δ_{Cw}) of the weir coefficient is taken as 0.2.

Wave setup and wave runup are included in the hydrograph for each hurricane as provided by IPET (USACE 2006). The uncertainty in the wave setup can be added in the same manner by causing X_s in Eq. (7) to become the product of two lognormal random variables, the aleatory uncertainty random factor with a lognormal distribution, and the wave setup factor with a lognor-

Table 4. Hurricane Runs, Rates, and Reach Overtopping Volume Results

		Overtopping volume (ft^3)							
		For Basin1-1		For Ba	asin1-2	For Basin2-1			
Hurricane run number	Hurricane rate (events/year)	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation		
1	1.00E-01	0.00E+00	0.00E+00	0.00E + 00	0.00E + 00	8.28E+07	1.66E+07		
2	5.00E - 02	0.00E + 00	0.00E + 00	0.00E + 00	0.00E + 00	1.07E + 08	3.31E+07		
3	1.00E - 02	6.57E + 07	1.22E + 07	8.28E + 07	1.66E + 07	8.28E + 07	1.66E+07		
4	1.00E - 02	7.87E + 07	2.11E+07	8.28E + 07	1.66E + 07	8.28E + 07	1.66E+07		
5	1.00E - 02	0.00E + 00	0.00E + 00	0.00E + 00	0.00E + 00	9.67E + 07	3.30E+07		
6	1.50E-01	0.00E + 00	0.00E + 00	0.00E + 00	0.00E + 00	7.92E + 07	1.89E+07		
7	5.00E-03	1.24E + 08	2.39E + 07	1.90E+08	3.76E + 07	1.90E + 08	3.76E+07		
8	9.00E - 02	8.69E + 07	2.99E + 07	7.99E + 07	1.99E+07	6.78E + 06	1.79E+07		
9	1.00E - 02	0.00E + 00	0.00E + 00	0.00E + 00	0.00E + 00	1.03E + 08	2.43E+07		
10	5.00E - 02	0.00E+00	0.00E+00	0.00E+00	0.00E+00	1.03E+08	3.21E+07		

Note: 1 ft=0.3048 m.

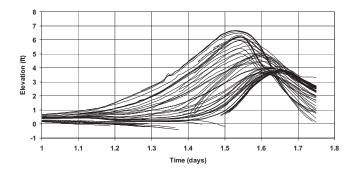


Fig. 7. Hydrographs at selected stations defining hurricane protection system for notional storm (1 ft=0.3048 m)

mal distribution (e.g., a total uncertainty represented by 0.15 log standard deviation and any median of interest).

As stated previously, Table 4 provides illustrative overtopping results that were aggregated by subbasins as illustrated in Table 5. The overtopping results for a subbasin include the overtopping volume based on an overtopping condition, i.e., V|O. The probability that overtopping (O) will occur in one or more reaches in a basin, i.e., P(O), can be computed using system reliability for independent events as

$$P(O) = 1 - \prod_{i=1}^{n} (1 - P_i(O))$$
(9)

where $P_i(O)$ =probability of overtopping of reach i in a subbasin or basin with n reaches (see for example, Ayyub and McCuen 2003; Ayyub 2003).

Breach Volume and Probability Models

Three cases of breach failure within reaches are considered. The risk quantification was effectively performed by examining three cases of breach failure that correspond to branches presented in the event tree of Fig. 6. The three cases are as follows:

- Breach given overtopping;
- Breach given no overtopping; and
- Breach due to transition failure.

The first case of breach given overtopping is primarily driven by erosion resulting from overtopping water flow. Fragility curves

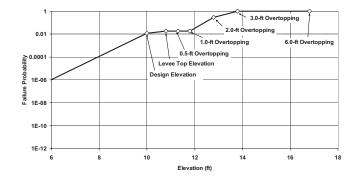


Fig. 8. Typical fragility curve for levee, floodwall, or transition (1 ft=0.3048 m)

for these cases were developed expressed as failure probabilities as functions of water depth starting from zero to overtopping. An example of fragility curve is shown in Fig. 8.

The breaching scenarios require knowledge of the breach size, depth, and surge hydrograph at the breach in order to determine basin inflows. The Katrina experience was reviewed to identify basic characteristics of the major breaches in order to develop general rules to use in the risk model for breach size. One critical characteristic that determines the volume of water flowing through a breach is the duration of time that the breach is open. Katrina showed that the breaches could not be repaired in time to have an effect on the level of water achieved inside the basins. The duration that the breach was open was therefore assumed to have no effect on inflow volumes and water elevations.

The London Avenue South and 17th Street canal breaches of New Orleans due to Katrina occurred before the water level in the canals reached the top of the wall and appear to have been the result of the deflection of I-walls, seepage, or due to foundation. This case is an example of a breach given no overtopping scenario in the risk analysis. The high water marks (HWMs) experienced during Katrina inside the Orleans basin where the canal breaches occurred and the length of time that surge elevations exceeded lake levels in the canals were examined. The HWM experienced during Katrina in the basins were very close (within about 1 ft) to the peak surges in the canals. For example, the London Avenue South breach occurred when the canal water level was at about 7–8 ft, or 3 ft or so below the top of the wall. The

Table 5. Tabulated Structure for Scenario Water Volumes for Hurricane by Subbasin

	11	ng volume	Precipitation volume (ft³)		Closure related volume (ft³)		Breach volume (ft ³)		Total volume (ft ³)	
Subbsin identifier	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation	Mean	Standard deviation
Basin1-1	0.00E+00	0.00E+00	6.67E+05	4.67E+05	1.33E+05	2.67E+04	4.00E+05	8.01E+04	1.20E+06	4.75E+05
Basin1-2	0.00E + 00	0.00E+00	6.57E + 05	4.60E + 05	1.31E+05	2.63E+04	3.94E + 05	7.89E + 04	394272	4.67E+05
Basin1-3	6.90E + 07	1.28E+07	6.90E + 06	4.83E+06	1.38E+06	2.76E+05	4.14E+06	8.27E + 05	4137210	1.37E+07
Basin1-4	8.69E + 07	1.74E+07	8.69E + 06	6.08E + 06	1.74E+06	3.48E+05	5.21E+06	1.04E + 06	5213880	1.84E+07
Basin1-5	8.69E + 07	1.74E + 07	8.69E + 06	6.08E + 06	1.74E + 06	3.48E+05	5.21E+06	1.04E+06	5213880	1.84E+07
Basin2-1	8.69E + 07	1.74E+07	8.69E + 06	6.08E + 06	1.74E+06	3.48E+05	5.21E+06	1.04E + 06	5213880	1.84E+07
Basin2-2	9.12E+07	3.14E+07	9.12E+06	6.39E + 06	1.82E+06	3.65E+05	5.47E + 06	1.09E + 06	5474700	3.20E+07
Basin2-3	8.38E + 07	2.09E+07	8.38E+06	5.87E + 06	1.68E+06	3.35E+05	5.03E + 06	1.01E+06	5030550	2.17E+07
Basin2-4	7.12E+06	1.88E+07	7.12E+05	4.98E+05	1.42E+05	2.85E+04	4.27E + 05	8.54E + 04	427140	1.88E+07

Note: 1 ft=0.3048 m.

Table 6. Breach Size due to Overtopping

		Overtopping depth (ft)							
		0-2 ft		2-5 ft		>5 ft			
Material	Symbol	Depth (ft)	Width (ft)	Depth (ft)	Width (ft)	Depth (ft)	Width (ft)		
Hydraulic fill	Н	1.569E+01	3.435E+02	1.680E+01	4.005E+02	1.766E+01	4.305E+02		
Clay	C	8.334E+00	4.515E+01	8.787E+00	1.350E+02	1.250E+01	1.350E + 02		
Sand	S	1.529E+01	3.000E + 02	1.765E+01	3.450E+02	1.845E+01	3.795E+02		
Unknown (average)	U	1.503E+01	2.296E+02	1.590E + 01	2.935E+02	1.724E+01	3.150E+02		
Wall	W	1.503E+01	2.296E+02	1.590E+01	2.935E+02	1.724E+01	3.150E+02		

Note: 1 ft=0.3048 m.

peak surge in the area was about 10–11 ft and HWM is also about 10 ft. The hydrographs experienced in those areas show that the duration of the surge elevation exceeding the elevation at failure was on the order of several hours. The water elevations inside the basin therefore closely followed the surge levels. The inverts of the canal breaches were at or below the normal lake level; therefore water flowed back into the lake after the surge passed. Based on this case and other similar cases, the peak surge level can be used as the water elevation achieved inside the basin when a catastrophic breach (full levee height) occurs during a nonovertopping event, and the following nonovertopping breach assumptions can be used:

- 1. All nonovertopping breaches are a result of a structural or foundation failure, and hence would be catastrophic (full depth of levee or floodwall);
- The breach depth would extend to or below lake or river level; and
- 3. The maximum interior water levels caused by the breach would be the same as the maximum surge level experienced adjacent to the breach.

For the case of a breach during an overtopping event, a probabilistic model for overtopping erosion was developed such that a levee (or a floodwall) is expected to show different breach inverts based on the amount of overtopping from surge or waves and the soil type at the levee's protection side. In the case where the breach invert is higher than the lake or river level, the depth and length of the breach, the duration of time that the surge exceeds the breach invert, and the weir coefficient through the breach are required to calculate inflow volumes. The breach widths for the levees and floodwalls could also be expected to be similar to that experienced during Katrina. Breach widths at the major canal breaches varied (from about 450 to 1,000 ft), but were all on the order of several hundred feet. At the industrial canal of New Orleans where overtopping did occur, the two Lower Ninth Ward breaches were similar in width to the other canals where overtopping did not occur, and the depth of the breaches were below the normal canal water levels so water also flowed back through these breaches when the surge passed. The following assumptions are used in the risk model:

- Breaches result from an erosion or seepage failure mode due to overtopping from surge and/or waves;
- The depth of overtopping required to cause a breach is dependent upon soil properties, and the breach size is also dependent upon soil properties; and
- Durations of water flow into a reach or subbasin are based on the surge hydrographs. Assuming that reach failures are independent events, the breach failure probability for a subba-

sin or basin consisting of n reaches, i.e., P(B) can be computed as

$$P(B) = 1 - \prod_{i=1}^{n} (1 - P_i(B))$$
 (10)

where $P_i(B)$ =breach probability for the reach as a function of surge height as determined from the corresponding fragility curve (Fig. 8). Thus, Eq. (10) gives the probability that one or more reaches within in subbasin suffer a breach.

Following the procedures for calculating overtopping volume, the volume flow rate due to breach of a single reach can be obtained as

$$Q = C_{w} L_{R} H_{R}^{3/2} \tag{11}$$

where L_B =width of the breach; H_B =height of water in excess of the reach minus the depth of the breach; and C_w =weir coefficient for the breach (taken to be 2.0). Values for breach height and depth are a function of reach or transition length and material, and maximum surge height of the hydrograph. For convenience, breach height and depth were specified in discrete form such as shown in Table 6. The total volume entering a subbasin due to breach of a given reach can be calculated using Eq. (7). The variance on this volume is found in a manner identical to Eq. (8).

Closure Volume and Probability Models

The hurricane protection system includes *closures* that could contribute to water volume making its way to the protected areas during a hurricane. These closures include the following:

- · Gates that are left open or failed to close; and
- Ramps, e.g., structures on both sides of a roadway, that could be left open.

The probability that all closures are closed in a subbasin or basin consisting of n reaches during a hurricane event, P(C), can be obtained using a systems reliability approach as follows:

$$P(C) = \prod_{i=1}^{n} (1 - P_i(\bar{C}))$$
 (12)

where $P_i(\bar{C})$ =probability that the gates in reach i are not closed. For reaches consisting of multiple gates, the probability of non-closure among these gates is assumed to be perfectly correlated.

Following the procedures for calculating overtopping and breach volume, the volume flow rate due to closures of a reach being open during a hurricane event can be obtained as

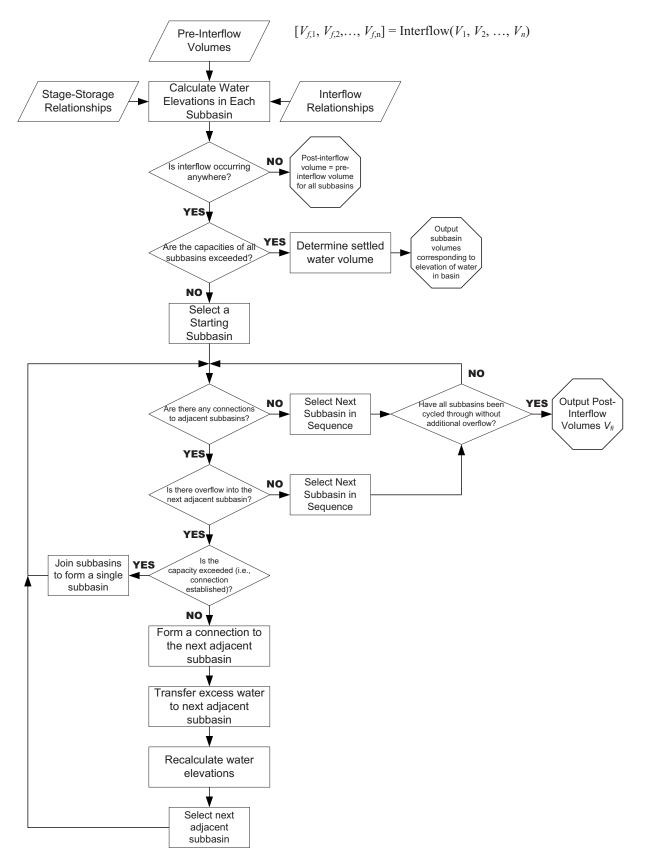


Fig. 9. Algorithm for subbasin interflow function

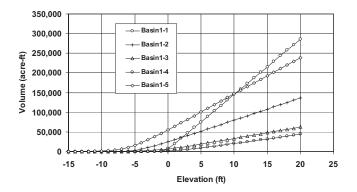


Fig. 10. Stage-storage relationships of subbasins and basin New Orleans East (1 ft=0.3048 m, 1 acre $ft=43,560 \text{ ft}^3$)

$$Q = C_w L_C H_C^{3/2} \tag{13}$$

where L_C =total open width of all closures in the reach; H_C =height of water in excess of the average bottom elevation of the closures; and C_w =weir coefficient for water flowing through the closures (taken to be 2.0). The total volume entering a subbasin or basin due to open closures in a given reach can be calculated using Eq. (7). The variance on this volume is found in a manner identical to Eq. (8).

Pumping, Rainfall, and Total Water Volume in Subbasin

Given the volume contributions due to overtopping, breach, and open closures, the total volume entering a subbasin (as a random variable with mean and standard deviation) can be calculated for each branch of the event tree in Fig. 6 by adding the corresponding volumes and water volume from rainfall minus the effect of pumping. The pumping system in New Orleans is designed to remove rainfall from tropical storms up to a 10-year event, and thus the effect of pumping on subbasin inflow water volumes can be approximated by subtracting a portion of the 10-year rainfall that considers degraded pump reliabilities and efficiencies as a function of water level accumulated in a subbasin.

Table 7. Computational Summary for Branches of Event Tree of Fig. 6 for Hurricane and Basin

Branch	Branch probability (see Fig. 6)
1	(1-P(O))(1-P(B))P(C)P(P)
2	(1-P(O))(1-P(B))P(C)(1-P(P))
3	(1-P(O))(1-P(B))(1-P(C))P(P)
4	(1-P(O))(1-P(B))(1-P(C))(1-P(P))
5	(1 - P(O))P(B)P(C)P(P)
6	(1-P(O))P(B)P(C)(1-P(P))
7	(1-P(O))P(B)(1-P(C))P(P)
8	(1-P(O))P(B)(1-P(C))(1-P(P))
9	P(O)(1-P(B))P(C)P(P)
10	P(O)(1-P(B))P(C)(1-P(P))
11	P(O)(1-P(B))(1-P(C))P(P)
12	P(O)(1-P(B))(1-P(C))(1-P(P))
13	P(O)P(B)P(C)P(P)
14	P(O)P(B)P(C)(1-P(P))
15	P(O)P(B)(1-P(C))P(P)
16	P(O)P(B)(1-P(C))(1-P(P))

Table 8. Computational Summary for Water Volumes Associated with Branches of Event Tree of Fig. 6 for Hurricane and Basin

	Contributions to branch water volume in basin
Branch	or subbasin (see Fig. 6)
1	Precipitation minus pumping
2	Precipitation
3	Precipitation and open closures minus pumping
4	Precipitation and open closures
5	Precipitation and breaches minus pumping
6	Precipitation and breaches
7	Precipitation, open closures, and breaches minus
	pumping
8	Precipitation, open closures, and breaches
9	Precipitation and overtopping minus pumping
10	Precipitation and overtopping
11	Precipitation, overtopping, and open closures minus pumping
12	Precipitation, overtopping, and open closures
13	Precipitation, overtopping, and breaches minus pumping
14	Precipitation, overtopping, and breaches
15	Precipitation, overtopping, open closures, and breaches minus pumping
16	Precipitation, overtopping, open closures, and breaches

Water Interflow among Basins and Subbasins

As illustrated in Fig. 1, several basins of the HPS can be divided into several subbasins. Consequently, the water entering a subbasin may, under certain conditions, overflow into adjacent subbasins. Thus, prior to calculating the final volume of water in the subbasins and basins for each of the 16 branches in the event tree of Fig. 6, the interflow among subbasins in a basin needs to be considered.

Given a basin consisting of m interconnected subbasins with mean preinterflow water volumes V_i , $i=1,2,\ldots,m$, the postinterflow water volumes can be computed as

$$[V_{f,1}, V_{f,2}, \dots, V_{f,m}] = \text{Interflow}(V_1, V_2, \dots V_m)$$
 (14)

where $V_{f,i}$ =mean final postinterflow volume in subbasin i; and the function "Interflow" is represented by the algorithm illustrated in Fig. 9. For simplicity, the coefficient of variation on water volume in a subbasin is preserved through the interflow function, i.e., the COV on the postinterflow volume for a given subbasin equals the preinterflow COV.

Expressed in terms of elevations, the postinterflow elevation of water in a subbasin, E_f , can be obtained as

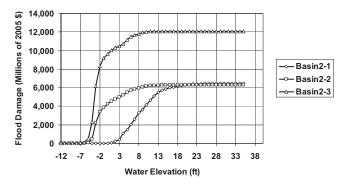


Fig. 11. Elevation-loss curves for hypothetical subbasins (1 ft = 0.3048 m)

$$E_f = g(V_f) \tag{15}$$

where the function g defines the stage-storage relationship for the subbasin, i.e., water elevation (stage) as a function of water volume (storage). Typical stage-storage curves are illustrated in Fig. 10. Using first-order approximation for uncertainty propagation, the variance of the final water elevation can be obtained as

$$\sigma_{Ef}^2 = \left(\left. \frac{dg}{dV} \right|_{V_f} \right)^2 \sigma_{V_f}^2 \tag{16}$$

where the derivative of the stage-storage relationships with respect to a change in volume evaluated at V_f can be determined numerically.

Branch Probabilities and Water Elevations

Based on the events described in the event tree of Fig. 6, the probabilities for each branch can be calculated using the expressions described in Table 7. Table 8 summarizes the respective procedures for water volume and elevation computation. It should be noted that the water volume associated with the branches involving not-all-gates closed, one or more breaches, and one or more failed pumps requires a procedure to account for all possible combinations of not-all-gates closed, and reach and transition breaches. Let i be the index denoting a unique scenario among the set of 2^{m+n+q} scenarios of closure open/closed, reach or transition breach/no breach, and pump failed/not failed combinations (m =number of uncorrelated gates, n=number of reaches and transitions, q=number of reaches with pumps). The aggregate conditional cumulative distribution function (CDF) for the water elevation in a subbasin given the occurrence of a breach, closure, or pump failure event considering all scenarios, F_E , is

$$F_E = \frac{\sum_{i=1}^{2^{m+n+q}} p_i F_{E,i}}{\sum_{i=1}^{2^{m+n+q}} p_i}$$
 (17)

where $F_{E,i}$ =CDF of the water elevation in the subbasin; and p_i =multinomial probability of the *i*th scenario.

Risk Profile by Basins and Storms

Economic and casualty losses were estimated and results were provided as subbasin elevation-loss curves, l=L(e), such as that shown in Fig. 11 for a variety of percentile values on loss for each elevation increment. Fig. 10 provides results using notional data for hypothetical subbasins for the purpose of illustration. The CDF for total direct loss (direct economic or casualty), F_L , associated with a basin consisting of n subbasins for a given branch and storm can be obtained from the water elevation CDFs, F_E , and elevation-loss curves per subbasin as (assuming perfect correlation on elevation among all interconnected subbasins)

$$F_L^{-1}(p) = \sum_{i=1}^n F_{L,i}^{-1}(p)$$
 (18)

where $F_L^{-1}(p)$ =inverse of the CDF as a function of percentile value p; and the CDF on loss in a given subbasin is determined as

$$F_{L,i}(L(e)) = F_{E,i}(e) \tag{19}$$

where e denotes elevation. The CDF on total loss associated with a basin for a given storm can be obtained by summing the results across all 16 event branches as follows:

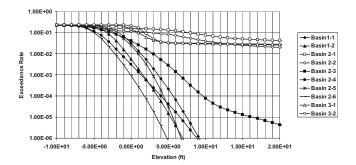


Fig. 12. Illustrative flooding elevation hazard profile for selected subbasins (1 ft=0.3048 m)

$$F_L = \sum_{j=1}^{16} p_j F_{L,j} \tag{20}$$

where p_j =probability of branch j. Noting that F=P(L < l), The loss-exceedance probability for a given basin affected by storm, h, can be obtained from Eqs. (2) and (20) as

$$P(L > l|h) = 1 - P(L < l|h) = 1 - F_{L|h}(l)$$
 (21)

The loss-exceedance rate corresponding to Eq. (21) follows from Eq. (3) where the rate, λ , corresponds to the recurrence rate of the associated storm. Moreover, the total loss-exceedance rate considering all storms can be obtained by summing the loss-exceedance rates for the individual storms.

The flooding elevation hazard profile for selected subbasins is illustrated in Fig. 12. The aggregate risk profile for the HPS is expressed in terms of the direct economic (as illustrated by Fig. 13) and life loss consequences (as illustrated in Fig. 14) can be obtained by considering all combinations of branch events among all basins in the system. This risk profile requires that all storms be evaluated for all possible combinations of all the branches for all the basins with dependency modeling. Dependency among the basins has not been examined in order to reduce the number of possible combinations; however the risk results obtained by examining the individual basins is considered to be adequate for evaluating the relative risks and vulnerabilities of the HPS.

The CDF for total loss in a single year can be obtained using techniques for loss accumulation with constant annual rate of occurrence, λ as follows (Ayyub 2003):

$$F(l) = \sum_{n=0}^{\infty} e^{-\lambda} \frac{\lambda^n}{n!} F_L^{(n)}(l)$$
 (22)

where n=number of events occurring in the year and $F_l^{(n)}$ =n-fold convolution of the CDF on loss given an event were to occur, or

$$F_L^{(n)}(l) = P(L + L + \dots + L < l)$$
 (23)

Note that Eqs. (22) and (23) assume uncorrelated severities between storm events; however, Eq. (23) can be modified to account for decreased loss potential of subsequent hurricanes, such as would occur if few people decided to return to a region after the occurrence of a devastating hurricane event.

Inundation Maps

Given elevation-exceedence probabilities and rates for a branch, storm, or considering all storms, flood water inundation maps

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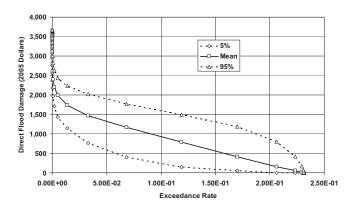


Fig. 13. Illustrative direct flood damage risk profile in 2005 dollars for subbasin

can be developed as illustrated in Fig. 15. The inundation maps can be supplemented with return periods corresponding to respective elevations.

Benefit-Cost Analysis

Given baseline risk information for a HPS, benefit-cost analysis can be used to assess the cost effectiveness of alternative risk mitigation strategies. In the context of protecting a region against floods resulting from posthurricane surges, risk mitigation options include strengthening levees, increasing the span and depth of the levees, relocating residential and commercial centers, and enhancing emergency response procedures. The benefit of a risk mitigation action is the difference between the total annual risk before and after its implementation (Ayyub 2003). The benefit-to-cost ratio is given by

$$\frac{\text{benefit}}{\text{cost}} = \frac{\text{unmitigated risk-mitigated risk}}{\text{cost to implement}}$$
 (24)

where higher-valued ratios indicate better risk mitigation actions from a cost-effectiveness standpoint. The probability that a favorable benefit-to-cost ratio will be realized can be represented as

$$P\left(\frac{\text{benefit}}{\text{cost}} \ge \alpha\right) = 1 - P(\text{benefit} - \alpha \cdot \text{cost} \le 0)$$
 (25)

where α =acceptability criterion specified according to the dimensions of benefit and cost, also known as the desired benefit-cost ratio. In addition to the results of Eq. (25), selection of a suitable risk mitigation action must also consider the affordability of each alternative and whether it achieves risk reduction objectives.

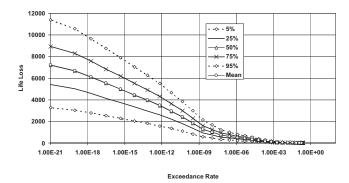


Fig. 14. Illustrative direct flood life loss risk profile for subbasin

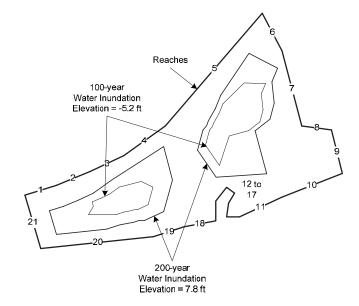


Fig. 15. Illustrative inundation map using hypothetical information (1 ft=0.3048 m)

Discussion and Conclusions

Hurricane Katrina was an extraordinary act of nature which resulted in the most destructive natural disaster in American history by creating a human tragedy and laying waste to 90,000 mi² (233,000 km²) of land, obliterating Louisiana and Mississippi coastal communities and leaving thousands destitute, killing 1,500 in New Orleans, and leading to the suffering of thousands without basic essentials for weeks along the Gulf Coast.

In developing the risk analysis methodology for protected hurricane-prone regions, the needs of decision and policy makers were the drivers that led to the requirements of producing an analytic, transparent, defensible, quantitative, probabilistic, and consistent methodology. Quantifying risk using a probabilistic framework produces elevation and loss-exceedance rates based on a spectrum of hurricanes according to the joint probability distribution of the characteristic parameters that define hurricane intensity and the resulting surges, waves, and precipitation. The methodology provides a process for evaluating the performance of a hurricane protection system consisting of levees, floodwalls, transitions, closure gates, drainage systems and pumping stations, and measures population and property at risk by considering the stage-storage relationships of subbasins. The quantification of risk will enable decision makers to consider various alternatives to manage risk through the enhancement of the hurricane protection systems, controlling land use, improving evacuation effectiveness, and improving system operations. It also provides public and private stakeholders with information that can be used to increase hurricane preparedness and the awareness of the risks associated with living in a hurricane prone environment.

Although the methodology provided herein models many aspects of the complexity associated with hurricanes, protections systems, performance, and losses, and produces a relatively practical and realistic framework for informing decisions, the methodology can be improved by embedding it into a simulation process to quantify the epistemic uncertainty in the resulting elevation and loss-exceedance curves, enhancing the modeling of drainage and pumping system, accounting for spatial aspects of

economic impacts, and perhaps enabling it to produce time history of inundations for respective hurricanes.

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