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DISSERTATION

Improving Flood Risk Estimates and Mitigation Policies in Coastal Louisiana under Deep Uncertainty

David R. Johnson

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This document was submitted as a dissertation in June 2013 in partial fulfillment of the requirements of the doctoral degree in public policy analysis at the Pardee RAND Graduate School. The faculty committee that supervised and approved the dissertation consisted of Henry H. Willis (Chair), Jordan R. Fischbach, and Nicholas E. Burger.

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Overview

After being pelted by an unprecedented string of destructive storms—Hurricanes Ivan, Katrina, Rita, Gustav, Isaac, and others all in the last decade—Louisiana's coastal communities are confronting difficult questions about their future. The state has long been aware of its vulnerability to Atlantic hurricanes but historically has lacked sufficient funding to protect itself and been unable to reach consensus about what should be done.

Since Hurricane Katrina, however, Louisiana has worked to rectify this problem with a renewed sense of purpose. Alongside the U.S. Army Corps of Engineers (USACE), Federal Emergency Management Agency (FEMA), Department of Homeland Security, and other agencies, the state has provided $14.5 billion in repairs and upgrades to the Greater New Orleans Hurricane and Storm Damage and Risk Reduction System (HSDRRS). Louisiana's Coastal Protection and Restoration Authority (CPRA) convened a large consortium of experts to develop its 2012 Comprehensive Master Plan for a Sustainable Coast, an action-oriented plan consisting of over one hundred projects designed to minimize future land loss and flood risk while simultaneously considering negative impacts on fisheries and other ecosystem services.

RAND was engaged as part of this effort in two capacities. One team developed a Planning Tool used to compare the impacts of hundreds of candidate projects and support the deliberative process by identifying the tradeoffs between various high-performing groups of projects. I was part of the other RAND team, tasked with evaluating coastal flood risk from storm surge events under a range of future uncertainties and with different configurations of protection projects in place across the landscape.

This dissertation consists of three essays that summarize my contributions to the study of flood risk in coastal Louisiana during and following the Master Plan process. The first paper introduces a new methodology for estimating the probability distribution of flooding on the interior of a ring levee/floodwall system. It argues for the superiority of the method by comparing the flood depth and damage exceedances it calculates in New Orleans to those generated by a previous methodology utilized by another recent study of Louisiana flood risk.

The second paper describes the Coastal Louisiana Risk Assessment (CLARA) model, of which I was the lead developer. This model fully implements the methodology outlined in the first paper and was used to evaluate the impacts of candidate protection projects on flood risk. The essay delineates CLARA's features, describes how it works, and provides summary results about future flood risk with and without the Master Plan in place.

The third manuscript relates work done subsequent to the Master Plan's approval. It uses CLARA to develop a framework for allocating the $10.2 billion designated for nonstructural risk reduction measures such as elevating homes and floodproofing commercial and industrial properties. A pseudo-optimization algorithm is used to identify cost-effective nonstructural strategies that are robust to future uncertainties.

Abbreviations and Acronyms

ACS	American Community Survey
ADCIRC	ADvanced CIRCulation model
AEP	annual exceedance probability
BFE	base flood elevation
BHU	basic hydrologic unit
CBP	County Business Patterns
CDF	cumulative distribution function
CLARA	Coastal Louisiana Risk Assessment [model]
CPRA	Coastal Protection and Restoration Authority of Louisiana
CSVR	contents-to-structure value ratio
DEM	digital elevation model
DFIRM	digital flood insurance rate map
EAD	expected annual damage
EST	empirical simulation technique
FEMA	Federal Emergency Management Agency
FOS	factor of safety
FWOA	future without action
FWP	future with projects
G60	Grid 60 (Future Without Action alignment)
G62	Grid 62 (Master Plan alignment)
GBS	General Building Stock
GNOCDC	Greater New Orleans Community Data Center
Hazus-MH	FEMA Hazus-Multi-Hazards model
HEAG	highest elevation adjacent grade
HMGP	Hazard Mitigation Grant Program
HPS	hurricane protection system
HSDRRS	Hurricane and Storm Damage Risk Reduction System
IPET	Interagency Performance Evaluation Task Force
JPM-OS	Joint Probability Method with Optimal Sampling
LACPR	Louisiana Coastal Protection and Restoration
LIDAR	light detection and ranging
LSU AgCenter	Louisiana State University Agricultural Center
mb	millibar
NASS	National Agricultural Statistics Service
NAVD88	North American Vertical Datum of 1988
NFIP	National Flood Insurance Program
nm	nautical mile

NOAA	National Oceanic and Atmospheric Administration
NPV	net present value
OLS	ordinary least squares
PDF	probability distribution function
RMSE	root mean squared error
RSLR	relative sea-level rise
SD	standard deviation
SI	International System of Units
SLOSH	Sea, Lake and Overland Surges from Hurricanes model
SLR	sea level rise
SSE	sum of squared errors
STWAVE	Steady State Spectral Wave model
SWAN	Simulating Waves Nearshore model
SWP	surge and wave point
TRMM	Tropical Rainfall Measuring Mission
USACE	U.S. Army Corps of Engineers
USCS	Unified Soil Classification System
USGS	U.S. Geological Survey

Glossary of Terms

Acquisition threshold: an elevation level for nonstructural mitigation, relative to ground level, beyond which properties will be subject to a voluntary acquisition policy

Annual exceedance probability (AEP): the probability that a quantity (flood elevations, depths, *etc.*) occurs or is exceeded in a given year; see **Exceedance probability curve**; *ex.* "The 1% AEP flood depth in this area is 3 feet."

Basic hydrologic unit (BHU): an aggregation of census blocks that forms one of CLARA's spatial units of analysis; BHUs are designed to be hydrologically independent up to a certain elevation (see **interflow elevation**), because of natural or constructed features along their boundaries

Breaching, elevation-based: a fragility mode used by CLARA which assumes that, upon a system failure or breach, the resulting interior flood elevation is equal to the elevation of the surge which caused the failure

Breaching, volume-based: a fragility mode used by CLARA which estimates water volumes that would pass through a point of failure in a hurricane protection system, based on the elevation of surge over time and the characteristics of the failure

Consequences: the direct economic damage incurred by a given flood depth; in other contexts, may refer to other results of flooding such as casualties or regional spillover effects

Depth-damage curve: a function relating the proportion of an asset's value that is lost during a flood event, as a function of the flood depth relative to the structure's foundation

Dispersion parameter: the proportion of the coast's population living in urban clusters, rather than rural areas; along with the overall growth rate, one of two parameters used by CLARA to specify an economic growth scenario

Exceedance probability curve: a function, similar to a cumulative probability distribution, that describes the probability of a quantity (flood elevations, depths, *etc.*) occurring or being exceeded in a given time period (a year in this analysis)

Expected annual damage: metric representing the average damage experienced in a given year from storm surge-based flooding; combines the overall frequency of storms with the probability distribution of damage conditional on a surge event occurring

Fragility: the probability that protection system elements will fail to function or operate as intended during a surge or flood event

Fragility mode: a mechanism by which a protection system might fail. CLARA models 1) overtopping failures, where overtopped water erodes a structure's back side, 2) seepage failures, where water flows through soil underneath a levee or floodwall, damaging its structural integrity, and 3) slope stability failures, where excessive pressure against the slope of a levee causes it to slip out from under itself.

Freeboard: an elevation beyond a **nonstructural reference standard** up to which nonstructural mitigation measures are recommended or provided; here, typically 1 or 4 feet

Future Without Action: a **landscape**, also known as G60, in which no further structural protection or restoration projects are implemented

Hazard: the probability of a storm with any given set of characteristics occurring

Hydrograph, surge: the elevation of surge measured over time during a surge event

Interflow elevation: the elevation at which flood waters begin to flow from one basic hydrologic unit to another; the minimum elevation along the boundary between the units

Landscape: the configuration of structural protection and restoration features across the coast; may refer to the Master Plan landscape, in which all Master Plan structural and restoration projects have been implemented, or the Future Without Action (FWOA) landscape, in which no further projects are put into place; in concert with a **scenario**, determines the probability distribution of flooding

Master Plan: Louisiana's 2012 Comprehensive Master Plan for a Sustainable Coast; may also refer to the Master Plan landscape, also known as G62, in which implementation of the plan's structural protection and restoration projects has taken place

Nonstructural risk reduction: refers to capital projects, such as floodproofing or home elevations, which reduce the consequences of flooding without changing the local probability distribution of flood depths

Project, nonstructural: refers to the implementation of a nonstructural risk reduction policy within a given spatial unit, such as a census tract

Reference standard, nonstructural: the elevation (relative to a fixed elevation datum like NAVD88) used as the basis for determining to what level nonstructural mitigation is recommended or provided

Restoration: capital projects, such as river diversions or sediment piping, intended to rebuild coastal lands or prevent erosion; may also refer to measures that maintain desirable coastal conditions, like salinity barriers to prevent intrusion of saltwater into freshwater bays or marshes

Scenario: a realization of a particular future outcome regarding various uncertainties, such as sea level rise or the frequency of future Atlantic cyclones; in concert with a **landscape**, determines the probability distribution of flooding

Stage-storage curve: a function that relates a volume of flood-water present in a BHU to the standing water elevation that would result

Strategy, nonstructural: an aggregation of nonstructural **projects** that specifies how nonstructural risk reduction policy should be implemented coastwide; a strategy may specify that different project types should be applied in different census tracts, or that some tracts receive no nonstructural risk reduction at all

Structural risk reduction: refers to capital projects, such as levees or floodwalls, which alter the course of flooding by blocking or redirecting it, thereby changing the probability distribution of flooding from a given event

Surge surface method: a method for calculating flood depth exceedances within a ring levee system by which a given flood depth exceedance is estimated as equaling the flood depths resulting from a surge event which consists of the corresponding surge exceedance impacting the levee system everywhere along the system exterior

Target community: one of 56 spatial units designed by CPRA for estimating the risk reduction effects of nonstructural mitigation measures during the Master Plan analysis

Threat: see **Hazard**

Vulnerability: the probability distribution of flooding caused by a given storm, as dictated by the performance of pumps, gates, levees, and other elements of the protection system

Improved Methods for Estimating Flood Depth Exceedances within Hurricane Protection Systems

David R. Johnson

ABSTRACT

Future climate change presents a threat of increased hurricane flood risks to many coastal cities. In the wake of Hurricanes Katrina and Rita in 2005 and Hurricane Ike in 2008, the U.S. Army Corps of Engineers has provided $14.5 billion of repairs and upgrades to the Greater New Orleans Hurricane and Storm Damage and Risk Reduction System (HSDRRS) to provide New Orleans with protection from a "100-year" flood event, defined as the storm surge flood level with a 1 percent chance of occurring or being exceeded annually.

A previous study of risk in coastal Louisiana estimated the 100-year flooding and economic damage within the HSDRRS by estimating 100-year surge levels at each point along the system boundary, calculating overtopping rates from this surge surface, and then passing the resulting volumes of water through an interior drainage model to calculate interior flood depths. This "surge surface" methodology can produce misleading results, as a storm producing a 100-year surge at one point along the system is unlikely to simultaneously produce 100-year surge levels everywhere around the system exterior.

The Coastal Louisiana Risk Assessment (CLARA) model instead estimates surge and wave characteristics from a large set of synthetic storms. Each storm is run through the interior drainage model separately, and the resulting flood depths are weighted by a parameterized likelihood of each synthetic storm. This results in an empirical distribution of interior flood depths that accounts for the geographic variation in surge response inherent to any individual storm.

100-year and 500-year flood depth exceedances within the New Orleans HSDRRS calculated by our new methodology differ from those estimated by the surge surface method, suggesting a need to re-evaluate current design philosophies for hurricane risk reduction systems. Rather than setting design elevations based on inputs (e.g., a "100-year storm event"), they should be set with an eye towards consequences (e.g., to reduce 100-year interior flood depths to an acceptable level).

INTRODUCTION

Storm surge flooding produced by Hurricane Katrina devastated the City of New Orleans in 2005, flooding 80 percent of the city and destroying 200,000 homes and 15,000 apartment units (Brinkley, 2006). The storm was responsible for at least 1,800 casualties, and total losses have been estimated at $108 billion (Knabb, Rhome and Brown, 2011). The U.S. Army Corps of Engineers (USACE) has constructed $14.5 billion of repairs and upgrades to the Greater New Orleans Hurricane and Storm Damage and Risk Reduction System (HSDRRS), intending to provide New Orleans with protection from a "100-year" flood event (U.S. Army Corps of

Engineers, 2011), defined as the flood level with a 1 percent chance of occurring or being exceeded in a given year; this is also referred to as a 1% annual exceedance probability (AEP).

Recent studies argue, however, that dense urban areas such as New Orleans should receive more than a 100-year risk reduction standard (Interagency Performance Evaluation Taskforce, 2006; National Research Council, 2009; Dijkman, 2007; Jonkman et al., 2009). Even disregarding the historic cultural value attributed to the Louisiana coast, it is likely economically preferable to do so: several approaches, such as minimizing the total cost of implementing protection measures and expected damage from residual risk (Jonkman et al., 2009) and decision-tree analysis (von Winterfeldt, 2006), have reached this conclusion. Future change in the hazard associated with storm surge is uncertain as a consequence of non-stationarity in Atlantic hurricane characteristics (Emanuel, 2005; Landsea et al., 2006; Grinsted, Moore and Jevrejeva, 2013; Bender et al., 2010; Hill and Lackmann, 2011), and the Louisiana coastline may become more vulnerable to storm surge flooding as coastal land subsides and sea levels rise (Barras et al., 2003; Meehl et al., 2005). Risk will be further compounded in the future by ordinary economic growth, as well as development induced by the provision of structural protection measures (Burby, 2006; Kahan et al., 2006; Olshansky, 2006; Montz, 2000).

Further upgrades to the HSDRRS have been approved as part of Louisiana's *2012 Comprehensive Master Plan for a Sustainable Coast*. The Master Plan utilized an integrated assessment of flood risk that incorporates structural protection into a broader collection of risk mitigation actions (Louisiana Coastal Protection and Restoration Authority, 2012a). Approved unanimously by the state legislature in May 2012, the $50 billion, 50-year plan recommends a suite of 109 protection and coastal restoration projects that include new levees and floodwalls, upgrades to existing systems, river diversions, marsh stabilization projects, and programs for home elevation and floodproofing. Structural protection systems and restoration projects alter the coastal landscape, mitigating flood risk by blocking, redirecting, and slowing the advance of storm surge. Elevating residences and floodproofing commercial and industrial properties reduces the vulnerability of individual assets to flood damage.

To choose among different risk reduction options and make reasoned decisions based on cost-benefit analysis, planners need tools at their disposal to accurately estimate economic risk. Since flooding is a dominant mode of damage in storm events like Katrina, the accuracy of risk estimates is strongly dependent on the accuracy of estimates of flood depths. Over the last fifty years, estimates of flood risk have evolved from modeling a single extreme storm, to techniques based on historical observations, and now to detailed hydrodynamic models capable of simulating a large number of storms at high spatial resolution. I present here a new technique developed in support of the Master Plan study and compare its results to those produced by a method used in a previous study of Louisiana flood risk.

METHODS

The process of estimating flood depth exceedances on the interior of a protection system can be broken into three conceptual steps:

1. Storm selection – deciding what storms (observed or simulated) should be considered to capture the range of variation in storm surge and flooding that can impact a region
2. Flood modeling – combining the surge, wave and rain characteristics with system characteristics and performance to calculate the flood depths resulting from a given storm
3. Frequency analysis – determining how individual storms are statistically aggregated into an exceedance probability curve

Each step has its own set of associated methodologies that can be evaluated and improved independently. I first provide an overview of each step and background on the methods used in this study. Then I describe and analyze improvements made to the frequency analysis component, the focus of this paper.

Storm Selection

Statistical models of flood risk aggregate the information about flood depths resulting from a suite of storms (observed or simulated) of varying characteristics into a probability distribution that describes the likelihood of flooding of any given depth occurring.

Beginning in the 1960s, levee design was based on estimated performance against a single, relatively extreme Standard Project Hurricane (U.S. Army Corps of Engineers, 1965). The concept of a reference Standard Project Flood is still in use for flood planning today (Galloway et al., 2007), but as computing resources and scientific knowledge have grown over time, more sophisticated methods have been employed to evaluate an ever-larger number of storms. The Joint Probability Method (JPM) is based on simulation of hundreds to thousands of storms that are parameterized by a series of descriptive variables, including central pressure deficit, radius of maximum wind speeds, forward velocity, landfall location, landfall angle, and Holland B parameter. Recent studies in coastal Louisiana utilize JPM with Optimal Sampling (JPM-OS). This method examines a smaller number of storms—still characterized using the same set of parameters—interpolating and extrapolating the surge response from storms with parameter values not in the JPM-OS storm suite (Resio, 2007; Toro et al., 2010). As planners recognize the need for long-term projections of risk across a wide range of future uncertainties, the number of uncertain futures to model must be balanced with the number of storms that can be run over a reasonable timespan, even with advances in computing power. The response surface developed by JPM-OS obviates some of the need for large storm sets, enabling greater exploration of uncertainty. A smaller storm set also enables the use of more complex, high-resolution models

such as the ADCIRC (ADvanced CIRCulation) model, as opposed to low-resolution models like SLOSH (Sea, Lake and Overland Surges from Hurricanes) that do not adequately capture the dynamics of the convoluted Louisiana coastline and the impact of protection features and other berms like highways (International Hurricane Research Center, 2013).

The post-Katrina Interagency Performance Evaluation Taskforce (IPET) and Louisiana Coastal Protection and Restoration (LACPR) studies developed a set of 304 storms intended to bracket the 1% AEP storm surge for use with the JPM-OS response surface methodology across the Louisiana coast (U.S. Army Corps of Engineers, 2009a; Resio, 2007). These storms span the parameter space described above by varying along ten different landfall tracks and three values each for landfall angle, intensity, radius, and forward velocity. Variation in the Holland B parameter was accounted for by an error term applied probabilistically to the response surface generated over the other parameters (Resio, 2007). The work described in this paper is based on 40 storms, a subset of the 304-storm set. These were selected for use in the Master Plan based on their performance in predicting surge statistics at points across the coast when compared to the statistics generated by the full storm set (Fischbach et al., 2012; Louisiana Coastal Protection and Restoration Authority, 2012c). The resulting storm set varies along ten landfall tracks and takes four different combinations of central pressure deficit and radius; mean values were used for landfall angle and forward velocity.

Flood Modeling

To better estimate the economic risk to New Orleans and the entire Louisiana coast from storm surge flooding, the RAND Gulf States Policy Institute has developed the RAND Coastal Louisiana Risk Assessment (CLARA) model. Developed in support of the Master Plan, CLARA uses state-of-the-art models of storm surge, protection system fragility and interior drainage. Following is a brief conceptual outline of CLARA's approach to flood risk estimation; additional details are presented in Fischbach et al. (2012) and Johnson et al. (2013).

CLARA starts with protection system data, reads in surge and wave inputs from detailed hydrodynamic models (Louisiana Coastal Protection and Restoration Authority, 2012b), and processes these into a geospatial database. A flood module estimates flood depths using these data, and an economics module estimates the damage resulting from given levels of flooding.

In Greater New Orleans, the flood depth module samples points along the boundary of the HSDRRS no further than every 300 meters apart, including corners, endpoints and transitions between system elements (e.g., levees, floodwalls, gates). At each point, data is provided on a per-storm basis consisting of peak surge height, wave height, and wave period; and a surge hydrograph representing surge height at 15-minute intervals over a four-day span. This is

combined with information about the protection system (e.g., crest height, slope geometry, fill type) to calculate the volume of water that overtops into the interior at that point.

Overtopping volumes are combined with rainfall, and any pumping volumes are subtracted (in New Orleans, for example, water can be pumped into Lake Pontchartrain through several outfall canals or into the Mississippi River). The resulting water volume initializes the interior drainage module. This step subdivides the interior into a number of subunits called basic hydrologic units (BHUs), defined by natural or manmade elevation features running along the unit boundaries. For each BHU, a digital elevation model is used to calculate a stage-storage curve; this defines the volume of water required to flood the BHU up to a given flood elevation. Interflow elevations, the elevation at which water begins to flow from one BHU into another adjacent unit, are also calculated along each BHU boundary. This allows us to run an iterative process allocating the initial water volumes from each BHU throughout the interior, joining units as necessary, to reach a final standing flood elevation. Flood elevations in each BHU are then converted to flood depths for each census block using block definitions from the 2000 U.S. Census and average block elevations from LIDAR data.

CLARA is computationally light, capable of running hundreds of storms under many scenarios that reflect uncertainties in sea level rise (SLR), land subsidence, storm frequency and intensity, operational pumping capacity, regional growth, and urbanization patterns.

Frequency Analysis

As described above, each storm in the selected storm set is characterized using parameters like central pressure deficit, ΔP, and radius of maximum wind speeds, R_{max}. Probability distributions for each variable, Λ_1 through Λ_5 below, describe how likely the characteristics from any given storm are. Each parameter's marginal probability distribution is independent of the others, but in some cases, they are conditional on the value of another variable. This is done to account for correlations between parameters. For instance, the radius of maximum wind speeds is conditional on and inversely related to the central pressure deficit. I adopt the relationships developed in Resio (2007), which are specific to the Louisiana coastline and take observed historical storms into account. In the following, x represents the degree of longitude at landfall, v_f is the forward velocity of the storm, and θ_l is the angle of the storm's track at landfall.

$$\begin{aligned} \Lambda_1 &= f_1(\Delta P|x) \\ \Lambda_2 &= f_2(R_{max}|\Delta P) \\ \Lambda_3 &= f_3(v_f|\theta_l) \\ \Lambda_4 &= f_4(\theta_l|x) \\ \Lambda_5 &= f_5(x) \end{aligned}$$

Each marginal distribution is truncated so that each parameter is only supported over a range of possible values. For example, central pressure ranges from 960 millibars (mb), approximately the cutoff between Category 2 and Category 3 storms[1], to a theoretical minimum pressure of 882 mb. Given the assumption of conditional independence, the joint distribution representing the likelihood of observing a storm with any particular set of characteristics is just

$$f(\Delta P, R_{max}, \theta_l, v_f, x) = \Lambda_1 \cdot \Lambda_2 \cdot \Lambda_3 \cdot \Lambda_4 \cdot \Lambda_5$$

The parameter space formed by the plausible ranges of each storm characteristic is divided into cells, with the boundaries chosen such that each cell contains the parameters of only one storm in a given storm suite. Each storm in the suite is assumed to be representative of all possible hurricanes with parameters that fall within its cell.

To generate surge exceedances from any suite of m storms, each denoted S_i for i from 1 to m, the parameter space is partitioned into m cells as described above. This partition determines the probability masses $\Pr(S_i) = p_i$ assigned to each storm as the definite integral of the joint probability distribution function over the parameter ranges of the cell it represents. Then the n-year surge elevation exceedance E_n at any point is calculated by inverting an empirical cumulative distribution function (CDF). If e_i is the surge elevation from storm S_i, then

$$E_n = F^{-1}(1 - 1/n)$$

where

$$F(E_n) = \Pr(e \leq E_n) = \left(\sum_{e_i \leq E_n} p_i\right)^{\alpha}$$

Here α is the overall frequency of Category 3 and greater storms, expressed as the expected number of storms per year per degree of longitude in the study region. This converts the CDF from a *per-storm* basis—the probability of surge from a single storm event, to a *per-year* basis—the probability associated with the maximum observed surge in a single year.

LACPR's "Surge Surface" Methodology for Interior Frequency Analysis

LACPR projected 100-year (1% AEP) flood levels interior to the HSDRRS by estimating 100-year surge exceedances at each point along the system boundary and calculating the rate at

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[1] The modern Saffir-Simpson Hurricane Wind Scale is technically a measure of maximum sustained wind speeds, but a central pressure of 964 mb has historically been associated with the boundary between Category 2 and 3 hurricanes. The two parameters are highly correlated.

which water from the 100-year surge overtops the levees from waves and surge run-up. The 100-year interior flood elevations are estimated as those produced by passing the resulting volumes of water through an interior drainage model (U.S. Army Corps of Engineers, 2009a).

This "surge surface" method can produce misleading results, as a storm producing a 100-year surge at one point in a large system is unlikely to produce 100-year surge everywhere simultaneously. In practice, a real storm that produces 100-year flood depths on the interior is likely to exhibit storm surge greater than the 100-year elevation at some points and less than the 100-year elevation at others. The relationship between incoming storm surge and overtopping rates is highly nonlinear (van der Meer, 2002). For levees built to protect against 100-year surge, smaller surge heights produce little to no overtopping; surge near the 100-year level results in modest overtopping from wave run-up; but more extreme surge events can produce enormous overtopping, as the surge flows right over the top of the barrier into the city.

As such, it makes sense that interior flooding is driven by the areas along the system boundary that exhibit the most extreme surge levels. Within-storm variation in surge levels can produce interior flood exceedances much different than the flood depths produced by a constant surge surface of the same exceedance threshold. *A priori*, it is not obvious whether the probabilities associated with more extreme exterior surge would sum up to produce an estimate of 100-year flood depths on the interior that is greater than or less than the actual 100-year flood exceedance.

CLARA's "Coupled Dynamics" Methodology for Interior Frequency Analysis

Rather than basing estimates of the probability distributions of interior flooding on the distribution of exterior surge, CLARA's new approach is to run each synthetic storm through the flood model individually. Probability weights for each synthetic storm are associated with the resulting interior BHU flood elevations. Ordering the synthetic storms by flood depth at each point leads to an empirical CDF for the interior flood depths, which can then be inverted to obtain annual exceedance probabilities (AEP). CLARA's treatment of system fragility, used later in the Results section, is a natural extension of this method: the probability mass assigned to each synthetic storm is further subdivided by the probability distribution of flood depths that it causes.

We refer to this approach as the *coupled dynamics* method because it models the interactions between surge levels, the engineered protection system, and interior drainage for each individual storm. By contrast, the surge surface methodology used by LACPR decouples these relationships by summarizing the distribution of surge across all storms before considering the performance of the system.

CLARA runs a Monte Carlo simulation of multiple failure modes[2] along the protection system perimeter. The breach volumes associated with any failure are added to overtopping and rainfall volumes, net of any pumping capacity, before distributing the water using the interior drainage module. The frequency of resulting flood depths over the iterations is assumed to be an unbiased approximation of the actual probability distribution of flood depths from each particular synthetic storm. Since each iterate is independent, the empirical CDF is adjusted to incorporate the probabilities of flooding conditional on each storm. Where D_i is the set of flood depths associated with a storm S_i, the n-year flood depth exceedance D_n satisfies

$$F(D_n) = \Pr(d_n \leq D_n) = \left(\sum_{S_i} \sum_{\substack{d \in D_i, \\ d \leq D_n}} \Pr_S(S_i) \Pr_{D|S}(d|S_i) \right)^{\alpha} = 1 - \frac{1}{n}$$

The no-fragility case discussed earlier is simply a special case of this equation, where each synthetic storm only has a single possible flood outcome with probability equal to 1. (See Johnson, et al. (2013), the second paper in this dissertation, for additional detail on CLARA's interior drainage algorithm and treatment of system fragility.)

IPET's Methodology for Interior Frequency Analysis

IPET used a similar concept but did not carry it through to its logical conclusion. Interior flood elevations were calculated for each storm in the JPM-OS set based on surge-based overtopping and the consequences of multiple failure modes. However, wave overtopping, pumping volumes, and interflow between basins were not considered until after exceedances in each basin were estimated (Interagency Performance Evaluation Taskforce, 2009c). These factors can have substantial impact on the final flood depths from individual storms, so accounting for them in an aggregate fashion is not appropriate. IPET used a restricted subset of 76 storms on eastern tracks in their risk analysis; it is unclear how their response surface was generated and how many synthetic storms with intermediate parameter values were simulated. IPET also utilized an event-tree model of system fragility with twelve branches representing possible combinations of failures from gates, pumping systems, and breaches. They explicitly estimated probabilities for each branch. This limited the IPET model's results to at most twelve possible outcomes for flood depths in a given case, rather than capturing the wide range of depths associated with having single or multiple breaches at various points along a basin's boundary.

[2] CLARA models 1) overtopping failures, where overtopped water erodes a structure's back side, 2) seepage failures, where water flows through soil underneath a levee or floodwall, damaging its structural integrity, and 3) slope stability failures, where excessive pressure against the slope of a levee causes it to slip out from under itself.

Details about LACPR and IPET's overtopping and interior drainage models, as well as IPET's treatment of fragility, are described here to provide a fuller picture of the differences between these models and CLARA. This analysis only compares the statistical approaches used by the CLARA and LACPR models to aggregate multiple storms into an exceedance probability curve. All of the proceeding results were generated using CLARA's storm selection, overtopping, and interior drainage algorithms. In this way, any divergence in results is only due to the choice of statistical approach.

Experimental Design

The surge surface and coupled dynamics methods were run through CLARA using the same set of 720 synthetic storms, which are designed to represent the feasible parameter space of hurricanes rated Category 3 or greater on the Saffir-Simpson Hurricane Scale along three parameters: central pressure (in millibars), radius of max winds (in nautical miles), and storm track (spanning tracks spaced across the coastline). Nominal values are used for forward velocity and landfall angle. Surge and wave characteristics from each storm are estimated at each point using a response surface interpolation modeled after the JPM-OS technique (Toro et al., 2010), based on the Master Plan training set of 40 storms.

Our synthetic storm set consists of a full factorial over 10 storm tracks that make landfall to an idealized Louisiana coastline at 29.5 degrees North, from 94.4 to 88.5 degrees West; 9 values for central pressure ranging from 960 mb to 882 mb; and 8 values for R_{max} ranging from 5 nm to 40 nm. A large set of hundreds or thousands of synthetic storms makes the resulting CDFs smoother, which is needed to capture the nonlinear interactions between exterior surge and interior flood levels. Probability weights are assigned to each synthetic storm using the probability density distributions developed by JPM-OS.

To replicate the surge surface methodology used by LACPR, these probabilities are used to estimate a CDF of surge elevations at each point on the system exterior, from which we can obtain the 100-year and 500-year surge levels (1% and 0.2% AEP). The same regression models used to predict wave heights for each synthetic storm are used to estimate wave characteristics associated with 100- and 500-year surge. Estimates of the interior flood exceedances are then obtained by running through CLARA's flood depth module a surface consisting of the corresponding surge and wave levels at every exterior point. LACPR used a stochastic overtopping model that feeds the 90^{th} percentile of overtopping volumes associated with the 100- and 500-year surge and waves into its interior drainage model. CLARA's overtopping calculations are deterministic. This means that the overtopping volumes actually produced by the LACPR model may differ from those used here to produce flood depth exceedances using the surge surface method; the CLARA overtopping module is used in both cases so that the resulting differences are only due to the statistical approach and not the overtopping algorithm.

To sum up: in the surge surface method, all the statistics are performed before running the flood model, which is only run once for a given scenario. By contrast, the coupled dynamics methodology does the statistical aggregation after the flood modeling. Every synthetic storm is run through the flood model independently, and then the associated probabilities are used to produce the CDF of flood depths.

Each method was run across a set of scenarios reflecting different assumptions about environmental and operational uncertainties. In general, results were found to be consistent across scenarios, but for clarity, this paper restricts its attention to one illustrative case. All figures correspond to flood risk in 2061 on the interior of the Greater New Orleans HSDRRS, in a future where no additional mitigative actions are taken, including the projects approved by the 2012 Master Plan. Assumptions about sea level rise, land subsidence, and future storm characteristics are derived from the Less Optimistic landscape scenario developed for the Master Plan study. This reflects sea level rise of 0.45 m over 50 years, land subsidence at a rate of 0-25 mm/year (values vary spatially across the coast), and storms 20% more intense [than the current distribution of central pressure deficits] and 5% more frequent on average. Economic growth was modeled using the Master Plan's baseline assumptions: a coastal average growth rate of 0.67% per year and urbanization remaining at current levels. A fuller description of model assumptions and scenarios is available in the Risk Assessment appendix of the 2012 Master Plan (Louisiana Coastal Protection and Restoration Authority, 2012c).

It is important to reiterate that the modeled protection system and flood model used in both cases is the same. All differences presented here are due solely to the statistical methods; they are not simply a comparison of results from the LACPR and Master Plan studies.

RESULTS AND DISCUSSION

Flood depths with a 0.2% AEP (i.e., 500-year), as calculated by both methodologies, are illustrated in Figure 1 (surge surface method) and Figure 2 (coupled dynamics method) on the following page. The figure depicts the less optimistic environmental scenario, in 2061, with 50% of pumping capacity operating and no fragility. For ease of comparison, Figure 3 shows the difference between the surge surface and coupled dynamics flood depths depicted in Figure 1 and Figure 2. The same color scale is used where the surge surface estimates are greater than the coupled dynamics values. Since this is generally the case where discrepancies occur, the identical scale makes it easy to compare the relative difference between methods to the absolute flood depths. A blue scale is applied where the surge surface depths are less than the coupled dynamics'.

The surge surface method generally indicates more extensive and severe flooding than the coupled dynamics estimates. In Kenner and Metairie, along the south shore of Lake Pontchartrain in the west of the HSDRRS, the surge surface estimates are more than four feet greater than estimates produced by the coupled dynamics method. Neighborhoods on the west bank of the Mississippi River also see differences of three to five feet.

These differences are also significant when considering the economic damage corresponding to these levels of flooding. For assets within the HSDRRS, the damage associated with the 0.2% AEP flood depths, as calculated by the surge surface method, is $209 billion; when using the coupled dynamics flood depths, the damage is $148 billion—a difference of 29%. (See Johnson, et al. (2013), the second paper in this dissertation, for details on how CLARA estimates damage and the asset types included in the model.)

The surge surface method does not uniformly produce greater estimates of flooding for a given exceedance. Within the same case described above, the 0.2% AEP flood depths from the coupled dynamics method are six to nine inches greater than the surge surface values in St. Charles (along the Mississippi, at the far west extent of the HSDRRS). The differences can also change sign in the same neighborhood at different exceedances. The 1% AEP surge surface predicts no flooding in Kenner and Metairie, but the coupled dynamics method shows a small amount. Likewise, in St. Charles the coupled dynamics method predicts 1% AEP flood depths nearly a foot lower than the surge surface values.

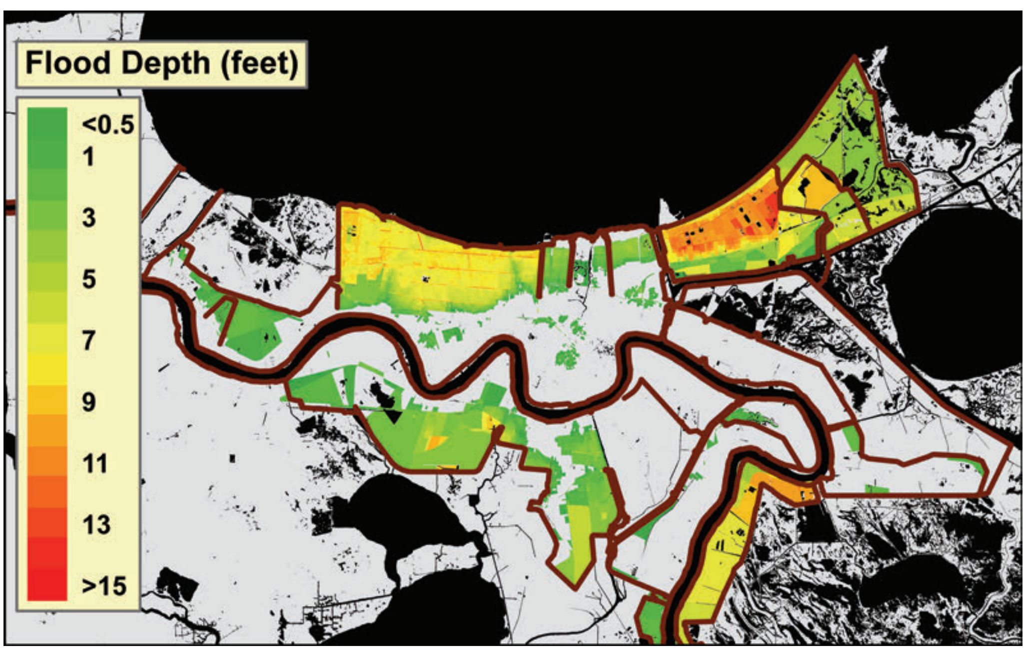

Figure 1: 500-year (0.2% AEP) flood depths calculated by the surge surface methodology (2061, less optimistic scenario, 50% pumping, no fragility)

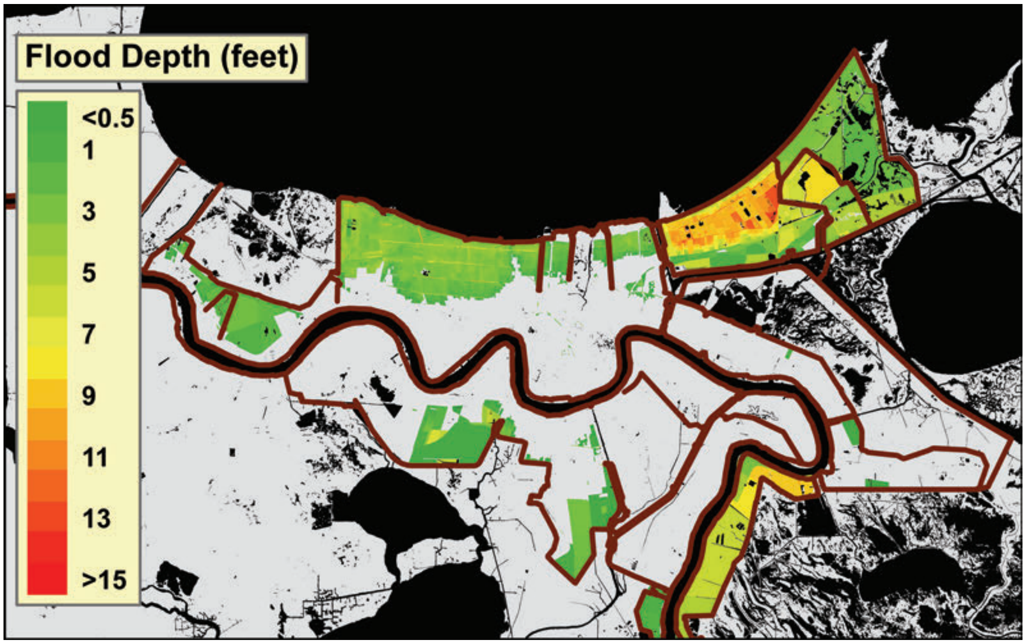

Figure 2: 500-year (0.2% AEP) flood depths calculated by the coupled dynamics methodology (2061, less optimistic scenario, 50% pumping, no fragility)

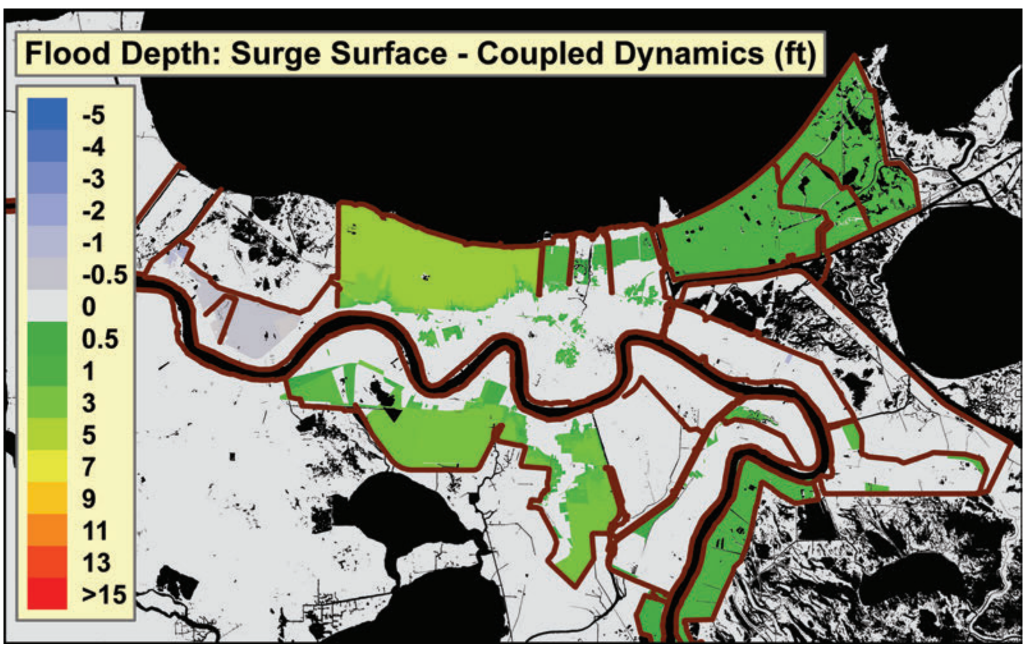

Figure 3: Difference in 500-year (0.2% AEP) flood depths between the surge surface and coupled dynamics methods (2061, less optimistic scenario, 50% pumping, no fragility)

Interpreting Discrepancies between the Surge Surface and Coupled Dynamics Methods

The disparities between methods at different exceedance thresholds depend on the probability distribution of exterior surge and waves, as well as the levee heights and other protection system characteristics. Although there are exceptions, the coupled dynamics exceedances are greater than or closer to the surge surface estimates at higher-frequency

intervals where flood levels are lower. At the extreme tail of the interior flooding distribution, the surge surface estimates are generally higher.

The U.S. Army Corps of Engineers recently certified the post-Katrina upgrades to the New Orleans HSDRRS as providing 100-year protection to the city. As described above, no flooding is seen in Kenner and Metairie at a 1% AEP using the coupled dynamics method (under the less optimistic scenario, in 2061, without further system upgrades). In 2061, the current system is still projected to provide protection from 100-year surge and wave overtopping at each point along the reaches protecting these neighborhoods, so the 100-year surge surface does not produce flooding on the interior. However, flooding can result from overtopping in storm events that produce slightly greater surge at some points along the system boundary, and the probabilities associated with storms that do so are sufficient to cause a small amount of flooding with a 1% AEP when the storms are aggregated using the coupled dynamics method.

The HSDRRS is not expected to prevent flooding at the 0.2% AEP level, however. Since the levee heights were not designed to protect against 500-year surge, the surge surface method results in a surface that pours large quantities of water into the city through surge overtopping at many points of entry along the system boundary. By contrast, extreme individual storms that cause surge greater than or equal to the 500-year surge levels in some areas would produce less than 500-year surge in other areas; for example, a storm approaching New Orleans from due south might produce the greatest surge along the west bank of the Mississippi, with less extreme surge impacting the city from the north, along Lake Pontchartrain. Storms producing greater interior flooding than a 500-year surge surface must be very low-probability events. In aggregate, then, the same flood depths would tend to be farther out into the tail of the distribution using the coupled dynamics method.

Incorporating System Fragility

To model the consequences of system failure, CLARA generates a probability distribution of flood depths resulting from each synthetic storm, based on Monte Carlo simulation. The probability of failure is estimated at points spaced no more than 300 meters apart along the system centerlines, as a function of surge height, protection feature heights and geotechnical characteristics like soil type and levee geometry. Failures at each point are modeled as independent events, though the probabilities of failure are strongly correlated due to spatial correlations in surge levels and system characteristics.

Flood depth exceedances are then calculated based on the probability masses associated with synthetic storms, combined with the probability distribution of flood depths resulting from each synthetic storm. A 100-year (1% AEP) flood depth could be caused by a variety of storm events;

it might result from the 90th percentile of flooding associated with one storm, or it may be associated with the 10th percentile of flooding caused by a more severe storm.

No analogous procedure exists for incorporating system fragility into the storm surface approach; LACPR did not consider the consequences of failure in their study. CLARA can run a Monte Carlo simulation of breaches resulting from a 500-year surge surface, but it is unclear whether a "500-year exceedance including fragility" should be reported as the median result from the Monte Carlo study, the 90th percentile, or some other value.

However, LACPR used a stochastic overtopping model. Design heights for the levee projects considered by LACPR were set by determining a height that would result in overtopping rates less than 0.1 cubic feet per second per linear foot of levee, with 90% confidence. For example, a levee would be certified as meeting a "100-year design criterion" if the 90th percentile of overtopping rates produced by 100-year surge levels were less than this threshold rate.

The overtopping confidence level used to set design heights is unrelated to an arbitrary choice of confidence levels for adapting fragility to the surge surface method. For consistency, however, we can consider a flood depth exceedance with fragility to be the 90th percentile of depths produced by a Monte Carlo simulation of a surge surface corresponding to the same AEP. Figure 4 shows the resulting 500-year (0.2% AEP) flood depths within the HSDRRS; Figure 5 shows the corresponding exceedance when calculated using the coupled dynamics method. Again, Figure 6 illustrates the differences between the two methods' estimated exceedances.

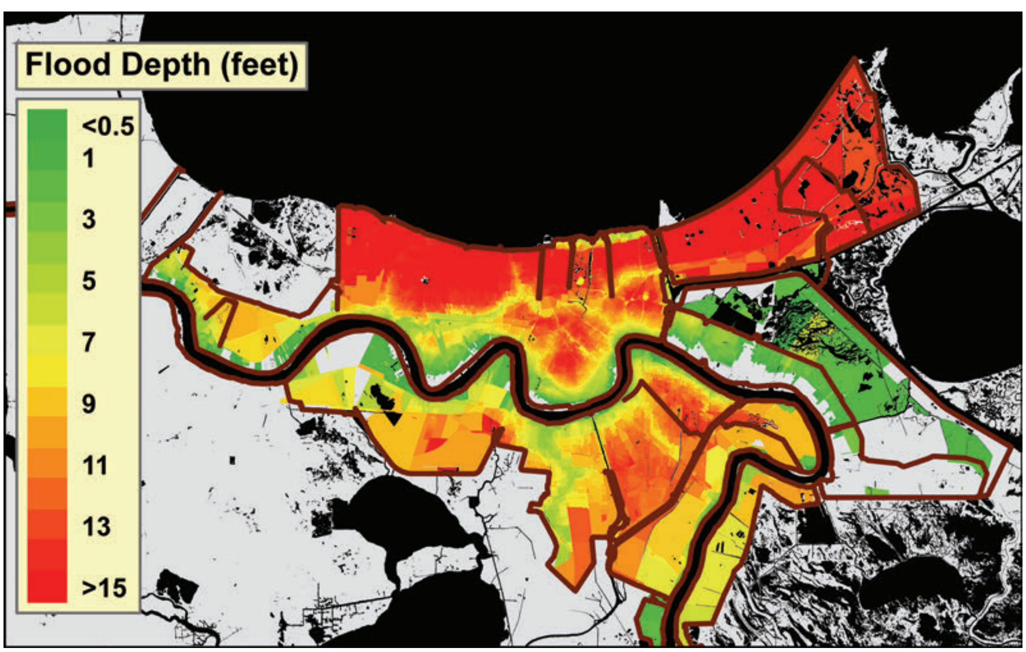

Figure 4: 500-year (0.2% AEP) flood depths calculated by the surge surface methodology (2061, less optimistic scenario, 50% pumping, with fragility)

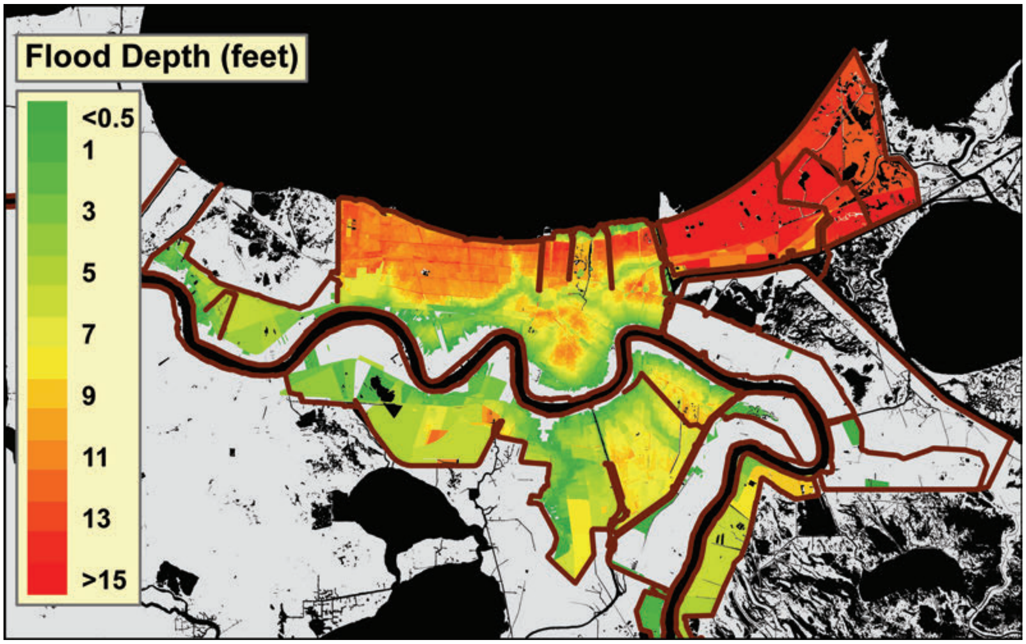

Figure 5: 500-year (0.2% AEP) flood depths calculated by the coupled dynamics methodology (2061, less optimistic scenario, 50% pumping, with fragility)

Clearly, fragility has a major impact on flooding from low-frequency, severe surge events; nearly the entire city experiences flooding under both methods, although the surge surface method again produces estimates that are greater than the corresponding coupled dynamics values. The proportional difference in damage associated with the estimates is similar to the case without fragility: the surge surface method results in $609 billion compared to $478 billion from the coupled dynamics method, a difference of 22%.

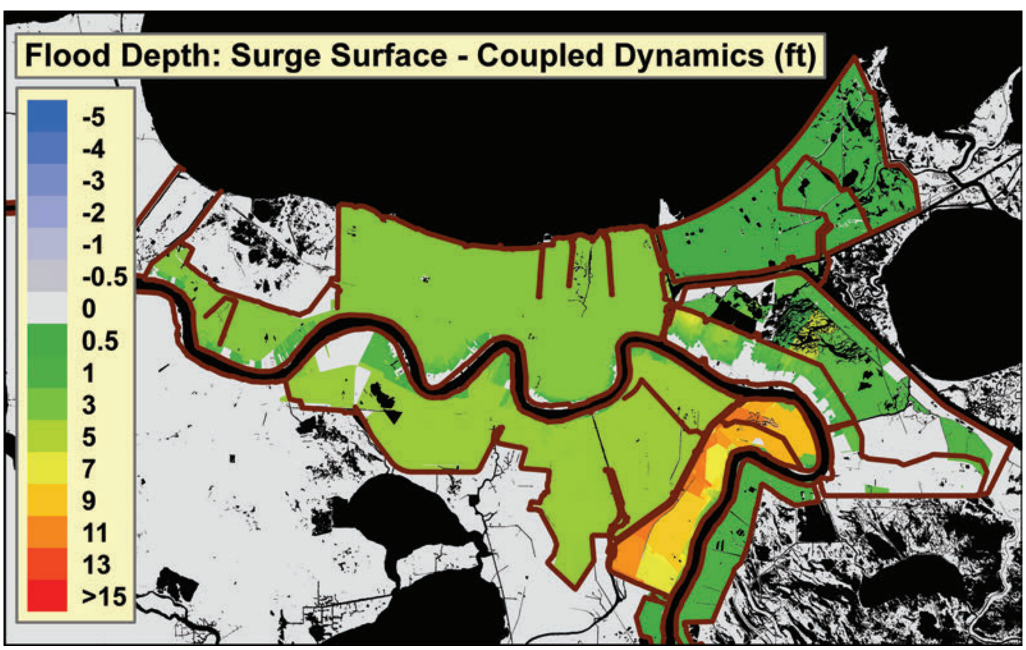

Figure 6: Difference in 500-year (0.2% AEP) flood depths between the surge surface and coupled dynamics methods (2061, less optimistic scenario, 50% pumping, with fragility)

With fragility included, the differences between methods are even more stark at the 1% AEP level. The coupled dynamics method (Figure 8) does not predict any flooding in Algiers, Harvey Gretna, or the Lower 9th Ward, but these neighborhoods have substantial 100-year flooding under the surge surface projections shown in Figure 7; differences in the 1% AEP values are in Figure 9. Damage associated with the former is $77 billion within the HSDRRS, whereas the greater extent of flooding in the latter case produces $235 billion in losses.

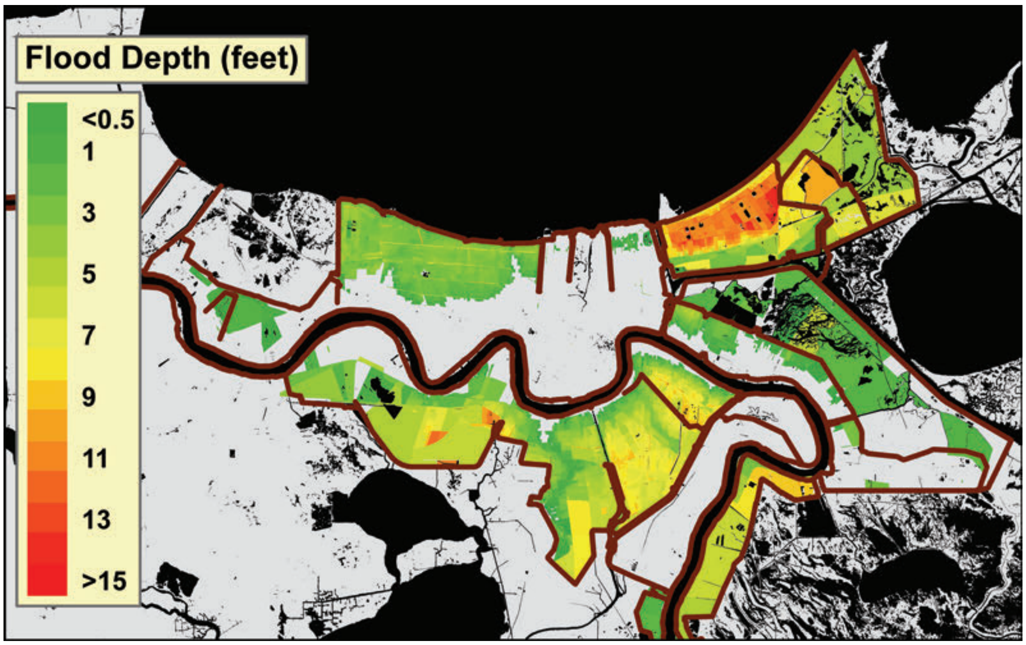

Figure 7: 100-year (1% AEP) flood depths calculated by the surge surface methodology (2061, less optimistic scenario, 50% pumping, with fragility)

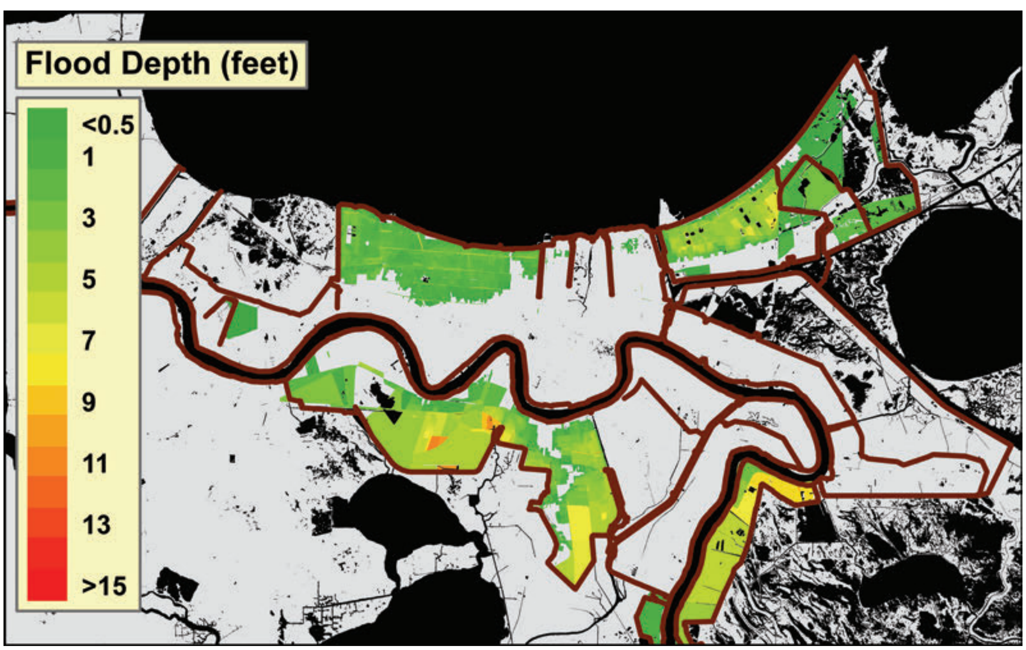

Figure 8: 100-year (1% AEP) flood depths calculated by the coupled dynamics methodology (2061, less optimistic scenario, 50% pumping, with fragility)

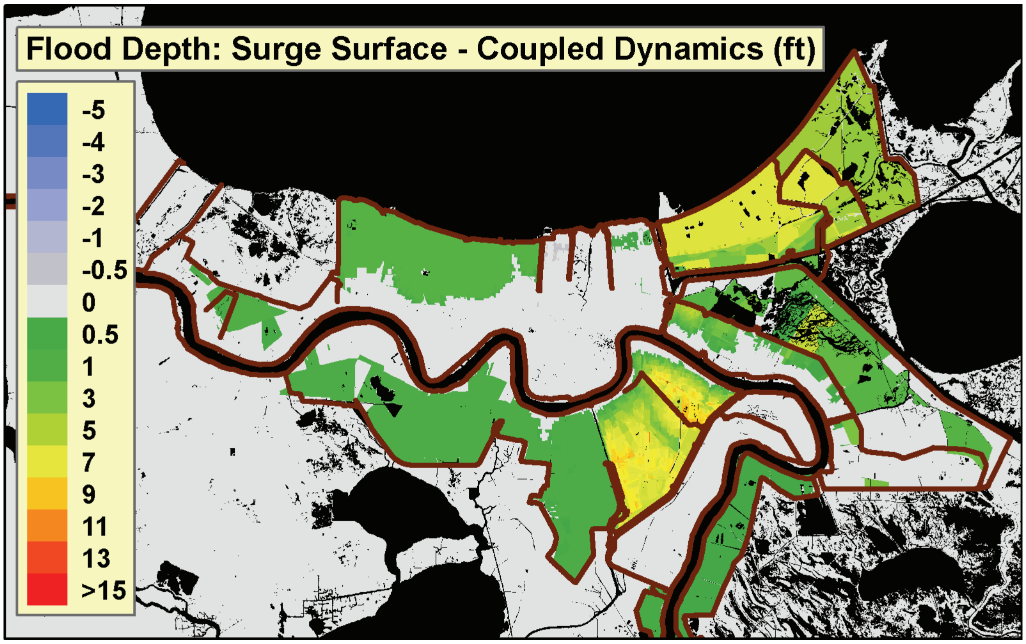

Figure 9: Difference in 100-year (1% AEP) flood depths between the surge surface and coupled dynamics methods (2061, less optimistic scenario, 50% pumping, with fragility)

Figure 10 shows the distribution of possible outcomes introduced by considering system fragility. Each solid dot represents a potential standing water elevation that could result from a 100-year surge surface. The color of the dot indicates the cumulative probability that the flood elevation is less than or equal to that point's elevation, as estimated by the frequency distribution of elevations generated from a Monte Carlo simulation of fragility. For convenience, the 90th percentile value adopted as the "100-year exceedance with fragility" illustrated in Figure 7 is identified by a larger size. The 100-year (1% AEP) flood elevation [with fragility] produced by the coupled dynamics method is shown, for comparison, as the large hollow circle.

The blocks within a given BHU vary in elevation, so flood depths are not constant for an entire BHU. Accordingly, the values in Figure 10 are presented as standing-water flood elevations relative to the NAVD88 datum rather than flood depths. If the reported elevation is equal to the minimum elevation within a BHU, this indicates that there is no flooding present.

The 100-year surge surface is still sometimes consistent with the coupled dynamics result, producing no flooding in Algiers, Harvey Gretna, the Lower 9th Ward, Violet Marsh, and Bayou Bienvenue. In the first two neighborhoods, this has about a 30% chance of occurring; in the St. Bernard BHUs, the probability is about 68%. The large gap between these dots and the next possible outcome indicates the large difference in flood outcomes between a case where no failures occur and the case where breaches introduce large volumes of water into the interior. The remaining spread in the distribution is indicative of the potential for multiple failures, or for breaches in different locations that produce varying results. Even if we adopt median elevations

rather than 90th percentile values for our definition of a surge surface exceedance with fragility, this would result in a discrepancy of 15 feet of flooding in Algiers.

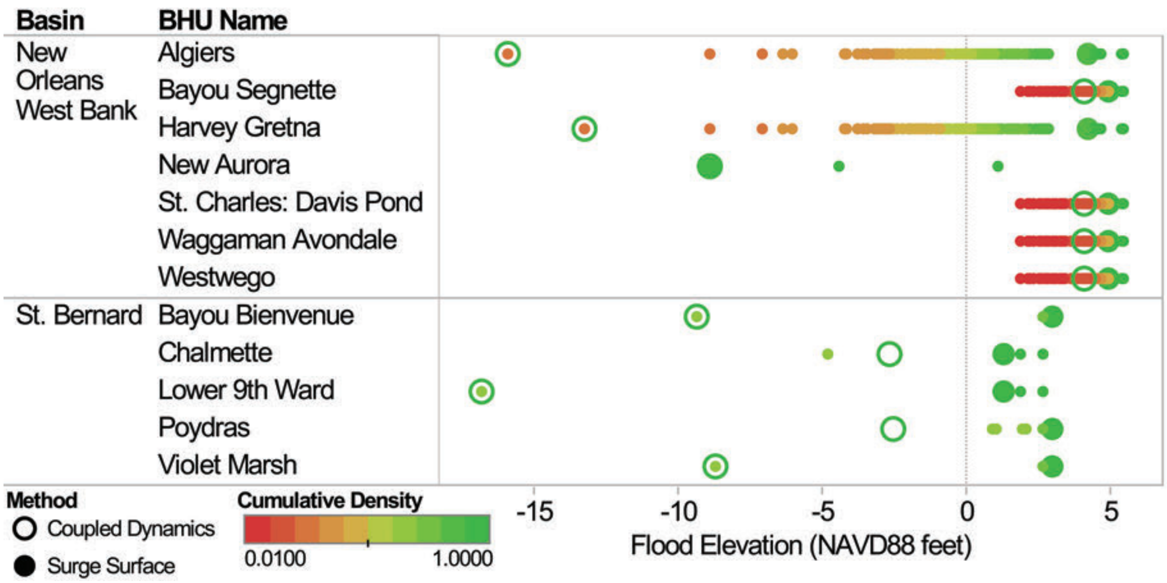

Figure 10: Frequency distribution of selected 100-year (1% AEP) flood elevations from Monte Carlo simulation of fragility

CONCLUSIONS

Louisiana has trended towards greater urbanization in the last fifty years, although that trend has slowed in the last two decades (US Census, 2010). Hurricane Katrina had a devastating impact on the region, and the threat of future disaster poses a serious challenge to rebuilding efforts in New Orleans. Proper protection responding to an accurate understanding of risk is vital to the viability of urban centers on the Gulf Coast. Our proposed coupled dynamics method is based on aggregating the interior flood depths from a large suite of storms, whereas the surge surface method represents the interior flood depths resulting from aggregation of surge exceedances on the system exterior. It should be clear then that the coupled dynamics method is conceptually preferred, since aggregated exterior surge does not represent a plausible real-world event. The CLARA model demonstrates that contemporary computing power is sufficient to meet the method's greater computational demands.

Differences in estimates of flood depth exceedances between LACPR's surge surface methodology and the coupled dynamics approach reveal that the newly upgraded HSDRRS may not provide the level of risk reduction anticipated by its designers. It was designed using an operational definition of interior exceedances driven by exterior surge exceedances rather than flood depths from storms that could occur in nature. This has serious implications on levee design. The current levee design paradigm has the advantage of setting the levee height at a

given point solely as a function of surge exceedances at that point. This allows upgrades or extensions of a system to be designed without having to account for the messy geospatial relationships that define drainage behavior on a system's interior.

However, the interior is precisely what the system is designed to protect. Understanding how a proposed project will impact risk must be part of the design process, not an *a posteriori* analysis. Protection systems should not be designed based solely on estimates of surge exceedances along the boundaries. Plans should also incorporate more holistic knowledge of the likelihood of various storm tracks and other features of the local topology. The coupled dynamics method described here provides that capability.

In instances where the surge surface method underestimates a particular flood depth exceedance, an area faces greater actual risk than predicted. System designs based on this method would underperform and fail to meet expectations for risk reduction. On the contrary, when the surge surface method overestimates hazard, it could lead to overbuilt systems that provide greater risk reduction but at a potentially much greater cost.

In a resource- and politically-constrained world, this may result in reduced efficiency by achieving targets for risk mitigation in a suboptimal manner with respect to cost effectiveness. Even small errors in the flood depth exceedances produced by the surge surface method have significant impact on projections of damage. When modeling the benefits of proposed upgrades or new protection systems, these discrepancies would propagate to estimates of cost-benefit ratios or other cost effectiveness metrics. This could potentially lead to approval of projects with no actual net benefit or misappropriation of funds to projects that are less beneficial than others.

Accurate estimates of flood risk in vulnerable areas are crucial to future development and planning to prevent future catastrophes such as that experienced by New Orleans in 2005. Any inaccuracies only further confound the uncertainty introduced by sea level rise, land subsidence, and changes in hurricane patterns.

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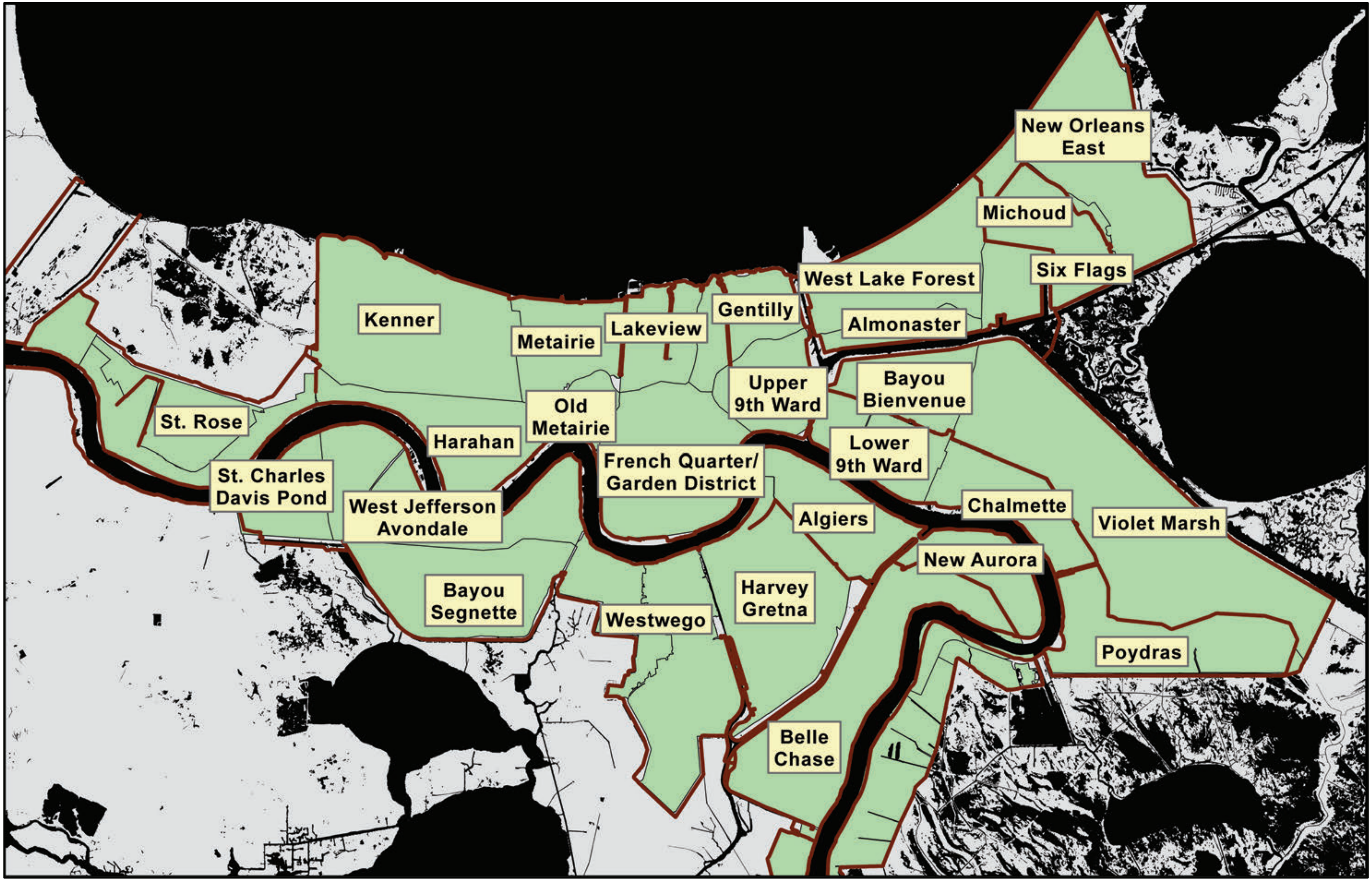
Appendix A: Map of Greater New Orleans



Appendix B: Frequency distribution of 100-year (1% AEP) flood elevations with simulated fragility

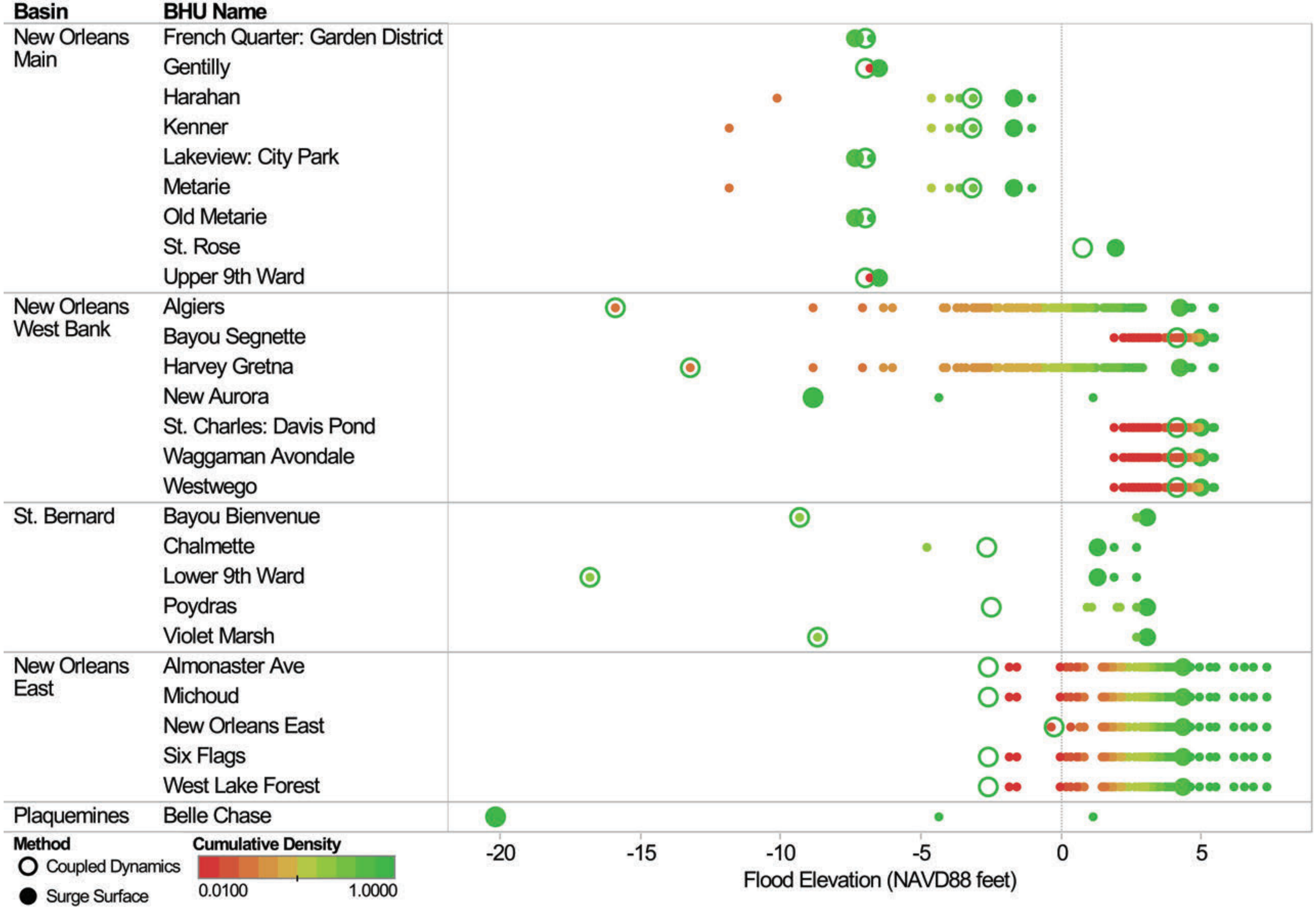


Figure B-1: Frequency distribution of 100-year (1% AEP) flood elevations with simulated fragility (2061, less optimistic scenario, 50% pumping)

Appendix C: Frequency distribution of 500-year (0.2% AEP) flood elevations with simulated fragility

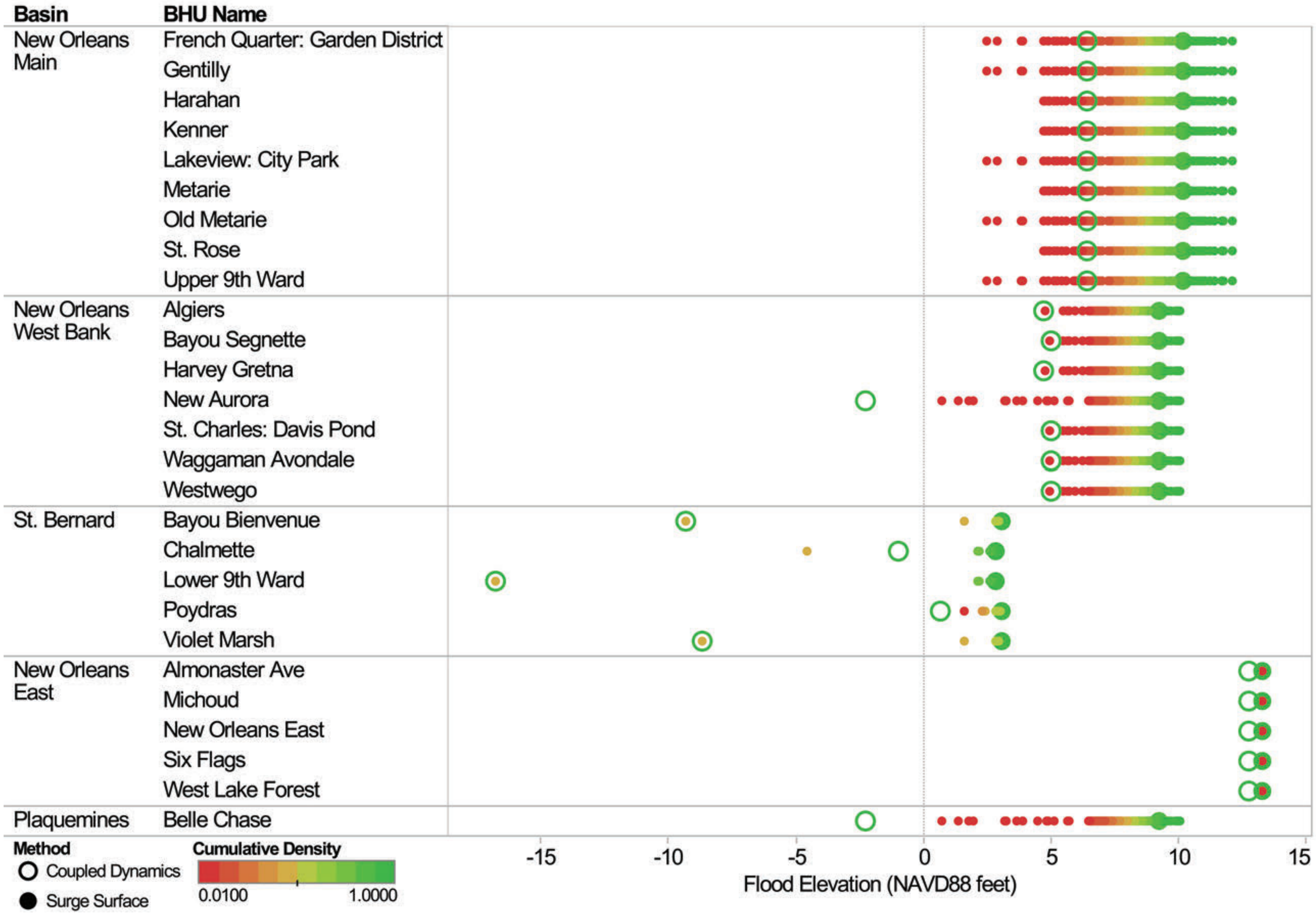


Figure C-1: Frequency distribution of 500-year (0.2% AEP) flood elevations with simulated fragility (2061, less optimistic scenario, 50% pumping)

Estimating Surge-Based Flood Risk with the Coastal Louisiana Risk Assessment Model

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ABSTRACT

The Coastal Louisiana Risk Assessment model (CLARA) was designed to facilitate comparisons of current and future flood risk under a variety of protection system configurations in a wide range of environmental, operational and economic uncertainties. It builds on previous studies of coastal risk by incorporating system fragility and a larger number of future scenarios than previously analyzed. Flood depths and direct economic damage from a wide range of simulated storm events are aggregated to produce a statistical summary of coastal risk under different assumptions about future conditions. CLARA's estimates of project-level effects on flood risk reduction were used as one of the key decision drivers in selecting the risk reduction projects included in the Master Plan. Depending on the scenario, the final alternative is projected to reduce expected annual damage by approximately 60-80% over the next 50 years relative to a future without action and, at the same time, balance other decision criteria.

INTRODUCTION[3]

The specter of catastrophic flooding—the recent memories of hurricanes Katrina, Rita, Gustav, Ike, and Isaac, as well as the inevitability of future storms—threatens the sustainability of Louisiana's vibrant coastal communities and heritage. Louisiana's 2012 Comprehensive Master Plan for a Sustainable Coast is the state's most ambitious proposal to date to address the long-term risk of flooding in both urban and rural areas.

Reduction of future flood risk was one of the two primary decision criteria that drove the selection of the Master Plan's suite of protection and restoration measures (along with prevention of land loss). The Coastal Louisiana Risk Assessment model (CLARA) was developed to meet the planning needs of the Master Plan by flexibly evaluating flood risk over the next fifty years under numerous protection system configurations and a wide range of future environmental and economic uncertainties.

Purpose of CLARA

CLARA estimates the flood depths resulting from a variety of possible storms, models the associated direct economic damage, and aggregates results from a large set of storms to produce a statistical summary of coastal risk under different assumptions about future conditions.

[3] This paper is adapted largely from the technical documentation and results of the Risk Assessment team provided in Appendix D-25 to the Master Plan and in Fischbach, et al. (2012). At various points, the reader is directed to consult these sources for more technical details.

Master Plan Context

CLARA was used to compare the risk reduction benefits of 34 potential structural protection projects and 116 candidate nonstructural protection projects under consideration for inclusion in the Master Plan. The individual project effects estimated by CLARA were used as one input among many, including expert judgment on project synergies and thousands of public comments, to the Planning Tool to select the final set of 109 protection and restoration projects included in the Plan. This paper provides a general overview of model mechanics and discusses the impact of the final Master Plan alternative on flood depths and damage, relative to the Future Without Action (FWOA) conditions. More detail is provided in the other articles in the Journal of Coastal Research's special issue on how the Planning Tool compared the cost-effectiveness of flood risk reduction projects to the impacts of restoration projects on land loss and on other ecosystem services to produce the final plan.

Previous Assessments of Risk in Coastal Louisiana

The CLARA model builds on other recent efforts to examine the risk of flooding to coastal Louisiana. With a series of reports published from 2006 to 2009, the Interagency Performance Evaluation Task Force (IPET) study examined flood risk to the Greater New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS) (Interagency Performance Evaluation Taskforce, 2006, 2009b). Intended to assess improvements in the HSDRRS made in response to the failures during Hurricane Katrina, it modeled three system configurations: as the HSDRRS looked in 2005 just before Katrina, as it existed in June 2007 after initial repairs and upgrades were completed, and as it was projected to look in 2011 after a more comprehensive set of upgrades. With the charter to examine a small set of past and current conditions, IPET devoted a large amount of resources to creating a complex event-chain model of system failure to estimate the likelihood of breaches like those that occurred during Katrina and to understand what other failures might be most likely to have catastrophic consequences.

The Louisiana Coastal Protection and Restoration (LACPR) study, published in 2009, expanded on the scope of IPET by investigating risk coastwide over time from 2010 to 2060 (U.S. Army Corps of Engineers, 2009a). Their model, like CLARA, was used for planning purposes to evaluate multiple options for structural risk reduction. LACPR analyzed uncertainty through scenario analysis by considering a maintained and a degraded future landscape, as well as compact and dispersed scenarios of future urban development. Modeling a larger set of scenarios and system configurations required a simpler risk model that did not account for the possibility of system failure.

CLARA seeks to combine the strengths of its predecessors. Leveraging recent advances in computing power and understanding of storm dynamics, we have developed a model that

flexibly estimates flood risk under a wider range of future environmental uncertainties and system configurations than those considered by LACPR. It also retains the ability to model the probabilities and consequences of system failures using a simplified breaching model sufficient for the comparative planning demands of the Master Plan.

MODEL DESCRIPTION

Risk Framework and Theory

CLARA was designed with standard principles of risk analysis in mind, wherein the risk associated with a particular event is defined as the product of the probability of said event occurring and its *consequences* as measured by a given metric.

Protection systems are designed to block or reroute storm surge away from the valued assets they protect, but even well-engineered systems may fail under excess stress. Uncertainty about system performance leads to uncertainty about the flood depths that a given storm would produce on the interior of a protected area. As such, we further divide the probability of flooding from storms into two parts. The first is *threat* or *hazard*, the probability of a storm with any given set of characteristics occurring. The second is *vulnerability*, the probability of the storm causing any particular level of flooding, as dictated by the performance of pumps, gates, levees, and other elements of the system. In the context of flood risk, we are interested in estimating *consequences* as the direct economic damage from tropical storm events that produce specified levels of flooding. This three-part formulation of flood risk—threat, vulnerability and consequences—comes from the risk literature and has been adopted by previous studies of coastal flooding (Morgan and Henrion, 1990; U.S. Army Corps of Engineers, 2009a; Fischbach, 2010).

Specifically, threat is defined as the probability of an event of interest occurring; for the Master Plan, we were interested in the hazard of a tropical hurricane rated Category 3 or higher when nearing landfall along the Louisiana coastline. The probability of such a storm is estimated using an approach, described later, adapted from the Joint Probability Method with Optimal Sampling (JPM-OS) (Toro et al., 2010). The overall frequency of storms of interest is estimated separately for each degree of longitude along the coast based on historical observation.

Vulnerability describes the probability distribution of flooding that results from a particular storm. In an ideal world where protection systems cannot fail and always operate in an optimal fashion (*i.e.*, gates are always closed when appropriate), CLARA models the interior flood depths that result from overtopping and rainfall deterministically; flood levels associated with any particular storm are certain. When considering the possibility of system failures, however, the resulting flood depths are modeled probabilistically using Monte Carlo simulation.

The consequences of a storm event are defined as the direct economic losses caused by storm surge-based flooding (including the impact of waves and rain). For this analysis, we define this as not only the repair/replacement costs of damaged structures and their contents, but also categories like lost rents, wages, and disruption costs that occur during the reconstruction period. Damage is modeled deterministically for any given level of flooding. For the purposes of CLARA and the Master Plan, other consequences such as loss of life or indirect spillover effects are not considered; flood risk as used here refers only to the risk of direct economic losses from storm surge-based flooding.

Mathematically, the risk from any particular depth of flooding d_f associated with a storm event S can be expressed as

$$Flood\ Risk = \Pr(S) \times \Pr\left(D_f = d_f \middle| S\right) \times L\left(d_f\right)$$

where $L\left(d_f\right)$ represents the estimated damage as a function of flood depth. To estimate flood depth exceedances, we aggregate over the space of all Category 3 and greater hurricanes, empirically building a cumulative distribution function (CDF) that describes the probability of flooding being less than or equal to a particular level D_f:

$$F\left(D_f\right) = \Pr\left(d_f \leq D_f\right) = \left(\int_S \int_{d_f \leq D_f} f_S(S)\, f_{D_f|S}\left(d_f \middle| S\right) dd_f\, dS\right)^{\alpha}$$

The 100-year flood depth exceedance is the depth of flooding that has a one percent chance of occurring or being exceeded in any given year. The double integral above describes the probability of flooding conditional on a storm occurring; exponentiating by α, the overall mean frequency of Category 3 or greater storms making landfall in the region of interest (expressed as the expected number of storms per year per degree of longitude), converts the probability from a per-storm basis to a per-year basis, under the assumption that each storm is an independent event. This also assumes that $\alpha \ll 1$, such that the probability of seeing two or more storms per degree of longitude in a single year is negligible; based on the historical record of storms observed in the region of interest before JPM-OS's development, the baseline frequency used by CLARA is $\alpha \approx 0.052$. Generally, then, the n-year flood depth exceedance is defined as $D_n = F^{-1}(1 - 1/n)$, the flood depth D_n that satisfies $F(D_n) = 1 - 1/n$.

Because damage is modeled as a deterministic and increasing function of flood depth, the corresponding n-year damage exceedance is simply $L(D_n)$.

Overview of CLARA

Scope and Units of Analysis

The geographic region encompassed by the CLARA model consists of 35,556 census blocks (as defined by the 2000 U.S. Census) spanning the coastal region of Louisiana, extending northward to boundaries roughly defined by interstate highways 10 and 12. This region represents the extent of the 1,000-year floodplain estimated by LACPR.

Each census block is mapped to one of approximately 1,000 subunits referred to as Basic Hydrologic Units (BHUs). These correspond to the subunits used as the spatial unit of analysis by LACPR, except in the Greater New Orleans area where CLARA adopts the higher-fidelity sub-polders defined by IPET. Standing flood elevations in *protected* areas—regions interior to a protection system that fully encloses the region in a ring—or *semiprotected* areas—regions protected by levees or floodwalls that do not completely enclose the area—are calculated at the BHU level. Flood elevations for each BHU are then converted to flood depths at the census-block level by subtracting the mean elevations of each block within a BHU from the BHU's flood elevation; the model assumes that no flooding occurs in a block if this result is less than or equal to zero. In *unprotected* areas lacking any constructed barriers to flooding, flood elevations are calculated directly at the census block level.

Economic damage is calculated at the census block level and aggregated to a set of 56 *target communities* defined by CPRA.

For the Master Plan, CLARA calculated risk results for the study region as it now exists under the current 2012 conditions, as well as under various projected scenarios 25 and 50 years in the future, in 2036 and 2061.

Model Organization

CLARA is subdivided into a series of submodules that can be grouped into the structure shown by Figure 1. Loosely, the input preprocessing module is related to the calculation of threat. It defines the set of synthetic storms that are run through the rest of the model and generates surge and wave characteristics for each synthetic storm at thousands of spatial points required by the flood depth module. It also estimates the rainfall volumes produced by each synthetic storm at the BHU level, since rainwater also contributes to the flood hazard.

Vulnerability is handled in the flood depth module. For protected BHUs, this module determines the standing flood elevations that result from each synthetic storm generated by the preprocessing. The overtopping submodule calculates the volume of water entering a protected BHU from storm surge and waves that crest the top of the protection system elements. The

system fragility submodule estimates the probability and consequences of failures that may occur as a function of surge elevations and system characteristics like levee heights, floodwall geometry, and fill type. The interior drainage submodule then distributes the flood volumes throughout the protected BHUs using a simplified drainage model to determine the resulting standing flood elevations once equilibrium is reached.

The consequences of flooding are then processed by the economic module. First, the assets at risk—the number of structures and vehicles, miles of roads, *etc*.—must be calculated for current conditions and future growth scenarios in the asset inventory submodule. We then estimate the value of assets at risk using methods derived from the Federal Emergency Management Agency (FEMA) Hazus-Multi-Hazard (MH) model and data from Hazus-MH, LACPR, and other sources (Calthorpe Associates and U.S. Army Corps of Engineers, 2008; Federal Emergency Management Agency, 2005, 2009b; U.S. Army Corps of Engineers, 2009a, 2011; U.S. Census Bureau, 2011, 2010; U.S. Department of Agriculture, 2012). Finally, the direct economic damage is calculated as a function of flood depth. This is done specifically at the 50-, 100-, and 500-year flood depths to produce estimates of the 50-, 100-, and 500-year damage exceedances. However, damage is also modeled over the full range of possible flood depths to calculate the expected annual damage (EAD) that a target community is projected to bear in a given year.

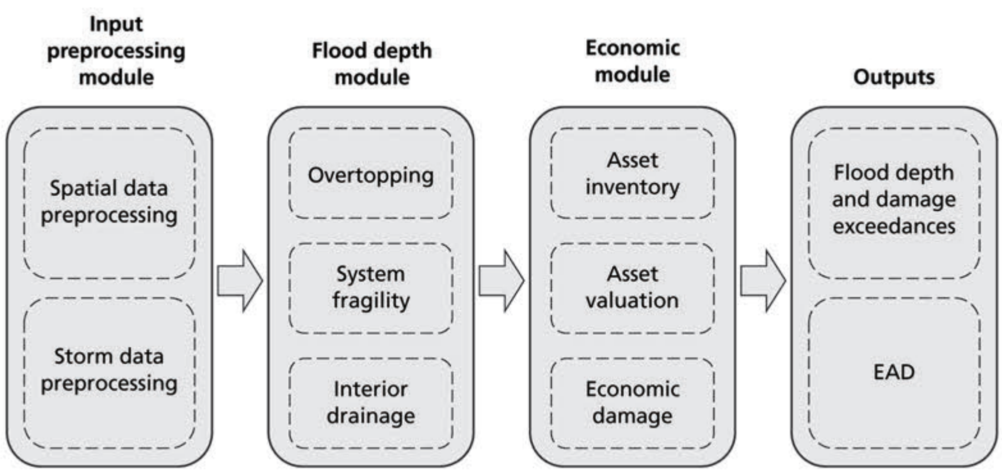

Figure 1: Coastal Louisiana Risk Assessment model structure and primary submodules

Input Data

CLARA integrates a large amount of data from previous models of Louisiana flood risk such as LACPR, IPET and Hazus-MH, as well as data provided by CPRA, the 2010 U.S. Census, and other sources. The data types and sources used by each module are summarized in Tables 1 and 2 and described in more detail in later sections. Precedence is generally given to more recent or Louisiana-specific data; where multiple sources existed, this ordering is provided below.

Table 1: Input data for preprocessing and flood depth modules

Data Element	Source
Surge hydrographs	Storm Surge/Wave Model
Wave period	Storm Surge/Wave Model
Significant wave height	Storm Surge/Wave Model
DEM of Louisiana	U.S. Geological Survey (USGS); Wetland Morphology Model
Wave free crest height	Storm Surge/Wave Model
Foreshore armor of protection structures	State of Louisiana/USACE
Presence of floodwall	State of Louisiana/USACE
Floodwall geometry	State of Louisiana/USACE
Length of protection structure's foreshore	State of Louisiana/USACE
Geotechnical data regarding protection system	State of Louisiana/USACE
Pumping rates for each BHU	Sewerage and Water Board of New Orleans; USACE MS Valley, New Orleans District
Rainfall	Storm Surge/Wave Model

Note: The foreshore is the part of the levee exposed to the water that lies between average low tide and average high tide.

Estimating Threat of Individual Storms

Estimation of threat—the probability that a particular storm event occurs—can be split into two separate tasks in the context of estimating risk from hurricane-based flooding. The first task is to identify a set of storm events that adequately spans the range of possible surge, and consequent flooding, responses over the entirety of the Louisiana coastline. Once a storm set has been selected, the second task is to assign probability weights to each storm in the set based on their relative likelihoods of occurrence.

Storm Selection

Approaches to the first problem, storm selection, have evolved significantly in recent years with the advent of greater computing power and better understanding of how surge generally responds to variations in different storm parameters. Levees in the 1960s were designed in response to a model of a single, relatively extreme Standard Project Hurricane. Estimates of flood risk gradually incorporated more data from the historical record to develop parametric and nonparametric estimates of surge response. However, those approaches, such as the Empirical Simulation Technique (EST), produced uncertain results because of the relatively small sample of historic events; estimates produced by EST are highly sensitive to the addition of new data—for example, the addition of hurricanes Katrina, Rita, Ike and Isaac from 2005-12 for coastal Louisiana (Resio, Irish and Cialone, 2009). Further, since the frequency and distribution of storm characteristics may be nonstationary, there is no reason to expect methods based on historical observation to be stable over time (Bender et al., 2010; Hill and Lackmann, 2011).

Table 2: Input data for economic module

Subset	Data Element	Asset Class(es)	Source (by precedence)
Inventory	Number of structures	All residential classes	GNOCDC, ACS, LACPR, Hazus
	Number of structures	All nonresidential, structural classes	LACPR, Hazus, U.S. Census
	Acreage of agricultural crops	Agricultural crops	LACPR, NASS, LSU AgCenter
	Number of vehicles	Vehicles	ACS, LACPR
	Inventory of roads and bridges	Infrastructure	LACPR
	Square footage	All structural classes	LACPR, Hazus
Valuation	Structural characteristics	All structural classes	Hazus
	Replacement cost per sqft	All structural classes	Hazus
	Proportion of structures by construction class	All residential classes	Hazus
	CSVR	All structural classes	LACPR
	Value of inventory per sqft	Commercial, industrial	Hazus
	Repair costs per mile	Infrastructure	LACPR, Hazus
	Agriculture valuations	Agricultural crops	LACPR
	Proportion of structures by construction method	All structural classes	Hazus
Damage	Structural elevation above grade	All structural classes	LACPR, Road Home, HMGP
	Depth-restoration time curve	All structural classes	Hazus
	Depth-damage curves for structure	All structural classes	Hazus
	Depth-damage curves for contents	All structural classes	Hazus
	Depth-damage curves for inventory	Commercial, industrial	Hazus
	Lost income, lost wages, lost sales, disruption costs, relocation rental costs	All structural classes	LACPR, Hazus
	Evacuation and subsistence costs	All residential classes	LACPR
	Landscaping repair, debris removal, other cleanup	All structural classes	LACPR

Physics-based computer models now provide the capability to more easily simulate surge response from a wide range of tropical storms. These models have led to the development of methods such as the Joint Probability Method (JPM), which is based on the simulation of hundreds or thousands of storms that span some parameterized space of possible storms by varying characteristics such as central pressure deficit, radius of maximum winds, forward velocity, and landfall location. The Joint Probability Method with Optimal Sampling (JPM-OS) builds on this approach. A fitted "surge response surface" estimates surge as a function of the storm parameters using regression methods, relying on a smaller set of storms whose

characteristics are carefully chosen to span the range of plausible values for each characteristic. The fitted response surface is then paired with a continuous probability distribution function (PDF) over the storm parameters, allowing estimation of the surge probability distribution and exceedances by numerical integration (Irish, Resio and Cialone, 2009; Resio, 2007).

In general, the storm selection problem is to choose a set of simulated storms with parameterized characteristics that, when included in the surge response surface, produces a probability distribution of surge that accurately reflects the true distribution. For the IPET and LACPR analyses, Resio and others developed a set of 304 storms parameterized by central pressure deficit ΔP, radius of maximum winds R_{max}, forward velocity v_f, degree of longitude x, and angle of incidence θ_l at landfall (where landfall is defined as the point where the eye of the storm passes over an idealized Louisiana shoreline at 29.5° N latitude).

Time constraints prevented the Storm Surge/Wave Team from developing additional simulated storms as part of the Master Plan process. For lack of a better benchmark, the surge distributions produced from the full LACPR storm set were used as a standard when selecting the set of 40 storms eventually used in the Master Plan, referred to as the CPRA storm set. The Master Plan objective of analyzing system performance under a wide range of uncertain future scenarios dictated that the full LACPR storm set could not be adopted, so the Master Plan storm selection process became an effort to identify smaller subsets of storms that produce estimates of surge exceedances similar to those produced by the full 304 storms.

Assigning Storm Probabilities

To generate surge exceedances from any subset of m storms, each denoted as S_i for i from 1 to m, we need a discrete PDF that assigns a probability mass $\Pr(S_i) = p_i$ to each storm event. Once these probabilities have been defined, then the n-year surge elevation exceedance E_n at any point is calculated as before, using the discrete form of the CDF; if e_i is the surge elevation from storm S_i, then

$$E_n = F^{-1}(1 - 1/n)$$

where

$$F(E_n) = \Pr(e \leq E_n) = \left(\sum_{e_i \leq E_n} p_i \right)^{\alpha}$$

For a continuous space of possible storms, Resio (2007) provides a probability density function where the likelihood of any storm is given by

$$f(S_i) = \Lambda_1 \cdot \Lambda_2 \cdot \Lambda_3 \cdot \Lambda_4 \cdot \Lambda_5$$

where each Λ_i represents a marginal probability for one of the storm parameters. Intuitively, the likelihood of any storm is modeled as the product of the marginal likelihood, Λ_i, of observing each of its characteristics individually. To account for correlations between some characteristics, the distributions of some parameters are conditioned on the value of others:

$$\Lambda_1 = f_1(\Delta P|x)$$
$$\Lambda_2 = f_2(R_{max}|\Delta P)$$
$$\Lambda_3 = f_3(v_f|\theta_l)$$
$$\Lambda_4 = f_4(\theta_l|x)$$
$$\Lambda_5 = f_5(x)$$

For example, Λ_2 treats R_{max} as a function of central pressure, reflecting the relationship that relatively more intense storms are more likely to be smaller in size.

The marginal distributions given by Resio (2007) are truncated so that each parameter is defined only over a range of plausible values. Central pressure ranges from 960 millibars (mb), the approximate cutoff between Category 2 and Category 3 storms, to a theoretical minimum pressure of 882 mb. R_{max} is defined between 5 and 40 nautical miles (nm); landfall location x from 94° 24' to 88° 30' W degrees longitude; and landfall angle ranging from due west to due east. Forward velocity is restricted to be positive.

Our general strategy is to partition the entire parameter space into cells, where each cell encompasses the characteristics of exactly one storm, referred to as a *synthetic storm*. Any synthetic storm is taken to be representative of all storms with characteristics that fall within the synthetic storm's cell. The probability mass assigned to each synthetic storm is found by integrating the continuous joint PDF described above over the domain of its cell.

We divide the parameter space into a grid of 2,160 synthetic storms, composed of a full factorial of 10 storm tracks, 3 landfall angles (the mean angle for each landfall location as reported by Resio (2007), and $\pm 45°$ from the mean), 9 values for central pressure, and 8 values for R_{max}. Surge estimates for the synthetic storms are predicted by linear interpolation over central pressure and R_{max} of storms in a candidate storm set; predictions are performed separately for each combination of landfall track and angle. The number of scenarios, protection project alignments, and time periods modeled constrained the number of storms that could be run, so we only considered storms with a forward velocity of 11 knots (the central value modeled by LACPR); variations in forward velocity account for less variation in the storm surge response than do the other storm parameters (Resio, 2007).

The CPRA Storm Set

To select the CPRA storm set, we evaluated 449 sample points along the coast where surge elevations were modeled by LACPR for each of the 304 LACPR storms. At each point, we calculated 50-, 100-, and 500-year surge exceedances for 46 candidate storm sets, ranging from 8 to 77 storms.

The exceedances generated by this procedure for each candidate storm set were compared to exceedances generated by the set of all storms in the LACPR storm set with a forward velocity of 11 knots (154 of the 304 storms). The sum of squared errors across all points and recurrence intervals was used a metric for comparison between candidate storm sets. Promising candidates balanced low bias with a relatively small number of storms. The selected CPRA storm set that best balanced this tradeoff contained 40 storms, four each making landfall at 10 locations at the mean landfall angle of incidence. On a given track, the four storms vary by central pressure and radius; two storms have central pressures of 930 mb and two have 900 mb, with a radius to maximum wind speed of 17.7 and 25.8 nm for the 930-mb storms and 14.9 and 21.8 nm for the 900-mb storms.

This set produced a bias of less than 0.46 m (1.5 ft) at nearly every geographic point evaluated; a handful of points where more extreme bias ranging from -0.61 to 1.52 m (-2 to 5 ft) was observed were found to be points with abnormal topology or points where few storms produced surge, resulting in a small sample for estimation. For more details and analysis of the storm selection process, see Fischbach, et al. (2012).

Estimating Synthetic Storm Characteristics

Because the final CPRA storm set does not vary by landfall angle, the mean-angle storms are taken as representative of storms with otherwise identical characteristics at the off-angles. This reduces the number of synthetic storms in the synthetic storm set by a factor of 3; from this point on, any mention of the synthetic storm set refers to a set of 720 synthetic storms rather than the 2,160 defined in the above subsection. All analysis was based on running the model with 720 synthetic storms whose surge and wave characteristics are based on application of a response surface to results from the CPRA 40-storm set.

The CPRA storm set thus varies only by landfall location x, R_{max}, and ΔP. The forward velocity v_f and landfall angle θ_l are reduced to discrete random variables equal to 11 knots and the mean angle (as a function of landfall longitude), respectively, with probability 1. This simplifies the likelihood of any individual storm occurring to be $f(S_i) = \Lambda_1 \cdot \Lambda_2 \cdot \Lambda_5$.

With the storm set chosen and parameter space for the synthetic storm characteristics defined, we can fully define each synthetic storm event. For each storm in the CPRA set, the

Storm Surge/Wave Team provided peak significant wave heights (the mean height, from crest to trough, of the largest third of waves), average wave period, and surge hydrographs (surge elevation at 15-minute intervals for the 4-day period after landfall). The latter two quantities are used at points along the exterior of protected areas when calculating how much water enters the interior via overtopping and system breaches.

For each landfall track, the peak surge response from a synthetic storm is predicted as a linear function of R_{max} and ΔP using an ordinary least squares (OLS) regression fit on the CPRA storms from the same track. Synthetic storm wave heights and periods at any given point are fit as a function of the predicted peak surge and the point's distance from landfall using a natural spline with two knots. Several models were tested, including least squares and other spline fits, with and without the distance from landfall as a covariate. The chosen model performed best, both in terms of r^2 statistic (achieving values greater than 0.90 at the great majority of sample points) and in predictive performance when using 10-fold cross-validation using the 2009 LACPR storm data as a test set.

Synthetic surge hydrographs are estimated at points 200 m offshore from protection system elements, measured perpendicular to the orientation of the protection system. Points are spaced evenly at 300 m intervals along the system, with additional points placed at corners and at transitions between elements such as levees, floodwalls, or gates. In narrow spaces less than 200 m wide, such as outfall canals, the sample points are placed in the middle of the unprotected channel. The offshore points are referred to as *Surge/Wave Points* (SWP), and the points along the protection structures that correspond with each SWP are referred to as *reach points*.

Estimation of the surge hydrograph at each geographic point follows the approach described in more detail, including comments on the goodness of fit, by U.S. Army Corps of Engineers (2009a). The top 30% of surge values in the hydrograph for each CPRA storm (the period in which overtopping is most likely to occur) are fit to an idealized, two-sided bell curve. A normal distribution is fit to each half of the hydrograph by estimating a separate standard deviation σ_l for the left-hand side of the curve, representing surge build-up, and σ_r for the right-hand side, representing surge draw-down.

σ_l and σ_r are then estimated for each SWP as a function of peak surge by fitting a log-linear OLS regression model on the peak surge from each CPRA storm. These deviations are paired with the estimated peak surge for a given synthetic storm and used to generate the synthetic surge hydrograph.

Rainfall is calculated in protected areas using a two-step regression model based on the methods used by IPET (Chen, Knaff and Marks, 2006; Lonfat, Marks and Chen, 2004). Rain

volumes in any protected BHU are estimated as a function of storm characteristics as well as the orientation and distance of the BHU relative to the storm track. Details are provided in Fischbach, et al. (2012). A maximum rainfall for any storm of 16.5 cm (6.5 in) was adopted, corresponding to the 6-hour, 10-year rainfall event (U.S. Army Corps of Engineers, 2009a).

Estimating Vulnerability in Unprotected and Semiprotected Areas

Vulnerability is defined as the probability distribution of flooding associated with a particular storm event. Aggregating the flood depths resulting from each synthetic storm, we can then calculate flood depth exceedances as described in the "Risk Framework and Theory" section.

In unprotected and semiprotected areas, CLARA estimates the still-water flood elevation from a storm as being equal to the surge elevation. The flood depth relevant to calculating flood damage, however, also incorporates wave heights. The still-water flood elevation is converted to a standing flood depth by subtracting the mean block elevation in unprotected and semiprotected areas. Because of the physics of breaking waves, the predicted significant wave height is constrained to be no greater than 0.78 times the standing flood depth. The depth-limited significant wave height is then converted to a free wave crest height, the average height of waves above the mean surge level, by multiplying by a factor of 0.7 (Federal Emergency Management Agency, 2009b).

For each synthetic storm, the flood depth used when calculating exceedances and damage is the sum of the standing flood depth and the free wave crest height.

Estimating Vulnerability in Protected Areas

Flooding on the interior of protection systems is not directly based on surge and waves but, rather, on the accumulation and distribution of water entering the system *via* overtopping, breaches, and rainfall, minus any volumes removed from the system by pumping.

CLARA divides the task of estimating interior flood depths into three main submodules as depicted in Figure 1. The *overtopping module* combines surge and wave data on the exterior of a protection system with characteristics of the system such as crest heights, levee geometry and armoring to calculate the volume of water overtopping the protection elements. The *fragility module* estimates the probability of system elements failing because of the accumulated pressure of rising surge and pounding waves. It also runs a stochastic Monte Carlo simulation of system breaches and determines the consequences of each point of failure on interior flooding. The *interior drainage module* distributes flood volumes throughout each BHU that comprises the protected area to produce the final standing-water flood elevations on the system interior.

Calculating Surge and Wave Overtopping

During a storm, overtopping can operate through two mechanisms, depending on the height of storm surge and waves relative to the crest heights of levees, floodwalls, and other protection system elements. In one case, surge levels below the crown height of the protection structure, coupled with waves, produce a regime where overtopping only happens when waves break over the top of flood barriers. With higher surge levels, surge may flow over the structures and pour directly into the interior. As surge rises and falls over the course of a storm event, one or both of these regimes may occur. We use two-dimensional weir equations to calculate overtopping rates at each reach point in terms of volume of water per time per linear distance along the protection structure. These volumes are summed over the length of each reach and each period of the surge hydrograph to tally the overtopping water entering each BHU of the protected region over the course of the entire storm event.

In some instances, equations are presented in a simplified or reduced form based on parameter value assumptions or application of a general equation to the specific case of levee and floodwall geometry. At transition structures, such as gates, we approximated the two-dimensional overtopping rates by calculating them as if they had the same geometry as adjacent protection features. We also followed LACPR's simplifying assumption that surge and waves approach structures head-on.

Wave Overtopping

When only wave crests reach over the top of a protection structure, we use the approaches described by van der Meer (2002) and Franco and Franco (1999) to calculate overtopping rates. Because wave data are reported by the Storm Surge/Wave Team 200 m from the protection features, we need to convert the reported significant wave height (H_{200}) to the significant wave height at the structure (H_s) by accounting for the possibility of wave run-up and wave breaking as it approaches the structure:

$$H_s = \min\left(H_{200}, \gamma(\eta - z_{toe})\right)$$

where γ is a wave-breaking parameter, assumed to be 0.4 for typical levee and floodwall geometry, η is the surge elevation and z_{toe} is the toe elevation of the protection structure, assumed to be 0, in accordance with LACPR. This is similar conceptually to the depth-limited wave breaking described earlier when calculating flood depths in unprotected and semiprotected areas.

In the case of waves running up against a levee or a levee with a floodwall on top of it, we next calculated the surf similarity parameter ξ_0, which relates the slope of the protection structure to the steepness of the incoming waves. Where the angle at the base of the protection

structure is φ, this slope is $\tan\varphi$; we assumed it equaled 0.25, representing a grade of 4 m of run-up for every 1 m in height at the crest. The surf similarity parameter allowed us to predict how much wave breaking occurs and hence how much kinetic energy is preserved to propel incoming waves over the top of the structure;

$$\xi_0 = \tan\varphi \cdot \sqrt{\frac{gT^2}{2\pi H_s}}$$

where g is standard gravitational acceleration, $9.81\ m/s^2$, and T is the spectral wave period provided by the Storm Surge/Wave Team.

The functional form of the two-dimensional wave overtopping rate q depends on the value of the surf similarity parameter (van der Meer, 2002). If $\xi_0 \leq 5$, then

$$q = \frac{0.47\sqrt{gH_s^3}}{\sqrt{\tan\varphi}}\xi_0 \exp\left(-3.325\frac{R_c}{H_s\xi_0\gamma_v}\right)$$

where $R_c = z_c - \eta$ is the free crest height of the reach (in meters), the difference between the crest elevation of the protection feature and the still-water surge elevation η. In the wave-overtopping-only regime, $z_c > \eta$, so the free crest height is positive. γ_v is an influence parameter describing the influence of having a floodwall placed on top of a levee. If no such configuration is present, this parameter takes a value of 1; where it is present, a value of 0.65 is used.

When $\xi_0 \geq 7$,

$$q = 10^{-0.92}\sqrt{gH_s^3}\exp\left(-\frac{R_c}{H_s(0.33+0.022\xi_0)}\right).$$

In cases in which $5 < \xi_0 < 7$, a linear interpolation on $\log q$ between these two functional forms is used.

When waves are running up against a floodwall that is not paired with a levee, we employed the expressions derived by Franco and Franco (1999):

$$q = 0.082\sqrt{gH_s^3}\exp\left(-\frac{3.614R_c}{H_s}\right).$$

Surge Overtopping

For periods in the hydrograph when surge elevations rise above the crest height of the protection structure, water flows directly and continuously to the interior, as measured by the standard weir equation used by IPET and LACPR:

$$q = C_w(\eta - z_c)^{3/2}.$$

where C_w is a weir coefficient that describes how much the weir geometry aids or hinders flow over its top. CLARA adopts IPET's values of 1.68 $m^{1/2}/s$ for floodwalls, 1.45 $m^{1/2}/s$ for levees, and 1.12 $m^{1/2}/s$ for gates (Interagency Performance Evaluation Taskforce, 2009c).

Combining those values with wave overtopping that also occurs in conjunction with the flow of surge, we get a total overtopping rate of

$$q = C_w(\eta - z_c)^{3/2} + 0.13\sqrt{gH_s^3}.$$

Calculating Interior Drainage in Protected Areas

Initial water volumes were assigned to each BHU by adding overtopping and rain water, net any pumping volume. CLARA's interior drainage module distributes those initial volumes throughout the system, producing a set of equilibrium standing-flood elevations by BHU.

Aside from the use of surge hydrographs in the overtopping module, CLARA makes a number of simplifying assumptions to aggregate all operations into a single time period. All water is distributed throughout a polder simultaneously without use of a complicated routing model and without regard for different rain and overtopping arrival times in separate BHUs that comprise the same system. Pumping stations, designed primarily to prevent flooding from rainfall events, are assumed to operate continuously over the time of nonzero surge at points exterior to a protection system; that serves as an approximation for the time when rain affects the area, allowing a single, total pumping volume to be calculated for the duration of the storm.

Two key sets of input data facilitate the drainage calculations. A matrix of interflow elevations describes the lowest elevation along the boundary between each pair of BHUs, the point at which rising flood waters spill from one BHU into the other, effectively joining them together. Stage-storage curves for each BHU relate volumes of water to the flood elevation that results. These are calculated using a Digital Elevation Model to take cross-sectional slices of the free volume that lies above ground at half-foot intervals from the lowest point in a BHU up to its highest point. Stage-storage curves are also calculated for sets of multiple BHUs that can be joined together through interflow connections.

For a protection system to be in equilibrium, one of the following conditions must be satisfied for all possible pairs of BHUs in the system with an interflow connection:

1. Water elevations in the two BHUs are equal, or

2. If the water elevations are not equal, they must be less than or equal to the interflow elevation joining the BHUs together.

Otherwise, if one or both of the water elevations is above the interflow, water would flow from the higher elevation to the lower.

After converting the initial BHU volumes to an initial set of BHU water elevations disregarding any interflow connections to other BHUs or the system exterior, CLARA successively identifies a series of "pitcher" BHUs that pour water into a set of "cup" BHUs until equilibrium is reached. More specifically, the interior drainage module repeats the following steps:[4]

1. Check the system for imbalances.

    a. If the system is in equilibrium, return the standing flood elevations.
    b. If not in equilibrium, proceed to step 2.

2. Identify the pitcher(s). For efficiency, we look for the imbalance where the higher-elevation BHU has the greatest flood elevation out of all imbalances in the system. This BHU is referred to as the primary pitcher, but all other BHUs connected to the primary pitcher with the same current flood elevation are included in the pour.

3. For every BHU adjoining the set of pitchers, define a *pour elevation* as the greater of the water elevation in that BHU and the minimum interflow elevation connecting it to the pitchers.

4. Identify the primary cup(s) as the BHU(s) adjoining the pitchers with the lowest pour elevation. All other BHUs joined to the primary cup(s) at their current water elevation are also included as cups, because they will be filled indirectly through the join.

5. Balance the pitcher and cup BHUs by pouring flood water from the pitcher(s) into the cup(s). By definition, all pitcher BHUs are at the same water elevation, but that does not have to be true for the cups when more than one cup exists. When that occurs, water pours into all cups at the same rate; some cups may fill up to the pour elevation as a

[4] The algorithm described here was developed subsequent to the main Master Plan analysis. It is functionally equivalent to, but more computationally efficient, than the algorithm that was originally used. See Fischbach, *et al.* (2012) for details of the original algorithm.

result, leaving spare capacity in others.

The pour results in one of two outcomes:

a. If water in the cup is below the interflow connection between pitcher and cup, it is possible that all water in the pitcher can be poured into the cup without filling it to the brim. In this case, the final pitcher elevation is set to the interflow elevation, and the cup elevation is set to that elevation resulting from adding everything subtracted from the pitcher to the cup's previous volume.

b. If water in the cup is already above the interflow, or if the sum of pitcher and cup water would fill both sets above the interflow elevation, then the cup and pitcher are joined at the elevation resulting from both volumes being added together.

In the above algorithm, the system exterior is treated like a BHU with infinite capacity which can only be used as a cup. Interflow elevations to any BHU adjoining the exterior are set to a pour elevation for system features protecting that BHU. The pour elevation from each protected BHU to the exterior is set by taking the maximum of the reach height and surge elevation at each reach point protecting an interior BHU, then taking the minimum of those values. That allows for the possibility that a polder may become so inundated with flooding that water starts to pour back out of the system to the exterior through the lowest point in the protection system.

In some areas, such as the Greater New Orleans HSDRRS, levees or floodwalls divide two interior BHUs from each other. Those features are designed to provide secondary barriers against exterior flooding. When system fragility is not considered, those features are reflected in the interflow elevations between the interior BHUs, but the interior drainage routine operates as normal. When the fragility module is active, the interior drainage algorithm runs once to distribute the initial volumes in the same way as if no failures occurred. The resulting differential flood elevations on each side of the interior levee are then used as inputs to estimate the probability that the interior levee fails. Any resulting failures are treated as full-depth breaches that reduce the interflow elevation between the interior BHUs to the base of the levee, and the drainage routine is run again with the reduced interflow elevation.

Estimating System Fragility and the Consequences of Failure

Breaches that occurred in multiple New Orleans levees and outlet canals during Hurricane Katrina underline the importance of estimating the probability and consequences of system failure. We define failure as the breaching of a protection element by water at an elevation below its crest elevation or, in the case of pumping systems, operation of system elements at less than their rated capacities.

IPET used a very sophisticated event-tree model to simulate a wide variety of stochastic and operational failure mechanisms; that was possible given the smaller number of system configurations and other uncertain scenarios modeled. By contrast, LACPR examined multiple future levee configurations under four future development and landscape scenarios but did not consider the possibility of failure in any case.

The planning philosophy of the Master Plan process was to compare structural project effects over a wide range of uncertainties over multiple time periods. The large number of required model runs dictated that any consideration of system failure would be, by necessity, simpler than the IPET event-chain model. CLARA aimed to achieve a middle ground by implementing a relatively simple model of system fragility which could still be run quickly over many cases.

Probabilistic Failure Modes

Three main failure modes occur as a result of sustained load from rising surge and wave action against the flood barriers:

1. *Overtopping failures* occur when overtopped surge water erodes the protected back side of a structure, reducing its strength and leading to water breaking through to the protected interior.

2. *Seepage failures* occur when water flows through the soil underneath the levee or floodwall. This can exert upward pressure causing internal erosion that may cause rotation or cracks in the protection structure, leading to catastrophic failure.

3. *Slope stability failures* result from excessive pressure exerted by rising surge waters against the slope of a levee, causing it to slip out from under itself.

These failure modes were modeled as a function of surge elevations and the characteristics of the protection system, measured at reach points spaced every 300 m along the system features. Additional points were placed at corners and transition points between different structure types. Internal erosion was dropped from CLARA's list of failure modes after analysis indicated that its probability of occurring was at least an order of magnitude smaller than the other modes.

Failure probabilities are estimated using system characteristics of existing and proposed protection features provided by USACE. Standard engineering calculations, based on the data and methods employed by IPET, produced estimates of seepage and slope stability failures. Overtopping failure was modeled as a function of the height of surge above the reach crests; as a result, that mode typically dominated the others. The technical equations and data used to determine failure probabilities for each mode of failure are found in Fischbach, et al. (2012).

Each failure mode was evaluated independently and aggregated to calculate a "two-dimensional" probability of failure p for a single "characteristic reach" length of 300 m. For reach points that represent smaller reaches, the estimated probability was rescaled accordingly, so that, for any reach of length L (in meters), the "three-dimensional" probability of failure is

$$P_f = 1 - (1 - p)^{L/300}.$$

Gates and other transition features are assumed to have the same two-dimensional probability of failure as the nearest adjacent levee or floodwall on either side.

Each reach is considered independent of other reaches when evaluating failure. CLARA assumes that any breach is full-depth and, in keeping with IPET, that breaches occur at the time of peak surge (and thus maximum load on the system). The model assumes the resulting interior flood elevation rises to the same elevation as the surge that caused the breach. This assumption about the consequences of failure is rather aggressive and likely overstates the resulting flood depths for most storms. The consequent flood depth distributions and exceedances are likely skewed high as well. However, CLARA also evaluates the flood depths resulting from a case where no system failures occur, so the results from those two cases should bracket the actual flood risk. Subsequent versions of CLARA can employ an intermediate failure algorithm that calculates a breach volume resulting from any given point of failure, but that feature was not yet developed or available during Master Plan development.

Using the estimated P_f for each reach, CLARA employs Monte Carlo simulation with 200 iterations to approximate the distribution of failures. For each run of the simulation, the initial flood elevations from the interior drainage module are replaced by the breach elevations in polders where breaches occur, producing a distribution of potential flood elevations associated with any given synthetic storm.

Operational Failure Modes

Aside from system elements that have a probabilistic chance of buckling under excess load, other failures can occur through suboptimal operation of the protection system. This primarily entails leaving gates or spillways open when they are best left closed (or vice versa), or not running pumping stations at full capacity. Pumping systems may be down for maintenance or may simply be overwhelmed in cases with large quantities of overtopping.

Pumping thus has the possibility for operational or probabilistic failure, but lacking good means to assess probabilities or estimate at what point during a storm failure may happen, CLARA treats pumping failures operationally. The model runs each synthetic storm under multiple cases where pumps operate at various levels of output: 100% of rated operational

capacity, 50%, and no pumping. This simple approach does not account for the effect of pump station performance varying geographically, but, like the cases run with and without stochastic system fragility, it provides useful bounds on the risk of flood depth and subsequent damage with and without operational pumping systems.

For lack of a justifiable estimate of the probability that gates might be left open in the event of a storm, CLARA assumes that they will be properly closed before landfall, and thus, the system is subject only to the stochastic modes of failure described above.

Aggregation of Synthetic Storm Flood Distributions

Output from the flood depth module consists of a probability distribution of the potential flood elevations in each protected BHU associated with each of the 720 synthetic storms. Elevations at the BHU level are converted to flood depths at the census block level by subtracting the mean block elevation of each census block from the flood elevation in the BHU to which it belongs. The probability of seeing any particular level of flooding can be combined with the probability masses assigned to each synthetic storm to form an empirical CDF of flooding. Where D_i is the set of flood depths resulting from synthetic storm S_i, the probability of the greatest flooding seen in a given year, d_f, being less than some D_f is

$$F(D_f) = \Pr(d_f \leq D_f) = \left(\sum_{i=1}^{720} \sum_{\substack{d \in D_i, \\ d \leq D_f}} \Pr_S(S_i) \Pr_{D|S}(d|S_i) \right)^{\alpha}.$$

As before, the n-year flood depth exceedance is defined as $D_n = F^{-1}(1 - 1/n)$, the flood depth D_n that satisfies $F(D_n) = 1 - 1/n$. Because we calculated flood depths in protected areas using Monte Carlo simulation, the probability $\Pr_{D|S}(d|S_i)$ was estimated as the frequency in which depth d occurred during the simulation. The resulting flood depths were also implicitly conditional on the scenario and alignment of structural protection projects. The synthetic storm probability $\Pr_S(S_i)$ depends on the characteristics of the storm S_i and the scenario-dependent assumptions about changes in future storm intensity.

This is identical to how exceedances were calculated in unprotected and semiprotected areas, or in the case where no fragility is considered; in those instances, each synthetic storm simply produces a single flood depth at each point with probability 1.

Estimating the Consequences of Flooding

Flood risk reduction is one of the two primary decision drivers guiding the development of the Master Plan, as measured not by a reduction in the likelihood of flooding, but instead by the expected annual damage (EAD) from flooding. Reducing the risk of flooding to an unpopulated area with no economic assets is of low priority, so EAD provides a singular metric describing the value of how much flood risk reduction a project achieves (Peyronnin et al., 2013). A baseline level of damage is calculated that corresponds to current conditions, and future damage is calculated for the FWOA and Master Plan alternatives in years 25 and 50 (2036 and 2061).

Damage modeled by CLARA is limited to direct economic losses caused by storm surge-based flooding to properties, their contents and their residents and/or owners. It does include some costs borne during the repair and reconstruction period, such as lost wages and lost rents. It does not, however, include indirect impacts such as regional spillover effects or spikes in oil prices from decreased refining capacity. CLARA also excludes other metrics such as loss of life.

Secondary decision drivers included reduction of damage associated with flooding at the 50-, 100-, and 500-year levels. Each community was assigned a target for provision of flood risk reduction at one of those three levels, and progress toward the goal was measured by the percentage reduction in the targeted damage exceedance with the Master Plan alternative in place, relative to the same FWOA scenario.

The general methods used for estimating damage were adapted from the FEMA Hazus-MH model, version MR4. The economic module splits the estimation into three tasks for a given scenario and year: tallying the projected inventory of assets for each asset class, valuing those assets, and calculating the resulting damage as a function of flood depth. A flow chart illustrating the logic of the economic module can be found in Figure 7.1 of Fischbach, et al. (2012).

Asset Inventory Module

The inventory module is CLARA's model of economic growth. Damage was calculated for the following categories of assets: single-family residences; manufactured homes; small, multifamily residences (*e.g.*, duplex, triplex); large, multifamily residences (*e.g.*, apartment building, condominium complex); commercial facilities; industrial facilities; public facilities; transport infrastructure (*e.g.*, roads, bridges, rail); vehicles; agriculture structures and properties; and agricultural crops.

Baseline Inventories

Asset counts were tracked over time at the census block level, starting with a baseline inventory of residential structures and infrastructure adapted from the LACPR economics database. That dataset was originally sourced from Hazus-MH MR2 (Federal Emergency

Management Agency, 2005) and updated to represent the second quarter of 2005 (pre-Katrina) by Calthorpe Associates (Calthorpe Associates and U.S. Army Corps of Engineers, 2008). Baseline counts for nonresidential structures came from the General Building Stock (GBS) inventory in the FEMA Hazus-MH MR4 model, developed by Dun and Bradstreet (Federal Emergency Management Agency, 2009b).

The original LACPR dataset was adjusted to represent current conditions using additional data from the Greater New Orleans Community Data Center, the 2010 U.S. Census, and the Census Bureau's American Community Survey. The nonresidential baseline was adjusted at the parish level using the Census Bureau's County Business Patterns database. Baselines for vehicles came from census estimates, and commercial license data came from the Louisiana Department of Motor Vehicles. Crop data were compiled at the block level by LACPR.

Scenarios of Future Growth

Future economic growth in coastal Louisiana is highly uncertain, largely because of the still-unknown, long-term rebound from recent hurricanes like Katrina and Rita and the threat of similar events in the future. The Risk Assessment Team developed a set of scenarios portraying economic uncertainty that are applied independently of the environmental uncertainties modeled by other teams. These scenarios were defined using an overall growth rate indicating the average annual growth throughout the entire study region, a dispersion parameter representing future changes in the ratio of urban and rural population, and a participation rate describing the success of nonstructural mitigation measures prescribed by the Master Plan.

Several parishes in the New Orleans area affected by Hurricane Katrina had lower populations in 2009 than they did in early 2005. *Growth rates* have varied greatly over the coastal region, with some areas rebounding strongly and others declining. As such, we set a nominal overall growth rate of 0.67% per year, approximately the average growth rate in the region between 1990 and 2000. Alternate scenarios posit a zero-growth case, in which any gains in one area were balanced by losses in other areas, and a high-end rate of 1.5%, approximately the average growth rate for the coast from 1950 to 2000.

In general, all assets, except transport infrastructure and agricultural assets, were assumed to change proportionally with projected population growth.

The *dispersion parameter* accounts for the possibility that growth may occur differentially between parishes. For simplicity, CLARA assumes that this differentiation would occur primarily between urban and rural areas; perhaps, economic factors or the threat of future storms would drive people more toward better-protected urban centers. The nominal scenario assumed

that the proportion of urban residents remains constant at approximately 81%; alternative scenarios produced a shift of ±5% over the next 50 years.

The *participation rate* in nonstructural mitigation programs, like floodproofing and residential elevation, primarily affects damage calculations, not growth. However, in low-lying census blocks where flood depths are projected to be very large, proposed buyouts and easements reduce the number of structures projected to exist in the future. Those are modeled as voluntary policies, so different participation scenarios described in a later section do produce variation in the asset inventory.

CLARA assumes no induced development effects on asset growth rates based on perceptions of risk reduction in newly protected areas. Current literature on this topic is inconclusive (Burby, 2006; Cordes and Yezer, 1998; Landry and Hindsley, 2006), and further, the long-term effect of induced growth would depend on the order in which projects are implemented. That information was not available during the Master Plan analysis, so for these reasons, induced development was excluded from CLARA's scope.

Asset Valuation Module

Assets were valued according to their expected repair or replacement costs, as an estimate of the actual losses that would occur in the event of storm damage. As such, CLARA assumed that assets damaged by a storm event are actually replaced, so that the estimates of replacement costs are incurred as losses. IPET and LACPR, by contrast, apply depreciation schedules that devalue structural assets as they age. Given the older building stock present in the coastal region (particularly when modeling assets pre-Katrina), that can produce major differences in damage estimates between CLARA and other studies. Note that the term *value* here is in reference to the potential financial impacts of reconstruction or repair efforts, not the depreciated exposure value that might be assigned to structures in a more typical loss estimation context. In practice, flood insurance policies cover replacement costs in some instances and actual cash value reflecting depreciation in others, so actual losses likely fall somewhere between the values that would be predicted by each approach.

Modeling losses equal to replacement costs may produce overestimates of actual losses if reconstruction does not occur, or if reconstructed assets differ substantially from the original structures. On the other hand, estimating costs in this way for individual structures may underestimate the total impact of a catastrophic event if the sudden spike in demand for construction materials and labor causes a corresponding rise in regional prices. Because CLARA does not include a larger macroeconomic component, these sort of scale-based fluctuations are not captured in damage results. Similarly, future estimates of damage implicitly assume that construction costs track inflation.

Depreciated exposure values could underestimate losses to a larger degree, however; exploratory analysis using depreciation tables from Hazus-MH indicated that depreciated values in large areas of the coast would be less than 25% of the modeled replacement costs. Any systematic bias in asset valuation from either method would likely be consistent across the coast and have little effect on the relative comparison of risk reduction impacts between projects (both structural and nonstructural).

Aside from the lack of depreciation, valuation was performed using methodology very similar to other studies, which all draw from Hazus-MH. Average replacement costs were calculated by stratifying across a set of characteristics that varies for different asset types. That categorization was most complex for single-family residences, which are derived on a per-structure basis that accounts for the number of stories, square footage, construction class (economy, average, custom, luxury), presence of a garage, *etc*. Inventories were allocated proportionally among those different characteristics according to street surveys and other block-level data, such as median household income.

Replacement costs for other structural assets were calculated by taking the product of estimates of average replacement costs per square foot, paired with average square footage per structure stratified by GBS code.

Structure contents (physical assets in the structure which are not for sale) were valued by applying a contents-to-structure value ratio (CSVR) that estimated the average value of contents as a proportion of the structure value. This valuation strategy was adopted by LACPR using Louisiana-specific ratios developed from field surveys and expert panels in 1996 and 2006 (Federal Emergency Management Agency, 2009b). Goods for sale are classified as stocked inventory in commercial, industrial and agricultural complexes and were evaluated differently, using a figure for average gross sales or production per square foot of space. Sales lost over the period of repair/reconstruction were estimated separately.

Repair costs for roads, replacement costs for vehicles, and other costs of cleanup, debris removal, and landscaping were all tallied using the same values estimated by LACPR. That effort also used extensive interviews to estimate the cost per day of other direct losses related to displacement and disruption to local economic activity during reconstruction. These categories included lost sales, wages, and rents; relocation costs associated with temporary storage and housing; and evacuation costs.

Economic Damage Module

The damage and losses sustained to each property or structure are dependent on the depth of flooding relative to the structure's foundation. Within a census block, elevation is assumed to be constant, equal to the mean block elevation determined by a Light Detection and Ranging (LIDAR) data set that adjusts the mean elevation to account for culverts and other drainage features in the block. Mean foundation heights are added to the mean block elevation to determine the relative flood depths used by the damage module; these values are based on street surveys performed by LACPR, with separate values for pier and slab foundations. Foundation heights are adjusted for single-family and small multi-family residences mitigated through the Road Home or Hazard Mitigation Grant Programs and for structures projected to receive mitigation through the Master Plan's proposed nonstructural mitigation policies. These structures are assumed to have higher foundations equal to the block's Base Flood Elevation (BFE) plus 0.305 m (1 ft) of additional freeboard.[5]

Damage incurred by a physical asset was calculated as a percentage of its value, and the function relating flood depths to this proportion is called a depth-damage curve. These curves come from Hazus-MH and are derived from actual insurance claims from past flood events in Orleans Parish; separate curves exist by asset class for damage to contents, inventory, and the structure itself.

CLARA only accounts for damage resulting from inundation by surge-based flooding. The policy options under consideration by the Master Plan have little effect on wind damage, so it was not modeled. Computational constraints also dictated that we not estimate losses caused by the possibility of structural collapse from the velocity of incoming surge; expert judgment suggested that velocity-based damage in addition to that caused by inundation would not be consequential enough to impact project selection.

The time required for repairs and/or reconstruction was estimated as a function of the structural damage, using values originating from Hazus-MH. Any building that receives damage greater than 50% of its value is assumed to be demolished and rebuilt, incurring the maximum reconstruction period. The restoration time is combined with the per-day costs of lost sales, lost rents, relocation costs, *etc*., to estimate a total disruption cost for each applicable asset type. These assumptions and costs also come from Hazus-MH and are consistent with the modeling approaches used by LACPR and IPET.

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[5] During the project-level analysis phase, the Risk Assessment Team also modeled nonstructural policies that protected up to BFE plus 1.22 m (4 ft) of freeboard.

Nonstructural Mitigation

In addition to large-scale flood risk reduction and restoration projects, the Master Plan also studied the effect of nonstructural mitigation policies—programs that do not alter flood elevations directly, but are instead designed to protect individual properties from the consequences of flooding. Such policies include elevation of single-family residences, small multi-family structures, and manufactured homes; floodproofing of residential, commercial, and industrial buildings; and acquisition of high-risk, low-lying properties followed by easements against future development.

Elevation raises the home by increasing the height of pier foundations or the thickness of a slab foundation; flooding now must rise by the same amount before an equivalent level of damage occurs. *Floodproofing* directly alters the depth-damage curve itself by eliminating all damage up to the mitigated level of protection. *Acquisitions* directly reduce the number of assets at risk in a community.

Damage Exceedance and Expected Annual Damage Calculations

All damage calculations are performed at the census block level and can then be summed in numerous ways. For the Master Plan, results were aggregated for each of the 56 target communities defined by CPRA.

Because damage was modeled as a deterministic and increasing function of flood depth, damage exceedances are simply the damage resulting from the corresponding flood depth exceedances.

Some projects may provide risk reduction over ranges of flooding that do not correspond to the 50-, 100-, and 500-year levels estimated by CLARA, so it is important to understand how protection systems perform over the entire range of possible storm events they may encounter. Expected annual damage provides a summary metric for that purpose.

In every block, each of the 720 synthetic storms was grouped into bins according to its resulting flood depth. One bin was provided for synthetic storms that produce no flooding at all, and additional bins grouped the flood depths at 1-foot (0.305 m) intervals up to 20 ft (6.10 m). Each bin is assigned a probability by summing the probability masses of every synthetic storm in the group. The flood depth associated with each bin is the mean flood depth of its constituent synthetic storms, weighted by their relative likelihoods.

Binning is done for computational efficiency, to avoid running the economic module for all 720 synthetic storms, many of which produce extremely similar levels of flooding across wide swaths of the coast. Instead, the flood depths for each bin are run through the economic module

to produce a mean damage for the synthetic storms in each bin. The bin probabilities were then used to calculate a weighted average that represents the expected damage from a Category 3 or greater storm. That was then multiplied by the scenario-dependent frequency of such storms to obtain the EAD metric.

APPLICATION OF CLARA TO THE MASTER PLAN

Overview

Because flood risk reduction was one of two primary decision drivers guiding the planning process, CLARA was involved at every stage of the Master Plan's development. In the project-level analysis, the coast was divided into a set of grids, each containing three to seven structural protection projects; each project in a grid was deemed by expert judgment and initial analysis of storm surge not to have an effect on any other in the same grid. Comparison of the *Future With Projects* flood depths and damage to the *Future Without Action* grid with no active projects enabled the Planning Tool to calculate the individual effects of each risk reduction project. The effects of restoration projects on flood risk were not considered in this phase of analysis.

Once the draft and final Master Plan alternatives were selected on the basis of the individual project effects, CLARA was used to evaluate the coastwide risk reduction benefits of having the entire suite of Master Plan projects in place (including both protection and restoration projects). The Master Plan alternative was analyzed 25 and 50 years into the future (2036 and 2061) according to a preliminary schedule of construction times and project sequencing. We focus here on presenting results from the alternative-level analysis, identifying the areas that received the greatest benefits from the Master Plan and discussing how projected benefits vary across the different future scenarios modeled.

Future Without Action

When discussing the benefits of the Master Plan alternative, the FWOA case serves as the baseline. It represents a future in which no protection or restoration projects are put in place beyond those already funded and under construction in 2012. The protection heights of existing systems decline over time because of scenario-dependent land subsidence and sea level rise, but the structural integrity of features was assumed to be maintained.

For the analysis of the final alternative, we modeled the FWOA case under the complete set of uncertain environmental, system, and economic scenarios affecting risk reduction. A full factorial of system and economic uncertainties was run against each of the *moderate*, *moderate with high SLR*, and *less optimistic* landscape scenarios. A summary of those parameters is included in Table 3. This resulted in a total of 654 model runs, when accounting for current conditions, two future time periods, and separate cases for the FWOA and the final Master Plan.

Table 3: Environmental and economic uncertainties used in the analysis of alternatives

Environmental Uncertainty	Moderate Scenario	Moderate with High Sea Level Rise Scenario	Less Optimistic Scenario
Sea Level Rise	0.27 m over 50 years	0.78 m over 50 years	0.45 m over 50 years
Subsidence (varies spatially)	0-19 mm/year	0-19 mm/year	0-25 mm/year
Storm Intensity	+10% of current average intensity	+10% of current average intensity	+20% of current average intensity
Storm Frequency	Current average storm frequency	Current average storm frequency	+5% of current average storm frequency
System Uncertainty	**Nominal Value**	**Values Run for Alternative Analysis**	
System Fragility	Fragility active	With and without fragility active	
Pumping Capacity	100% of rated operational capacity	0%, 50%, and 100% of rated operational capacity	
Economic Uncertainty	**Nominal Value**	**Low Value**	**High Value**
Overall Growth Rate	0.67% annual growth	0% annual growth	1.5% annual growth
Dispersion	81% (same as current conditions)	76%	86%

Final Master Plan

The final Master Plan includes 14 structural protection projects ranging from the creation of a new ring levee in Lafitte and open-ended barriers near Lake Charles, extending the reach of existing systems across wide portions of the coast, and providing further upgrades or lifts in areas like New Orleans, Larose and St. Mary's Parish. Although the final Master Plan provides all coastal parishes with access to funding for nonstructural mitigation measures, results presented here assume nonstructural policies are implemented in 42 of the 56 target communities. Excluded communities are generally in areas with significant structural risk reduction measures, like New Orleans, where additional nonstructural mitigation was found to have less marginal benefit.

Nonstructural measures are designed to protect assets up to the Base Flood Elevation plus 0.30 m (1 ft) of additional freeboard. In blocks where the elevation and structural foundation heights already rise above that standard, no assets were thus assumed to be mitigated. If the risk reduction standard dictated that less than 0.91 m (3 ft) of additional mitigation were needed, floodproofing was applied; elevation was applied for single-family residences, manufactured homes, and small multi-family structures where greater mitigation was called for. Where a block

would require 5.49 or more meters (18 or more feet) of mitigation to reach the risk reduction standard, a voluntary acquisition program with subsequent easements against future development was modeled. The participation rate for residential floodproofing is assumed to be 80%, with a 70% participation rate for the other measures.

Note that elevating up to 5.49 m (18 ft) may raise structures higher into a storm's wind field, so that reductions in flood damage might be balanced, somewhat, by additional wind damage. CLARA does not estimate wind damage, so that difference is not reflected in these results.

Representative Results

Estimates of EAD or flood depth and damage exceedances were not available in time for inclusion in the final Master Plan report (Louisiana Coastal Protection and Restoration Authority, 2012a). Detailed results across the range of scenarios tested are found in the appendix to Fischbach, et al. (2012); results presented here are for cases with 100% pumping capacity, system fragility active, and nominal economic growth assumptions, unless otherwise noted.

Flood Depth Reduction

In the FWOA case, CLARA projected that flood depths coastwide would increase over time, at all exceedance thresholds modeled, as sea levels rise and the landscape subsides. Without maintenance, the HSDRRS fails to provide 100-year protection for most of Greater New Orleans by 2061, resulting in catastrophic flooding. In the less optimistic landscape scenario, the west bank of the system floods even at the 50-year level.

As discussed previously, CLARA's aggressive assumption about the consequences of failure likely overstates flood exceedances when fragility is considered. That could adversely affect estimates of the benefits of nonstructural mitigation measures in protected areas. However, failures appear to dominate the distribution of flooding even at the 50-year level, making it clear that large portions of New Orleans would likely flood at the 100-year level and less, even under more moderate assumptions about breach volumes.

Figure 2 illustrates the coastwide effect of time on the 100-year flood depth exceedance for the FWOA case under the less optimistic scenario. The ring levee around Larose, like the HSDRRS, fails to provide the 100-year protection that it achieves in the current conditions case. Areas like Lake Charles, Houma, and Des Allemands all deteriorate significantly, with the 100-year flood depths increasing by 2.75 m or more (9 ft) in many blocks. The increases in 100-year depths portrayed in Figure 2 are typical of both the pattern and the magnitude of increases seen across all recurrence intervals.

Figure 3 shows the projects included in the Master Plan and their impact on the 100-year flood depths in 2061 relative to the FWOA, also in the less optimistic scenario. The upgrades to the HSDRRS restore protection to New Orleans, even at the 500-year level. The extensive Morganza to the Gulf and Iberia/Vermilion Upland levees provide substantial flood depth reduction of between 1.22 and 3.66 m (4-12 ft) over broad areas of the central coast. In the less optimistic scenario, the Greater Lake Charles levee system provides 500-year protection.

Note that areas in Plaquemines Parish and near Lake Calcasieu also see minor reductions in 100-year flood depths with the Master Plan in place. Though no structural protection projects affect those areas, some of the marsh restoration and river diversion projects are estimated to reduce flood risk in those parts of the coast.

Figure 3 also reveals increased flood depths south of the large new projects caused by surge pileup induced by the placement of new flood barriers. Generally, projects are designed so that any induced surge effects will be in areas that are unpopulated and devoid of any assets that would be affected by the increased vulnerability. In this case, however, the induced surge from the Morganza to the Gulf alignment also spills over into the Larose to Golden Meadow ring levee where it ties in to the northwest corner of that system. That results in increased flood depths of 0.30-0.61 m (1-2 ft) at both the 100- and 500-year levels.

Damage Reduction

The Master Plan's effect on future flood depths is accompanied by corresponding reductions in coastwide damage at all exceedances, as well as reductions in EAD. Those reductions are summarized in Figure 4, which contrasts the damage exceedances associated with FWOA (darker bars) and the final Master Plan (lighter bars) in each time period and Master Plan scenario. The percentages in white represent the proportional reduction in damage achieved by the Master Plan in each case, relative to the FWOA. In general, risk at each interval is approximately cut in half by 2036, with even greater reductions by 2061 once all the structural projects are in place. Figure 5 shows the corresponding reductions in EAD achieved by the Master Plan alternative.

Predictably, damage reduction is concentrated in communities where structural risk reduction projects are located, or where nonstructural mitigation policies are implemented. Some coastal restoration projects do have an effect on flooding—land creation helps to counteract sea level rise and subsidence, and marsh restoration creates vegetation that slows the advance of surge—but the bulk of risk reduction comes from protection projects. Consequently, some communities, such as Mandeville, on the north shore of Lake Pontchartrain (see Figure 3), receive no benefit from structural risk reduction and only modest reductions in EAD of 9% from nonstructural measures compared with the FWOA.

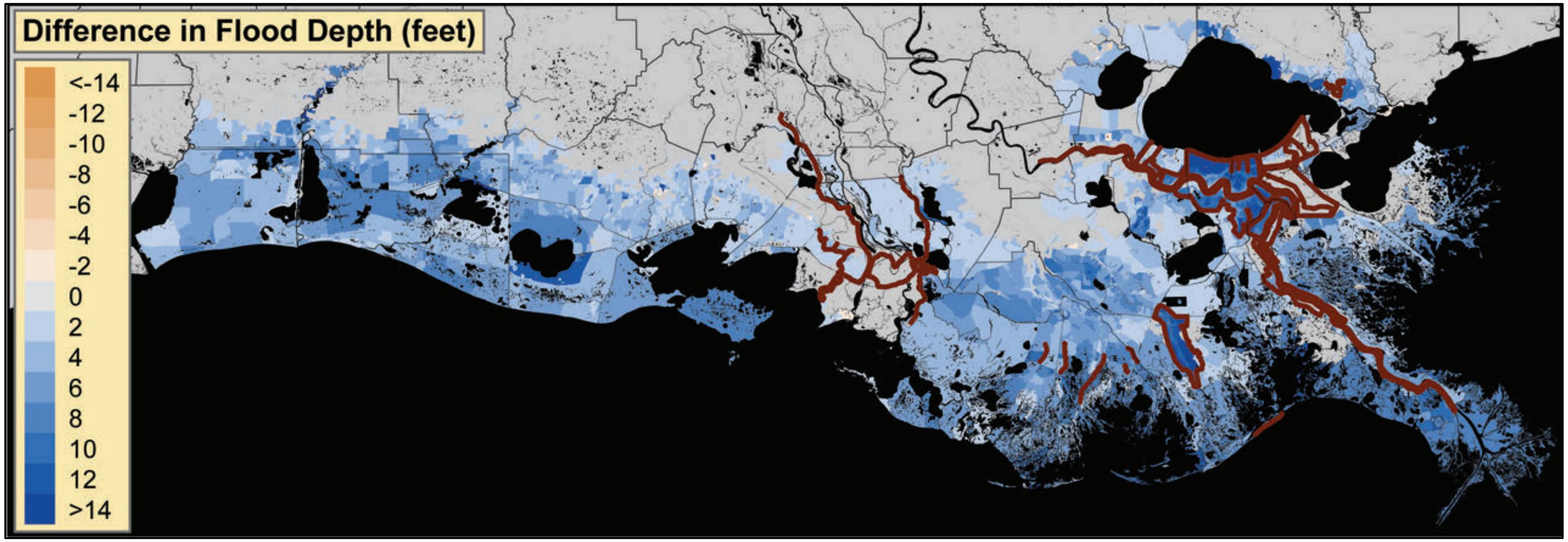

Figure 2: Estimated change in 100-year flood depth, 2012-2061 (Less Optimistic scenario)

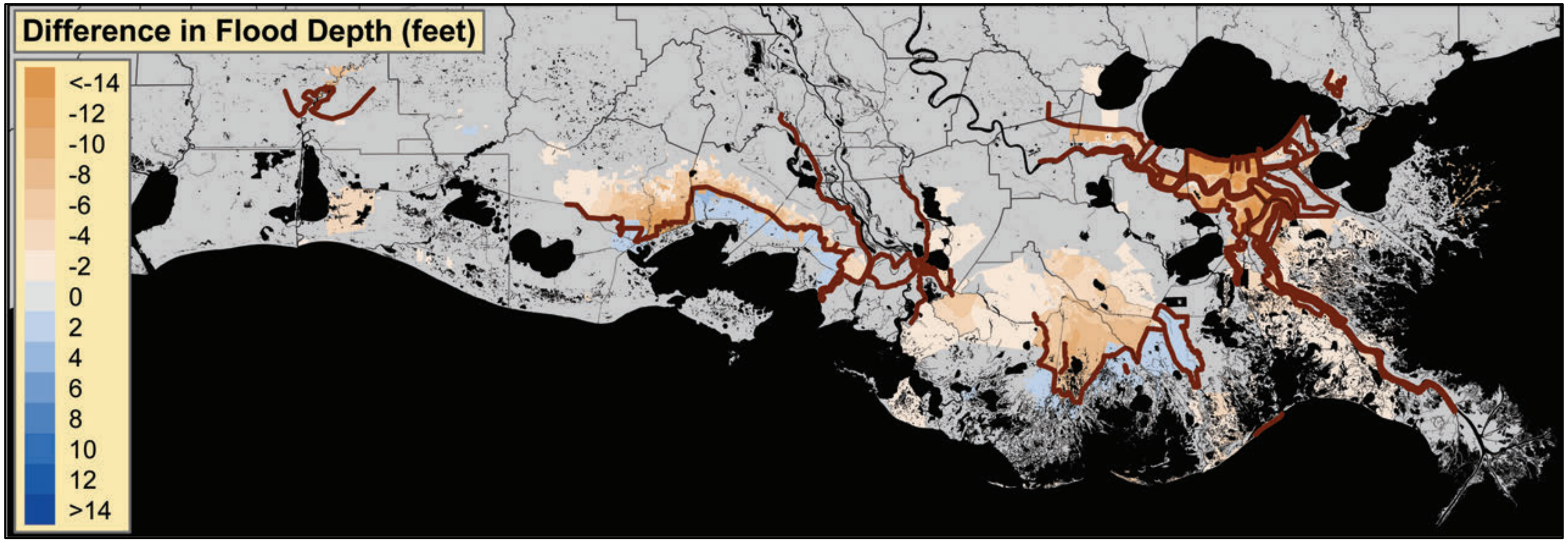

Figure 3: Estimated change in 100-year flood depth in 2061 with the Master Plan in place (Less Optimistic scenario)

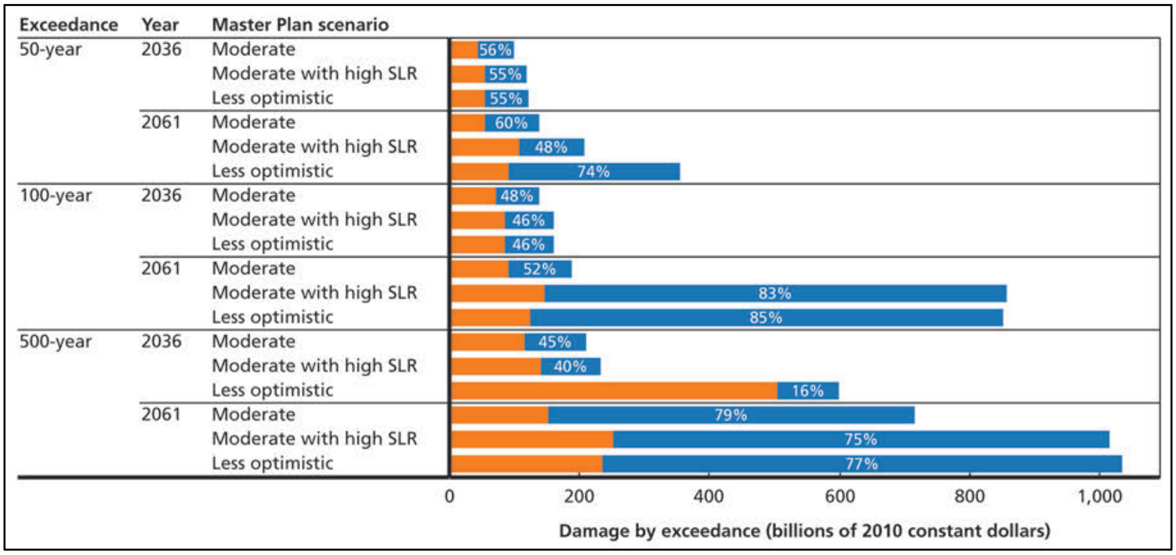

Figure 4: Estimated remaining flood damage and reduction in flood damage with the Master Plan in place, by year, scenario, and exceedance

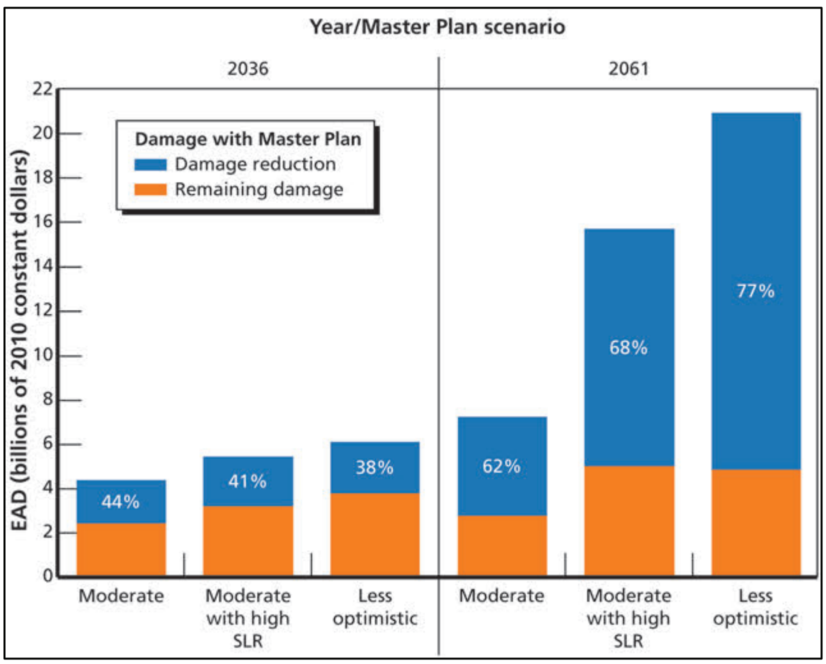

Figure 5: Estimated remaining EAD and reduction in EAD with the Master Plan in place, by year and Master Plan scenario

CONCLUSIONS

Closer examination of the distribution of flood risk shows that a significant portion of the increased risk in the FWOA comes in Greater New Orleans as the HSDRRS degrades over time because of the combined effects of subsidence and sea level rise. In the less optimistic scenario, coastwide EAD increases from $2 billion in the current conditions to $21 billion by 2061; $12.4 billion of the latter total is located in Greater New Orleans.

When the Master Plan is implemented, EAD in the same scenario drops to $4.85 billion coastwide. With the major projects to upgrade and maintain the HSDRRS, Greater New Orleans's share of the damage is only $500 million. This represents a total risk reduction, in terms of EAD, of 96%, far greater than the coastwide average reduction of 77% in the context of a case that considers system fragility. As previously discussed, CLARA's assumption, that failures cause flood elevations equal to the surge levels that caused the breach, likely results in overstated damage estimates for extreme storms. This would differentially affect damage estimates in the FWOA case, where failures occur more often and, thus, also impacts the damage reduction effect of the Master Plan.

When the flood depths from the Master Plan alternative are run through CLARA without the addition of active nonstructural mitigation policies, the total EAD in the study region in 2061 is $5.6 billion in the less optimistic scenario. Thus, only about $750 million of the $16 billion in EAD reduction provided by the Master Plan is attributable to nonstructural measures. Previously, we noted that nonstructural risk reduction projects were only modeled in a subset of communities but that the approved Master Plan provides a funding pool for the entire coast. Details for nonstructural policies have not yet been finalized and may differ substantially from the modeled implementation. A nonstructural policy that evaluates assets for mitigation at the street address level likely can produce much greater benefits than the modeled policy, which was based on BFEs made obsolete in many areas by structural measures and applied at the block level.

The 2012 Master Plan represents an unprecedented effort to protect the state's vibrant cultural heritage and economic livelihood from the threat of future flood risk. CLARA was developed to provide policymakers with a tool to evaluate risk flexibly under a variety of uncertainties about the future landscape, storm characteristics, and economic development. Using analysis from CLARA, CPRA was able to design a final alternative that was projected to reduce EAD by approximately 60-80% during the next 50 years while, at the same time, balancing other decision criteria.

Insights from CLARA, LACPR and IPET

Comparing CLARA's flood depths and damage estimates to those of previous studies is difficult. Despite using similar methods, the IPET and LACPR teams used very different data and assumptions intended to address different questions. Even when looking at current conditions, both efforts modeled a version of the HSDRRS developed in 2007-08 that is substantially different from the system that exists today in 2012. Differences in levee heights as great as 2.13 m (7 ft) or more exist between IPET and CLARA in areas like Orleans Main and the eastern edge of the HSDRRS, running from Lake Pontchartrain to Lake Borgne.

Levee heights represent concrete differences in the physical systems being modeled, but other more ephemeral differences exist in methodology. IPET, LACPR and CLARA all draw from the same storm set but, because of various constraints, used different numbers of storms from that set to estimate surge response surfaces. IPET and LACPR also used different wave models and previous versions of the ADvanced CIRCulation (ADCIRC) surge model, which can produce noticeably different estimates of the surge and wave characteristics for the same storm.

Damage estimates are, in many cases, widely divergent, partly because of the input flood depths but also because of CLARA's lack of depreciation. The estimates of asset inventories also differ because CLARA utilizes updated data from the 2010 U.S. Census and other local data sets tracking post-Katrina recovery.

CLARA represents an effort to build on the fragility analysis and detail of IPET and the uncertainty analysis and future projections of LACPR. It was designed to strike a balance between sophistication and computational efficiency, providing enough fidelity to be useful for a comparative planning study while allowing a flexible and rigorous exploration of environmental, economic, and operational uncertainties.

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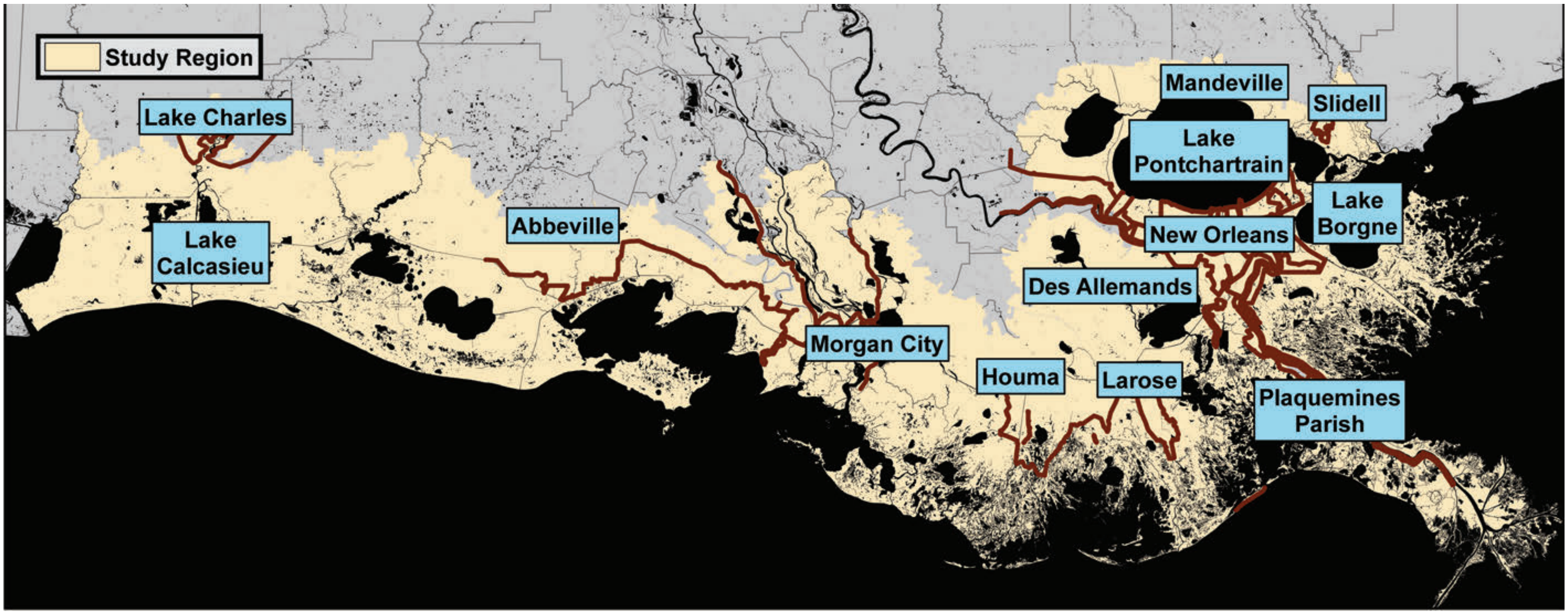
Appendix A: Map of Coastal Louisiana



Using Cost-Effective and Robust Strategies to Assess the Potential for Nonstructural Risk Reduction in Coastal Louisiana

David R. Johnson and Jordan R. Fischbach

ABSTRACT

Louisiana's 2012 Comprehensive Master Plan for a Sustainable Coast allocates $10.2 billion toward nonstructural risk reduction measures such as home elevation, floodproofing, and voluntary property acquisitions. This allocation was based on an evaluation of the costs and benefits of mitigating currently-existing properties up to the level of the "100-year" flood elevations (the level with a 1 percent annual chance of occurring or being exceeded) currently estimated by the Federal Emergency Management Agency, plus one foot of additional freeboard. The Plan, however, did not actually specify a nonstructural policy: what level of mitigation to provide, what measures to implement, or how to distribute the funding.

The benefits of any nonstructural policy depend on many uncertain factors, among them changes in future hurricane intensity or frequency, sea level rise, and timely provision of the restoration and structural protection projects approved by the Master Plan. This paper uses the Coastal Louisiana Risk Assessment model (CLARA) to identify combinations of nonstructural measures with a high potential for risk reduction across many future outcomes. We propose additional strategies for what level of mitigation to provide and for deciding what measures to apply in a given area. The most cost effective strategies would reduce expected annual damage from storm surge flooding in 2061 by $0.9 to $1.8 billion. Using a set of conservative, simplifying assumptions, we suggest that these strategies have a positive net present value under every future outcome modeled.

Our findings demonstrate that the expected annual damage faced by an area depends on the entire probability distribution of flood depths there. These distributions differ across the coast. Therefore, no mitigation standard based on a single point in the distribution (such as the 100-year exceedance) will be optimal everywhere. More cost effective risk reduction can be provided by tailoring the mitigation standard in accordance with the entire probability distribution.

INTRODUCTION

The threat of severe coastal flooding from tropical storms, compounded by sea level rise and land subsidence, poses severe challenges to Louisiana in maintaining its thriving coastal communities. To counter these effects, the state adopted its *Comprehensive Master Plan for a Sustainable Coast* (Master Plan) in May 2012. As part of the 50-year effort to reduce flood risk and land loss, $10.2 billion of the plan's total budget of $50 billion is allocated to *nonstructural risk reduction measures*: options like home elevation, floodproofing and voluntary acquisitions that reduce the consequences of flooding without altering the actual probability distribution of flood depths occurring (Louisiana Coastal Protection and Restoration Authority, 2012a). By contrast, *structural risk reduction measures* consist of large projects, like levees and floodwalls, which alter the physical landscape of an area, blocking or redirecting storm surge and thereby changing the probability of floods occurring in the areas they are designed to protect. The Master

Plan represents a commitment to the "integration of structural and nonstructural flood protection with coastal restoration" referred to as a "multiple lines of defense" strategy (Lopez, 2009).

Planning agencies in the United States have historically adopted a broad view of nonstructural flood control measures. Federal code defines them as including "modifications of public policy, management practice, regulatory policy, and pricing policy." (Office of the Federal Register, 1983) The U.S. Army Corps of Engineers (USACE) sums up these practices as "keep[ing] the people and damageable property away from the floods." (U.S. Army Corps of Engineers, 2009b) In practice, public policy has emphasized passive options like land use and zoning guidelines, development planning, flood insurance, and raising public awareness of risk. Many organizations, in Louisiana and elsewhere, have published guides to best practices for coastal development that discuss nonstructural adaptation strategies (Center for Planning Excellence, 2012; Andjelkovic, 2001; Association of State Flood Plain Managers, 2003; Kahan et al., 2006; Wilkins et al., 2008). Individual homeowners also can utilize federal, state and local programs that support floodproofing and other active measures (Federal Emergency Management Agency, 2009a; U.S. Army Corps of Engineers, 1993).

Evaluation of the impact of nonstructural risk mitigation measures varies greatly by option. Scopus has indexed hundreds of articles related to flood insurance. A more modest literature is devoted to the economics of land use regulations. For example, Burby and Dalton analyzed the effectiveness of state mandates on the adoption of local policies to limit development in coastal communities (Burby and Dalton, 1994). Landry and Hindsley used a hedonic pricing model to estimate willingness-to-pay for reductions in erosion and flood risks (Landry and Hindsley, 2006). Other studies estimate the cost of inaction by examining the response of property markets to changes in perceived risk due to sea level rise (West, Small and Dowlatabadi, 2001; Michael, 2007; Yohe et al., 1996; Yohe and Schlesinger, 1998). Research is inconclusive about the extent to which mitigation measures induce additional development in risky areas (Burby, 2006; Cordes and Yezer, 1998; Landry and Hindsley, 2006).

Relatively few papers in the scientific literature assess the value of integrated nonstructural hazard mitigation planning rather than individual measures in isolation; typically these large-scale analyses have been carried out by government agencies doing long-term planning (USACE, 2009c; Environment Agency, 2012). Hayes compares the costs and benefits of a building elevation, floodproofing and property acquisition strategy to two more-expensive structural alternatives developed by USACE (Hayes, 2004). This paper builds on a study of the potential for flood risk management through elevation and buyouts of single-family residences in Greater New Orleans (Fischbach, 2010) by extending the study region to coastal Louisiana. It also considers a larger suite of nonstructural mitigation options and uses updated estimates of future flood risk developed for the 2012 Master Plan.

The Master Plan allocated its funding for nonstructural measures by comparing cost and risk reduction estimates from a basic nonstructural plan to the costs and impacts of a suite of proposed restoration and structural risk reduction projects. However, it did not specify how individual nonstructural projects should be designed or implemented. In this paper, we use the Coastal Louisiana Risk Assessment (CLARA) model (Johnson, Fischbach and Ortiz, 2013; Fischbach et al., 2012) and simulation data generated for the Master Plan to address the question of how the State of Louisiana could use nonstructural mitigation projects to produce the greatest reduction in flood risk with the $10.2 billion provided for such purpose. We identify census tracts as a suitable geographic unit of analysis for discussing nonstructural policies and comparing projects, pinpoint specific areas with a substantial potential for nonstructural risk reduction, and evaluate an additional set of nonstructural mitigation policies in areas where the proposals modeled during the Master Plan study do not provide adequate risk reduction. The resulting discussion and recommendations presented here can be used to advance the development of a coastwide nonstructural program. We also briefly discuss robustness of strategies against the uncertain future landscape.

METHODS

To explore the cost effectiveness of a wide range of nonstructural risk reduction options, we have developed a set of candidate strategies that prescribe when assets should receive mitigation measures, which measure to apply, and to what elevation mitigation should be applied. The measures considered for mitigation were residential and non-residential floodproofing, residential elevation, and acquisitions. For each strategy, we estimate the cost of implementation as well as the impact on risk in terms of the change in expected annual damage (EAD) from storm-surge based flooding with and without the strategy in place. We identify the most cost-effective strategy for each census tract as the one which provides the greatest reduction in EAD per dollar of cost. We then apply a simple pseudo-optimization algorithm to compile a coastwide assemblage of strategies at the tract level, which maximize risk reduction under the $10.2 billion constraint imposed by the Master Plan.

Note that the possible benefits provided by each strategy in each census tract depend on the flood risk faced in that location in the future. A variety of factors affect future flood risk: environmental uncertainties such as sea level rise, land subsidence, and the frequency and average intensity of future hurricanes; scenarios such as the year and whether structural projects funded by the Master Plan have been put in place; and uncertainties about system failures and the performance of structural projects. Thus, the optimal measure for an area may vary across different assumptions about the future. In this analysis, we look for measures that perform well under a range of uncertain outcomes.

Estimating Flood Risk with the CLARA Model

The Coastal Louisiana Risk Assessment model is a peer-reviewed model that was developed by RAND Corporation as part of the Master Plan effort (Fischbach et al., 2012; Johnson, Fischbach and Ortiz, 2013). It provides a flexible means for comparing current and future flood risk along the Louisiana coastline with a variety of different protection system configurations in place and under a range of environmental, operational, and landscape uncertainties.

CLARA builds on other post-Katrina studies of coastal Louisiana. In particular, the Interagency Performance Evaluation Task Force (IPET) examined the Greater New Orleans Hurricane and Storm Damage Risk Reduction System (HSDRRS) (Interagency Performance Evaluation Taskforce, 2006). It evaluated flood risk to New Orleans at three past time periods: 1) as the HSDRRS existed just prior to Hurricane Katrina, 2) after initial upgrades and repairs in June 2007, and 3) as the system was projected to look in 2011. It utilized a complex event-chain model of multiple modes of failure to simulate system fragility (Interagency Performance Evaluation Taskforce, 2009c). By contrast, the Louisiana Coastal Protection and Restoration study (LACPR) projected risk into the future from 2010 to 2060 in four scenarios, reflecting a combination of maintained or degraded landscape with compact or dispersed economic growth scenarios (U.S. Army Corps of Engineers, 2009a). However, the LACPR study did not model the possibility of system failure.

CLARA draws from both previous models to create a tool for evaluating flood risk that uses a simple model of system fragility (the probability that protection systems will fail in various ways) and can evaluate a wider range of environmental, economic, and system configuration scenarios than considered by LACPR or IPET. It models each piece of a standard threat-vulnerability-consequences framework of risk (Morgan and Henrion, 1990; Kaplan and Garrick, 1981), where *threat* represents the probability of a storm surge event of interest occurring. For the Master Plan, storms of interest were those classified as Category 3 or greater on the Saffir-Simpson Hurricane scale. *Vulnerability* represents the probability distribution of flood depths that occur as a result of a given surge event. *Consequences* are measured in terms of the direct economic damage incurred by a given flood depth; the types of damage included are outlined in more detail later. CLARA simulates the surge response and subsequent flooding from hundreds or thousands of storms that vary according to their landfall track, landfall angle, forward velocity, central pressure deficit, and radius[6].

The resulting flood distributions are tallied up, along with the probability masses associated with each simulated storm and the overall average frequency of storms of interest, to calculate an

[6] Full details on CLARA's flood modeling methodology are provided in Fischbach, *et al.* (2012) and Johnson, *et al.* (2013).

empirical cumulative distribution function (CDF) of flood depths at the centroid of each census block in the study region. The CDF defines the probability that the maximum flood depth observed in a single year is less than or equal to a given value. It can be inverted to identify the flood depths with a 2%, 1%, and 0.2% annual exceedance probability (AEP). Since these depths have a 1-in-50, -100, and -500 chance of being exceeded in a given year, they are also respectively referred to as 50-, 100-, and 500-year flood depth exceedances.

For the purposes of this study, we take the flood depth probability distributions and AEPs for each scenario as exogenous inputs, since nonstructural mitigation measures are not designed to alter flood depths relative to ground elevations. In areas enclosed by a protection system, we use the distributions that result from a fragility mode, referred to as *volume-based breaching*, that estimates the volume of water spilling into the system interior from a breach using the modeled surge levels over time at the location of the breach(es). To simplify the time dynamics and computational demands of this mode, we assume that breaches occur when exterior surge levels are at their peak (when hydrostatic pressure on the system is greatest), and that breaches are always full-depth (producing a worst-case volume of breach water entering the interior). This breach volume is added to rainfall, along with overtopping volumes elsewhere in the system. We assume that pumping systems operate at fifty percent of rated capacity, subtract the resulting volume of water pumped out of the system, and then distribute the remaining volume throughout the protected area using CLARA's interior drainage module.[7]

Other scenarios, not presented here, modeled pumping systems operating at full capacity or not running at all; the three pumping scenarios are intended to reflect a range of possibilities where some pumps might be non-operational or overwhelmed during a storm event. In practice, pumping capacity has very little impact on the results of this analysis, since it impacts flood depths in enclosed structural protection systems, like the HSDRRS, where nonstructural measures are generally less cost effective.

To understand the risk reduction impact of various nonstructural policy options, we rely on CLARA's economic module, which is largely based on the methodologies adopted by the FEMA Hazus Multi-Hazard (HazusMH) model (Federal Emergency Management Agency, 2009b). Figure 1 illustrates the logic. A valuation module calculates a value for each asset type within a block using assumptions about average square footage per structure, replacement costs per

[7] During the 2012 Master Plan process, flood depths were calculated using two fragility modes. In the first mode, CLARA assumes no fragility, i.e., protection features do not fail. The second mode is referred to as *elevation-based breaching* and assumes that all system failures result in interior flood elevations equal to the elevation of the surge that caused the breach. This is a very aggressive assumption that likely overstates resulting flood depths in many cases; volume-based breaching more realistically models the actual consequences of system failure.

square foot, and the number of structures in a block. The following asset classes are included: single-family residences, manufactured homes, small multifamily residences (e.g., duplex, triplex), large multifamily residences (e.g., apartment building, condominium complex), commercial, industrial, public facilities, transport infrastructure (e.g., roads, bridges), vehicles, structures and properties used for agriculture, and agricultural crops.

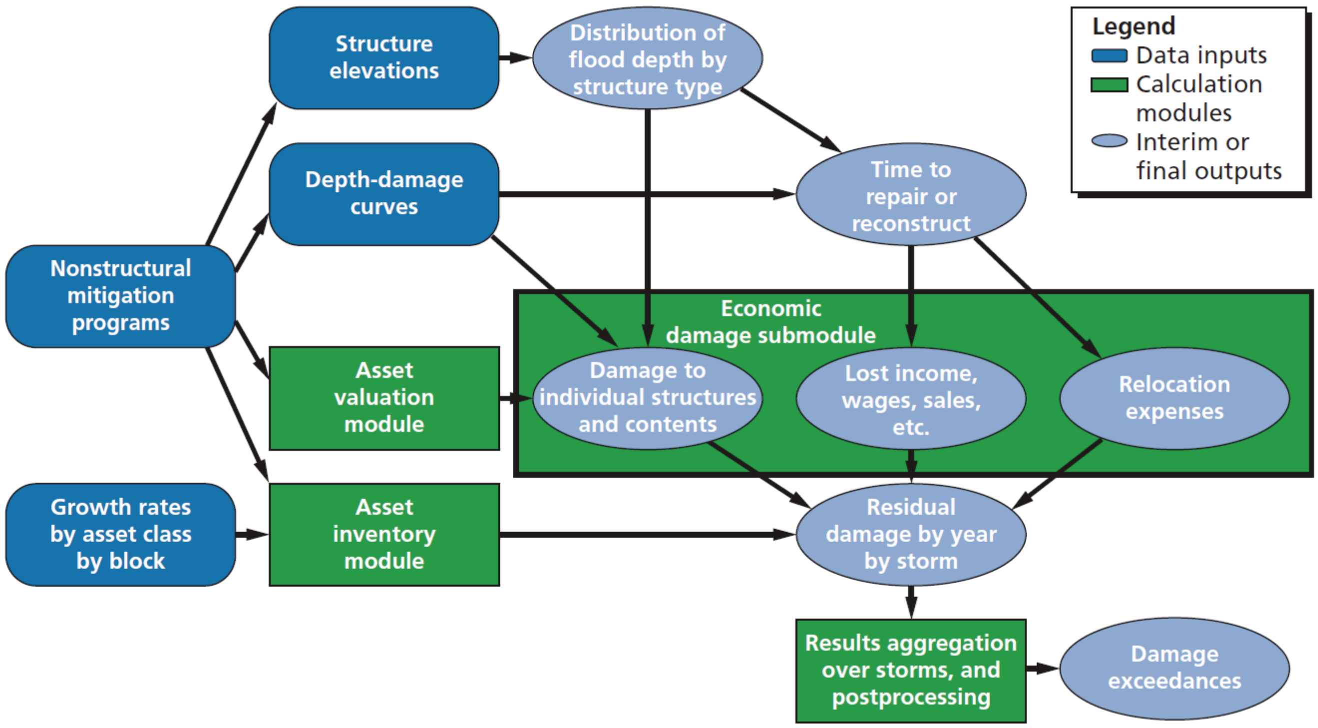


Figure 1: Summary of CLARA Economic Module Calculations (Source: Fischbach, *et al.* (2012), Figure 7.1)

Asset inventories in the 2012 base year come from a database, originating in Hazus-MH MR2 and MR4, which was updated by Calthorpe Associates to represent the second quarter of 2005 (preceding Katrina). The 2005 asset inventory was used by the LACPR study and was adjusted for CLARA using census data and information from the Greater New Orleans Community Data Center. See Johnson (2013) for more details.

Depth-damage curves relate the proportion of a structure's value that is damaged as a function of flood elevations, relative to the structure's foundation height. Foundation heights are estimated separately as block-level averages for pier and slab foundations using a street-level survey performed by USACE in 1991 (USACE, 2009a). For existing structures repaired after Hurricanes Katrina and Rita and which received funding from the Louisiana Road Home program or FEMA Hazard Mitigation Grant Program, CLARA assumes foundations are elevated

to the FEMA Base Flood Elevation (BFE)[8] plus one additional foot of freeboard in order to qualify for coverage under the National Flood Insurance Program (NFIP) (Federal Emergency Management Agency, 2013b).

CLARA also calculates damage to contents and sales inventory within structures, as well as the estimated duration of repairs/reconstruction. This time is used to calculate direct economic losses associated with lost sales, rents, etc., and the cost of temporary relocation. Much as IPET and LACPR did, CLARA follows the HazusMH methods for calculating the disruption time. Where available, we substitute cost data collected by LACPR in the wake of Katrina and Rita (for example, relocation expenses are based on average travel distances, hotel and food costs for Katrina victims based on their actual evacuation routes and experiences during reconstruction).

Nonstructural mitigation measures affect the model calculations in various ways. Elevating structures alters their foundation heights, directly reducing the effective flood depths impacting the building during a storm event. Floodproofing does not change the exposure of a building to flooding, but it reduces the consequences by changing the depth-damage curve so that no damage is incurred by flooding up to the height where floodproofing stops. Property acquisitions and easements directly reduce the inventory of structures at risk.

Defining Nonstructural Risk Reduction Projects and Strategies

We define nonstructural risk reduction projects by specifying a *nonstructural reference standard*, an elevation (relative to a fixed elevation datum like NAVD88) up to which mitigation is required. If the foundation of a building already extends above the reference standard, no mitigation is required. If the foundation is three feet or less below the reference standard, we assume that residential, commercial, industrial and public buildings can receive dry floodproofing. Elevation-in-place is modeled for single-family homes, manufactured homes, and small multi-family residences (i.e., duplexes and triplexes) when the reference standard calls for more than three feet of additional protection. We also specify an *acquisition threshold* for each policy, the level beyond which properties are bought out rather than elevated.

Nonstructural *projects* are defined as the implementation of nonstructural mitigation within a particular spatial unit. *Strategies* represent coastwide aggregations of projects; we can define a strategy that applies the same measures in each location, or a strategy could be defined as a blend of multiple project types applied in different parts of the coast.

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[8] The BFEs adopted by CLARA are the preliminary Digital Flood Insurance Rate Maps (DFIRMs) issued by FEMA from November 2008 to May 2011; these elevations were incorporated even in areas where the preliminary DFIRMS had not yet been adopted. In areas where no DFIRMS had been issued by May 2011, we used the previous BFEs.

Only two nonstructural risk reduction project types were evaluated during the Master Plan process; each used the existing FEMA BFEs as its reference standard. One required an additional one foot of freeboard; the other used four additional feet. Both strategies set the acquisition threshold at 18 feet above the Highest Elevation Adjacent Grade (HEAG); in other words, acquisitions take place when the reference standard plus freeboard target reaches 18 feet or more above ground level.

We evaluated additional project types that expand on those described above. For instance, because elevating structures up to 18 feet above ground level may subject them to additional risk through exposure to a more severe wind field during storm events, we have examined the impact of lowering the acquisition threshold to 14 or 10 feet.

The FEMA BFEs are based on estimates of the 100-year floodplain under current or historic conditions; in many cases they differ from CLARA's estimated 100-year flood exceedances. The BFEs do not incorporate future uncertainty and will become progressively more obsolete over the next fifty years as coastal conditions change and Master Plan projects are implemented; even now, they do not consider the risk reduction benefits of any levees or protection structures which are not certified by the U.S. Army Corps of Engineers to provide 100-year protection.

The National Research Council's Committee on Levees and the NFIP has recommended that the NFIP move to a "modern risk analysis that makes use of modern methods" that incorporate state-of-the-art flood hazard analysis, levee fragility, a systems analysis of all features affecting flooding (such as pumping systems and non-certified levees), an assessment of levee breach and inundation consequences, and uncertainty analysis (National Research Council, 2013). CLARA takes account of each of these factors, so we believe the risk profiles estimated for the Master Plan effort represent modern reference standards suitable for exploring the potential of nonstructural risk reduction policies. In consideration of nonstructural measures as a long-term investment, we have therefore also considered the risk reduction benefits of replacing the BFE mitigation standards with updated estimates of the 100-year flood exceedances from CLARA in 2061 under an adverse future scenario, the Less Optimistic Master Plan scenario. The key features of this scenario are sea level rise of 0.45 meters over the next 50 years, moderately high land subsidence, an increase in average storm intensity of 20%, and an increase in storm frequency of 5%. In protected areas, we calculate exceedances using the volume-based breaching method and assuming that the pumps operate at fifty percent of capacity. More details on the definitions of each Master Plan scenario are found in Figure 3.3 of the main Master Plan document (Louisiana Coastal Protection and Restoration Authority, 2012a).

We chose to model the Less Optimistic scenario's 100-year exceedances because this scenario, with and without the Master Plan structural projects in place, produces a range of 100-year exceedance values that contrast with the FEMA BFEs. Using this reference standard allowed us to examine strategies with some variation that still had a physically interpretable definition (i.e., consistently corresponding to a particular exceedance across the entire coast). This modeling choice should not be viewed as an endorsement of the likelihood of any particular scenario coming to pass. We are also not recommending any *a priori* planning principle that would result in basing decisions on the Less Optimistic reference standard.

A summary of the strategy set which was evaluated is shown in Table 1 below. We refer to strategies using a short-form name based on the reference standard used, target height for freeboard above the standard, and the strategy's acquisition threshold. We have modeled two classes of strategies, based on their elevation standard: *BFE strategies* use the FEMA BFEs as a reference standard for protection, and *CLARA-based strategies* use reference standards produced by the CLARA model. Since some parts of the coast may receive nonstructural risk reduction many years before structural protection projects are completed in those areas, we modeled reference standards using the 100-year exceedances that would occur in 2061 both with and without implementation of the Master Plan structural protection and restoration projects.

During the Master Plan study, the *FWOA landscape*, defined as the physical configuration of the coast with no additional structural projects implemented, was internally referred to as Grid 60; we abbreviate this as *G60*. The *Master Plan landscape*, the future landscape with the final Master Plan structural and restoration projects in place, was referred to as Grid 62, or *G62*.

We define the G60 reference standard as the 100-year flood depth exceedances in a future without action in 2061; the G62 reference standard corresponds to the 100-year flood depth exceedances in 2061 that would occur with the Master Plan structural and restoration projects in place. As such, a *G60 strategy* is one that provides mitigation up to the G60 reference standard, which is based on the FWOA landscape's 100-year flood depth exceedances.

By contrast, a phrase like "running the FWOA landscape" refers to running CLARA using the flood depths associated with the FWOA coastal landscape (no matter what nonstructural reference standard is being applied to mitigated properties). Use of the term "Master Plan landscape" refers to running CLARA with the Master Plan projects in place. This is why we have introduced the terms "G60" and "G62"; they are used to refer to modeling a particular nonstructural strategy, allowing "FWOA landscape" and "Master Plan landscape" to henceforth refer only to the flood depths CLARA uses to calculating damage.

The format of the naming convention is summarized below:

$$\underbrace{\text{BFE}}_{\substack{reference \\ standard}} + \underbrace{1}_{\substack{freeboard \\ target}}, \underbrace{10}_{\substack{acquisition \\ threshold}}$$

Equation 1: Naming Convention for Nonstructural Project Types

As an instructive example, suppose we want to evaluate how the "G60+1, 18" strategy would perform in a future where the Master Plan projects are not implemented. To do so, CLARA alters the inventory of residential, commercial and industrial properties so that they receive elevation or floodproofing up to the G60 reference standard, plus one additional foot of freeboard. In other words, as G60 is defined above, they are mitigated up to the level of the 100-year flood depth exceedances that occur in 2061 in a future without action, plus the additional freeboard. CLARA then calculates the damage these mitigated properties would receive from the flood depths that occur in a future where the Master Plan projects are not implemented; this is what is meant by running the model with the FWOA landscape.

In many areas, the G60 and G62 reference standards are lower in elevation than BFEs. Local ordinances and regulations may dictate that any construction or retrofitting mitigate to at least the BFE level, regardless of whether the Master Plan is slated to provide new or upgraded structural protection to an area (and thus reduce its actual 100-year flood depth exceedances, sometimes drastically). Since we are interested in assessing the maximum potential cost effectiveness of these standards, we did not incorporate current building codes or other restrictions like this into the modeling.

Table 1: Summary of Additional Nonstructural Project Types Evaluated

Project Type Name	Reference Standard	Freeboard Target (ft)	Acquisition Threshold (ft)
BFE+1, 10	FEMA BFE	1	10
BFE+1, 14	FEMA BFE	1	14
BFE+1, 18	FEMA BFE	1	18
BFE+4, 10	FEMA BFE	4	10
BFE+4, 14	FEMA BFE	4	14
BFE+4, 18	FEMA BFE	4	18
G60+1, 10	FWOA 100-year	1	10
G60+1, 14	FWOA 100-year	1	14
G60+1, 18	FWOA 100-year	1	18
G62+1, 10	Master Plan 100-year	1	10
G62+1, 14	Master Plan 100-year	1	14
G62+1, 18	Master Plan 100-year	1	18

The above list of strategies was chosen not to be exhaustive, but rather to span a range of plausible policy actions. A more detailed analysis might examine the benefits of intermediate values such as a 12-foot acquisition threshold, for example.

Each strategy was evaluated with CLARA's economic module to estimate the resulting flood damage under a variety of uncertainties. Expected annual damage (EAD), along with 50-, 100- and 500-year damage exceedances, was computed across multiple time periods, landscape scenarios, system performance scenarios, nonstructural policy participation rates, and protection system configurations. All cases used the default economic growth assumptions developed for the Master Plan. We modeled the impact of nonstructural policies implemented on current assets over the next five years, so future growth patterns would affect overall future exposure but not the risk reduction afforded to current assets. The cases run for each strategy are summarized in Table 2.

Table 2: Cases Evaluated with CLARA for Additional Nonstructural Project Types

Parameter	Number of Cases	Values
System Landscape	2	FWOA, Master Plan
Scenario	2	Moderate, Less Optimistic
Year	2	2036, 2061
System Performance	2	Full pumping, elevation-based breaching Fifty percent pumping, volume-based breaching
Participation Rate	2	Medium-High, Full cases from Master Plan

Choosing an Appropriate Spatial Unit of Analysis

One goal of this study was to identify the largest spatial unit of analysis appropriate for describing the composition, costs and impacts of nonstructural risk reduction projects. It is impractical to summarize and disseminate this data individually for each of the 35,556 census blocks that serve as the baseline unit of analysis for the CLARA damage module. For parsimony, we wanted to aggregate data up to a smaller number of larger spatial units.

However, having too few spatial units is also problematic. For example, the coastal study region contains portions of 23 Louisiana parishes; some of them are so large that applying the same nonstructural strategy to every block in the parish would be much less effective at reducing risk than mixing strategies in different blocks. An ideal spatial unit is small enough so that planners would choose to do the same thing nearly everywhere within the unit, but large enough to result in a small total number of units. It should also respect actual planning boundaries like city limits or levee district boundaries.

To explore this tradeoff, we say that a census block is *selected* by a given strategy if the foundations of unmitigated assets are not already above the strategy's reference standard elevation for that block's location, plus the additional freeboard target. We denote as a *nonstructural project* the implementation of a particular strategy within a given spatial unit. Finally, we say that a spatial unit is *homogeneous* under a strategy if either less than 10% or greater than 90% of blocks in the unit are selected. Under this definition, an ideal spatial unit balances the total number of units against the proportion of homogeneous units.

Exploratory analysis of various spatial units (block group, tract, Master Plan target community[9], and parish) indicated that a tract-level analysis provides the best balance for a planning-level exploration of nonstructural mitigation; as shown in Table 3, the percentage of homogeneous tracts is nearly equal to the percentage of homogeneous block groups, but using block groups would require nearly tripling the total number of units. Aggregating the spatial unit further, to target communities or parishes, sacrifices a significant degree of homogeneity, particularly when using the Future Without Action (G60) and Master Plan (G62) reference standards.

Table 3: Homogeneity of Spatial Units by Strategy

Strategy	Spatial Unit	Total Units	Homogeneous Units (#)	Homog. Units (%)	<10% Blocks Selected (%)	>90% Blocks Selected (%)
BFE+1, 18	Census Block	35,556	35,556	100.0%	9.0%	91.1%
BFE+1, 18	Block Group	1,413	1,024	72.5%	0.4%	72.1%
BFE+1, 18	Census Tract	510	367	72.0%	0.2%	71.8%
BFE+1, 18	Community	56	35	62.5%	0.0%	62.5%
BFE+1, 18	Parish	23	13	56.5%	0.0%	56.5%
G60+1, 18	Census Block	35,556	35,556	100.0%	49.4%	50.6%
G60+1, 18	Block Group	1,413	1,171	82.9%	47.6%	35.3%
G60+1, 18	Census Tract	510	396	77.6%	43.1%	34.5%
G60+1, 18	Community	56	29	51.8%	8.9%	42.9%
G60+1, 18	Parish	23	9	39.1%	4.3%	34.8%
G62+1, 18	Census Block	35,556	35,556	100.0%	72.5%	27.5%
G62+1, 18	Block Group	1,413	1,205	85.3%	68.9%	16.4%
G62+1, 18	Census Tract	510	417	81.8%	59.2%	22.6%
G62+1, 18	Community	56	32	57.1%	14.3%	42.8%
G62+1, 18	Parish	23	9	39.1%	4.3%	34.8%

[9] The Master Plan defined a set of 56 communities that were each targeted for 50-, 100-, or 500-year level of protection. The extent to which risk was reduced at the target exceedance threshold for each community was one of the criteria used by the Planning Tool for project selection (Louisiana Coastal Protection and Restoration Authority, 2012d).

Note that approximately half of the 35,556 census blocks and 190 of the 510 census tracts are situated outside of the Greater New Orleans HSDRRS. Within the HSDRRS, we will see that nonstructural risk reduction measures are less cost-effective because of the structural measures already provided to New Orleans: $14.5 billion spent on improvements after Hurricane Katrina, along with further structural upgrades proposed by the Master Plan. This also accounts for the difference in the number of blocks selected for nonstructural mitigation between the BFE standard (91.1%, as seen in Table 3), which is not based upon the final state of the upgraded HSDRRS (Federal Emergency Management Agency, 2013b), and the G60 standard (50.6%), which does. The recent HSDRRS improvements reduce the 100-year flood depth exceedances in New Orleans, meaning that many fewer blocks fail to meet the G60 reference standard and get selected. The G62 standard is based on 100-year flood depths with the full set of Master Plan projects in place, so under this reference only 27.5% of blocks are selected for mitigation.

Choosing a Measure of Cost Effectiveness

Past studies of flood risk have considered a variety of risk metrics. These typically include points on the flood depth and damage exceedance curves, such as 50-year flood depths (2% AEP). The HSDRRS upgrades completed in 2012 were designed using a 100-year standard for protection (i.e., intended to produce a negligible 1% damage AEP). IPET reported 50-, 100-, and 500-year flood and damage exceedances (Interagency Performance Evaluation Taskforce, 2009a). LACPR reported 100-, 400-, and 1000-year flood depths along with 10-, 100-, 400-, 1000-, and 2000-year damage exceedances (USACE, 2009b).

Expected Annual Damage

LACPR also calculated “annual equivalent” damages, in essence the mean damage expected in any given year. We refer to this as expected annual damage (EAD); details on how this value is calculated are in Johnson (2013). EAD summarizes information about the entire distribution of possible damage, so it provides a convenient single metric for comparison between strategies.

EAD is only one possible metric for understanding the impact of nonstructural measures on flood risk. However, decision makers in Louisiana are already familiar with EAD, as it was used during the Master Plan process as the primary metric for selecting risk reduction projects; since communities may go many years without a serious flood or they may experience floods for several years in a row, an annual expectation of losses is an appropriate summary metric (Groves, Sharon and Knopman, 2012). When calculated over time, it can also be used in a traditional cost-benefit analysis (understanding that non-stationarity may demand the use of different values for EAD in different years).

Project Costs

We tracked the cost of implementing each project. Costs were broken out by type of action (elevation, floodproofing, and acquisitions/easements for residential assets), and costs for flood-proofing commercial, industrial and public structures were also compiled separately. The number of structures mitigated was also tallied for each action. All cost and damage figures are reported in constant 2010 dollars without discounting (consistent with the Master Plan analysis). This does involve making some implicit assumptions about the future, such as that construction costs track inflation over time, and that capital and labor requirements for construction do not change.

The resulting cost effectiveness measure used throughout this paper is thus the change in EAD per dollar spent on nonstructural risk reduction. EAD, and thus cost effectiveness, varies according to the landscape, scenario and year being modeled; except where otherwise specified, the discussion refers to risk reduction and damage in 2061 under the Less Optimistic scenario and with all Master Plan projects in place. We also present results assuming full participation by all eligible residents and structure owners in order to convey a project's maximum potential.

A traditional cost-benefit analysis would examine the accrual of benefits over time to estimate the net present value (NPV) of each strategy. As mentioned, the performance of nonstructural measures is highly dependent in some areas on synergies with structural projects. Since the timeline and sequencing of these projects is as-yet undetermined, it is impossible to model the full stream of benefits with any confidence. Nonetheless, we later estimate the total benefits over time of some proposed strategies using a set of simplified assumptions.

RESULTS

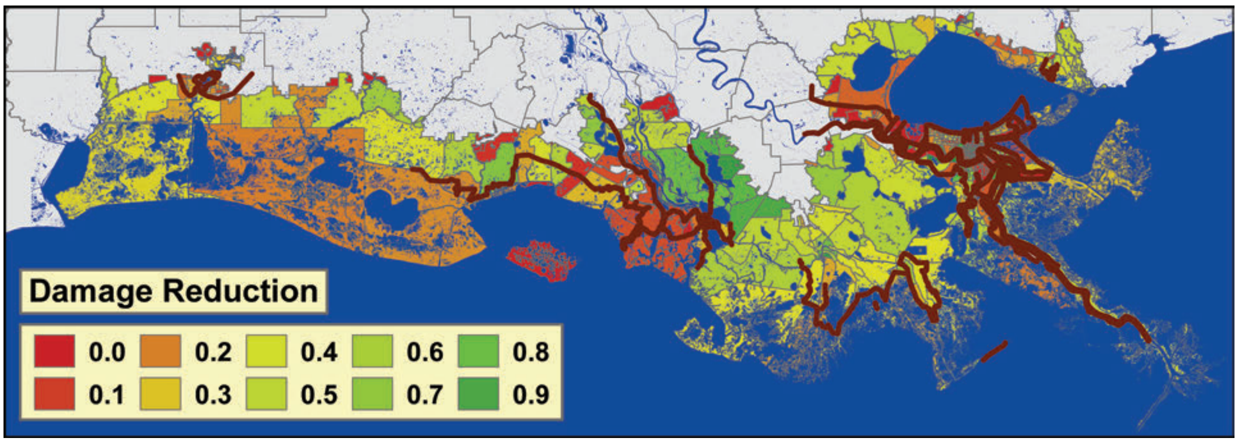
Assessing the Potential for Nonstructural Risk Reduction

This analysis proceeded in several steps. First, we identified areas with low potential for nonstructural mitigation benefits by looking for census tracts in which no structures are selected to receive nonstructural risk reduction. Note that selection does not depend on the acquisition threshold; this only impacts what type of measure is applied. Very few tracts are never chosen for nonstructural mitigation. These low-potential tracts include areas with only agricultural assets and roads (around Vermilion Bay, on Marsh Island, and west of Lake Maurepas) and areas at higher ground elevations on the edge of the study region. Large portions of New Orleans are only selected for mitigation when using the BFE reference standard. (See Appendix A for a map showing where all places referred to in this paper are located.)

Next, in every tract we estimated the maximum amount of damage reduction generated over the set of project types considered. We did this to identify tracts where mitigation is called for in

some areas but is ineffective at reducing damage, either because the risk is already quite low or because the actions taken are insufficient to reduce flood damage.

For each case, we compared the EAD without nonstructural risk reduction to the EAD calculated with each project type implemented. Figure 2 shows the proportion of EAD in 2061 reduced by the best-performing project modeled, relative to no nonstructural mitigation. By this metric, many of the areas with high potential for nonstructural risk reduction are in the largely uninhabited wetlands around Lake Verret; regardless of the ability to mitigate a large proportion of the risk, those areas have very few assets to protect. However, cities like Houma, Raceland and Franklin also have high potential for additional damage reduction.



Notes: This map depicts the Less Optimistic scenario in 2061. The comparison assumes all Master Plan restoration and structural projects are implemented; existing and planned structural projects are outlined in brown.

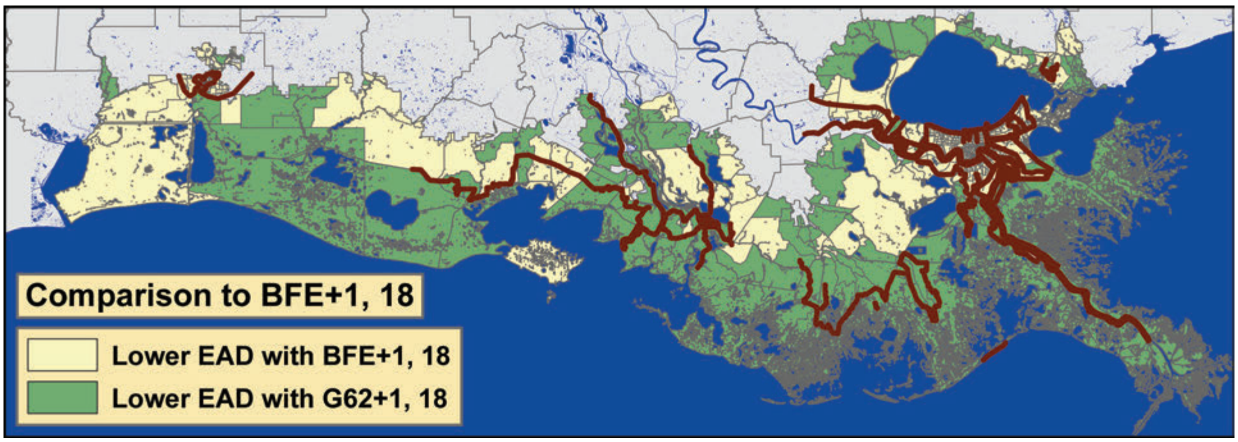
Figure 2: Best Proportional Risk Reduction Across All Project Types Modeled, by Census Tract

Then we identified census tracts where the additional strategies modeled in this paper perform better than the "BFE+1, 18" strategy modeled in the Master Plan analysis, consisting of projects that apply the BFE reference standard with 1 foot of additional freeboard and an 18-foot acquisition threshold. Table 4 counts the number of census tracts coast-wide (excluding those within the Greater New Orleans HSDRRS) in which EAD is reduced by an alternative strategy in the Less Optimistic scenario with the Master Plan in place. Exploratory analysis suggests these results do not rely heavily on the choice of scenario, landscape, or economic assumptions.

For example, a "G62+1, 18" strategy would improve upon the Master Plan in 81 census tracts coast-wide. Figure 3 shows where these differences occur; tracts highlighted in green denote where the "G62+1, 18" strategy performs best, while yellow tracts indicate better risk reduction from the Master Plan's "BFE+1, 18" strategy. We can see that the Master Plan projects are only consistently better than the "G62+1, 18" projects in the western part of the coast (Cameron Parish). The updated standard generally performs better in many other areas as the BFE+1 standard becomes outdated over time due to sea level rise and other factors.

Table 4: Census Tracts with Improved EAD Reduction From Another Strategy Compared to the "BFE+1, 18" Strategy Modeled for the 2012 Master Plan

Strategy Name	Non-HSDRRS Tracts	Non-HSDRRS Tracts (%)	Strategy Name	Non-HSDRRS Tracts	Non-HSDRRS Tracts (%)
BFE+1, 10	55	29%	G60+1, 10	110	58%
BFE+1, 14	26	14%	G60+1, 14	100	53%
BFE+1, 18	--	--	G60+1, 18	92	48%
BFE+4, 10	158	83%	G62+1, 10	92	48%
BFE+4, 14	157	83%	G62+1, 14	87	46%
BFE+4, 18	157	83%	G62+1, 18	81	43%



Notes: This map depicts the Less Optimistic scenario in 2061. The comparison assumes all Master Plan restoration and structural projects are implemented; existing and planned structural projects are outlined in brown.

Figure 3: Census Tracts with EAD Reduction from "G62+1, 18" Projects Relative to "BFE+1, 18" Projects

Where nonstructural measures can eliminate a large fraction of damage, it may be expensive to do so relative to the absolute risk reduction achieved. Figure 4 plots the cost of implementing each strategy in every census tract across the entire coast versus the resulting EAD and cost effectiveness (reduction in EAD in 2061 per dollar spent). Each reference standard is colored differently, and the size of each point indicates the acquisition threshold; the highest threshold, 18 feet, is given the smallest point since it produces the smallest number of acquisitions.

For example, if the cost effectiveness shown in Figure 4 is $0.10, then each $1 spent on that strategy now reduces EAD in 2061 by $0.10. This seems minor but only reflects the benefit in a single year; implementing nonstructural mitigation now would produce a stream of future benefits, so the total present value of benefits would be substantially greater than the value in the figure. This paper does not conduct a full cost-benefit analysis, but a later section does present estimated benefit-cost ratios using simple assumptions about future implementation.

We cannot make conclusions, based on the information presented here, about the relative preferences or overall justifications for or against the modeled strategies. A formal cost-benefit

analysis is not performed, and further, such an analysis may not be the only factor considered when designing nonstructural policies. However, the analysis suggests several implications.

First, each strategy's performance relative to other strategies, in terms of both risk reduction and cost effectiveness, is basically unchanged by the landscape scenario (circles for the Less Optimistic scenario, crosses for the Moderate scenario). The EAD for each strategy is scaled by approximately the same factor between the scenarios. This suggests that a limited number of landscape scenarios may be needed to evaluate nonstructural policies, although it would be useful to have a better understanding of the contribution of each uncertainty embedded in the scenarios to the inter-scenario variation in performance.

Second, for a given reference standard, lowering the buyout threshold and acquiring a greater number of structures reduces EAD but also generally reduces cost effectiveness. This is because buyouts are typically more expensive than elevating the same property. One exception is that when using the G60 reference standard, the 14-foot acquisition threshold is slightly more cost-effective than the 18-foot threshold. This exception is discussed in more detail in the next section. Buyouts are a complicated and politically sensitive proposal; they may have ancillary benefits in reducing risk of casualties and simplifying evacuations, but they also risk uprooting historic neighborhoods and having adverse impacts on community resilience.

Third, on a coast-wide basis, the project types that generate the greatest amount of EAD reduction per dollar invested in mitigation are clearly those based on the G62 reference standard. This is an intuitive result when run against the Master Plan landscape, since in this case we are using the protection system configuration to both set the reference standard and evaluate the subsequent damage reduction. Other reference standards may yield areas where the standard is inadequate and flood damage still occurs; in other areas, the standard may produce "overbuilt" mitigation that provides little additional damage reduction compared to the added expense. This underscores the importance of comprehensive planning that considers synergies between all policy measures: structural and nonstructural risk reduction as well as restoration. It is more cost effective to calibrate the nonstructural reference standard to the residual risk after implementation of the other Master Plan projects.

Finally, since the G60 reference standard is based on the FWOA flood exceedances, it produces more risk reduction than the G62 standard when run against the FWOA landscape. However, the G62 strategies are still more cost-effective when run in the FWOA case, due to the added expense of mitigating up to the higher G60 standard. This suggests that when considering new nonstructural investments, decision makers should weigh the greater absolute risk reduction provided by a "worst-case" standard like G60, which hedges against delays in completion of structural risk reduction projects, against the greater cost efficiency of the G62 standard.

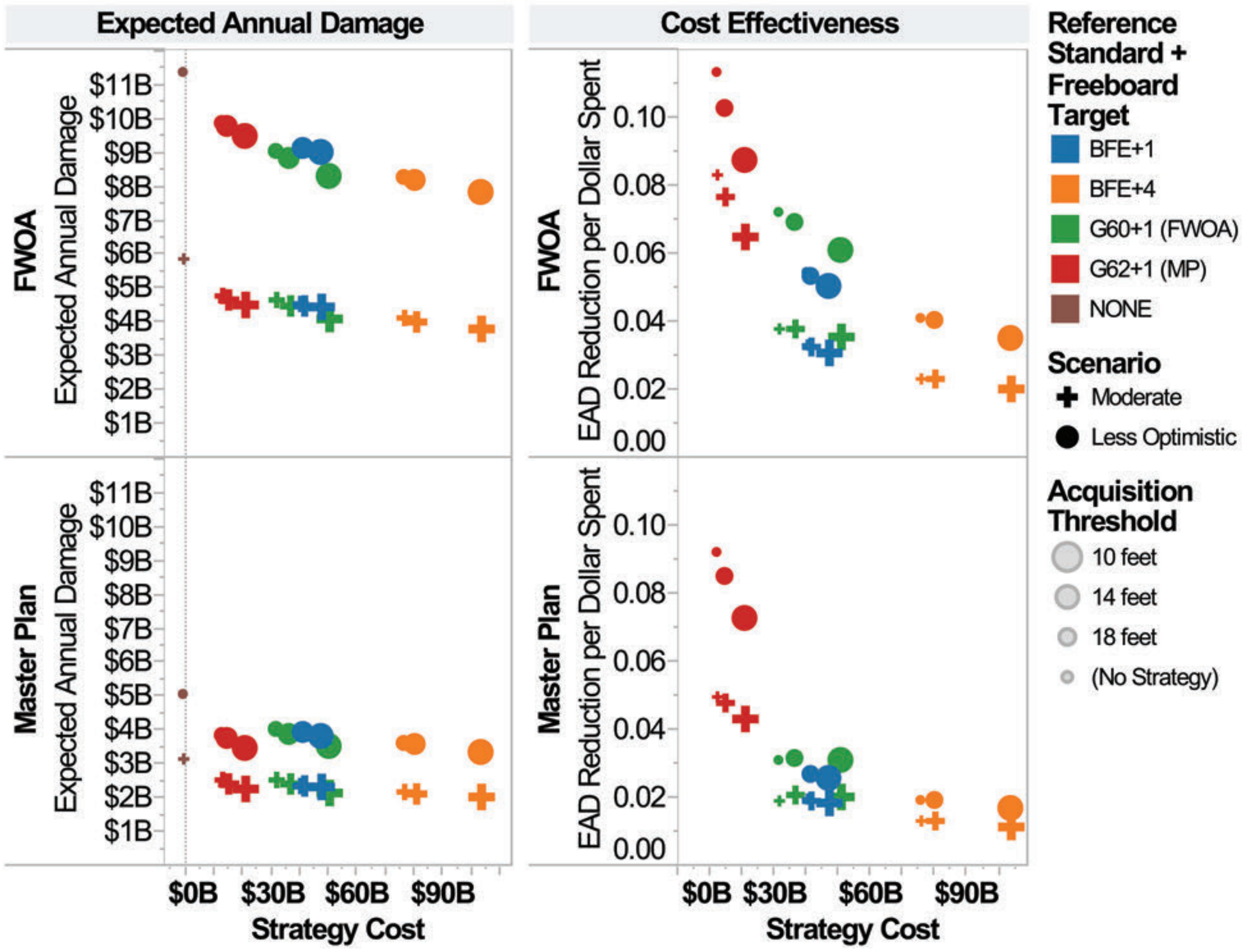


Figure 4: Coast-wide Expected Annual Damage and Cost Effectiveness of Nonstructural Strategies (2061)

Imposing Budget Constraints

Every strategy described above, if implemented across the coast with full participation, would cost more than the $10.2 billion allocated by the Master Plan. One sensible approach for allocating the constrained funding is to rank-order each census tract by its cost effectiveness under a given strategy and scenario, then successively select the most marginally cost-effective tracts until the $10.2 billion constraint is reached. Figure 5 shows the risk reduction achieved by this approach in the Less Optimistic scenario, with the Master Plan in place.

This illustrates that within the same reference standard and freeboard target, lowering the acquisition threshold (resulting in a larger number of acquisitions in a given tract) generally makes the strategy less cost-effective. G60+1 with an 18-foot acquisition threshold, however, performs slightly worse when the threshold is lowered to 14 feet. This difference in performance is minor in light of other uncertainties but is worth exploring. Two opposing forces are at play. On one hand, lowering the threshold requires more buyouts; each acquisition removes a property, eliminating all of the risk associated with it. However, acquiring a residence is usually

more costly than elevating or floodproofing the same home, so increasing the number of acquisitions means less money is available for mitigating other properties. As such, a strategy with a lower threshold selects fewer tracts, leaving more of them exposed to risk. Figure 5 demonstrates that the latter impact is typically greater than the former.

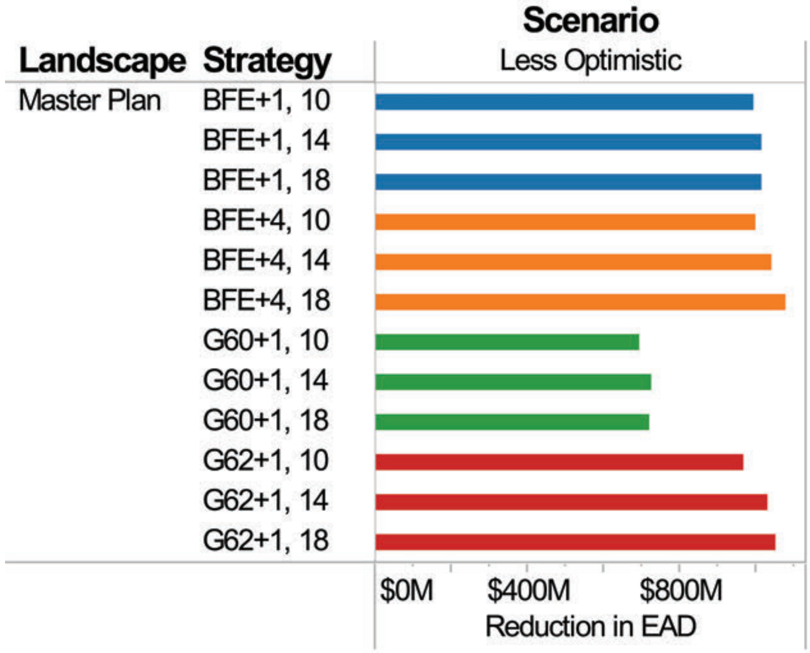


Figure 5: Reduction in EAD from Strategies Constrained to $10.2B (2061, Less Optimistic scenario, Master Plan landscape)

Figure 6 shows the reduction in EAD achieved in the other cases modeled; for ease of comparison, this figure only depicts strategies with an 18-foot acquisition threshold.

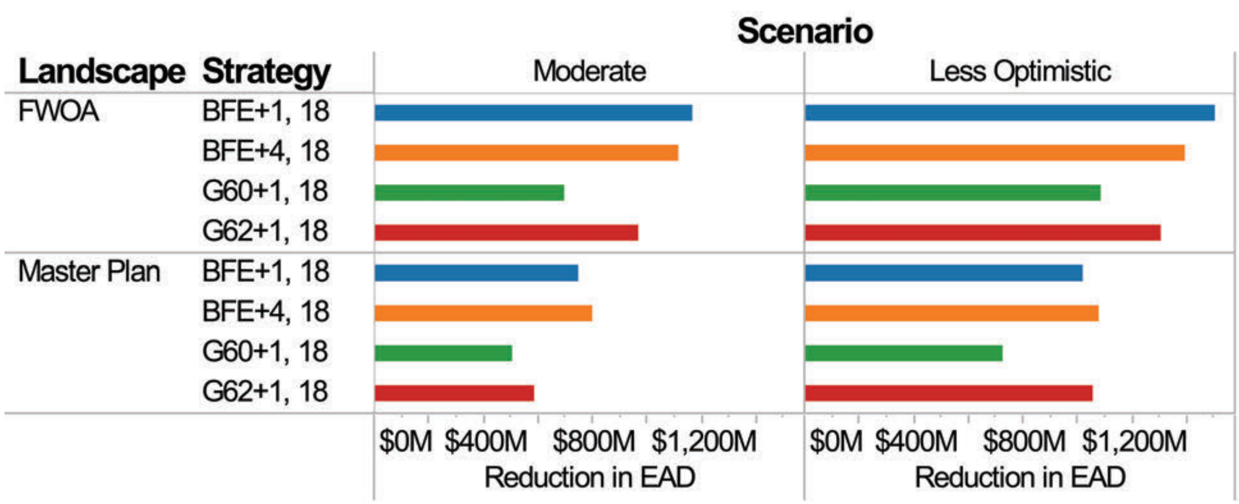


Figure 6: Reduction in EAD from Strategies Constrained to $10.2B (2061)

Using cost effectiveness as the rule for constraining each strategy to meet the budget, the variation in performance between strategies is much smaller than the full implementations shown

in Figure 4. In general, the G60 reference standard provides slightly less risk reduction; since the standard is based on a Future Without Action, it "overprotects" many areas where new structural protection is provided under the Master Plan. This drives up costs while providing little marginal risk reduction, so the strategy is able to implement projects in fewer census tracts before reaching the budget constraint. The other three standards are very similar. Unexpectedly, the BFE reference standard (with both 1 and 4 feet of freeboard) generally outperforms the G62 reference standard in terms of cost-effectiveness. The exception is in the Less Optimistic scenario with the Master Plan projects in place—the case which was used to define the G62 reference standard.

The contrast between the superior cost effectiveness of G62 in the unconstrained case and its weaker performance when constrained to \$10.2 billion of the most cost-effective projects is striking. It suggests that the cost effectiveness of the unconstrained BFE-based strategies must be skewed downward by a large number of projects that add very little marginal risk reduction. Figure 7 shows this to be the case. The dots in each curve illustrate the cumulative cost and EAD reduction of a strategy as each marginally cost-effective project is selected. Only strategies with an 18-foot acquisition threshold are shown. (Note that the axis showing EAD reduction is different for the FWOA and Master Plan alignments.)

This figure demonstrates that each strategy except for G62 is hampered by a large number of tracts which are selected for mitigation that provide little to no risk reduction. This is particularly true for the BFE-based strategies. In the Less Optimistic scenario with the Master Plan projects in place, the final \$50 billion in marginal cost required to mitigate up to 4 feet of additional freeboard only nets \$0.01 billion in marginal EAD reduction. With a freeboard target of only 1 foot, the final \$0.01 billion in EAD reduction still costs \$27 billion to mitigate.

The National Flood Insurance Program requires that homeowners mitigate up to the BFE plus 1 foot of freeboard to secure a federally-backed mortgage. We have estimated that providing nonstructural mitigation at that level to all existing assets in the coastal floodplain would cost \$40.6 billion (the end of the blue "BFE+1" lines in Figure 7). Clearly, once the Master Plan projects are in place, that level of mitigation will provide little benefit in large swathes of the coast. Many of these low-benefit, high-cost tracts are within the HSDRRS, but \$3.8 billion of the marginal \$27 billion referenced above comes from 62 tracts elsewhere in the study region. This strongly suggests that maintaining a standard based on current, unrevised BFEs in these areas imposes a deadweight loss wherein mitigating does not reduce risk if the Master Plan projects are in place. This same argument applies currently in New Orleans, since the FEMA BFEs are based on preliminary repairs to the HSDRRS completed in 2007 and have not been adjusted to reflect the lower risk profile resulting from all post-Katrina HSDRRS upgrades (Federal Emergency Management Agency, 2013a). Preliminary DFIRMs with updated BFEs and flood

hazard areas were released in November 2012. As of July 2013, the earliest they could take effect is April 2014 (Federal Emergency Management Agency, 2013b).

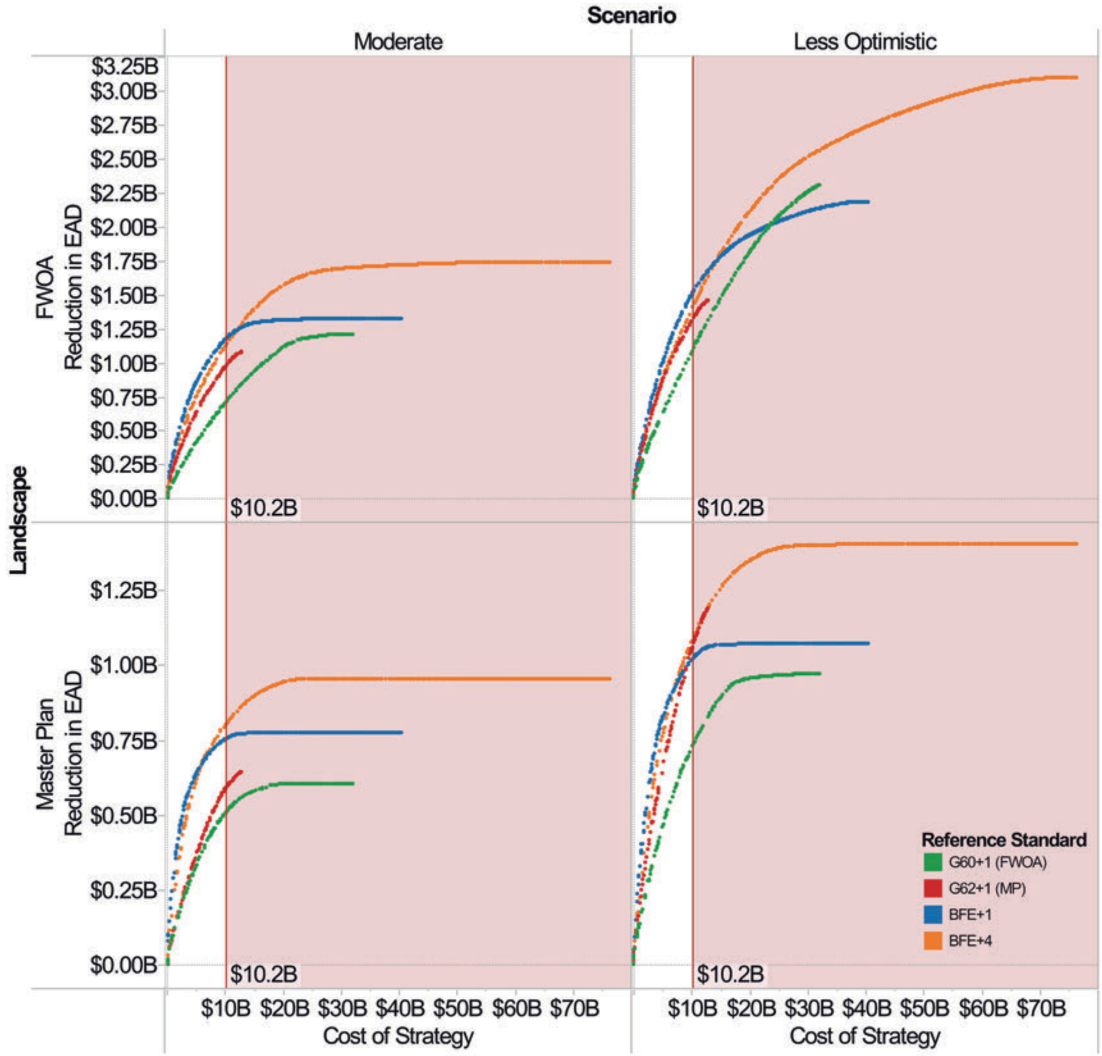


Figure 7: Marginal Risk Reduction Curves by Strategy (2061, 18-foot Acquisition Threshold)

Blending Strategies to Improve Constrained Cost Effectiveness

Clearly, some strategies are more cost-effective than others in individual census tracts. As a result, improved coast-wide strategies can be created by blending project types: take the most cost-effective approach to mitigation at the individual census tract level and allocate funds based on the cost effectiveness of the best-performing project type in each tract.

For example, we examined the additional benefits of blending the BFE+1 and G62+1 project types, each with an acquisition threshold of 18 feet. When we do this, 135 census tracts receive nonstructural funding. Of these, the G62 standard was more cost-efficient in 89 of them; the BFE+1 standard, alternately, was used in 46 census tracts. The hybrid strategy reduces EAD by an additional 7% over using either strategy in isolation (Less Optimistic scenario, Master Plan

landscape). This is due largely to the cost savings enabling investment in more census tracts than the single strategies are able to cover.

A blended strategy that chooses among the full set of 12 modeled project types produces even better results, as summarized in Table 5. When compared to the "best-performing" single strategy in each case (as can be identified from Figure 6), the full blended strategy reduces EAD by an additional 15-26%, depending on the scenario and system alignment. Note that each row of Table 5 represents a different blended strategy, since the best-performing project in a given census tract may vary by scenario or protection system alignment.

Table 5: Comparison of EAD Reduction from Single and Blended Strategies (2061)

Landscape	Scenario	Best Single Strategy	Single Strategy Reduction in EAD	Blended Strategy Reduction in EAD	Improvement from Blended Strategy
FWOA	Moderate	BFE+1, 18	$1.168B	$1.398B	19.7%
FWOA	Less Optimistic	BFE+1, 18	$1.502B	$1.784B	18.8%
Master Plan	Moderate	BFE+4, 18	$0.798B	$0.923B	15.7%
Master Plan	Less Optimistic	BFE+4, 18	$1.080B	$1.364B	26.3%

The proportional EAD reduction resulting from the blended strategy is shown below (Figure 8). Compared to the maximum potential for nonstructural risk reduction in Figure 2, the cost constraint prevents the strategy from achieving its full potential, though we do see substantial damage reduction in urban areas like Houma and Raceway.

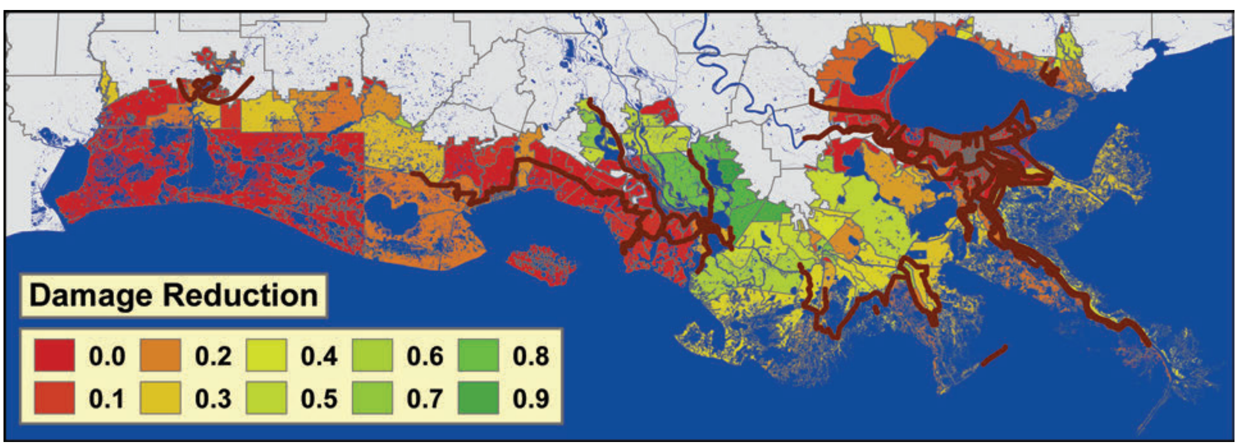


Figure 8: Proportional Damage Reduction from a Strategy Blended for Optimal Cost Effectiveness in the Less Optimistic Scenario with the Master Plan Landscape (2061)

Examining the Robustness of Blended Strategies

The cost effectiveness of a policy depends on the reduction in EAD it produces, which varies under different scenarios. The cost-constrained strategies discussed so far have been optimized for a particular combination of landscape scenario and protection system configuration. For example, if we assume that all of the Master Plan structural risk reduction projects will be implemented and that the future landscape will look similar to the Less Optimistic scenario (with respect to sea level rise, land subsidence, etc.), then the best approach is to implement the blended strategy shown in Figure 8. Its performance corresponds to the last row of Table 5.

However, we cannot say with certainty that the future will resemble the Less Optimistic scenario or that structural projects will be implemented on schedule. If we knew the probability distribution associated with each of these dimensions, we could identify strategies that maximize the expected reduction in EAD over both uncertainties. An alternative decision rule would be to choose the strategy that minimizes expected regret: the expected difference between its performance and the best-performing strategy in each future (Loomes and Sugden, 1982). However, we cannot calculate an expectation here since we cannot judge what the probability of any particular future landscape or scenario is.

When probabilities are unavailable, a minimax decision rule would seek to minimize the worst-case regret associated with each strategy (Savage, 1951). However, the limited set of scenarios modeled does not encompass all possible future outcomes; the true worst-case performance may result from a combination of uncertainties not represented here.

Robust decision-making (RDM) is a method that acknowledges the difficulty associated with reaching consensus among decision-makers on how probabilities are distributed, what uncertainties are most important, and what scenarios are representative of a likely future (Lempert, Popper and Bankes, 2003). Rather than prescribing a well-defined decision rule, RDM describes a general decision-support process. It consists of modeling the performance of strategies under a large range of uncertain scenarios and identifying futures, referred to as "vulnerable," where strategies perform poorly. Policy makers then reach a decision based on a careful examination of the tradeoffs between different performance metrics, their subjective beliefs about the likelihood of vulnerable futures coming to pass, and a balance between the potential for higher performance in favorable futures and avoiding low performance in unfavorable ones.

Since we have modeled the potential for nonstructural risk reduction without considering the possibility of low participation or other barriers to implementation, this paper does not present a formal RDM analysis or give any recommendation of what strategy to adopt. Instead, what

follows is an exploratory analysis of robustness that illustrates some of the performance metrics and tradeoffs that an RDM process would incorporate.

One common metric used to characterize vulnerability is related to regret; vulnerability might be defined as a case where an outcome metric falls below the 10th percentile of results over all futures and strategies modeled. The measure of regret presented here is the difference in performance between a given strategy and the best-performing strategy in that case (Loomes and Sugden, 1982; Lempert, Popper and Bankes, 2003), expressed in both absolute and relative terms. Table 6 summarizes this measure for each combination of landscape and scenario. Each column designates a different blended strategy, where the header defines the case under which the strategy is optimal (i.e., the "Moderate, FWOA" blended strategy is defined as the best-performing blended strategy when run against the Moderate scenario and FWOA landscape). Each cell provides the absolute regret associated with a given strategy in a given case when comparing to the other strategies run against the same case (in the same row), and the value in parentheses denotes the relative regret. The bolded cells are the best-performing strategies for each case and thus have zero regret.

Table 6: Robustness of Strategies Blended for Optimal Cost Effectiveness Under Various Cases

Model Case		Model Case Used To Generate Blended Strategy			
		Absolute Regret (Relative Regret)			
Landscape	Scenario	Moderate, FWOA	Less Optimistic, FWOA	Moderate, Master Plan	Less Optimistic, Master Plan
FWOA	Moderate	**$0B (0%)**	$0.15 (10.5%)	$0.19B (13.4%)	$0.16B (11.7%)
FWOA	Less Optimistic	$0.14B (8%)	**$0B (0%)**	$0.33B (18.6%)	$0.24B (13.5%)
Master Plan	Moderate	$0.08B (8.9%)	$0.14B (14.6%)	**$0B (0%)**	$0.01B (0.9%)
Master Plan	Less Optimistic	$0.15B (10.9%)	$0.17B (12.4%)	$0.06B (4.4%)	**$0B (0%)**

From this table, we can see that both strategies optimized for the Master Plan landscape perform near-optimally in both scenarios, as long as the Master Plan is actually implemented. They are not particularly robust in a Future Without Action landscape, however, with relative regrets ranging from 11.7% to 18.6%. By contrast, policies optimized for the FWOA landscape are more sensitive to alternate scenarios and have relatively less regret with the Master Plan in place.

One explanation for this is the difference in how many tracts are selected by each strategy. The policies optimized for FWOA provide mitigation to 125 and 123 tracts (Moderate and Less Optimistic scenarios, respectively), compared to 143 and 131 tracts for the strategies optimized for the Master Plan landscape. The FWOA-optimized strategies reduce risk less since they provide less overall coverage across the coast. However, this is balanced by the FWOA-

optimized strategies providing equal or greater risk reduction in tracts that are selected by all strategies (since the 100-year flood depth exceedances their reference standards are based on are generally higher).

Figure 9 shows where the four blended strategies described above overlap. The different colors indicate how many of the four strategies select each census tract for nonstructural mitigation measures. Virtually no tract within the HSDRRS is ever selected for mitigation. The north shore of Lake Pontchartrain and large areas of the central coast are almost always selected. The lesser coverage provided by the FWOA-optimized strategies is also evident; the large orange and yellow areas in the western third of the coast are selected by one or both of the Master Plan-optimized strategies but by neither of the FWOA-optimized ones.

Laplace, west of the HSDRRS and on the north/east bank of the Mississippi River, is only selected by the FWOA-optimized strategies. When the Master Plan's structural projects are implemented, they provide sufficient risk reduction to the region, such that additional nonstructural measures are unnecessary. Thus, the value of nonstructural measures in this area hinges on the sequence in which the Master Plan projects are implemented; if levee upgrades are not scheduled for construction until decades from now, nonstructural risk reduction may be a worthwhile stopgap measure.

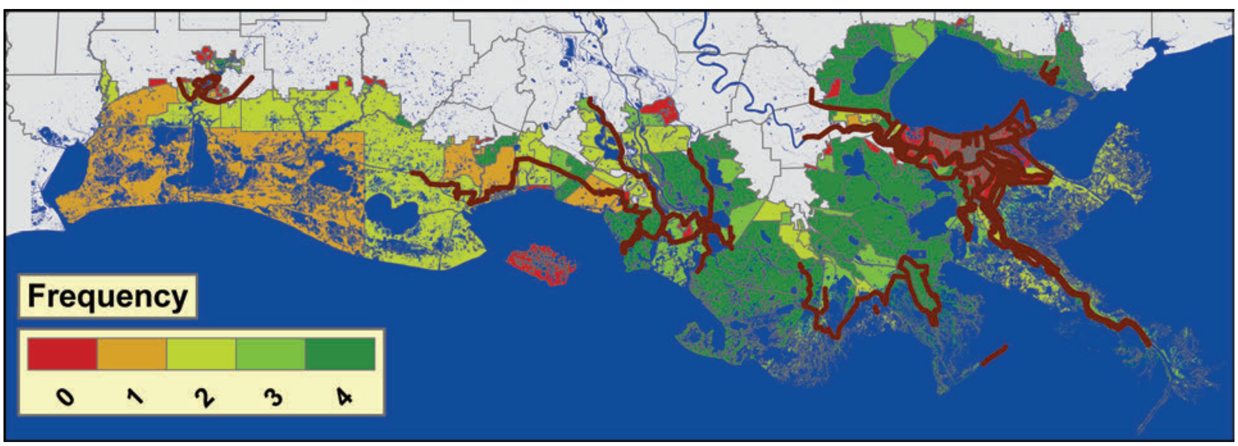


Figure 9: Frequency of Selection by the Four Blended Strategies Modeled

Estimating Benefit-Cost Ratios

We chose to present all results in terms of their projected reduction in EAD in 2061. As discussed previously, it is impossible to confidently predict how coastal flood risk will evolve over time due to uncertainty about the timing and sequence of implementation of the Master Plan's large structural risk reduction and land restoration projects. The timeline for nonstructural risk reduction measures is similarly uncertain. This makes a traditional cost-benefit analysis, which accounts for the full stream of future benefits, challenging.

Nonetheless, we can make a set of simplifying assumptions by comparing the performance of strategies in both 2036 and 2061. When running the four blended strategies against each case as described above, we found that the EAD reduction in 2036 was, on average, 78% of the reduction achieved in 2061 (in constant 2010 dollars). If we assume that, on average, risk reduction changes linearly over time, we can project the benefits in any year using these two points in time. We also assume that if the full $10.2 billion was available in 2013, construction would take approximately five years to achieve full implementation, with costs and benefits accruing linearly over that time period.

Under these assumptions, we can calculate the stream of benefits and costs from 2013 to 2061 (to be conservative, we ignore benefits beyond 2061). With costs paid over five years and benefits accrued at a constant rate for the 49-year period, a $10.2 billion nonstructural program would have a positive NPV as long as each dollar spent produces at least 5.9 cents in EAD reduction in 2061 (using the 3.75% federal discount rate for Fiscal Year 2013 used by USACE) (U.S. Army Corps of Engineers, 2012).

Table 7 gives the ratios of EAD reduction in 2061 per dollar spent on mitigation for each combination of blended strategy and model case. As a reminder, all strategies cost $10.2 billion, so the EAD reduction of each strategy in each case (in billions of 2010 U.S. dollars) can be calculated by multiplying the values in Table 7 by 10.2. In all cases, this ratio is greater than 0.059, implying a positive NPV and a benefit-cost ratio greater than 1. The implied benefit-cost ratios are provided in Table 8. As expected, the benefit-cost ratios are greatest in the Less Optimistic scenario when no structural action is taken, as this is the case with the greatest coastwide risk to mitigate through nonstructural measures. Conversely, the ratios are smallest in the Moderate scenario with the Master Plan in place. However, the worst-performing case still has an implied benefit-cost ratio greater than 1; this is true even under a more aggressive 5% discount rate. Despite our strong simplifying assumptions, this suggests that a more rigorous cost-benefit analysis would still find the strategies to be beneficial.

Table 7: Cost Effectiveness Ratios (EAD Reduction in 2061 per Dollar Spent) by Strategy and Case

Model Case		Model Case Used To Generate Blended Strategy: Cost Effectiveness Ratio (2061 EAD Reduction / $10.2B cost)			
Landscape	Scenario	Moderate, FWOA	Less Optimistic, FWOA	Moderate, Master Plan	Less Optimistic, Master Plan
FWOA	Moderate	0.137	0.123	0.119	0.121
FWOA	Less Optimistic	0.161	0.175	0.142	0.151
Master Plan	Moderate	0.082	0.077	0.090	0.090
Master Plan	Less Optimistic	0.119	0.117	0.128	0.134

Table 8: Implied Benefit-Cost Ratios by Strategy and Case

Model Case		Model Case Used To Generate Blended Strategy			
		Implied Benefit-Cost Ratio			
Landscape	Scenario	Moderate, FWOA	Less Optimistic, FWOA	Moderate, Master Plan	Less Optimistic, Master Plan
FWOA	Moderate	2.48	2.22	2.15	2.19
FWOA	Less Optimistic	2.91	3.16	2.57	2.74
Master Plan	Moderate	1.49	1.40	1.64	1.62
Master Plan	Less Optimistic	2.16	2.12	2.31	2.42

CONCLUSIONS

This analysis provides a useful framework for moving beyond the simple strategy modeled by the Master Plan to a more sophisticated coastwide strategy for nonstructural risk reduction. First, we identified the census tract as an appropriate unit of analysis for future comparisons of nonstructural risk reduction projects. Using a relatively small set of additional nonstructural project types, we showed that a large number of coastal census tracts could be provided greater risk reduction than that provided by the strategy modeled during the Master Plan analysis. Any strategy applied uniformly across the coast, however, would cost more than $10.2 billion (assuming full participation). As a result, decision makers will still need to determine where best to invest future nonstructural funds by balancing the total risk reduction provided to selected communities and the overall cost effectiveness of the coast-wide nonstructural investment.

No single project type performs best in every part of the coast, either by risk reduction or cost effectiveness. This demonstrates the primary point of this paper: the expected annual damage faced by an area is dependent upon the entire probability distribution of flood depths, and these distributions differ across the coast. Therefore, no standard based on a single point in the distribution (in this paper, the 100-year exceedance) will be optimal everywhere. More cost effective risk reduction can be provided by tailoring the mitigation standard in accordance with the entire probability distribution.

In this analysis, we used a basic measure of cost effectiveness, the number of dollars in EAD reduced in 2061 per dollar spent on nonstructural projects. A blended strategy that selects from multiple project types using a cost effectiveness criterion showed that significant risk reduction could be achieved over the initial Master Plan nonstructural strategy while staying within the allocated budget. A more detailed assessment would account for the accumulation of benefits over time, accounting for the sequencing of landscape-altering structural and restoration projects. However, the simple calculations performed here suggest that a more rigorous cost-benefit analysis would conclude that the four blended strategies outlined here have a positive NPV, and that this finding is robust over the uncertainties modeled.

This paper makes a number of simplifying assumptions that, while suitable for exploratory analysis with a planning model, are inappropriate for design and implementation of a nonstructural program. In reality, the strategies outlined above may be able to cover larger portions of the coast, since full participation is highly unlikely; however, the same optimization framework can be used with a lower participation rate to explore this. Likewise, the preference for acquisitions versus elevation could change if costs for either option are lower or higher than modeled. Political considerations may dictate that funding be allocated more evenly—to all non-HSDRRS census tracts, for instance. Our findings are nonetheless useful in indicating the maximum potential for nonstructural risk reduction and how that potential is distributed along the coast.

A pilot program or series of surveys could narrow the uncertainty in mitigation costs and the likely participation rate, which would enable more accurate planning using the methods detailed here. Researchers should work with decision makers to develop minimum targets for the amount or proportion of risk reduction by census tract based on equity, vulnerable communities or any other concerns; these would be used as additional constraints in a more sophisticated optimization procedure. Additional options for reducing EAD, such as extending acquisitions to commercial and industrial properties, should be considered where existing project types do not perform well. Once more details are available about the timing and sequence for implementing the Master Plan's structural risk reduction projects, a full cost-benefit analysis can be performed that captures how benefits accrue over time, accounting for depreciation, economic growth, and changes to the future coastal landscape. This also requires more clarity on when funding streams will become available. Finally, a wider range of project types would enable the design of still more cost-effective strategies; in practice, these would be evaluated for each building individually rather than in aggregate.

This analysis, along with the next steps outlined above, provides a clear path forward to the design of a nonstructural risk reduction program for Louisiana.

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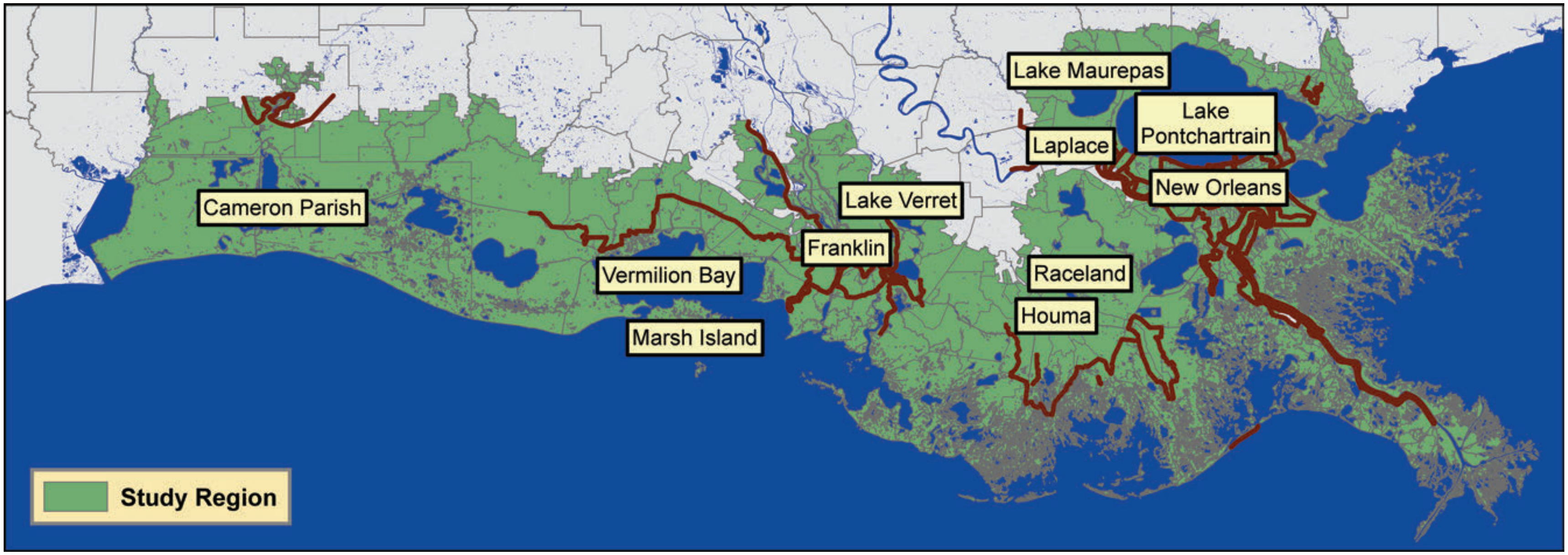
Appendix A: Map of Areas Referred to in the Main Text



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