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TECHNICAL REPORT

Coastal Louisiana Risk Assessment Model

Technical Description and 2012 Coastal Master Plan Analysis Results

*Jordan R. Fischbach • David R. Johnson • David S. Ortiz
Benjamin P. Bryant • Matthew Hoover • Jordan Ostwald*

Sponsored by the Coastal Protection and Restoration Authority of Louisiana



GULF STATES POLICY INSTITUTE

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This research was sponsored by the Coastal Protection and Restoration Authority of the State of Louisiana and was conducted in the RAND Gulf States Policy Institute and the Environment, Energy, and Economic Development Program within RAND Infrastructure, Safety, and Environment.

Library of Congress Control Number:

ISBN: 978-0-8330-7708-0

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Published 2012 by the RAND Corporation
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1200 South Hayes Street, Arlington, VA 22202-5050
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Preface

Catastrophic storms threaten coastal Louisiana. Hurricanes Katrina and Rita in 2005, Gustav and Ike in 2008, and Isaac in 2012 are among the most recent examples. Hurricanes flood cities, towns, and farmlands, forcing evacuations, damaging and destroying buildings and infrastructure, eroding wetlands, and threatening the health and safety of residents. The State of Louisiana responded to the threat of catastrophic hurricanes by engaging in a detailed modeling and simulation exercise, the results of which informed *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (the "Master Plan") (Coastal Protection and Restoration Authority of Louisiana [CPRA], 2012a).

The Master Plan includes a set of wetlands restoration and risk reduction actions or projects to be implemented in the coming decades to protect communities from the effects of catastrophic hurricanes and to help rebuild the Louisiana coast. When choosing actions to take to reduce the effects of hurricanes, the state needed to evaluate the extent to which each action, separately and in conjunction with others, might reduce damage to communities from the flooding that results from a hurricane's storm surge and waves. Based on these evaluations, actions could be chosen that provide the greatest degree of risk reduction at the lowest cost, consistent with other goals of the Master Plan.

CPRA asked the RAND Corporation to develop a hurricane flood risk model, the Coastal Louisiana Risk Assessment (CLARA) model, to assess the degree to which various projects help coastal communities avoid or reduce damage from hurricanes. CLARA made it possible to consistently and systematically evaluate potential projects for inclusion in the Master Plan on the basis of how well they reduce damage in Louisiana's coastal region.

This report describes how CLARA works and discusses results from an analysis of future flood damage outcomes with or without the Master Plan in place. It should be of interest to local, state, and federal decisionmakers and stakeholders with an interest in the methods used to estimate the risks posed by catastrophic storms and how those methods were used to inform the Master Plan. The methods described in this report build on prior research:

- Jordan R. Fischbach, *Managing New Orleans Flood Risk in an Uncertain Future Using Non-Structural Risk Mitigation*, Santa Monica, Calif.: RAND Corporation, RGSD-262, 2010
- Robert J. Lempert and David G. Groves, "Identifying and Evaluating Robust Adaptive Policy Responses to Climate Change for Water," *Technological Forecasting and Social Change*, Vol. 77, No. 6, July 2010, pp. 960–974.

The report is also a companion to related RAND research supporting the Master Plan:

- David G. Groves, Christopher Sharon, and Debra Knopman, *Planning Tool to Support Louisiana's Decisionmaking on Coastal Protection and Restoration*, Santa Monica, Calif.: RAND Corporation, TR-1266-CPRA, 2012.

The RAND Environment, Energy, and Economic Development Program

This research was conducted in the Environment, Energy, and Economic Development Program (EEED) within RAND Infrastructure, Safety, and Environment (ISE). The mission of ISE is to improve the development, operation, use, and protection of society's essential physical assets and natural resources and to enhance the related social assets of safety and security of individuals in transit and in their workplaces and communities. The EEED research portfolio addresses environmental quality and regulation, energy resources and systems, water resources and systems, climate, natural hazards and disasters, and economic development—both domestically and internationally. EEED research is conducted for government, foundations, and the private sector.

Information about EEED is available online (<http://www.rand.org/ise/envIRON.html>). Inquiries about EEED projects should be sent to the following address:

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The RAND Gulf States Policy Institute

RAND created the Gulf States Policy Institute in 2005 to support hurricane recovery and long-term economic development in Louisiana, Mississippi, and Alabama. Today, RAND Gulf States provides objective analysis to federal, state, and local leaders in support of evidence-based policymaking and the well-being of individuals throughout the Gulf Coast region. With offices in New Orleans, Louisiana, and Jackson, Mississippi, RAND Gulf States is dedicated to helping the region address a wide range of challenges that include coastal protection and restoration, health care, and workforce development. More information about RAND Gulf States can be found at <http://www.rand.org/gulf-states.html>.

Questions or comments about this report should be sent to the project leaders, Jordan Fischbach (Jordan_Fischbach@rand.org) and David Ortiz (David_Ortiz@rand.org).

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Summary

Motivated in part by the devastating effects of Hurricanes Katrina and Rita in 2005 and Gustav and Ike in 2008, planners and policymakers in the State of Louisiana have updated *Louisiana’s Comprehensive Master Plan for a Sustainable Coast* (the “Master Plan”). The resulting Master Plan proposes a range of structural protection and coastal restoration projects to reduce storm surge flood risks to coastal communities and address other objectives to help create a more sustainable coast over the next 50 years. To support this process, the Coastal Protection and Restoration Authority of Louisiana (CPRA) convened a set of modeling teams to provide analytical support and help improve understanding of how coastal conditions might change in the future and how they could be improved through new investments in protection or restoration.

CPRA asked RAND to create an analytical model, the Coastal Louisiana Risk Assessment (CLARA) model, to estimate flood depths and damage that occur as a result of major storms. CLARA made it possible to systematically evaluate potential projects for inclusion in the Master Plan on the basis of how well they reduce flood damage in Louisiana’s coastal region.

CLARA’s outputs are inputs for the separate, RAND-developed Planning Tool, which assesses the overall benefits and costs of proposed protection and restoration projects, taking into account uncertainty regarding future conditions.

Overview of the CLARA Model

Theory

CLARA’s structure is based on the principles of quantitative risk analysis. Risk is typically described as the product of the *probability* or *likelihood* of a given event occurring—in this case, the annual probability of storm surge flooding at different depths—and the *consequences* of that event—the damage that results from the flooding. This formulation can be refined when applied to storm surge flood risk because engineered systems designed to prevent flooding may fail, introducing a new dimension of uncertainty.

The likelihood of flooding can be divided into two components: the *threat* or *hazard*, which represents the underlying probability that a surge-producing storm will occur, and the *vulnerability* of hurricane protection infrastructure (e.g., levees, pumps, gates) to partial or complete failure given that a storm surge event occurs. The resulting three-part characterization of flood risk—threat, vulnerability, and consequences—serves as the basic organizing principle for CLARA (U.S. Army Corps of Engineers [USACE], 2009b; Morgan and Hen-

tion, 1990; Fischbach, 2010). The consequences of flooding can include all possible impacts, including direct or indirect economic damage or losses, loss of life, and environmental damage. In our framework, references to flood risk are best understood as *flood risk to structures, physical infrastructure, and other local economic assets*.

Inputs

CLARA uses two types of information to estimate flood depths and resulting damage:

- **Estimated peak storm surge and wave heights that occur as a result of hurricanes.** CLARA uses estimated surge and wave heights from 40 simulated storms across the Louisiana coast selected to best represent the range of possible coastal flooding threats. The model also accounts for *subsidence* over time, the natural sinking of the land compared with sea level, and *rising sea levels* that could result from the effects of global climate change.
- **Data that characterize the hurricane protection system.** One of the key decisions to be made as part of the planning process was where to construct or improve levees, floodwalls, and other structures to protect Louisiana from storms. These structures define which areas are protected from hurricanes and which areas are not.

RAND conducted the CLARA modeling after other teams working in support of the Master Plan had run their models and produced the necessary input data. For example, the Storm Surge/Wave Team provided estimates of surge elevation over the course of each storm for the 40 simulated storms in both unprotected and protected areas. The Storm Surge/Wave Team also provided estimates of significant wave heights in unprotected areas and wave characteristics along the structural elements to facilitate the calculation of *overtopping*—water that enters the protection system because of waves or storm surge spilling over the crest of a protective structure. Other data inputs, including land elevation, geotechnical and construction characteristics of levees and floodwalls, connecting interior heights between hydrologic basins, and an inventory of economic assets, were provided to RAND by CPRA, the USACE, and other CPRA modeling teams.

Outputs

Risks are estimated in terms of damage in dollars that results from surge-based flood events caused by Category 3 and higher storms. We measure damage from flooding in two ways. First, we use *exceedance probabilities*, which are statistical estimates of the flooding and damage expected to recur with a certain probability in each year. For example, the 1-percent or 100-year flood exceedance is the flood depth that has a 1-percent chance of occurring or being exceeded in each year. This is commonly referred to as the *1-in-100* or *100-year flood*. We calculate flood and damage exceedances at three levels: 50 year (2-percent chance), 100 year (1-percent chance), and 500 year (0.2-percent chance). We also measure flood damage using *expected annual damage* (EAD). EAD is the average damage from Category 3 and higher storms projected to occur in a single year, taking into account both the effective damage from such a storm and the overall likelihood of a storm of this intensity occurring in a given year.

Certain types of assets, including strategic assets (e.g., oil and gas infrastructure) and culturally significant and historic properties, were not included in damage estimates because of a lack of data regarding the value of these assets. In these cases, 50-, 100-, and 500-year flood

depth exceedances were provided directly to other CPRA modeling teams to determine the number of properties in each category flooded at each exceedance interval.

Assumptions

Flooding is a result of a complex set of factors, so by necessity CLARA simplified what actually occurs. For example, when considering the possibility that portions of hurricane protection systems might fail, we considered only peak storm surge that occurs during a storm, ignoring the period of buildup and withdrawal. We also made assumptions that dramatically simplify the patterns of flooding if a system breach occurs. We assumed that floodgates used to seal off protected areas are closed properly prior to a storm. Pumping scenarios are simplified and pumps are assumed to be on, off, or operating at 50-percent capacity. These and other assumptions were carefully tested for their influence on our results.

Time Period, Three Scenarios, and Geographical Scope

CLARA results from our final analysis of the Master Plan are presented for current conditions (2012), as well as in two future time periods: 2036 (25 years from present) and 2061 (50 years from present). We describe results from three scenarios that were used for the entire Master Plan modeling effort: the *moderate*, *moderate with high sea-level rise (SLR)*, and *less optimistic* future scenarios.

The study area and northern boundary were adopted directly from the recent USACE Louisiana Coastal Protection and Restoration analysis, which divided the Louisiana coast into a series of five Planning Units and approximately 1,000 Planning Subunits (USACE, 2009a) also known as “basic hydrologic units” (BHUs). The northern boundary of this area roughly follows Interstates 10 and 12; storm surges are not expected to affect areas to the north of these highways.

CLARA labels each BHU as *unprotected*, *semiprotected*, or *protected* (USACE, 2009a). Unprotected areas have no levees, floodwalls, or other barriers to prevent flooding due to storm surges. Semiprotected areas have levee or floodwall protection, but these protection structures do not fully enclose the population at risk. As a result, storm surge could “run around” the structures and flood the area from behind. Protected areas have hurricane protection that is fully enclosed in a ring, defining an artificial hydrologic unit composed of one or more adjoining BHUs that is distinct from the exterior area. Key protected areas include the portions of Greater New Orleans enclosed within the Hurricane and Storm Damage Risk Reduction System (HSDRRS) built by the USACE.

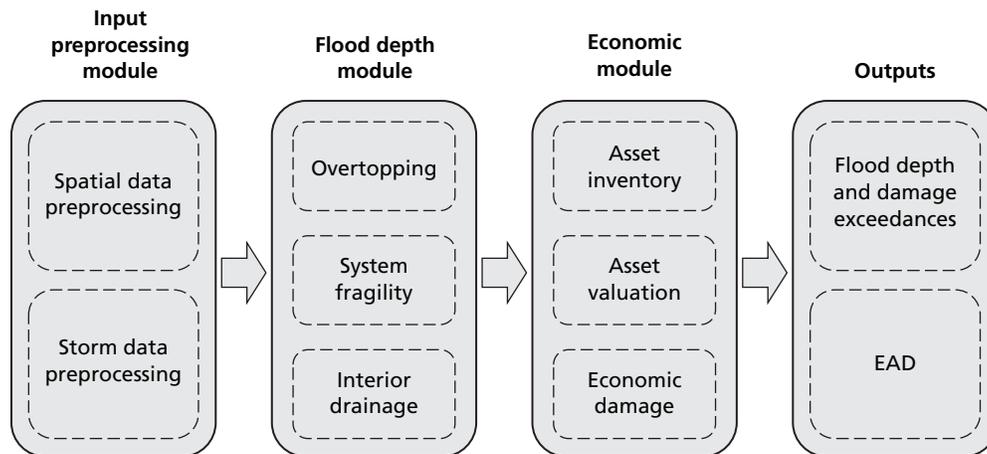
CLARA’s Analytical Structure

The structure of the CLARA model is illustrated in Figure S.1.

In the **input preprocessing module**, CLARA uses information about the study region and generates flood depth estimates in unprotected and semiprotected areas and storm hazard conditions for a sample of hypothetical storms. It also records surge and wave conditions along protection structures.

CLARA then estimates the volume of water that flows over structures into protected areas—i.e., it estimates flood depths in the **flood depth module** with particular focus on storm surge or wave overtopping and system fragility. CLARA handles system fragility by

Figure S.1
CLARA's Analytical Structure



RAND TR1259-S.1

bracketing between two extreme cases: one in which protection systems never fail and one in which breaches result in interior inundation up to the level of surge that initiated the breach.¹

CLARA also equalizes the flood depth among adjacent protected areas. If one neighborhood in New Orleans lies next to another neighborhood and the first neighborhood floods, the adjacent neighborhood will also flood unless some barrier separates them. The elevation of the connections among BHUs is determined using a high-resolution digital elevation model (DEM)—including embankments, roads, and other structures—compiled and provided by the Wetland Morphology Team.

The depth of the flood directly determines the amount of damage that occurs, so flood depths are inputs to the **economic module**. In this step, CLARA values the assets at risk from flooding and estimates damage. Damage is estimated by census block at the 50-, 100-, and 500-year damage exceedances. Damage depends on the inventory of assets, so we build an inventory of assets (for example, homes, roads, and agricultural buildings and crops) within each census block and place a value on the assets and their contents. Values depend on characteristics that vary by asset type. Single-family homes are valued at replacement cost per square foot, which in turn depends on a number of factors. In general, our model bases values on the Federal Emergency Management Agency's (FEMA's) Hazards–United States (Hazardus)–Multi-Hazard (Hazardus-MH) model, 2010 census data, and Louisiana-specific data provided by the Louisiana Coastal Protection and Restoration project.

In addition to damage to property, CLARA estimates the costs borne by victims who are displaced by flooding.

A key challenge was estimating potential future damage from flooding over the 50-year time horizon of the Master Plan. Patterns of settlement and economic growth will alter the kind and value of assets that could be damaged in a flood. We developed several scenarios of

¹ A structure suffers a *seepage failure* when water flows through soil under the levee or floodwall. A *slope stability failure* occurs when forces exerted by the floodwater against the levee or floodwall are greater than what the structure can resist. An *overtopping failure* occurs because of erosion of the protected side of the levee or floodwall from the rushing surge water.

future economic growth and the level of urbanization in coastal areas to provide a range of estimates of the future value of assets.

CLARA outputs are the damage exceedances and EAD.

Results of the CLARA Analysis and Contributions to the Master Plan

RAND's initial analysis with CLARA helped compare and rank projects for inclusion in the Master Plan based on flood depths and damage in dollars in a "future without action" to protect coastal Louisiana and in a future with the final Master Plan in place, in two time periods and two scenarios: 2012 (current conditions) and 2061 (50 years from present) in the *moderate* and *less optimistic* future scenarios, respectively. These scenarios reflect different assumptions regarding future SLR, coastal land subsidence rates, and other key uncertainties about the future. The moderate scenario assumes low to moderate SLR and subsidence rates, while the less optimistic scenario uses much higher assumptions.

Then we evaluated the combined damage reduction benefits from Master Plan investments in new or upgraded protection structures, nonstructural risk reduction projects, and coastal restoration in these same years and scenarios and also included an additional interim time period, 2036 (25 years from present), and additional future scenario, termed the *moderate future with high SLR*. This scenario matches the assumptions for the moderate scenario, except that it includes additional SLR over time.

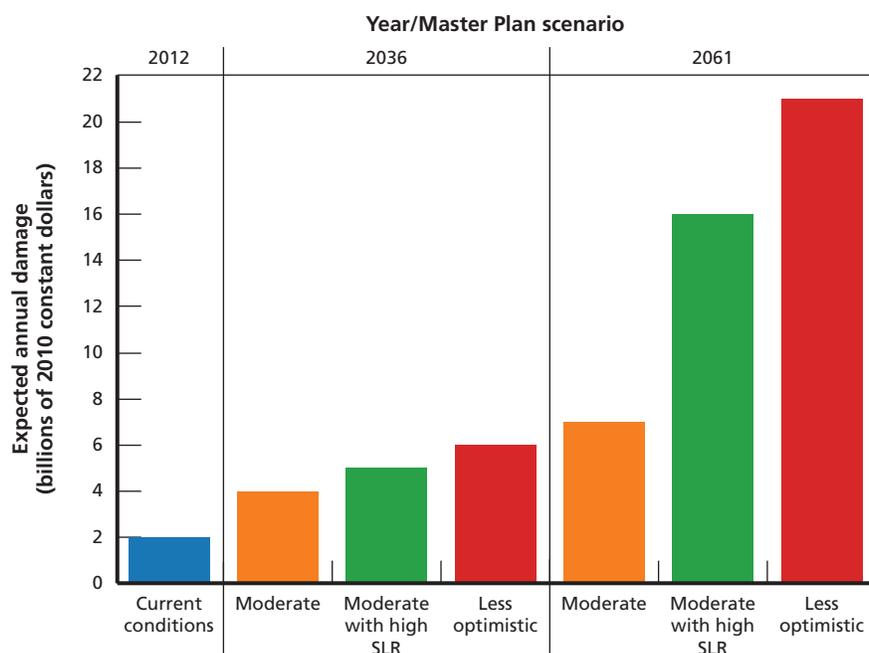
What Might We Expect in a Future Without Action?

In general, risk and damage results from the final Master Plan analysis show that storm surge flood damage represents a major threat to coastal Louisiana, and if no action is taken, this damage can be expected to grow substantially in the future. Figure S.2 illustrates the potential increase in flood depths over 50 years in a future without action.

Flood depths and damage outcomes both worsen over time in a future without action, with the amount of increased flood damage varying substantially by Master Plan scenario and with the assumed structural reliability of the New Orleans HSDRRS in future years. When we consider the potential for failures of the protection system, damage estimates increase substantially for New Orleans in some Master Plan scenarios. Results produced in the CLARA analysis may overstate this damage because of simplifying assumptions, but results nevertheless indicate that considering system fragility is critical to understanding the potential benefits and trade-offs associated with future protection system investments.

As Figure S.3 illustrates, EAD in the other Master Plan scenarios is not as large as in the less optimistic scenario, reaching \$7 billion in the moderate scenario and \$16 billion by 2061 in the moderate scenario with high SLR. In Greater New Orleans, 2061 EAD in the moderate scenario is \$1.5 billion, compared with \$6.9 billion in the moderate scenario with high SLR and \$12.4 billion in the less optimistic scenario. That means that the performance of the Greater New Orleans HSDRRS is responsible for about 78 percent of the difference in EAD between the moderate and less optimistic scenarios. The dramatic increase in EAD is thus driven by the impact of higher SLR and land subsidence on the fragility of existing protection systems; less severe, more frequent storms become more likely to cause catastrophic levee failures in protected areas with highly concentrated assets than in the moderate scenario.

Figure S.3
Estimated Expected Annual Storm Surge Flood Damage in the Future
Without Action, by Year and Master Plan Scenario



RAND TR1259-S.3

What Might We Expect in a Future with Master Plan Projects in Place?

The Master Plan helps to reduce flood damage in many areas of the coast through a combination of structural and nonstructural risk reduction investments and coastal restoration projects. For instance, Figure S.4 illustrates the coastwide reduction in 100-year flood depth in the less optimistic scenario with the Master Plan in place using our default assumptions. The projects associated with the Master Plan are also indicated on the map and include structural protection (in pink), river diversions to rebuild wetlands, and coastal restoration projects.

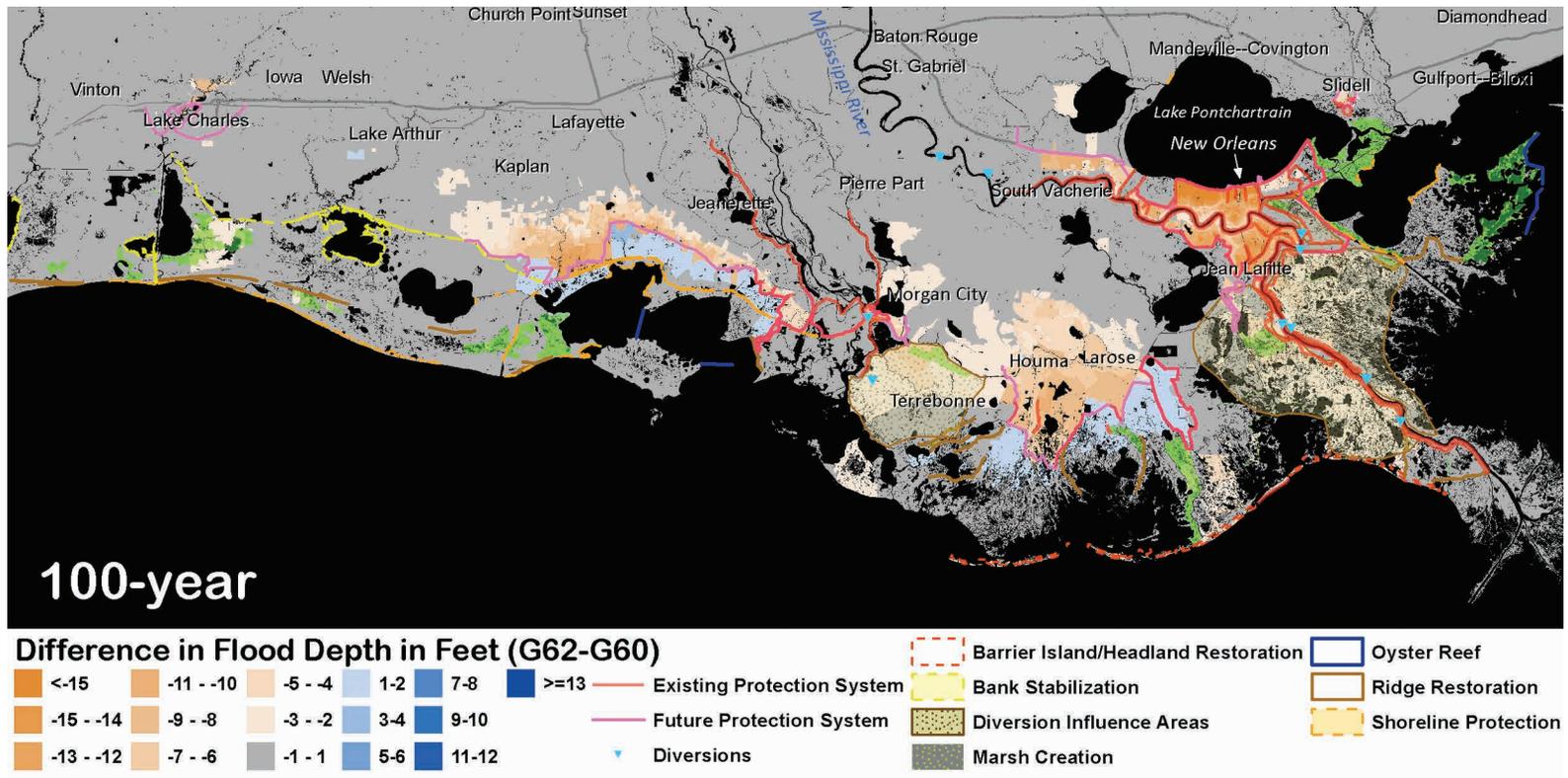
This map indicates the difference in flooding between the Master Plan and the future without action and shows substantial depth reduction (orange shading) in many areas of the coast.

Damage reduction is also notable across all three scenarios (Figure S.5). For instance, in 2061, EAD is projected to increase to between \$7 billion and \$21 billion in the future without action depending on the scenario, but, with the Master Plan in place, this damage level is reduced to between \$3 billion and \$5 billion. This corresponds to a reduction of approximately 60 to 80 percent compared with flood damage level in the future without action.

Different story lines emerge from different areas of the coast. For instance, a large proportion of the coastwide damage reduction occurs in Greater New Orleans after 2032 as a result of new investments that reduce the likelihood of the protection system being breached by waves or storm surges.

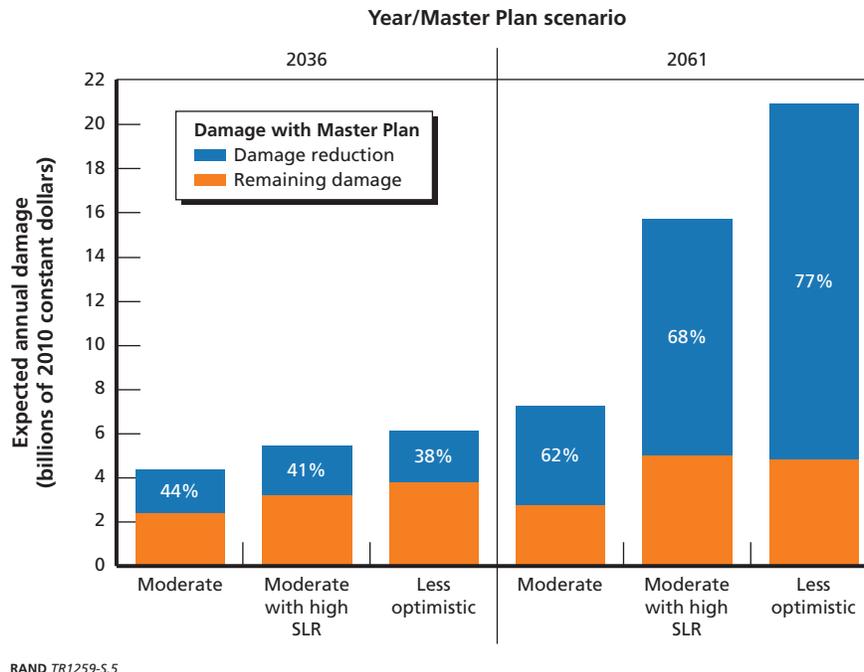
The new Morganza to the Gulf surge barrier, built to an elevation of 20 to 37 feet, provides substantial flood depth reduction and consequent damage reduction in the vicinity of Houma and Terrebonne. The final Master Plan analysis shows that the new alignment could provide substantial risk reduction benefits to Houma and the surrounding Terrebonne ridge

Figure S.4
Estimated Change in 100-Year Flood Exceedance in 2061 for Coastal Louisiana, by Census Block, with the Master Plan in Place (Less Optimistic Scenario)



RAND TR1259-S.4

Figure S.5
Estimated Remaining Expected Annual Damage and Reduction in Expected Annual Damage with the Master Plan in Place, by Year and Master Plan Scenario



communities. Analysis with CLARA shows that Morganza to the Gulf could reduce depths across all three flood exceedances considered, with depth reduction of 2 to 5 feet (50 year), 2 to 7 feet (100 year), and 2 to 11 feet (500 year), respectively. Depth reduction extends for a large area of the coast behind the new alignment, including other portions of Terrebonne Parish and some upland areas.

However, the Morganza to the Gulf levee also displaces surge that previously flooded areas to the north, leading to an increase in surge heights and flood depths for areas exterior to the levee system. In addition, a notable result is that the new levee displaces surge onto the existing Larose to Golden Meadow system, leading to induced flooding on the interior.

Finally, some areas receiving nonstructural investments in the Master Plan, such as the community of Mandeville on the north shore of Lake Pontchartrain, see very limited flood damage reduction from the Master Plan due to the limited range of nonstructural projects considered in this analysis. For these areas, a wider range of risk reduction alternatives may need to be considered to reduce vulnerability to damage from future storm surge events.

Conclusion

Louisiana faces a growing threat from increased future flood risk, but the 2012 Master Plan takes a major step toward protecting the state's vibrant cultural history and economic livelihood for years to come. CLARA was designed to support policymakers in a flexible exploration of options for protection projects. CLARA establishes the capability to perform comparative

evaluations of many options in a rigorous manner while accounting for a wide range of future uncertainties. Its development and use as part of the master planning process produced new methods for estimating flood depths and damage and provided timely information to support Master Plan development. CLARA can also serve as a roadmap for future evaluations of coastal flood damage or damage reduction in Louisiana and other coastal regions.

Acknowledgments

The authors would like to thank the staff of the Coastal Protection and Restoration Authority of Louisiana for their support throughout the modeling effort. We would especially like to thank Garret Graves, Kirk Rhinehart, Mandy Green, Karim Belhadjali, Carol Parsons Richards, and Natalie Snider. Our partner, Brown and Caldwell, has assisted us throughout this effort; Cindy Paulsen, Joanne Chamberlain, Alaina Owens, Hal Clarkson, Stephanie Hanses, and Joe Wyble have been especially helpful throughout the process. We have worked closely with other members of the project effects modeling teams, especially Hugh Roberts, Ryan Clark, and Zachary Cobell from ARCADIS, and Joseph Suhayda, who provided senior review. Denise Reed of the University of New Orleans has ably led the integrated modeling effort; we thank her for her leadership. Keven Lovetro, Tawanda Wilson-Prater, and Travis Creel from the U.S. Army Corps of Engineers, and Jason Byrd from the U.S. Geological Survey helped us to identify and gather the relevant data describing existing coastal protection systems. We have worked closely with David Groves and Christopher Sharon at RAND to ensure that the results from the Coastal Louisiana Risk Assessment are easily applied in the planning process for the Master Plan. Our colleague Lance Menthe, a senior physical scientist at RAND, reviewed the draft document and provided many helpful comments that greatly improved its content and structure. An anonymous reviewer also provided constructive comments, and we appreciate the timely and insightful feedback. Finally, we would like to thank Debra Knopman, vice president of RAND Infrastructure, Safety, and Environment, and Keith Crane, director of the Environment, Energy, and Economic Development Program, for their assistance throughout the effort and Anna Smith for helping see the document through to completion.

Abbreviations

ACS	American Community Survey
BFE	base flood elevation
BHU	basic hydrologic unit
CBP	County Business Patterns
CDF	cumulative distribution function
CLARA	Coastal Louisiana Risk Assessment
CPRA	Coastal Protection and Restoration Authority of Louisiana
CSVR	contents-to-structure value ratio
DEM	digital elevation model
EAD	expected annual damage
EEED	RAND Environment, Energy, and Economic Development Program
FEMA	Federal Emergency Management Agency
FOS	factor of safety
FWOA	future without action
FWP	future with project
GBS	General Building Stock
GNOCDC	Greater New Orleans Community Data Center
HMGP	Hazard Mitigation Grant Program
HPS	hurricane protection system
HSDRRS	Hurricane and Storm Damage Risk Reduction System
IPET	Interagency Performance Evaluation Task Force
ISE	RAND Infrastructure, Safety, and Environment
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
nm	nautical mile
NOAA	National Oceanic and Atmospheric Administration
OLS	ordinary least squares
QA	quality assurance
RMSE	root mean squared error
RSLR	relative sea-level rise
SD	standard deviation
SI	International System of Units
SLR	sea level rise
STWAVE	Steady State Spectral Wave
SWAN	Simulating Waves Nearshore
SWP	surge and wave point
TM	technical memorandum
TRMM	Tropical Rainfall Measuring Mission
USACE	U.S. Army Corps of Engineers
USCS	Unified Soil Classification System
USGS	U.S. Geological Survey

Introduction

Coastal Louisiana's built and natural environment faces risks from catastrophic tropical storms, of which Katrina and Rita in 2005 and Gustav and Ike in 2008 are among the most recent. Hurricanes flood cities, towns, and farmlands, forcing evacuations, damaging and destroying buildings and infrastructure, eroding wetlands, and threatening the health and safety of residents.

The State of Louisiana responded to the threat of catastrophic hurricanes by engaging in a new planning process to support the development of *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (the "Master Plan") (Coastal Protection and Restoration Authority of Louisiana [CPRA], 2012a). The Master Plan proposes a range of coastal restoration and structural protection projects to reduce storm surge flood risks to coastal communities and address other objectives to help create a more sustainable coast over the next 50 years. To support this process, CPRA convened a set of modeling teams to provide analytical support and help improve our understanding of how coastal conditions could be improved through new investments in hurricane protection or restoration projects.

As part of this effort, CPRA asked a team from the RAND Gulf States Policy Institute to develop a hurricane flood risk model to assess how proposed restoration and protection projects reduce damage over the next 50 years. In response, the RAND team developed the Coastal Louisiana Risk Assessment (CLARA) model, which systematically evaluates proposed flood risk reduction projects on the basis of how they reduce damage in Louisiana's coastal region.

This document does several things. First, it describes how CLARA works. It then outlines the analysis performed using CLARA in support of the development of the Master Plan. Finally, it provides results that characterize coastal flood risk with or without implementation of the final set of Master Plan projects. It should be of interest to policymakers concerned with how assets are valued in the coastal region and stakeholders interested in understanding how CLARA estimates hurricane protection system performance and handles uncertainty.

Purpose of CLARA

CLARA is an analytical model that estimates flooding damage resulting from storm surges. Flooding during and following hurricanes is costly, destroying buildings, infrastructure, and sensitive environmental areas. The damage from flooding is determined primarily by the depth of water that inundates the land. In coastal areas unprotected by levees, floodwalls, or other structures, *flood depths* are determined by the height of the storm surge plus the height of the highest waves. The surge and waves, if high enough, can flow over the top of or around protec-

tive structures, flooding the areas that were supposed to be protected. Floodwalls and levees can also fail, as occurred during Hurricane Katrina. Rainfall can also inundate an area if pumping systems fail.

The modeling approach we describe draws heavily on previous analytical efforts, including the *Louisiana Coastal Protection and Restoration* [LACPR] *Technical Report* (U.S. Army Corps of Engineers [USACE], 2009a), *Interagency Performance Evaluation Task Force* [IPET] *Engineering and Operational Risk and Reliability Analysis* (USACE, 2009b), the Federal Emergency Management Agency (FEMA) Hazards–United States (Hazus)–Multi-Hazard (Hazus-MH) MR4 model (FEMA, 2009), and ongoing RAND research funded by the National Oceanic and Atmospheric Administration (NOAA) (Fischbach, 2010).

CLARA is only one piece of the broader analytical effort that supported the development of the Master Plan, and the model uses inputs from several CPRA modeling teams. CLARA in itself is not a decision support tool, but it provided inputs to the broader process of updating the Master Plan. The Storm Surge/Wave Team, led by ARCADIS, provided estimates of peak storm surge elevation and surge elevation over time (hydrographs) for a series of different storms for both unprotected and protected areas. The Storm Surge/Wave model also provided estimates of significant wave heights in unprotected areas and wave characteristics along the structural elements to facilitate the calculation of *overtopping*—water that enters the protection system because of waves spilling over a protective structure or storm surge pouring over the crest of the structure. Other data inputs, including land elevation, geotechnical and construction characteristics of levees and floodwalls, connecting interior heights between hydrologic basins, and an inventory of economic assets, were provided to RAND by CPRA, the USACE, and other CPRA modeling teams.

A full description of the process used by the Storm Surge/Wave Team to model the hydrodynamic response to storms under each landscape and scenario can be found in Appendix D-24 of the 2012 Coastal Master Plan (CPRA, 2012b). For more information on how the models work together to project future coastal conditions and estimate project performance, see the main text of Appendix D (CPRA, 2012b). In addition, outputs from this model fed into a separate quantitative tool, called the Planning Tool, which used the information to assess the overall benefits and costs of proposed protection and restoration projects and provide project rankings across different objectives. Outputs from CLARA to the Planning Tool are noted in the remainder of this document. For more information on the Planning Tool, see Appendix E of the Master Plan (CPRA, 2012b) or Groves, Sharon, and Knopman (2012).

Contribution to Planning Effort

The risk assessment model described here is an input to the Planning Tool that CPRA used to assist in the development of the Master Plan (CPRA, 2012a) and subsequent annual plans. The Planning Tool provides estimates of the performance of several proposed risk reduction and restoration projects across a series of scenarios reflecting uncertainty about the future. In order to provide risk estimates suitable for this framework, the model must do the following:

- Estimate the consequences of flooding from a representative range of possible storms.
- Evaluate alternative risk reduction projects that were considered for inclusion in the Master Plan.

- Provide an estimate of the risk within reasonable computation time, thereby enabling the rapid comparison of alternative measures.

CLARA was designed to meet these objectives and to provide a balance between the sophisticated and high-resolution storm surge and wave inputs and the need to estimate risk outputs for many scenarios and alternative risk reduction projects in a reasonable time span. Choices regarding input data sources, model resolution, and analytic approach were made to address these trade-offs and meet the requirements of a 50-year analysis taking into account considerable uncertainty regarding future conditions. As a result, CLARA is appropriate for use with similar long-term, planning-level risk reduction analyses or project comparisons but is not suitable for use to support project design or to set regulations.

Risk and Damage Metrics

CLARA produces estimates of direct damage and other direct economic losses that could occur as a result of flooding due to catastrophic storms of Category 3 or higher on the Saffir-Simpson scale. Specifically, we measure damage associated with flooding produced by storm surge, overtopping, rainfall, and breaches of the protection system. We also estimate how often, on average, this damage will recur.

Risks are estimated in terms of residual damage (in dollars) that results from floods. Residual damage is the amount of damage produced by storm surge flooding after all risk reduction actions have been implemented. We measure residual damage from flooding in two ways. First, we use *exceedance probabilities* (hereafter, *exceedances*), which are statistical estimates of the flooding and damage expected to recur with a certain probability in each year. For example, the 1-percent flood exceedance is the flood depth with a 1-percent chance of occurring or being exceeded in each year. This is commonly referred to as the *1-in-100* or *100-year flood*. To determine the 1-percent damage exceedance, then, we calculate the amount of damage associated with the 1-percent flood depth. We also measure residual damage using *expected annual damage* (EAD). Unlike exceedance calculations, EAD represents the *average damage* projected to occur from a storm surge flooding event from a Category 3 or greater storm in any given year, taking into account both the expected damage and the overall chance of such a storm occurring. We calculate damage exceedances at three intervals—50 year (2 percent), 100 year (1 percent), and 500 year (0.2 percent)—and EAD for each coastal census block at two time intervals (2011 and 2061).

These damage results are summed for each CPRA-defined coastal community and provided as inputs to the Planning Tool. The Planning Tool calculates the reduction in EAD that occurs when a new risk reduction project is implemented and uses this change in EAD as an estimate of projected benefits for cost-effectiveness calculations and comparisons across projects. In addition, CPRA identified a target level of risk reduction for each coastal community that corresponds to the 50-, 100-, or 500-year damage exceedance, with the 100- or 500-year targets corresponding to areas with greater concentration of assets. In each case, the goal is to bring the damage exceedance as close to zero as possible with the new risk reduction projects in place.

Certain types of assets, including strategic assets (e.g., oil and gas infrastructure) and culturally significant and historic properties, were not included in damage estimates because of

a lack of data regarding the value of these assets. In these cases, 50-, 100-, and 500-year flood exceedances were provided directly to other CPRA modeling teams to determine the number of properties in each category flooded at each exceedance interval. See, for example, Appendix K of the Master Plan (CPRA, 2012b).

Treatment of Uncertainty

The Planning Tool was designed to account for the substantial uncertainty that complicates planning for coastal restoration and protection into the process for developing the Master Plan. How well any set of structural protection or coastal restoration projects reduces the risks of flooding depends significantly on many uncertain factors, including the intensity and frequency of storm events, performance of levees and floodwalls, and assets at risk from flooding. To support the application of the Planning Tool to developing the Master Plan, CLARA was designed to be run many times quickly, producing a range of flood and damage estimates that depend on uncertain parameters and scenarios for the evolution of the Louisiana coast over the next 50 years.

CLARA addresses uncertainty primarily by identifying key variables in the model and then varying their values to capture a wide range of possible outcomes using scenario analysis. This approach makes the important assumption that the uncertainty associated with the key variables over the 50-year planning period is greater and more significant for long-term planning decisions than other parametric or model uncertainties not fully captured in the uncertainty analysis. The assumption is consistent with the overall treatment of uncertainty throughout the Master Plan process.

The impact of system fragility on flood depths is estimated by using Monte Carlo simulation, a statistical approach that allows CLARA to construct a probability distribution of flood depths associated with random failures throughout the protection system. Other uncertainties, such as the effect of seasonality and tidal forces on storm surge, are not specifically varied but are taken into account when calculating flood depth probabilities. Given a particular flood depth within a particular scenario, however, damage is calculated deterministically—that is, without making assumptions about the probability of occurrence. Because of the complexity of the uncertainties and the lack of full knowledge about probability distributions for many of the key variables, CLARA does not produce estimates of parametric uncertainty or probabilistic confidence intervals for damage estimates.

Overview of This Document

The remainder of this technical description of CLARA is organized as follows: Chapter Two provides an overview of how CLARA functions, followed by a series of chapters giving more detail on each primary step of the model. Chapter Three describes the underlying hazard framework and statistical methods used to estimate flood exceedances. Chapters Four through Six discuss the major components of the flood depth module in more detail: Chapter Four covers the surge and wave overtopping calculations, Chapter Five outlines CLARA's approach to estimating system fragility and the consequences of failures, and Chapter Six details the

interior drainage calculations used to convert flood volumes entering an enclosed protected system to standing flood elevations.

Chapter Seven outlines the economic module that characterizes the value of current assets, projects future growth, and translates flood depths into direct economic damage. Chapter Eight describes how CLARA handles uncertainty and presents results from an analysis of uncertainty related to the sample of storms selected.

Chapter Nine describes how the model was actually used to support the development of the Master Plan (CPRA, 2012a). Chapter Ten presents results characterizing coastal Louisiana's future flood risk with and without the final Master Plan and comparing it with current conditions. Chapter Eleven provides conclusions based on these results and outlines areas for future study and improvement. Appendix A, available online, provides additional maps showing modeled flood depth results with or without the final Master Plan in place in all years, Master Plan scenarios, and flood depth exceedances considered in this analysis.

Overview of CLARA

Theory

CLARA's structure is based on well-described principles of quantitative risk analysis. Mathematically, risk is typically described as the product of the *probability* or *likelihood* of a given event occurring—in this case, the annual probability of storm surge flooding occurring at different depths—and the *consequences* of that event. This formulation can be further refined when applied to storm surge flood risk because engineered systems designed to prevent flooding—which do not always function as designed and can themselves fail—introduce a new dimension of uncertainty.

As a result, the likelihood of flooding can be divided into two components: the *threat* or *hazard*, which represents the underlying probability that a surge-producing storm will occur, and the *vulnerability* of hurricane protection infrastructure (e.g., levees, pumps, gates) to partial or complete failure given that a storm surge event occurs. The resulting three-part characterization of flood risk serves as the basic organizing principle for CLARA (USACE, 2009b; Morgan and Henrion, 1990; Fischbach, 2010). Specifically, each component can be described in a simplified framework as follows:

- **Threat.** In CLARA, we define the *threat* as the annual probability of storm surge and associated waves occurring from hurricanes of Category 3 or higher (i.e., with central pressures of approximately 960 millibars [mb] or lower), mathematically, $\Pr(\textit{storm})$ (USACE, 2009b). The threat is represented by the storm surge and wave inputs provided by the Storm Surge/Wave model, and the associated probabilities of recurrence are estimated using a modified version of the Joint Probability Method with Optimal Sampling statistics approach (JPM-OS) methodology (Toro et al., 2010). Detailed methods are described in “Storm Data Preprocessing” in Chapter Three.
- **Vulnerability.** For areas with enclosed protection systems, we define *vulnerability* as the conditional probability of flooding occurring on the interior given that a storm event occurs, or $\Pr(\textit{flood} | \textit{storm})$. Flooding can occur on the interior because of overtopping, breaching of the protection system, or operational error (e.g., failure to close floodgates). System vulnerability can be reduced by increasing the design parameters for the system, but it remains nonzero because of the complexity of engineered systems and the limitations of numeric modeling to project system performance under all possible conditions (Fischbach, 2010). Methods for estimating the recurrence and severity of flooding on the interior of the system are described in the section titled “Flood Depth Module” in Chapter Three. Unprotected or semiprotected areas are addressed separately with simplifying

assumptions as noted in “Calculating Flood Depths in Unprotected and Semiprotected Areas,” also in Chapter Three.

- **Consequences.** The consequences of flooding can include all possible impacts, including direct or indirect economic damage or losses, loss of life, and environmental damage. In our framework, this can be represented as $E(\text{damage} | \text{flood})$. CLARA estimates the consequences of flooding for one key category—direct economic losses—but does not include all possible adverse effects. The methods used for estimating direct economic losses are based on the approaches used in the FEMA Hazus-MH MR4 and Louisiana Coastal Protection and Restoration (LACPR) models and are described in detail in the “Economic Damage Submodule” section of Chapter Seven.

Using this simplified framework, the overall risk can be calculated as

$$\text{flood risk} = \text{threat} \times \text{vulnerability} \times \text{consequences},$$

or

$$\text{flood risk} = \Pr(\text{storm}) \times \Pr(\text{flood} | \text{storm}) \times E(\text{damage} | \text{flood}).$$

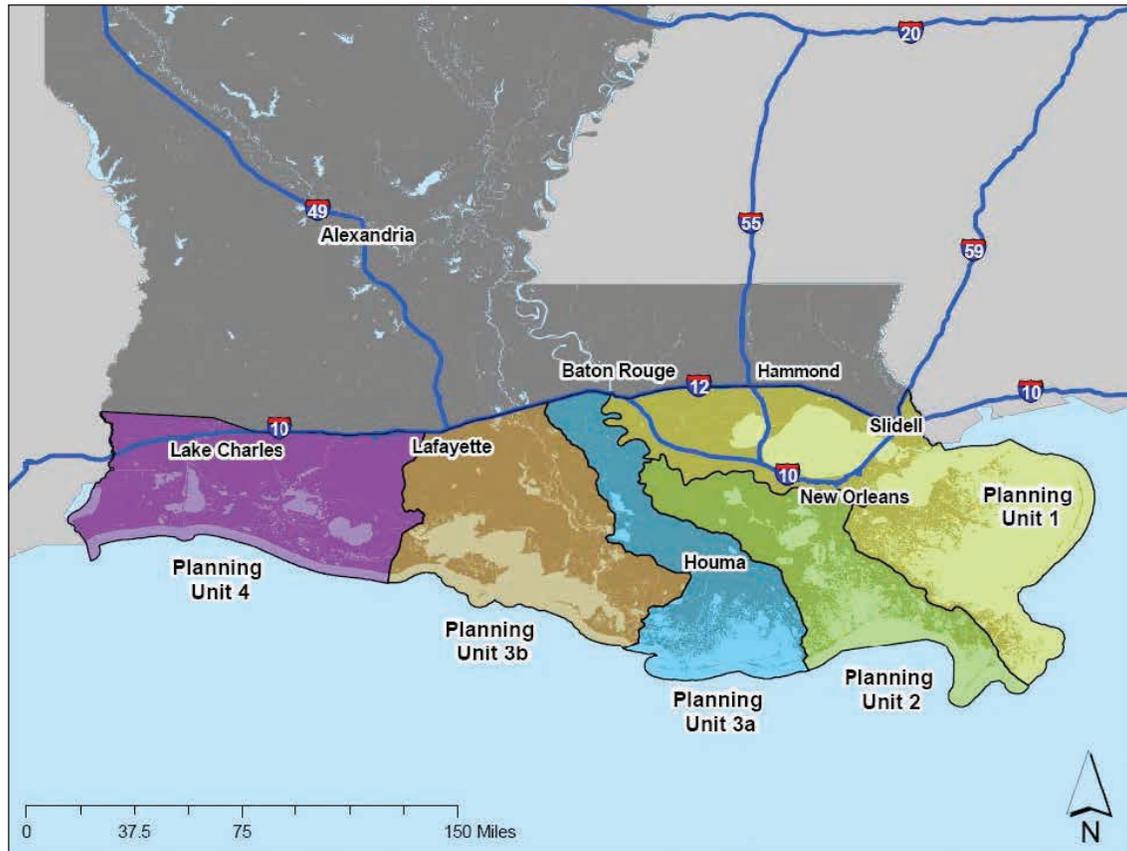
Note that these equations describe the flood risk for a particular storm event, and the consequences are restricted to direct economic damage; other consequences, such as loss of life and regional or national economic spillover effects, are not considered. Other modeling teams estimate the impact of the Master Plan projects on various other criteria but do not adopt this risk framework, so further references to flood risk are best understood as *flood risk to structures, physical infrastructure, and other local economic assets*. CLARA calculates risk by estimating risk exceedances based on a weighted average of the flood damage from the complete suite of storms. The more detailed methods used in CLARA to estimate each of these components are described in subsequent chapters.

Geographic Scope and Resolution

CLARA estimates flood depths and damage across coastal Louisiana. The study area and northern boundary were adopted directly from the recent USACE LACPR analysis, which divided the coast into a series of five Planning Units (Figure 2.1) and approximately 1,000 Planning Subunits (USACE, 2009a). The northern boundary of this area roughly follows Interstates 10 and 12; storm surges are not expected to affect areas to the north of these highways.

CLARA adopts the LACPR Planning Subunits as the basic spatial unit of analysis to determine flood elevations in protected areas. Hereafter, these subunits are referred to as basic hydrologic units (BHUs). CLARA labels each BHU as one of three types of areas: unprotected, semiprotected, or protected (USACE, 2009a). *Unprotected* areas have no levees, floodwalls, or other barriers to flooding. *Semiprotected* areas have levee or floodwall protection, but these protection structures do not fully enclose the population at risk. As a result, storm surge could “run around” the structures and flood the area from behind. *Protected* areas have hurricane protection that is fully enclosed in a ring, defining an artificial hydrologic unit (or *polder*) composed of one or more adjoining BHUs that is distinct from the exterior area. Key protected

Figure 2.1
Louisiana Coastal Protection and Restoration Planning Units and Study Area Extent



SOURCE: USACE, 2009a.

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areas include the portions of Greater New Orleans enclosed within the Hurricane and Storm Damage Risk Reduction System (HSDRRS) built by the USACE.

To calculate flood depths and damage, CLARA uses the approximately 35,500 census blocks defined by the 2000 U.S. census that fall within the study area as units of analysis.¹ Flood elevations for protected areas, relative to sea level, are calculated for each BHU. These elevations are converted to flood depths at the census-block level using the average elevation for each census block within a given BHU. For unprotected or semiprotected areas, alternatively, flood depths are calculated directly from the storm surge and wave input values for the centroids of each block. Finally, all damage calculations are performed separately for each census block in the study area.

Economic damage is aggregated from census blocks to a set of approximately 50 *target communities* defined by CPRA based on geographic proximity and different levels of targeted protection (Figure 2.2). Damage levels at the target-community level are reported to the

¹ Several key data sources, including Planning Subunits and economic information provided by LACPR, use census blocks defined by the 2000 census as a primary spatial unit. LACPR constructed the Planning Subunits so that the 2000 census-block boundaries are fully contained within the Planning Subunit boundaries. Census blocks defined in the 2010 census are not commensurate with these units; as a result, we deliberately organized CLARA using the 2000 spatial units.

Planning Tool for use in comparing the effects of different structural and nonstructural risk reduction projects.

CLARA Calculation Steps

CLARA employs a nine-step approach to assess the risks and potential flood damage to coastal Louisiana resulting from storm surge described in this chapter. These steps are split across three primary modules:

- The *input preprocessing module* parses certain data inputs for later use and generates flood exceedances for unprotected and semiprotected areas. Steps 1–4 are calculated in the input preprocessing module.
- The *flood depth module* calculates standing flood depths in protected areas. Steps 5–8 are calculated in the flood depth module.
- The *economic module* calculates the direct damage and other flood losses resulting from given flood depths. Step 9, described in Chapter Seven, is performed in the economic module.

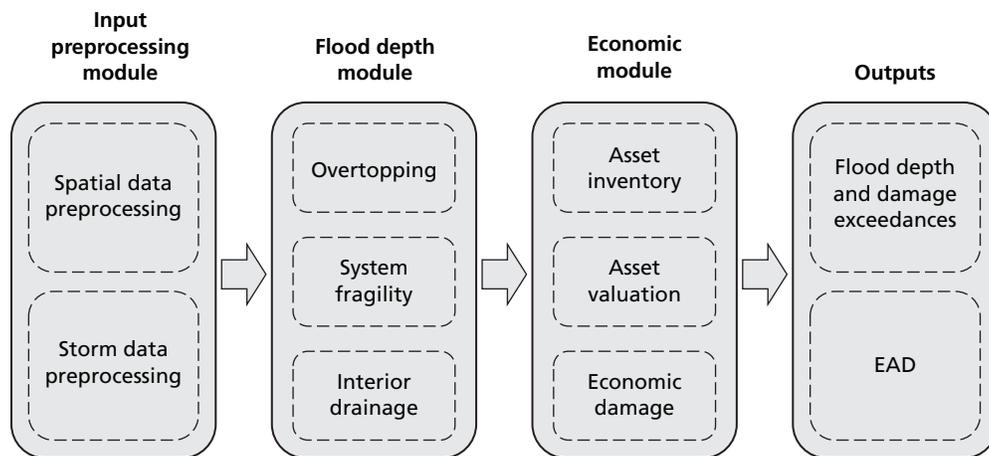
Figure 2.3 illustrates the basic structure of the model, flow of calculations, and primary submodules.

The following nine steps are taken in making the calculation.

1. Preprocess Geospatial Data

Information about the study region must be processed in order to identify many of the data elements required as inputs by the rest of the model. This involves defining the BHUs, identifying the geospatial point sets (map coordinates) at which storm data should be reported, calculating the minimum elevations dividing interior BHUs, and developing the stage-storage curves that define the relationship between water volumes and flood elevations and other associated metadata.

Figure 2.3
Coastal Louisiana Risk Assessment Model Structure and Primary Submodules



2. Estimate Flood Depths in Unprotected and Semiprotected Areas

The model first records the elevation of the storm surge and waves from a sample of 40 storms simulated by the Storm Surge/Wave Team for census blocks without enclosed levee or flood-wall protection. Using a modified version of the JPM-OS (see “Storm Data Preprocessing” in Chapter Three) applied by the USACE (USACE, 2009b), CLARA then estimates a cumulative distribution function (CDF) for surge and wave elevations in each block; extracts the flood elevations corresponding to exceedances of 50, 100, and 500 years; and converts them to flood depths using average ground elevations for these areas. Exceedances for unprotected and semi-protected areas are calculated as part of the storm data preprocessing submodule because they do not need to run through the flood depth module since they are not interior to a protection system.

3. Record Surge and Wave Conditions Along Protection Structures

To evaluate the flooding that may occur in enclosed protected areas, CLARA first records surge and wave characteristics along the protection structures from a sample of 40 storms simulated by the Storm Surge/Wave model. These data include peak surge heights, peak significant wave height, wave period by storm, and surge heights at regular time intervals over the duration of the storm (hydrographs). The data points at which these are provided are 200 meters offshore from the structures along the entire coast; these points were chosen to facilitate calculation of overtopping and estimating the probability of failure of protection system elements.

4. Generate Storm Hazard Conditions for a Large Sample of “Synthetic” Storms

Using data from the 40 storms simulated along protection structures in the previous step, CLARA next uses a modified statistical approach based on JPM-OS to interpolate and extrapolate across key storm parameters and develop estimates of surge for 720 “synthetic” storms. This experimental design of storms varies by central pressure, size of the storm—as measured by the radius to the maximum wind speed—and storm track. The coefficients that represent the contribution of each storm to the flood surface from the modified JPM-OS are stored and used to estimate the flood exceedances. Regression analysis is also used to estimate surge hydrographs, wave conditions, and rainfall associated with each synthetic storm, using methods adopted from the LACPR and IPET analyses.

5. Estimate Inflows Due to Overtopping

For each exceedance and point along the protection system, the model then estimates the amount of water that enters protected areas because of overtopping of the hurricane risk reduction system. Standard methods for estimating flows over structures are used. This is done on a storm-by-storm basis for each of the 720 synthetic storms.

6. Estimate Interior Flooding Due to Levee or Floodwall Breaches

Next, flooding due to system failure is estimated for each storm. These systems fail as a result of the stresses placed on them by hurricanes. CLARA models three failure modes: seepage, slope stability, and overtopping:²

² CLARA ignores several potential failure modes. The action of waves on levees may cause erosion and lead to failure, especially at elevated surge levels. However, insufficient data exist by which to estimate a coastwide failure due to this mode. Also, CLARA was originally implemented with internal erosion as a failure mode, but internal erosion was dropped when it was discovered that the probability of failure for this mode was an order of magnitude less than the probability of failure from other modes.

- A *seepage failure* occurs when water flows through soil under the levee or floodwall. This can lead to failure if the upward pressure of water flowing through the soil exceeds the downward pressure from the weight of the soil above it.
- A *slope stability failure* occurs when forces exerted by the floodwater against the levee or floodwall are greater than what the structure can resist.
- An *overtopping failure* occurs because of erosion of the protected side of the levee or floodwall from the rushing surge water.

If a levee or floodwall fails by any of these three modes, the height of flooding is assumed to be the height of the peak storm surge exterior to the system.

To determine the *fragility* of the systems, the term generally used to describe the vulnerability of structures to failure, we use data regarding (1) hurricane protection system characteristics, including the location, type of reach (e.g., levee or floodwall), the presence of armor-ing, and transitions and (2) geotechnical characteristics derived from boring logs at or near the levees. When specific geotechnical data are not available, we use typical characteristics as documented by IPET and others. These data are used two ways: The data on the location and structure of a hurricane protection system are used to translate a two-dimensional estimate of fragility to a three-dimensional estimate, and the geotechnical characteristics are parameters used to estimate the factor of safety that underlies the estimation of slope stability and seepage failures.

Overtopping is the dominant failure mode in our analysis. Probability of failure is estimated using data reported in a lookup table originally used by the USACE (2009b). In practice, the probability of seepage and slope stability failures is quite low, especially for low and moderate surges. Because failures are probabilistic events, we run our model many times for each storm using Monte Carlo simulation to characterize likely flooding that would occur due to failure.

7. Estimate Equilibrium Flood Heights for Protected Areas

The final step to determine flood elevations for protected areas is to equalize the flood elevation among adjacent protected areas using a simplified model of interior drainage. For example, if one neighborhood in New Orleans lies next to another neighborhood, and the first neighborhood floods, the adjacent neighborhood will also flood unless some barrier lies between them. The minimum connecting elevation is known as the *interflow elevation*. These interflow elevations are determined using a high-resolution digital elevation model (DEM) derived from light detection and ranging (LIDAR) maps of the coast—including embankments, roads, and other structures—compiled and provided by the Wetland Morphology Team.

8. Derive Interior Flood Depths and Depth Statistics

Flood elevation results for interior areas from each storm are compared with census-block elevations to produce flood depths that result from individual storms. Using the probability weightings from the modified JPM-OS, we derive 50-, 100-, and 500-year flood depth estimates by census block.

9. Estimate Damage from Flooding

To estimate the consequences of flooding, we employed tools developed by RAND, FEMA, the LACPR study, and IPET. For each foot of flood depth, CLARA assigns a value in dollars of the estimated resulting damage.

Damage is estimated by census block at the 50-, 100-, and 500-year exceedances for different types of assets (e.g., residential, commercial) using the asset inventory and depth-damage curves adopted from FEMA's Hazus-MH MR4 model and the LACPR study (USACE, 2009a; FEMA, 2009).³ Damage depends on the inventory of assets in each block. This inventory includes homes and dwellings; commercial, industrial, and public-sector properties; and roads, highways, and agricultural buildings and crops. Inventories in 2011 were estimated from several sources of data, such as FEMA's Hazus-MH model, 2010 census data, and Louisiana-specific economic updates provided by LACPR. We then projected out to 2061 using scenario-dependent assumptions about regional growth and urbanization. Assets are assumed to grow proportionally with population growth, with the exception of agricultural assets and transportation infrastructure (roads and bridges).

In addition to damage associated with specific exceedances, CLARA also estimates EAD, the primary metric used for evaluating the performance of protection projects, for each census block by aggregating damage from synthetic storms, weighted by the probability associated with each storm and adjusting for the scenario-dependent overall frequency of Category 3 or greater hurricanes affecting the study region. Damage from individual storm events is not explicitly calculated by CLARA or considered by the Planning Tool.

Input Data

Inputs to the flood depth and economic modules include storm surge and related data (hydrographs and wave characteristics), protection system data (locations and characteristics), and data regarding assets and value of assets in protected and unprotected areas. Primary sources of data are listed in Tables 2.1 and 2.2.

Output Data

The outputs from CLARA are the flood depth and damage estimates at the 50-year, 100-year, and 500-year exceedance intervals and EAD. All outputs are reported for each coastal census block and each CPRA target community. A map of sample output showing modeled flood depth results by census block is provided in Figure 2.4, and a screenshot showing example damage output data by community is shown in Figure 2.5. Note that these figures are illustrative examples and are not intended to be representative of any given project or scenario result.

For the purpose of supporting the Master Plan, these outputs are recorded in a database allowing the Planning Tool to retrieve results for many different scenarios and accounting for a range of uncertainties.

Model results are difficult to validate against previous study results because the protection system being evaluated has been substantially upgraded from the system studied by IPET and LACPR. Initial flood depths from the future-without-action (FWOA) scenario—the baseline scenario in which no new actions are taken over the next 50 years—have been compared with LACPR flood depths and subjected to expert review to determine that the results are plausible

³ The relationship between flood depth and the damage inflicted as a proportion of an asset's value is known as a *depth-damage curve*.

Table 2.1
Input Data for Flood Depth Module

Data Name	Source
Surge hydrographs	ARCADIS; Storm Surge/Wave model
Wave period	ARCADIS; Storm Surge/Wave model
Significant wave height	ARCADIS; Storm Surge/Wave model
DEM of Louisiana	U.S. Geological Survey (USGS); Wetland Morphology model
Wave free crest height	ARCADIS; 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
Rainfall	ARCADIS; 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.

based on the extent of upgrades to the 2011 baseline protection system in New Orleans. In unprotected areas, surge and flood results are similar to those reported by previous studies.

Model outputs were, however, subjected to a multiple-step quality assurance (QA) process. The model technical lead reviewed all results and discussed any problems or issues with the lead developer. Once any issues identified were resolved at this level, output summaries (in map and tabular form) were provided to the flood depth module QA manager or damage module QA manager, respectively, for additional review. Finally, summary outputs were posted for review by CPRA staff, and a final round of review and clarification was conducted based on CPRA comments before the results were considered final.

Key Assumptions

Substantial portions of the methodologies used by CLARA borrow from methods used by IPET, LACPR, and the FEMA Hazus-MH MR4 model. These include the use of the response surface developed by JPM-OS to predict surge from synthetic storms, regression models for wave heights and periods, the implementation of system fragility, the valuation methods for structural assets, and the depth-damage curves used to determine damage as a function of flood depth. As such, much of the model methodology has been previously subjected to thorough vetting by experts at FEMA and the USACE or to peer review for publication in the academic literature.

This means that CLARA represents the latest scientific and economic understanding of these processes that can be brought to bear. However, modeling the complex interactions

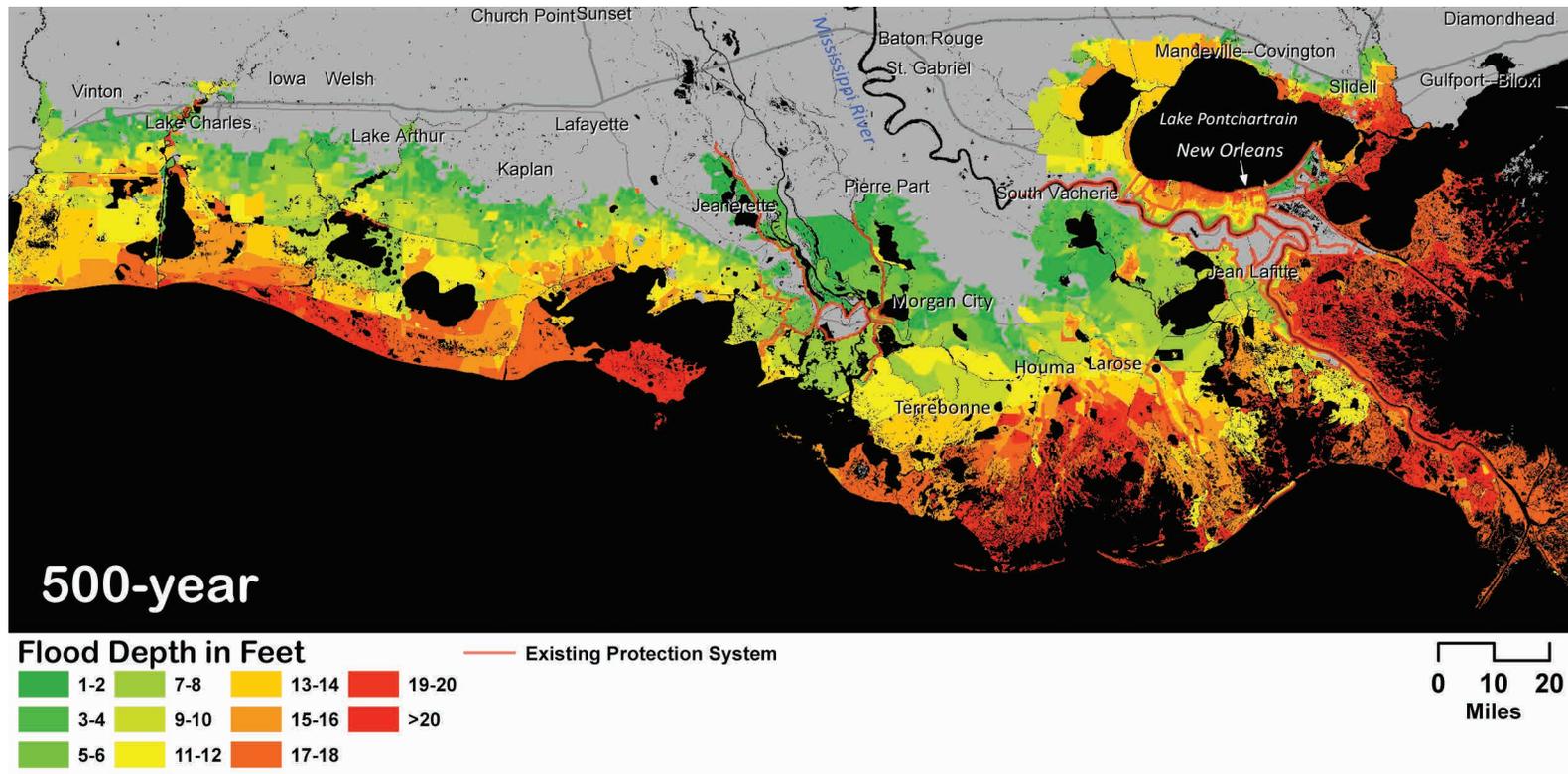
Table 2.2
Input Data for Economic Module

Subset	Data Element	Asset Class	Source (in order of precedence)
Inventory	Number of structures	All residential classes	GNOCDC, ACS, LACPR, Hazus-MH MR4
	Number of structures	All nonresidential, structural classes	LACPR, Hazus-MH, U.S. census
	Acreage of agricultural crops	Agricultural crops	LACPR, NASS, LSU AgCenter
	Number of vehicles	Vehicles	LACPR (adjusted by ACS)
	Inventory of roads and bridges	Infrastructure	LACPR
	Square footage	All structural classes	LACPR, Hazus-MH
Valuation	Structural characteristics for each asset class	All structural classes	Hazus-MH
	Replacement cost per square foot	All structural classes	Hazus-MH
	Proportion of structures by construction class (economy, average, custom, luxury)	All residential classes	Hazus-MH
	CSV	All structural classes	LACPR
	Value of inventory per square foot	Commercial, industrial	Hazus-MH
	Repair costs per mile	Infrastructure	LACPR, Hazus-MH
	Agriculture valuations	Agricultural crops	LACPR
	Proportion of structures by construction method (e.g., wood frame, masonry)	All structural classes	Hazus-MH
	Flood elevations	N/A	Calculated by model
	Damage	Structural elevation above grade	All structural classes
Depth-restoration time curve		All structural classes	Hazus-MH
Depth-damage curves for structure		All structural classes, infrastructure	Hazus-MH
Depth-damage curves for contents		All structural classes	Hazus-MH
Depth-damage curves for inventory		Commercial, industrial	Hazus-MH
Costs dependent on displacement time: lost income, lost wages, lost sales, disruption costs, relocation rental costs		All structural classes	LACPR, Hazus-MH
Costs dependent on displacement time: evacuation and subsistence costs		All residential classes	LACPR
Post-flood response costs: landscaping repair, debris removal, other cleanup		All structural classes	LACPR

SOURCES: FEMA, 2012; U.S. Census Bureau, 2012; Calthorpe Associates and USACE, 2008; U.S. Department of Agriculture, undated.

NOTE: GNOCDC = Greater New Orleans Community Data Center. ACS = American Community Survey. NASS = National Agricultural Statistics Service. LSU AgCenter = Louisiana State University Agricultural Center. CSV = contents-to-structure value ratio. N/A = not applicable. Road Home = Road Home post-Katrina housing recovery program. HMGP = Hazard Mitigation Grant Program.

Figure 2.4
Example Flood Depth Map (500-Year Flood Exceedance)



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Figure 2.5
Example Damage Results, by Target Community

	A	B	C	D	E
1	Community_ids	50yr	100yr	500yr	EAD
2	ABB.100	\$ 19,476,589	\$ 108,120,974	\$ 685,558,687	\$ 3,846,225
3	ACA.050	\$ 4,265	\$ 1,888,604	\$ 96,432,249	\$ 477,436
4	ALG.100	\$ —	\$ —	\$ —	\$ 34,751
5	ASC.050	\$ 873,087	\$ 873,087	\$ 873,087	\$ 45,800
6	ASU.050	\$ 9,982,378	\$ 119,936,081	\$ 726,161,018	\$ 1,183,806
7	BAL.100	\$ 3,954,533	\$ 4,841,698	\$ 92,157,791	\$ 785,564
8	BBL.100	\$ 191,931,527	\$ 233,535,561	\$ 719,739,799	\$ 7,108,757
9	BCH.100	\$ 9,939	\$ 351,990	\$ 1,031,344	\$ 16,037
10	BVI.100	\$ —	\$ —	\$ —	\$ 162,372
11	CAL.050	\$ 75,446,080	\$ 646,911,330	\$ 3,296,525,978	\$ 21,549,538
12	CAM.050	\$1,338,254,592	\$2,969,271,667	\$ 4,230,955,039	\$ 55,035,571
13	CHA.100	\$ 557	\$ 557	\$ 27,633	\$ 3,086,047
14	DES.100	\$ —	\$ —	\$ —	\$ 4,010,377
15	FRA.100	\$ 3,444,754	\$ 33,749,605	\$ 1,467,530,064	\$ 6,694,200
16	HOU.100	\$2,437,077,082	\$6,117,085,304	\$15,267,825,585	\$136,608,769
17	IBE.050	\$1,319,539,639	\$3,372,518,741	\$ 5,357,325,186	\$ 61,857,638
18	IBV.050	\$ —	\$ —	\$ —	\$ —
19	JEA.100	\$ —	\$ —	\$ —	\$ —
20	JED.050	\$ 4,080,593	\$ 32,241,981	\$ 274,734,261	\$ 1,637,953
21	JEF.050	\$ 623,065,880	\$1,205,802,673	\$ 1,657,693,657	\$ 26,405,455

NOTE: Columns refer to the community identifier; 50-, 100-, and 500-year damage exceedances; and EAD (2010 dollars), respectively.

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necessary to represent the underlying risk of catastrophic flooding and the resulting losses requires making some simplifying assumptions.

Constraints dictate that many data inputs need to be used creatively. For example, CLARA utilizes the state-of-the-art JPM-OS method for estimating surge exceedance intervals but modifies the methodology to use a base storm set of only 40 storms rather than the 304 storms originally used to develop JPM-OS. These 40 storms do not include any storms that make landfall at an angle other than the mean angle observed from the historical record, so the model represents the real-world system to the extent that these mean-angle storms can be used to represent the entire range of possible surge responses across varying landfall angles.

Issues such as this, and CLARA's methodology to deal with limitations imposed by them, are addressed in this chapter. To an extent, these limitations are also a large part of the motivation for the scenario-based uncertainty analysis the model enables. All assumptions and simplifications that we make are based on existing methods employed in the literature and are intended to facilitate the development of a model at the appropriate level of detail to support long-term planning. Key assumptions and model limitations are listed in this chapter, sorted by CLARA's modules and submodules.

Input Preprocessing Module Assumptions

Storm Data Preprocessing Submodule

- *Storm intensity is characterized by the central pressure.* Exceedances are based on observed characteristics of historical storms as used by IPET. The Saffir-Simpson Hurricane Scale also characterizes storm intensity using peak sustained wind speeds, but these factors are generally correlated.
- *The set of 40 storms used to generate the surge and wave data adequately captures the range of possible storm surge and wave effects anticipated to affect the Louisiana coast over the next 50 years.* This assumption and the storm set selection process are discussed in more detail in the next chapter.
- *We can extrapolate storm characteristics.* The statistics used to predict surge and wave characteristics in synthetic storms are based on a relatively small sample of 40 storms run by the Storm Surge/Wave model. Accurate prediction relies on the response surface methodology described by JPM-OS (Resio, Irish, and Cialone, 2009); these storms vary by track, central pressure, and radius. Although the surge response is virtually linear in pressure and radius, the small sample may mean that predictions are less accurate for synthetic storms with parameters further outside of the sample storm set.

Flood Depth Module Assumptions

Overtopping Submodule

- *The crest of the levee acts as a rectangular weir.* A weir is essentially a dam below the surface of the water. The shape of the weir determines the rate at which water flows over it, as characterized by its weir coefficient. The coefficient depends on the type of structure: 1.68 for floodwalls, 1.45 for levees, and 1.12 for gates when International System of Units (SI) units are used (USACE, 2009b). The application of the weir coefficient is described in Chapter Four. This assumption was adopted previously by IPET and LACPR, as it was judged to be sufficiently accurate for existing protection features. If future system designs for projects recommended by the Master Plan differ significantly from existing designs, that difference may necessitate a reevaluation of the appropriate values.
- *The effect of the breaking of waves can be represented by a parameter.* The long foreshore of coastal Louisiana induces waves to break. As noted earlier, our estimates of wave characteristics are taken 200 meters offshore of the structure. A breaking parameter is used to adjust the height of the wave to account for breaking that occurs (USACE, 2009a). This parameter was used by IPET and LACPR in accordance with literature on the physical behavior of breaking waves on a long, shallow foreshore (Meer, 2002).
- *The slope of levees is one unit height per four units length.* We assume the standard slope of a levee to be 25 percent, or one foot of height for every four feet of length across the cross-section of the levee (USACE, 2009a, 2009b).
- *The influence of the berm of the levee is minimal.* The berm of the levee is the flat area on the crest. We assume that variations in the width of the berm are relatively small, applying the same assumptions about berm width as made by IPET and LACPR.
- *The incidence of wave angle is assumed to be zero in all cases.* Consistent with LACPR, we assume that waves approach protection features head-on when calculating the effects of wave run-up and breaking. This may not be true for all protection system alignments or

storm tracks, but it is a conservative simplifying assumption that produces greater overtopping volumes than if the actual angle of incidence was tracked.

System Fragility Submodule

- *Operational failures are not considered.* All gates, locks, and other closures are assumed to be closed properly prior to any storm surge event. These types of operational failures could be treated as equivalent to breaches in the system fragility submodule; for example, IPET assumed specific probabilities that gates would remain open during a storm event. Given that system operations are directly controllable, the actual probability is most likely nonzero but is also unknown. Any estimates of operational failure probabilities would be uninformed because of a lack of historical data and may not account for safeguards and procedures updated in the wake of recent storms. Further, given the conservative breaching model incorporated by CLARA, consideration of operational failures would likely make little difference in the overall risk profile unless the probability of improper operation was judged to be high.
- Because of technical limitations, *CLARA assumes that levees that do not completely encircle an area (i.e., an area is semiprotected) never fail and are not subject to wave overtopping.* These areas can, however, receive flooding through storm surge overtopping or surge “run-around.” This likely underestimates the local flood depths and damage in areas near the boundary of a semiprotecting system in cases in which failures would occur or in which wave overtopping contributes significantly to flooding on the system interior.
- *Protection system failures are based on a two-dimensional model of the levee or floodwall extrapolated over its length.* That is, the potential for a failure is based on the analysis of a vertical cross-section of the levee from the protected side to the unprotected side. We assume that each cross-section has uniform characteristics over a characteristic length, which we assume to be 300 meters (984 feet). By stringing together the failure probabilities over the complete length of the levee, which is potentially many characteristic lengths, we are able to estimate the probability that the actual levee fails at at least one point. The characteristic length used by CLARA was developed by IPET based on the design characteristics of existing protection systems and samples of soil characteristics in protected regions. If the characteristics vary over shorter spans in places receiving new protection from Master Plan projects, the modeled probabilities of failure may vary somewhat from the actual probabilities. However, this likely would produce minimal error in risk calculations, given that failures are predominantly driven by the overtopping failure mode in CLARA, which is independent of these characteristics.
- *Failures of levees depend only on the maximum surge, not on the time history of the storm surge.* The implication of this assumption is that we consider only the maximum static load on the levee when calculating its probability of failure. This is a conservative assumption that generally results in larger probabilities of failure (compared with calculating probabilities at other times in the surge hydrograph). If failure occurs after the point of maximum surge, then the consequences of failure may be less severe than what is estimated in CLARA.
- Similarly, *CLARA ignores the effects of wave action, which can erode a levee over time, when determining the probability of levee failure.* This simplifying assumption was necessary because the fragility calculations are not able to account for the time history of waves

and thus cannot track the steady progression of levee erosion over time. This assumption likely leads to an underestimate of failure probabilities for earthen levees. We judged the downward bias to be acceptable within this simplified framework, however, and assumed that the effect would be small when compared with the other simplifications made to remove the time dimension.

- The three failure modes are *slope stability*, *seepage*, and *overtopping causing erosion and failure on the protected side*. Other failure modes were originally included in CLARA, but preliminary analysis suggested that the probabilities of failure from the remaining modes were one or more orders of magnitude greater than from other modes.

Interior Drainage Submodule

- *Time dynamics are not accounted for.* CLARA's interior drainage submodule does not explicitly account for the time required for floodwaters to move from one BHU to another; it relies instead on a series of assumptions about peak flood levels resulting from breaches or overtopping. Rainfall is also added to the overall flood volumes as if it occurs simultaneously with overtopping and pumping volumes. This may overestimate local flood depths in some cases and underestimate them in others, but simplifying the interior drainage submodule to a single time step drastically reduces CLARA's computational complexity, allowing exploration of a much greater range of project effects and uncertainty.
- *There is no inertia-based overflow.* We assume that water entering a BHU from overtopping is traveling with sufficiently low kinetic energy such that it will not cross boundaries to other BHUs without first filling the current BHU to the level of an interconnecting cut. This may not hold for unusually small BHUs that are created when new alignments split preexisting BHUs, but, if they are small enough for this to be a concern, we assume that they likely hold little asset value.
- *Pumping rates are assumed.* We have data on pumping capacities in each BHU. In overtopping-only cases, we consider three different levels of performance via scenario analysis at 0, 50, and 100 percent of rated capacity. This approach is derived from the IPET (USACE, 2009b) risk and reliability analysis. In breaching cases, alternatively, we adopt the IPET assumption that pumps in affected BHUs would be overwhelmed by the breach volume, and pumping rates are assumed to be zero. These capacities are assumed to be irrelevant from the perspective of determining the flood elevation.
- If a protection system element fails, *the height of the flood in the area that it protects is set equal to the maximum surge height.* Because it instantaneously equalizes exterior and interior water levels, the model does not take into account the movement of water over time or limits in water flow rate through a levee breach. As a result, CLARA very likely overestimates the resulting damage when a failure occurs. A more detailed justification for and discussion of this key assumption can be found in Chapter Five ("Estimating Protection System Fragility") and Chapter Ten ("Results from the Final Master Plan Analysis").

Economic Module Assumptions

Asset Inventory Submodule

- *Land-use patterns remain constant over the next 50 years.* This could change in many ways through zoning laws or more organic redevelopment. Data did not, however, support the

assumption of anything but maintenance of the status quo, and this was judged sufficient for the purposes of a comparative study.

- *Assets at risk from flooding grow in proportion with population growth*, except for certain categories, such as roads. This assumes that the net effect of densification, changes in consumer habits, and overall population demographics is negligible with respect to the value of assets per capita. Again, data did not support changes in future projections, and this effect was not judged a sufficiently important parameter to development varying future scenarios.
- *Population growth rates from 2011 to 2061 are represented by discrete, uncertain scenarios*. The nominal (baseline) scenario assumes a population growth rate similar to the rate observed from 1990 to 2000 (i.e., before the disruption from Hurricanes Katrina and Rita in 2005). Other cases posit greater and less growth over time, representing an upper and lower bound of likely population growth scenarios.
- *The fraction of future population growth in urban areas versus rural areas is also represented by discrete, uncertain scenarios*. The nominal (baseline) scenario reflects urbanization in 2061 equal to levels reported by the 2010 U.S. census for the study region (81 percent urban). Other cases posit shifts of 5 percentage points greater or less than this value by 2061. Future growth outside of these ranges would shift the risk reduction benefits of projects targeting urban areas relative to those in rural areas, but the modeled scenarios were informed by historical levels and trends in urbanization from past census estimates; the scenarios other than the baseline represent what we believe to be an upper and lower bound on the changes that could plausibly occur over the next 50 years.
- *The effectiveness of nonstructural projects is characterized by level of participation only*. Participation rates vary by nonstructural project type—elevation, floodproofing, acquisitions, and easements—and range over four different scenario assumptions representing low, medium, medium-high, and full participation.
- *Asset growth assumes no induced development effects*—changes in growth rates as a result of perceived risk reduction in newly protected areas. Literature in this area is inconclusive. The cumulative effect of any induced development over the 50-year timescale of the Master Plan will inevitably be linked with the schedule for when projects are implemented, and this schedule was unknown during the initial phases of analysis. As a result, modeling induced development scenarios was judged to be outside the scope of this analysis.

Other Capabilities and Limitations

- CLARA does not consider noneconomic damage or effects, and dollar losses are not calculated for some asset types (e.g., oil and gas infrastructure). This was judged to be outside the scope of analysis for the Master Plan development.
- CLARA uses scenario analysis to evaluate uncertainty in risk estimates and does not produce statistical confidence intervals. The consequences of this design choice are discussed in more detail in Chapter Eight, “Uncertainty in CLARA.”

Measuring Hurricane Hazard and Flood Recurrence

Overview

This chapter provides information on how the flood depth module operates to produce estimates of flood exceedances, starting from a limited set of simulated storm inputs. The underlying statistical method for estimating flood exceedances is described, along with details on how the storm inputs were chosen for this application to the Louisiana coast. The basic structure of the flood depth module is also provided, although details of each component module are left for later chapters.

Storm Data Preprocessing

Statistical Methodology and Experimental Design of Storms

The statistical methodology that produces estimates of damage at different flood exceedances and EAD calculated by CLARA is derived from the JPM-OS method initially applied by IPET (Resio, 2007; Toro et al., 2010). The model is designed to leverage previous modeling efforts, such as the IPET and LACPR studies.

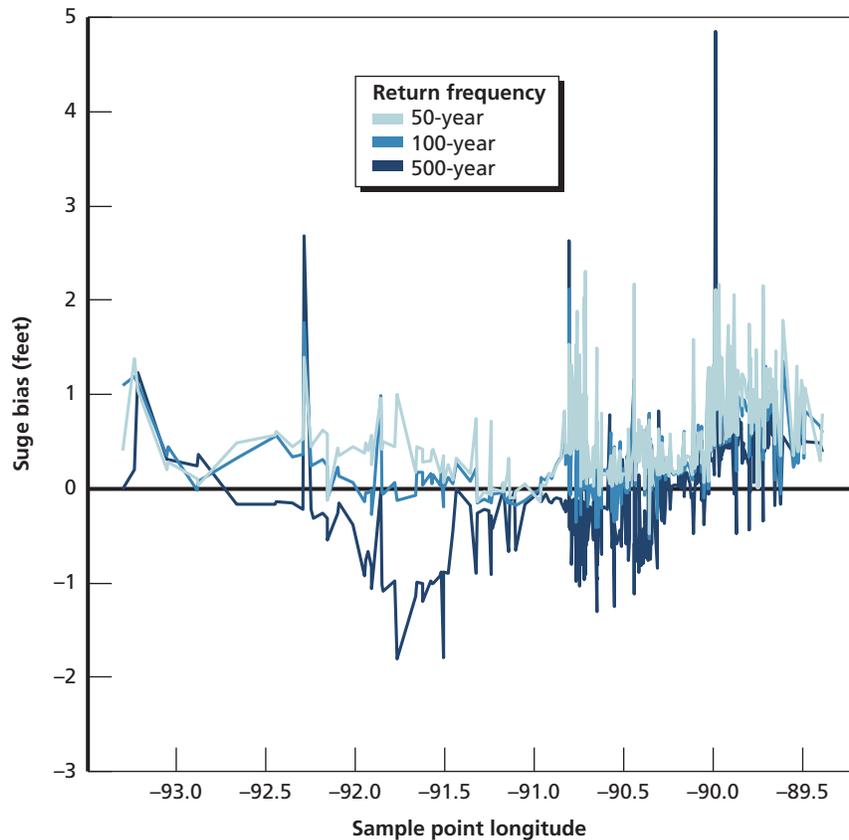
The LACPR study team applied JPM-OS to the Louisiana coastline using a suite of 304 storms that vary across five parameters: radius to maximum wind speed, storm intensity (as measured by the central pressure), forward velocity, landfall location, and angle of incidence at landfall. Ideally, the full storm set would be used to estimate an empirical cumulative probability distribution function for storm surge, but constraints on time and computing resources for the Master Plan effort dictated that CLARA be deployed with a smaller set of storms.

To choose a subset of storms to use in this effort, we conducted a quantitative experiment for storm selection using peak storm surge data initially generated for the LACPR analysis. Specifically, we modified a version of the JPM-OS methodology to estimate surge exceedances using smaller subsets of the full LACPR storm set and compared the exceedance values calculated from a more complete subset with those of smaller subsets to determine the potential biasing that would occur in different areas. In order to complete the number of ADCIRC runs necessary to test dozens of proposed hurricane protection projects in multiple future scenarios, CPRA indicated that the number of simulated storms should be minimized to the extent possible.

We selected 449 sample points along the coast from the larger set used as part of the LACPR analysis, removing those in which storm surge never or almost never occurred. Next, we estimated 50-, 100-, and 500-year surge exceedances at each of these points from different

storm subsets and compared them with the exceedances estimated using a more complete set of 154 storms (varying all parameters except forward velocity). A total of 46 potential subsets were considered, ranging from eight to 77 storms, to arrive at a 40-storm subset that best balances predictive accuracy at the 50-, 100-, and 500-year levels across a range of points along the coast with a minimal number of storms. Figure 3.1 shows a summary plot of this comparative analysis. The difference between the surge value estimated for each surge exceedance using the final 40-storm subset and a more complete 154-storm set (y-axis) is shown for each surge sample point (x-axis), with the sample points represented visually by their longitude values to better understand the spatial pattern of the resulting bias. The figure shows that the bias is generally within 1.0 to 1.5 feet and tends to be more positive for the more frequent intervals (50 and 100 years). A pattern of increasing upward bias is noted moving from west to east starting at longitude -90.75 through -89.5 , but the magnitude does not substantially increase. There are selected points with notably greater bias, however; these more extreme values range from -2 feet to 5 feet. Some of these are the result of anomalies in local topology or points where few storms produce surge, resulting in a small sample from which to interpolate the entire response surface. This led to improvements in how nonwetting points are evaluated and reported by the Storm Surge/Wave Team. After reviewing this output with CPRA and the other team,

Figure 3.1
Difference in Predicted Surge (Bias) Between 40-Storm and 154-Storm
Sample at Louisiana Coastal Protection and Restoration Surge Sample
Points



we determined that the selected 40-storm subset would be sufficient for the initial protection project comparisons.

The chosen 40-storm subset, referred to as the *CPRA storm set*, consists of four storms following each of the ten storm tracks used in the LACPR study. Each storm has a forward velocity of 11 knots, which is the central value for velocity among the 304-storm set, and follows a path along the mean landfall angle described by Resio (2007). The four storms on each track vary by central pressure and size, consisting of storms with pressures of 930 and 900 mb, and with radii to maximum wind speed of 17.7 and 25.8 nautical miles (nm) for the 930 mb storms and 14.9 and 21.8 nm for the 900 mb storms, respectively.

In addition to peak surge, the CPRA storm set provided by the Storm Surge/Wave Team contains data on peak wave heights and peak wave period and a hydrograph that describes the rise and fall of surge over time for a four-day period after landfall of the storm (measured in 15-minute intervals for the FWOA scenario and one-hour intervals otherwise).

Calculating Flood Depths in Unprotected and Semiprotected Areas

In unprotected areas, flood depths for each synthetic storm are calculated at the census-block level by first converting surge elevations to depths by subtracting the mean block elevation and further subtracting any scenario-dependent subsidence based on the CPRA-defined subsidence zones (see CPRA, 2012b, Appendix C). Scenario-dependent values for sea-level rise (SLR) are already accounted for in the surge data sets provided by the Storm Surge/Wave model. The resulting depth value is referred to as the *still-water depth*. Significant wave heights for each synthetic storm are modeled by fitting a natural cubic spline model with two knots on the surge values from the CPRA storm set. The predicted significant wave height is capped by a physical limit of 0.78 times the still-water depth,¹ and then the significant wave height is converted to a free wave crest height by multiplying by a factor of 0.7 (FEMA, 2009). The total depth of inundation relevant for damage calculations can then be calculated by adding the crest height above the mean still-water level to the still-water depth.

In semiprotected areas, the same steps are performed, except that the initial surge elevations are calculated at the BHU level. This is converted to depths for each census block in the BHU using the mean block elevation, and the calculations proceed identically from that point onward. These steps, representing the flood depth calculations as applied only to unprotected and semiprotected areas, are summarized in Figure 3.2.

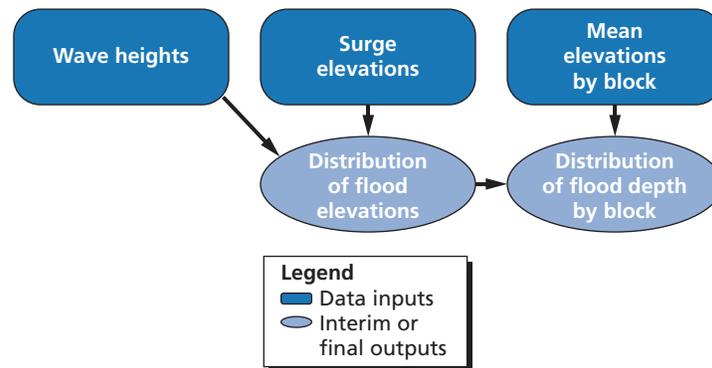
Expanded Storm Set for Flood Depth Module

The relationship between exterior storm surge and overtopping rates into the interior rises steeply as surge heights approach the top of the protection structure (Meer, 2002). For levees designed to protect against a 100-year surge, smaller surge heights produce little to no overtopping. A surge near the 100-year level results in modest overtopping from waves, but more-extreme surge events can produce very substantial overtopping because the surge flows right over the top of the barrier into the protected area. This nonlinearity cannot necessarily be captured in sufficient detail by a small set of 40 storms.

Because storm simulations with ADCIRC take substantial time and computing resources, JPM-OS utilizes a response surface to interpolate and extrapolate peak surge values as a func-

¹ Shan Zou, ARCADIS, personal communication, June 9, 2011.

Figure 3.2
Flood Depth Calculations in Unprotected and Semiprotected Areas



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tion of the radius of the storm’s maximum winds, the atmospheric pressure at the storm center, and forward velocity using modeled storms on the same track and landfall angle as a training set. CLARA uses this response surface to estimate peak surge elevation for a set of 720 “synthetic” parameterized storms. The synthetic storm set consists of a full factorial experimental design—sampling all possible combinations of sampled parameters—across ten storm tracks that make landfall at 29.5 degrees latitude ranging from -94.4 to -88.5 degrees longitude, nine values for central pressure ranging from 960 mb to 882 mb, and eight values for radius ranging from 5 nm to 40 nm. The larger set of synthetic storms, as opposed to the set of 40 storms, is needed to capture the relationship between exterior surge and interior flooding and to better identify the points at which modest, then severe, overtopping begins. The central values for forward velocity and landfall angle are used for all storms in the training set because the other storm parameters explain a greater share of the variation in surge response (Toro et al., 2010; Resio, 2007).

Surge Hydrographs and Wave Inputs

In protected areas, surge elevations are measured at points 200 meters perpendicular to and offshore from protection elements, such as floodwalls and levees. Points are specified for all transitions in the protection system, such as gates, at start and end points, and at any sharp corners; additional points are spaced evenly along the rest of the protection structure at a distance of 300 meters. In the case of outfall canals or other channels less than 200 meters wide, the surge and wave sample points are adjusted to fall in the middle of the channel on an unprotected side of the reach.

For each surge and wave point (SWP), peak wave heights from each storm are predicted by fitting wave heights from the CPRA storm set on the SWP’s distance from storm landfall and a natural cubic spline of the peak surge elevation. The same model is used to fit peak wave periods at SWPs.

Surge hydrographs at the SWPs are estimated by following the methodology used by LACPR (USACE, 2009a). This method fits a normal-shaped bell curve to the hydrographs in the CPRA storm set—specifically, the portion of the hydrograph in which surge values are greater than or equal to 70 percent of the observed peak surge elevation. A normal curve is

then fitted to each half of the hydrograph by estimating a standard deviation separately to the left-hand side where surge rises (σ_l) and the right-hand side where it falls (σ_r).

This yields values for σ_l and σ_r for each storm in the CPRA set that have been fitted on the peak surge at each SWP. A standard ordinary least squares (OLS) regression model is then applied to predict the hydrograph standard deviations as a function of peak surge elevation in order to generate synthetic hydrographs for each synthetic storm that peak at the predicted peak surge value. Analysis showed that, for the vast majority of storm and point combinations, all appreciable surge that could result in overtopping or lead to failures of the protection system due to structural fragility was contained within the two days leading up to peak surge and one day of surge recession.

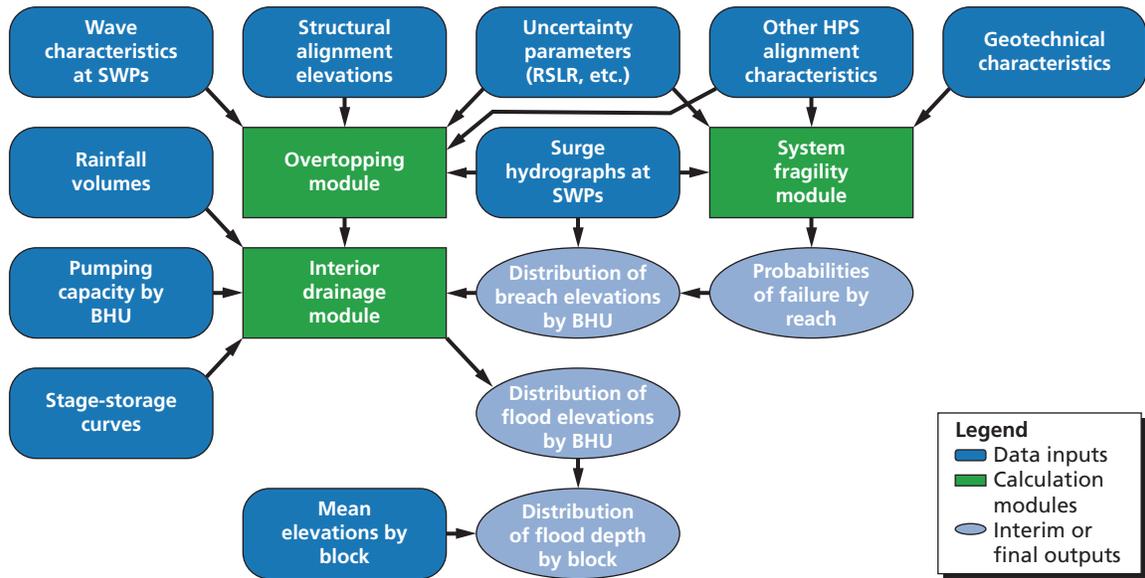
Flood Depth Module

This section describes the flood depth module, which generates estimates of flood depths for protected areas of the Louisiana coast that could result from storm surge flooding. For protected areas, the module considers multiple pathways to flooding, including overtopping and breaching. Overtopping volumes are calculated using standard methods by comparing the surge hydrographs (elevations over time), peak wave height, and wave period with the levee or floodwall crest heights. The probability of system failure is calculated as a function of peak surge elevation, crest heights, and characteristics, such as fill types and foreshore geometry, at each point. The stage-storage curves and interflow elevations between each BHU are then used to convert the initial overtopping volumes to an equilibrium peak standing water elevation, conditional on any system failures. This module estimates distributions of flood elevations by census block for each project condition, scenario, and storm, which are then passed to the economic module via the central database.

A summary of the flood depth calculation steps is shown in Figure 3.3; each step is described in detail in the chapters that follow. In the figure, green rectangles represent major modeling submodules, which are described in the next two chapters of this document (system fragility is discussed as part of both the overtopping and interior drainage chapters); the dark-blue, rounded-corner rectangles represent data inputs; and the light-blue ovals represent interim and final outputs.

CLARA also includes diagnostic tools to identify potential errors that can arise from unforeseen input conditions. The flood depth module produces a variety of diagnostic output files and data objects containing the results of intermediate calculations to verify that input data have correctly been read into the model and processed. Diagnostics also show the volume of water overtopping each reach segment into each BHU and provide intermediate flood elevations in every BHU at each iterative step in the interior drainage algorithm, enabling verification that flood volumes in protected areas are being allocated as expected.

Figure 3.3
Flood Depth Calculations in Protected Areas



NOTE: RSLR = relative SLR. HPS = hurricane protection system.

RAND TR1259-3.3

Calculating Surge and Wave Overtopping

Overview

This chapter describes the calculations performed in the overtopping submodule shown in Figure 2.3. During a storm event, overtopping occurs as a result of water entering the protection system because of waves spilling over a protective structure or storm surge pouring over the crest of the structure. The Storm Surge/Wave Team uses hydrodynamic models to generate the input data for the calculation of wave and surge overtopping.

We use two-dimensional weir equations from Meer (2002) and Franco and Franco (1999) to calculate overtopping rates (volume per time per linear distance along a protective structure) at each time step of the simulation at points along each element of the protection system.¹ The two-dimensional results are then converted to a three-dimensional volume of flow along the structure by multiplying them by the length of the protection system element.

Input Data

The Storm Surge/Wave model generates hydrographs representing the height of the storm surge over time for each storm. Surge heights are reported at 15-minute intervals over four days of the storm event. The hydrographs are reported at prespecified points along the protection structures. For protected areas, these points are 200 meters (660 feet) offshore from each protection structure and correspond to the distinguishing characteristics of the structure. These characteristics include bends in the linear structure as it follows the local topography, floodgates, pumping locations, and changes from earthen levees to engineered floodwalls. For semi-protected areas, these points are the centroids of each semiprotected BHU; for unprotected areas, these points are the census-block centroids. The point sets are defined initially for the FWOA case and are updated for with-project cases. Before running CLARA, the locations of the hydrograph point sets are determined and then converted to latitude and longitude.

¹ A weir is essentially a dam below the surface of the water. The shape of the weir determines the rate at which water flows over it, as characterized by its weir coefficient.

In addition to surge hydrographs, the Storm Surge/Wave model provides the following wave characteristics:

- Mean wave period in seconds (T_m) at the time of peak wave height. This is the average elapsed time from crest to crest.
- Peak significant wave height in meters (H_m). This is the vertical distance from the wave trough to the wave crest for approximately the highest third of waves.

For unprotected and semiprotected areas, peak surge elevations and significant wave heights are used, but wave periods and hydrographs of surge over time are not required.

Because of the long, shallow foreshore on the Louisiana coast, CLARA must account for wave breaking. To do this, wave characteristics are also reported 200 meters (660 feet) offshore of the protection structure in accordance with both IPET (USACE, 2009b) and LACPR (USACE, 2009a), and then are adjusted based on the geometry of the structure, as explained later in this chapter. Waves are assumed to approach the structure from a head-on angle, consistent with LACPR.

Data regarding structural characteristics of the protection system are also used (summarized in Table 4.1). These data include whether a structure is armored (on the protected side of the levee, on the side exposed to the surge, or both), the presence of a floodwall on top of a levee, its geometry, and its soil characteristics. These data were obtained by CPRA for current, planned, and future projects. In instances in which these data are not available, conservative cases are assumed for each parameter, as defined by tending to produce greater overtopping.

Wave-Only Overtopping

Wave-only overtopping refers to the case in which only the crest of the wave is above the height of the structure. To determine the volume of water flowing over the levee, we apply the approach outlined in Meer (2002) and Franco and Franco (1999) and review that approach in this chapter. We discuss pre-overtopping calculations, calculations for levees, and calculations for floodwalls.

Table 4.1
Data Used in the Overtopping Submodule

Data Name	Type of Data	Source	Notes
Surge hydrographs	Flat file	Storm Surge/Wave model	Point and storm dependent; reported at even intervals over the duration of the storm
Wave period	Flat file	Storm Surge/Wave model	
Significant wave height	Flat file	Storm Surge/Wave model	
Foreshore armor	Spatial	State of Louisiana/USACE	Armoring assumed for some future projects
Feature type	Spatial	State of Louisiana/USACE	Floodwall, levee, or gate
Floodwall geometry	Spatial	State of Louisiana/USACE	

The surge and wave data are provided 200 meters (660 feet) from the protection structure. The wave characteristics are scaled to account for the effects of breaking due to the long and shallow foreshore of the Louisiana coast. Using the approach outlined in USACE (2009a), we convert the wave height in meters as reported (H_{200}) to the wave height at the toe of the protection structure (H_s), ensuring that the breaking wave height does not exceed water depth at the structure toe:²

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

where

H_s =	significant wave height, adjusted for break, in meters
H_{200} =	significant wave height at 200 meters (660 feet), in meters
γ =	wave-breaking parameter = 0.4 (default for Louisiana coast)
η =	still-water elevation, in meters
z_{toe} =	elevation at toe of structure, in meters. ³

According to LACPR, z_{toe} was assumed to be zero.

To calculate wave overtopping for levees, one must first calculate the surf similarity parameter, ξ_0 (Meer, 2002). The surf similarity parameter is

$$\xi_0 = \frac{\tan \alpha}{\sqrt{s_0}},$$

where

$$s_0 = \frac{2\pi H_s}{g(T_{m-1,0})^2}$$

and

s_0 =	wave steepness
$T_{m-1,0}$ =	spectral wave period (seconds)
g =	gravitational acceleration = 9.81 (meters per second squared [m/s ²])
H_s =	significant wave height at the toe of the structure, in meters
$\tan \alpha$ =	slope of levee.

² After conducting the project-level analysis described in Chapter Nine, we identified an error in the code in the depth-limited wave-breaking function. The error resulted in a downward bias in wave overtopping volumes flowing into protected areas in most cases. This function is described correctly above, and the corrected version was used in the final Master Plan analysis described in Chapter Ten.

We compared selected uncorrected and corrected results to determine the magnitude of the bias. This comparison showed that the most notable changes occur in Plaquemines Parish, Larose to Golden Meadow, and Slidell, with interior flood elevations increasing by 1 to 5 feet. However, our review also indicates that, although the baseline flood depths change with the corrected function, there is no evidence to suggest that the fix would have notably changed project benefit estimates or the ranking of projects in the project-level analysis. Instead, the net effect of the correction is to shift flood depth and damage levels, both with and without new projects, upward relative to the previous baseline.

³ The elevation of the structure toe is the point at which the slope of the levee ends and the foreshore begins.

The values for $T_{m-1,0}$ and H_s are derived from data provided by the Storm Surge/Wave model, while the slope is assumed to be 0.25.

For levee overtopping, we follow Meer (2002), which fits the overtopping rate to the expected value of a normally distributed stochastic function with mean 4.75 and standard deviation 0.5:

$$\frac{q}{\sqrt{gH_s^3}} = \frac{0.67}{\sqrt{\tan \alpha}} \gamma_b \xi_0 \exp\left(-4.75 \frac{R_C}{H_s} \frac{1}{\xi_0 \gamma_b \gamma_f \gamma_\beta \gamma_v}\right),$$

where

- q = average wave overtopping rate (cubic meters per second per meter [$\text{m}^3/\text{s}/\text{m}$])
- g = gravitational acceleration = 9.81 (m/s^2)
- H_s = significant wave height at toe of structure (m)
- ξ_0 = surf similarity parameter
- $\tan \alpha$ = slope
- R_C = free crest height above still-water level (m)
- γ = influence parameters ([0,1], 0 = total influence, 1 = no influence):
 - b = berm influence
 - f = friction
 - β = angle of wave attack with respect to the protection structure
 - v = floodwall on levee.

The influence parameters in the Meer equation represent how particular elements of the levee affect wave overtopping. The parameter γ_b represents how much the berm attenuates the wave in wave overtopping; in both IPET (USACE, 2009b) and LACPR (USACE, 2009a), this parameter was assumed to be 0.7.

The parameter γ_f represents the effect of armor—e.g., a concrete breakwater—on the foreshore of the levee in attenuating the wave. Both IPET and LACPR assumed a value of 1 for this parameter, representing no armor; CLARA likewise assumes a default value for existing levees of 1 and a levee-specific value for new and upgraded structures if armoring is specified.

Consistent with IPET and LACPR, CLARA assumes a value of 1 (representing no influence) for γ_β , which is the angle of wave attack with respect to the protection structure, essentially assuming a perpendicular angle of wave attack.

Finally, γ_v indicates the influence of a floodwall on top of the levee. Again, IPET and LACPR assumed this value to be 1, which, in essence, assumes that there are no floodwalls on levees. When data indicate the presence of a floodwall, we adjust the parameter appropriately.

This estimated rate of overtopping holds for values of surf similarity parameter less than 5. If the surf similarity parameter is greater than 7, the more appropriate average wave overtopping formula is

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

Note that, if ξ_0 is between 5 and 7, the logarithm of q will be linearly interpolated from both approaches to estimating wave-only overtopping.

If the protection structure is a floodwall rather than a levee, then the equation from Franco and Franco (1999) is used in place of the Meer specification. The Franco and Franco function estimates the overtopping rate as the expected value of a normally distributed stochastic function with mean 3 and standard deviation 0.26, measured in cubic meters per second per meter. Its specification is

$$\frac{q}{\sqrt{gH_s^3}} = 0.082 \exp\left(-3 \frac{R_c}{H_s} \frac{1}{\gamma_\beta \gamma_s}\right),$$

where γ_s is the influence parameter for floodwall geometry.

Here, we adopt the IPET (USACE, 2009b) assumption that γ_s equals 1 (no influence) and that γ_β equals 0.83 to represent a plain impermeable floodwall and a perpendicular short-crest wave attack.

Surge Overtopping

When the height of the surge is higher than the crest of the levee, water will flow over the levee. If we ignore the action of waves with the surge, we refer to this situation as *surge-only overtopping*. For surge-only overtopping, flooding is calculated according to a weir equation. Assuming that the protection structure crest acts as a rectangular weir, then the following defines the volume of water that flows over it:

$$Q = C_w LH^{\frac{3}{2}},$$

where

$Q =$	volume of water (m ³ /s)
$C_w =$	weir coefficient (m ^{0.5} /s)
$L =$	water flow width (m)
$H =$	water flow height (m).

The weir coefficient is an empirically determined parameter that relates the flow of water to the geometry of the weir (USACE, 2009b, Vol. VIII, App. 9). The weir coefficient for a rectangular weir is 1.84. The values for the weir coefficient for other structures, according to IPET (USACE, 2009b), are 1.68 for floodwalls, 1.45 for levees, and 1.12 for gates when L and H are in meters.

Surge and Wave Overtopping

An extension of the prior case is when waves are present with an overtopping surge. A hybrid model accounts for both conditions:

$$Q = L \left(C_w H^{\frac{3}{2}} + 0.13 \sqrt{g H_s^3} \right),$$

where

$Q =$	total overtopping rate (m ³ water/s/linear m)
$C_w =$	weir coefficient (m ^{0.5} /s)
$g =$	gravitational acceleration = 9.81 (m/s ²)
$H =$	water flow height (m)
$L =$	length of reach (m)
$H_s =$	significant wave height (m).

The left term within the parentheses accounts for surge overtopping, and the right term accounts for wave overtopping.

Estimating Protection System Fragility

Overview

This chapter describes the calculation steps in the system fragility module shown in Figure 2.3 in Chapter Two. An important component of flood risk is the reliability of the structures designed for flood defense. These protection systems contain many components, each with several failure modes. Conceptually, it is possible to build a detailed, physics-based model to capture the full range of failure mechanisms for hurricane protection structures. In reality, however, empirical measurement would be difficult, if not impossible, for some parameters. Therefore, most analyses of failures in such systems are probabilistic and based on approximations. A failure is defined as the breaching of an element of the protection system due to the storm surge of the hurricane. In this simplified framework, the probability of failure, which we represent as P_f , can be expressed as a function of floodwater elevation and other variables that characterize the performance of the structure.

Elements of the structural protection system fail under the load of the storm surge or due to scour-induced erosion on the protected side from overtopping. Three failure modes are considered:

- A *seepage failure* occurs when water flows through soil under the levee or floodwall. This can lead to failure if the upward pressure of water flowing through the soil exceeds the downward pressure from the weight of the soil above it.
- A *slope stability failure* occurs when forces exerted by the floodwater against the levee or floodwall are greater than what the structure can resist.
- An *overtopping failure* occurs because of erosion of the protected side of the levee or floodwall from the rushing surge water.

We use data from the USACE to characterize existing and proposed elements of the protection system and standard engineering calculations from Volume VIII of IPET (USACE, 2009b) to estimate the probability of seepage and slope stability failures as a function of the maximum surge height. Overtopping failures dominate in practice and are assumed to be proportional to the height of the surge above the crest of the levee. Because failures are probabilistic events, we run the model 200 times for each storm using Monte Carlo simulation to characterize likely flooding that would occur due to failure. If a levee or floodwall fails, we assume that the area it is intended to protect floods to the height of the peak storm surge at the breach point.

Hurricane Protection System Components

For the fragility analysis, the HPS components are further divided into *reaches*. Reaches are continuous lengths of levees or floodwalls that are homogeneous in their geotechnical, hydrologic, and hydraulic loading conditions (USACE, 2009b). Reaches serve as independent components subject to the failure modes. Each of these failure modes is represented by a conditional probability of failure. These failure probabilities are combined to produce an aggregate probability of failure for the reach, conditioned on the attributes of the flood, soil characteristics, and reach shape.

Failure mechanisms are calculated in two dimensions for a cross-section of the reach and then extrapolated to three dimensions to estimate the probability of failure for the actual reach. Each reach is divided into characteristic lengths, each of which is assumed to be 300 meters (1,000 feet). Each characteristic length acts as a probabilistically independent section. Thus, as the total length of a reach increases, the probability of the reach failing rises as well. If the two-dimensional probability of failure is p , then the three-dimensional probability of failure is

$$P_f = 1 - (1 - p)^n,$$

where n is the number of characteristic lengths within the reach.

Failure Modes

Levees and Floodwalls

As noted earlier, there are three principal failure modes that we consider: (1) seepage, (2) slope stability, and (3) erosion of the landside toe from overtopping. We assume that modes 1 and 2 are always present during a surge and that mode 3 occurs as a result of overtopping due to a surge elevation above the crest of the structure. This assumption likely underestimates the failure probability because it ignores the potential for wave action and water flow along the waterside of the levee to contribute to erosion in cases in which overtopping does not occur.¹

Point Structure (Transitions and Gates)

Some parts of the HPS are essentially single points of failure. These include floodgates and the transition from one type of structure to the next. We cannot calculate the probability of failure for these parts of the protection system as if they were levees or floodwalls. To model the fragility of transitions and gates, we assign them the same probability of failure as the weakest adjoining levee or floodwall.

Pumping Stations

IPET estimated a wide range of potential failure modes for the pumping system. Because of the difficulty in quantifying many of the mechanical, electrical, and human modes of failure for pumping stations, we instead model the risk that the pumping system performs as designed through three scenarios: 100 percent of rated operational pumping capacity, 50 percent of pumping capacity, and no pumping. This differs from IPET, which used the total available capacities rather than the rated operational capacities; in some pumping stations, these capacities were equivalent, but in others, the operational capacities used as the 100 percent baseline

¹ We do not include internal erosion as a possible failure mode. Preliminary analysis indicated that the probability of failure due to internal erosion was an order of magnitude smaller than the failure modes we have retained.

for this analysis was less than half the total available capacity, reflecting that some pumps in a configuration would not be operational. We note that this simplified framework does not allow for the possibility that pump performance could vary by location, storm severity, or other variations but instead provides a basic means of analytically bounding the flood depth reduction and subsequent flood damage with and without pumping.

Input Data

In general, input data relevant to estimating the fragility of elements of the HPS fall into one of three categories: characteristics of the HPS, geotechnical (i.e., soil and subsurface) characteristics, and uncertain scenario parameters. These parameters vary across the HPS. Protection system characteristics are provided by CPRA and the USACE. Geotechnical parameters are provided from other models as inputs or estimated from boring-log data for the HPS. Where boring logs are unavailable or incomplete, to generate geotechnical parameters, we assume typical values for soil type and density for coastal Louisiana. This is particularly relevant for estimating the fragility of new or proposed elements of the protection system, for which it may not be possible to obtain data on geotechnical characteristics of the area but basic information on soil type may be known.

The input data are summarized in Tables 5.1 and 5.2. Table 5.1 lists the input parameters and source for each data value, while Table 5.2 shows the default parameter assumptions used for different soil types.

Estimating Individual Failure Modes

Seepage

Seepage occurs when water flows through soil pores under the levee or floodwall. This can lead to failure if the upward pressure of water flowing through the soil pores exceeds the downward pressure from the weight of the soil above it.

To calculate the probability of seepage failure, we follow these steps and explain them in more detail below:

1. Solve for the exit gradient² using methods from Technical Memorandum (TM) 3-424 (USACE, 1956).
2. Repeat calculation of exit gradient for each combination of input parameters using the Taylor series method as in USACE (1999):
 - 2.1. once for all inputs at their expected value
 - 2.2. once for +1 standard deviation holding all other inputs constant
 - 2.3. once for -1 standard deviation holding all other inputs constant.
3. Determine the expected value and standard deviation of the exit gradient.
4. Calculate the expected value and standard deviation of the natural logarithm of the exit gradient.

² Water seeping into the levee will result in an upward vertical force. This force is counteracted by the downward force of the water on the levee. The exit gradient is the difference in vertical hydraulic forcing.

Table 5.1
Input Parameters for System Fragility Submodule

Parameter	Unit	Failure Mode	Source
Geotechnical			
Substratum permeability, k_f	cm/s ft./s	Seepage	TM 3-424 and D10 grain size from boring logs
Top blanket permeability, k_b	cm/s ft./s	Seepage	TM 3-424 and D10 grain size from boring logs
Blanket thickness, Z	m	Seepage	Estimated from boring logs
Substratum thickness, d	m	Seepage	Estimated from boring logs
Friction angle of the levee embankment, ϕ_{emb}	Degree	Slope stability	Boring logs, penetration test correlations
Unit weight of soil, γ	kg/m ³ lb./ft. ³	Slope stability	Boring logs, penetration test correlations
Drained strength of foundation, cohesion, c'	kg/m ²	Slope stability	Boring logs, unconfined compression test ^a
Friction angle of the foundation, ϕ_{found}	Degree	Slope stability	Boring logs, penetration test correlations
Foundation material type	N/A	Overtopping	Boring logs
System shape			
Slope of reach	m	Seepage, slope stability	Topographic center line points and segment data
Width of reach	m	Seepage, slope stability	Topographic center line points and segment data
Reach height	m	Overtopping, seepage, slope stability	Topographic center line points and segment data
Storm			
Peak surge elevation	m	Overtopping, seepage, slope stability	ARCADIS; Storm Surge/Wave model

^a See California Department of Transportation, 2000.

- Calculate the probability that the exit gradient is greater than a critical value, which is assumed to be 1.0.

Step 1

Solve for the exit gradient using methods from TM 3-424 (USACE, 1956).

At the assumed values for all parameters, calculate the effective exit distance x_3 , where

$$x_3 = \sqrt{\frac{k_f}{k_b}} zd.$$

Table 5.2
Default Parameter Values by Unified Soil Classification System Soil Type

USCS Code	Description	Unit Weight (lb./ft. ³)	Unit Weight SD	Undrained Strength (lb./ft ²) Compressed	Undrained Strength (lb./ ft ²) SD	Friction Angle (degree)	Friction Angle SD	Permeability (cm/s)	Permeability SD
GW	Well-graded gravel, fine to coarse gravel	141	21.9	0	0	40.0	4.00	2.78E-01	4.84E-01
GP	Poorly graded gravel	133	25.5	0	0	37.5	3.75	3.70E+01	5.47E+01
GM	Silty gravel	123	46.0	—	—	42.5	4.25	2.78E-01	4.84E-01
GC	Clayey gravel	133	25.5	—	—	32.5	3.25	2.78E-01	4.84E-01
SW	Well-graded sand, fine to coarse sand	117	43.8	—	—	35.0	3.50	2.22E-04	4.37E-04
SP	Poorly graded sand	110	36.8	—	—	27.5	2.75	2.22E-04	4.37E-04
SM	Silty sand	115	38.2	1,050	315	32.5	3.25	2.22E-04	4.37E-04
SC	Clayey sand	124	33.2	1,050	315	7.50	0.75	2.22E-04	4.37E-04
ML	Silt	109	38.9	1,350	405	32.5	3.25	2.22E-04	4.37E-04
CL	Clay	114	27.6	1,800	540	7.50	0.75	2.78E-09	4.84E-09
OL	Organic silt, organic clay	109	31.1	800	240	7.50	0.75	2.78E-05	4.84E-05
MH	Silt of high plasticity, elastic silt	109	38.9	1,500	450	7.50	0.75	2.22E-04	4.37E-04
CH	Clay of high plasticity, fat clay	100	40.3	2,150	645	7.50	0.75	2.78E-05	4.84E-05
OH	Organic clay, organic silt	103	31.1	—	—	7.50	0.75	2.78E-05	4.84E-05
Pt	Peat	98	38.9	—	—	5.00	0.50	3.70E-03	5.47E-03

NOTE: USCS = Unified Soil Classification System. SD = standard deviation.

Next, calculate the distance, s , from the landside toe to the effective source of seepage entrance:

$$s = x_1 + x_2,$$

where x_1 is the distance from the waterside toes to the effective source of seepage entrance and x_2 is the base width of the levee.

Next, solve for the residual head (i.e., height of water) at the levee toe:

$$h_0 = \frac{Hx_3}{s + x_3},$$

where H is the floodwater elevation.

Finally, the landside toe exit gradient, i , is calculated as

$$i = \frac{h_0}{z}.$$

Step 2

Repeat calculation of exit gradient for each combination of input parameters in the Taylor series method.

In step 2, we calculate the exit gradient several times: one time with each parameter set at its nominal value; one time with each parameter set to one standard deviation greater than its nominal value; and one time with each parameter set to one standard deviation below its nominal value.

Step 3

Determine the expected value and standard deviation of the exit gradient.

The three components of the exit gradient from step 2 are then used to obtain the expected value (based on nominal parameters) and the total variance of the exit gradient, $\text{var}(i)$. The square root of this value is the standard deviation of the exit gradient.

Step 4

Calculate the expected value and standard deviation of the natural logarithm of the exit gradient, which is assumed to be lognormally distributed (USACE, 1999).

Step 5

Calculate the probability that the exit gradient is greater than a critical value (assumed to be 1.0).

We assume that the critical value for the exit gradient is 1.0: This is a common assumption in the soil mechanics literature because it is the point at which the forces preventing seepage equal the forces driving seepage (USACE, 2005). With the assumption that the critical exit gradient is 1.0, the probability of failure is

$$p_s(h) = p(\ln i > \ln 1),$$

or

$$p(\ln i > 0).$$

Finally, using the cumulative normal distribution function, we calculate

$$p_s(h) = 1 - F_{normal} \left(\frac{\ln i_{crit} - E(\ln i)}{\sigma_{\ln i}} \right),$$

where F_{normal} is the cumulative normal distribution function and $E(\cdot)$ is the expected value function.

Slope Stability

Slope stability is compromised when the forces exerted by the floodwater elevation are greater than those the structure can resist. For our analysis, we assume that the soils composing the levee have not yet reached steady-state seepage conditions (when pore pressure reaches equilibrium with floodwater conditions). This is appropriate for short-term flood loading analysis.

To calculate the probability of failure for slope stability, p_{SS} , we follow these steps, which are essentially similar to those used to calculate the probability of failure due to seepage. Here, we estimate the probability that a factor of safety (FOS) is exceeded rather than an exit gradient.³ The FOS represents the ratio of the forces that the structure is able to resist to the forces exerted by the floodwater; FOS of 2 indicates that the structure is able to exert twice the force of the floodwater. The steps to estimating the probability of failure for slope stability are outlined below:

1. Solve for FOS using Bishop's method (USACE, 2003).
2. Repeat solution for each combination of input parameters:
 - 2.1. once for all inputs at their expected value
 - 2.2. once for +1 standard deviation holding all other inputs constant
 - 2.3. once for -1 standard deviation holding all other inputs constant.
3. Determine the expected value and standard deviation of the FOS.
4. Calculate the expected value and standard deviation of the natural logarithm of the FOS.
5. Calculate the probability that the FOS is greater than a critical value (assumed to be 1.0).

In step 1, the FOS is solved iteratively through a procedure called the simplified Bishop's method, which is detailed in USACE (2003). The remaining steps, 2–5, are similar to those for the calculation of the probability of failure for seepage. The parameters used to estimate the FOS are listed in Tables 5.1 and 5.2.

³ FOS refers to the ratio of the internal forces maintaining the slope of the levee to those driving the levee to collapse. When it is 1, the forces are equal and the levee is unstable and may collapse.

Table 5.3
Empirical Probability of Failure Due to
Overtopping

Type of Structure	Height of Surge Above the Crest of the Structure (feet)			
	≤0.5	≤1.0	≤2.0	3
Levees				
Hydraulic fill	0	0	1	1
Clay	0	0	0.25	0.5
Protected	0	0	0	0.1
Walls				
Hydraulic fill	0	0	0.5	1
Clay	0	0	0.25	0.5
Protected	0	0	0	0.1

SOURCE: IPET, Vol. VIII, Appendix 10 (USACE, 2009b).

Surface Erosion and Overtopping

Overtopping failures occur when water from the storm surge flows over the structure and causes erosion on the protected side of the structure. Based on empirical observation, IPET estimated that floodwater elevations up to the crest of the levee or floodwall do not contribute additionally to failure via surface erosion. Therefore, if the surge is below the height of the crest, the overtopping failure mode does not contribute to the probability that the structure fails. When overtopping occurs, the probability of failure depends on the height of the surge above the crest of the levee. This function is dependent on the type of structure and type of fill material (USACE, 2009b). Table 5.3 lists the probabilities of failure for overtopping, p_{OR} .

Aggregate Reliability and Probability of Failure

As illustrated in the previous sections, each failure mode is associated with a conditional probability of failure dependent on floodwater elevation and other characteristics of the HPS. For each reach, it is necessary to combine each of the conditional failure probability modes to obtain a total conditional probability of failure as a function of the floodwater elevation. In this analysis, we assume that the failure modes are independent and uncorrelated. Correlations among failure modes are likely because one mode of failure may increase or decrease the probability of failure by some other mode. This is especially the case with seepage and slope stability failures, both of which depend on internal soil dynamics under load; this is likely less the case with overtopping failures that result in landside erosion of the levee. Unfortunately, little is known about these interrelationships, so we model them as independent.

With the assumption of three independent failure modes, the probability of not having a failure is the probability of no failure due to seepage, no failure due to slope stability, and no failure due to overtopping. Thus, the overall probability of no failure occurring (the reliability) is the product of the reliability values for that floodwater elevation:

$$R(h) = R_s(h)R_{SS}(h)R_{OT}(h),$$

where the subscripts refer to the three failure modes. Therefore, the total cross-sectional (two-dimensional) probability of failure at any floodwater elevation is

$$\begin{aligned} P_{f,2d} &= 1 - R \\ &= 1 - (1 - p_s)(1 - p_{SS})(1 - p_{OT}). \end{aligned}$$

The probability of failure needs to be converted into a probability of failure along the length of the reach. Each characteristic length acts as an independent section; thus, as total length of reach increases, the probability of the reach failing rises proportionally, as indicated by this equation:

$$P = 1 - (1 - p_{f,2d})^n,$$

where $p_{f,2d}$ is the cross-sectional probability of failure and n is the number of characteristic lengths within the reach. We assume that the characteristic length is 300 meters (1,000 feet) (USACE, 2009b). Therefore, if a reach is 1,600 meters (5,300 feet), the value for n is 5.3.

Failures at Transitions, Gates, and Other Structures

The HPS includes gates and transition structures in addition to levees and floodwalls. These become additional points at which the system may fail and represent the possible weak link that transitions often create. Although we assume that all floodgates are closed in a flood event, the possibility remains that they will fail. We regard these elements of the protection system as potential sources of failure. For each gate and transition in the protection system, we assume that the probability of failure for that element is equal to the maximum two-dimensional probability of failure of the adjacent elements of the protection system.

Estimating the Probability of Failure over the Course of the Storm

The probabilities of failure derived in the previous chapter refer to static events given the height of the storm surge against the levee or floodwall. Typically, a storm lasts several days and the storm surge rises and falls as the storm passes. We make the simplifying assumption that the probability of failure over the course of the storm is the probability of failure associated with the highest surge height during the storm. IPET makes the same simplifying assumption (USACE, 2009b).

Calculating Interior Drainage in Protected Areas

Overview

This chapter describes the calculation steps for the interior drainage module shown in Figure 2.3 in Chapter Two. The interior drainage module relates flooding and breaching around the boundaries of protected areas to the final flood elevations in each BHU in the protected area. In other words, it takes outputs from the overtopping and system fragility modules and determines how any resulting floodwaters are distributed through the interior of the protection system. This is a time-stepped equilibrium-based model: It does not dynamically track three-dimensional or even two-dimensional flows but instead distributes volumes at equilibrium among connected basins. This is the same general approach utilized in both the IPET (USACE, 2009b) and LACPR (USACE, 2009a) analyses. The conceptual model is that a protected area comprises a set of BHUs and that water entering a basin from overtopping or breach of an adjacent levee or floodwall reach will first fill the basin adjacent to the levee until water spills over to another basin, fill that until it spills into another basin, and so forth. Water may eventually rise to join and backfill basins as well; in the case of a breach, it is likely that a set of interconnected basins will equalize to the same flood elevation.

Input Data

The input data required to calculate interior flood elevations include topographic data, storm data, and intermediate outputs of the flood depth module. These data are summarized in Table 6.1; where necessary, we discuss them in greater detail in the algorithm section below as well as in Chapter Eight.

Rainfall

The additional flood volume that is produced by rainfall from a passing hurricane is estimated using a two-step process. First, we estimate rainfall volumes for the full JPM-OS experimental design of 304 storms for coastal Louisiana. We then fit a regression model to these data using parameters that define our synthetic storms along with information describing the storm track over time. This latter step allows us to generate approximate rainfall volumes for all BHUs using only one vectorized calculation for each storm.

To produce rainfall estimates for our calibration storms, we rely on the same method applied for the risk and reliability model in IPET (USACE, 2009b). IPET's approach is a fur-

Table 6.1
Data Requirements to Calculate Standing Interior Flood Elevations

Data Name	Description	Source
DEM of Louisiana coast	Coastal Louisiana 2011 land elevations at 30-meter resolution	USGS; Wetland Morphology model
Stage-storage curves for each BHU	Describes the one-to-one relationship between water elevation and volume stored in a BHU	Spatial processing of DEM (RAND)
Interflow elevations for all BHUs	Describes the elevation at which water will flow between adjacent subbasins and BHUs; stored as a symmetric sparse matrix	Spatial processing of DEM (RAND)
Overtopping	Overtopping volumes by BHU and storm and scenario	Overtopping model (RAND)
Fragility	Levee failures and associated elevations by BHU and Monte Carlo run	Fragility model (RAND)
Pumping rates for each BHU	Provided as pump locations and capacities	Sewerage and Water Board of New Orleans
Storm characteristics at hourly intervals	Storm parameters (central pressure deficit and radius of maximum wind speed), distance to each BHU, and azimuth to each BHU at one-hour time intervals for a training set of 304 simulated storms	ARCADIS; Storm Surge/Wave model
Rainfall	Per-area rainfall rates or rainfall volumes over the course of each storm	Distribution of rainfall predicted by regression model, capped at a maximum of 6.5 inches per 6 hours

ther approximation of a relationship developed by Lonfat, Marks, and Chen (2004) based on hurricane observations from the Tropical Rainfall Measuring Mission (TRMM). The first step is to identify a baseline rainfall rate for each interior BHU, which is later adjusted to account for the asymmetric rainfall rates observed in different quadrants of the observed storms (i.e., higher rainfall rates on one side or in one quadrant of the tropical cyclone). The baseline rate is assumed to be a linear function of central pressure deficit (ΔP) inside the radius to maximum wind speed (R_{\max}) and to exponentially decay with distance beyond R_{\max} . Specifically, it takes the form

$$I = 1.14 + 0.12\Delta P \text{ for } r \leq R_{\max}$$

or

$$I = (1.14 + 0.12\Delta P) \exp\left(-0.3\left(\frac{r - R_{\max}}{R_{\max}}\right)\right) \text{ for } r > R_{\max},$$

where I gives rainfall intensity in millimeters per hour (USACE, 2009b).

Rainfall rates also depend on the quadrant of the storm in which a given point is located at different times as the storm moves along its track, which can be described by the *azimuth*, or angle from the center of the storm to the observed point relative to true north. This azimuthal

dependency varies according to storm features, but, for the set of high-intensity storms considered here and by IPET, there is a general increase in intensity in the northeast quadrant (relative to the storm track) and a decrease in the southwest quadrant. IPET does not reduce the baseline rate for areas falling to the left of a storm track (so as not to underpredict rainfall) and multiplies it by 1.5 for areas falling to the right to account for azimuthal and landfall effects (USACE, 2009b). For our modeling, the radius and the azimuth are determined relative to the BHU centroids. Unlike IPET, we do not consider variance in rainfall.

To generate a set of BHU-specific rainfall rates for each storm, we calculate rainfall rates using these rules for each time step, convert rates to volumes by multiplying the rate by the area of the BHU, and use trapezoidal integration across the storm duration to produce total rainfall volumes over the course of each storm by BHU. These are combined into a database that is merged with the storm parameters. We then estimate BHU-specific rainfall rates as a function of storm parameters rather than from directly modeled storm outputs.

Using the estimated rainfall volumes in each protected BHU from the 304 LACPR storms as a training set, we then utilize regression analysis to interpolate and extrapolate these volumes to represent rainfall from the full range of synthetic storms. After testing different specifications using tenfold cross-validation, the following log-linear model provided the lowest range of root mean squared error (RMSE) across all interior BHUs:

$$\log(\text{rainfall}) = \beta_0 + \beta_1 C_p + \beta_2 R_{\max} + \beta_3 (C_p \times R_{\max}) + \sum_i \sum_j \beta_i \theta_i + \beta_j \alpha_j + \beta_{ij} (\theta_i \times \alpha_j),$$

where θ indexes the ten storm tracks and α indexes three storm angles, both treated as unordered categorical variables.

This equation was used to predict rainfall for each synthetic storm and protected BHU. A review of these outputs suggested that estimates for large or intense storms with characteristics outside the initial training set were increasing exponentially and were producing unrealistically large volumes. As a result, we set a maximum on these estimates corresponding to the six-hour, ten-year rainfall event (6.5 inches of precipitation) (USACE, 2009a). The final rainfall volumes vary by synthetic storm but are otherwise held constant across all scenarios to facilitate comparisons across different projects.

Pumping

Pump stations in protected areas provide the capacity for pumping floodwaters back out of the protected area through outfall canals or other outlets. Pumping capacity is rated in cubic meters per minute for each BHU based on the location of pumps, and scenarios allow the performance of pumping systems to be set at 0 percent, 50 percent, or 100 percent of rated capacity. In the event of a breach in a given protected area, CLARA assumes that pumps will be overwhelmed and have no net effect on the impact of catastrophic failure.

Because the interior drainage submodule is not time-stepped and overtopping volume is not calculated separately for each hour of the storm, we relied on assumptions regarding the length of time that pumps are needed. Pumps are designed primarily to prevent flooding from rainfall events, so it is likely that pumps would operate for a longer period than just when overtopping occurs. CLARA estimates the pumping time in each BHU to be the median time of

nonzero surge at all protection elements bordering the BHU over all storms from the FWOA storm set; because there is likely a period of surge buildup and recession in which levels are not high enough to cause overtopping, the time of all nonzero surge is taken to be an approximation for the length of time a storm is directly impacting a BHU, and thus when the most significant portion of rainfall would be occurring. For BHUs with no exterior-facing boundaries (and thus with no directly adjacent protection elements), CLARA uses the grand median of 94 hours over all points. In addition, the total amount of water pumped out of the system for a given BHU cannot be greater than the sum of overtopping volumes and rainfall volume into that BHU; pumping in a single BHU is assumed to have no effect on nearby BHUs in a protected area.

Spillover and Equalization Calculations

Calculation of interior water elevations begins with two modeling inputs: the overtopping volumes calculated for the boundaries of the protected area under the assumption of no breaching and the outputs of the Monte Carlo fragility runs, which specify which reaches fail in each run. The steps to determine interior flood elevations can be thought of as being made up of an outer and an inner algorithm. The outer overtopping and fragility algorithm determines the volume of water that enters a protected area, or the surge height for a basin (as in the case of a breach) and includes the overtopping and fragility calculations. The inner interior drainage algorithm distributes water trapped in a basin by calculating BHU interflows. This interior drainage module calculates the standing elevation of water that results.

We describe these algorithms sequentially in the next two sections.

Overtopping and Fragility Algorithm

Step 1: Calculate Elevations Under the Assumption of Overtopping Only, with No Breaches

Step 1a

Initialize boundary BHUs with the overtopping volumes on adjacent reaches, add rainfall, and subtract any pumping capacity that is effective in the given pumping scenario. The results are translated to elevations using the stage-storage curves that describe the relationship between water volumes and flood elevations for each BHU or grouping of BHUs.

Step 1b

For each boundary BHU with nonzero water volumes, apply the interior drainage algorithm (see below). The end result of this step is referred to as the *overtopping-only elevation* (e.g., without accounting for fragility). From this point, all BHUs are initialized with those values.

Step 2: For Each Monte Carlo Run of the Fragility Analysis, Perform These Steps

Step 2a

Identify which reaches, if any, failed in that particular run.

Step 2b

For each reach, identify the breach flood elevation. Following the IPET risk and reliability analysis, we set the flood elevation for the breach equal to the peak surge elevation exterior to the reach that failed (USACE, 2009b).

Step 2c

Within a single protected area, identify the maximum surge elevation associated with any breach on the boundaries of the protected region.

Step 2d

Apply the distribution algorithm with modified stopping criteria: Instead of allocating a fixed amount of water to its equilibrium condition, treat the breach as an arbitrarily large source, and terminate when all basins that connect via interflow elevations at the breach elevation have equilibrated to the height of the surge at the breach.

Step 2e

If necessary, repeat with other breaches having lower surge elevations. Flow from the highest-elevation breach may fail to reach BHUs adjacent to other lower breaches because of topographic features, structures within the protected area, or lack of data regarding interconnections. Thus, if there are BHUs adjacent to other breaches that were not flooded in the primary equilibration step, the same process is repeated, using adjacent breaches as the source.

Step 2f

At this point, all BHUs within the protected area will have an elevation of water—either the surge height as a result of a breach or the volume that would arise because of the distribution of overtopping volumes if those BHUs were not subject to flooding via system failure.

Step 3: Assess Convergence and Summarize Distribution

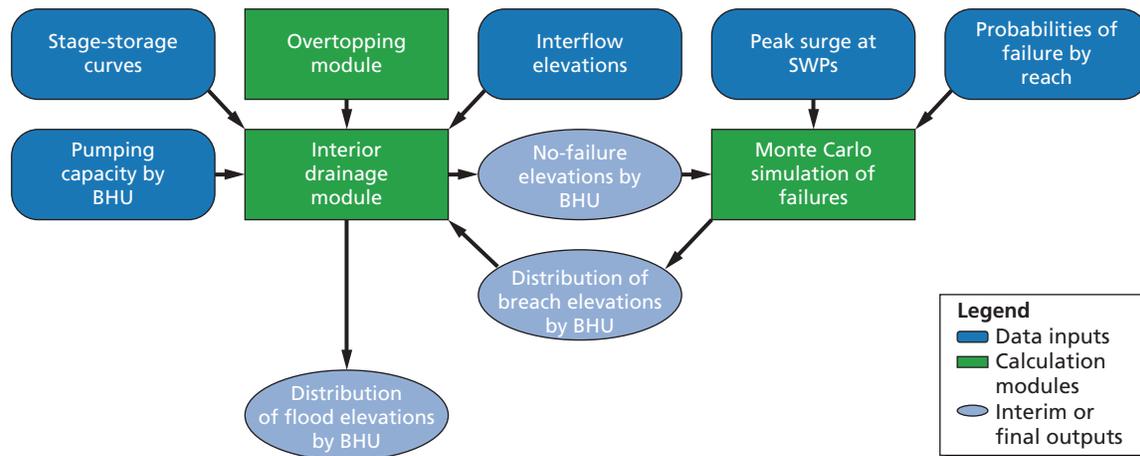
The result of the overtopping and fragility analyses is a probability distribution of flood heights. The overtopping-only elevations are the result of the case in which no failures occur. Monte Carlo simulations of failure determine the resulting distribution. Our testing indicated that running a relatively small number of iterations (200) produces stable results in the final flood exceedance calculations. This is likely due to the flood exceedances being based on 720 synthetic storms because each storm affects thousands of points along protected areas with highly correlated surge heights. Figure 6.1 depicts the process for aggregating calculations from the fragility and overtopping modules in the interior drainage module.

Interior Drainage Algorithm

This algorithm describes how overtopping volumes are distributed across BHUs within a shared protection system. It is a recursive algorithm applicable to any BHU containing a non-equilibrium volume of water, where *equilibrium* is defined as being in one of two conditions:

- Water elevation is below any connection to an adjacent BHU.
- Water elevation is the same as the elevation in any adjacent BHU that is connected by an interflow elevation.

Figure 6.1
Integration of Overtopping and Fragility Modules to Yield Flood Elevation Distributions



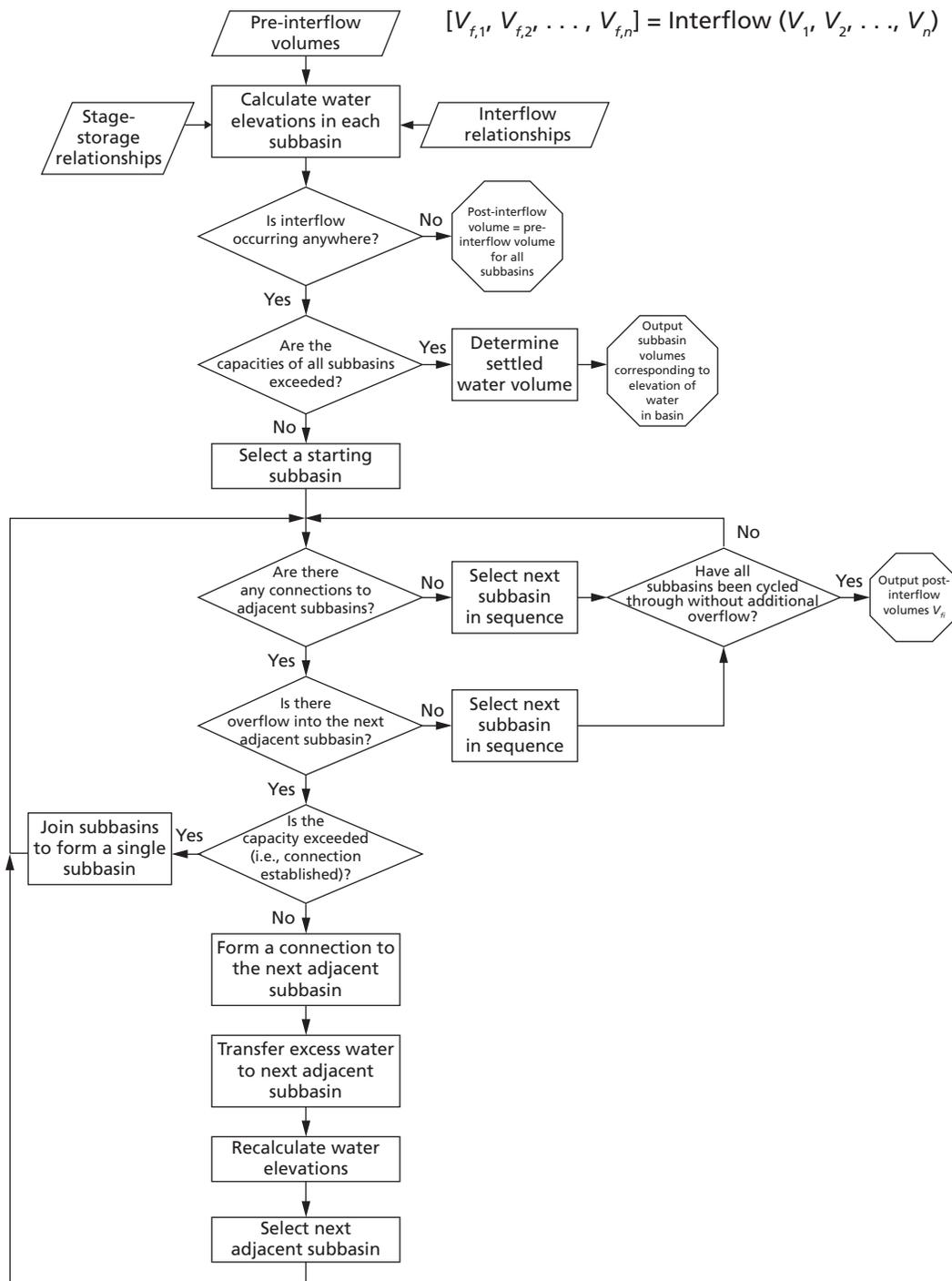
RAND TR1259-6.1

By definition, once the algorithm has been applied serially throughout the protected area, it will result in all BHUs in that area having an equilibrium (standing) water elevation. The fundamental algorithm is essentially the same as that used by IPET (USACE, 2009b), shown in Figure 6.2.

For the current BHU, consider the initial volume to be distributed, either directly from boundary overtopping (plus rainfall and net pumping) or a breach or from inflow from an “upstream” basin. If the source is a breach, assume an arbitrarily large volume of water that reaches a height equal to the storm surge for that breach:

1. Identify the potential interflow elevations (i.e., the hydrologic connection between the BHU of interest and adjacent BHUs).
2. Calculate the BHU flood elevation and remaining volume to distribute by calculating the difference in storage between the minimum interflow elevation and the current water elevation.
3. Allocate the minimum of either the remaining volume of water or the amount available for storage up to the lowest unsubmerged interflow elevation (in a breach case, peak surge elevation should be considered an interflow elevation as well). Then move to the BHU connected by that cut, and repeat the above process until either of the following conditions is met:
 - 3a. The volume left to be distributed is zero.
 - 3b. The minimum cut is connected to a basin that is already full. In this case, there are two possible procedures that need to be implemented:
 - If the newly connected BHU is full at the level of the interflow connection, the basins are treated as joined, the algorithm proceeds as usual with stage-storage curves combined, and the search for a minimum interflow connection looks across the boundary of joined BHUs.
 - If the newly connected BHU is on the boundary of the protection system and contains a volume of water that results in a current elevation being above

Figure 6.2
Algorithm for Calculating Equilibrium Flood Elevation



SOURCE: USACE, 2009b.
 RAND TR1259-6.2

the minimum interflow elevation, flow into that boundary BHU is treated as impossible and the algorithm searches across interflow elevations for the next BHU to join.

Alternative Stopping Criterion for Breach Case

In the event of water flowing in from a breach, the assumption of total inundation up to the peak surge elevation (or alternative single-elevation assumption) means that, instead of halting the distribution process once a prespecified volume has been allocated, the process stops when all BHUs joined with the breach-adjacent basin have elevation equal to the peak surge height.

The model stores the water elevations for each BHU within the protected area. The final outputs are water elevations at the end of the hydrograph for those BHUs unaffected by a breach or the peak elevation if a breach occurs.

Flood Depth Exceedances

The final outputs of the flood depth module are flood exceedances, which are used to calculate final damage exceedances in the economic module, as described in the next chapter. The flood depth module also produces an empirical distribution of flood depths used to calculate EAD.

After running the drainage model, flood depth results are compiled at each census block for each of the 720 synthetic storms. Probability weights are assigned to each synthetic storm using the probability densities described by Resio (2007). Each storm varies by track, central pressure, and radius; the probability space is partitioned into cells according to these three parameters, and each storm is assumed to be representative of all storms with parameters that fall within its cell. For example, a storm with a 20-mile radius and central pressure of 901.5 mb is assumed to produce surge results characteristic of any storm on the same track with a radius from 17.5 to 22.5 miles and central pressure from 896.625 to 906.375 mb.

The marginal probability density of each storm track is calculated based on the observed historical storm frequencies of storms making landfall at each one-degree interval of longitude shown in Figure 4-2 of IPET Vol. III, Appendix 8-2 (USACE, 2009b). Along the portion of the Gulf Coast in the study area, this frequency ranges from about 0.03 to 0.06 Category 3 or greater storms per year per degree of longitude. The marginal distribution of storm intensity is described by a Gumbel distribution with a mean value that is treated as uncertain and can be shifted in any scenario. For instance, the moderate scenario assumes that the mean delta in central pressure of future hurricanes increases by 10 percent in 2061.

Taking a sum of the synthetic flood depths weighted by the probability masses assigned to each synthetic storm yields an empirical CDF describing the probability of a given flood depth being exceeded by any given storm in our sample space of Category 3 or greater storms that make landfall at 29.5 degrees latitude anywhere from -94.4 to -88.5 degrees longitude.

To obtain a CDF describing the probability of a given flood depth being exceeded in any given year, the cumulative densities from the empirical CDF described above are exponentiated by the overall storm frequency describing how many storms of interest are on average seen each year. The baseline overall frequency of 0.0525 is based on historical observations in the study region and can be modified by a percentage-based factor in uncertainty scenarios.

The final CDF is then inverted in order to calculate the 50-year, 100-year, and 500-year flood exceedances, which are the flood depths with probabilities of occurring or being exceeded in a given year of 0.02, 0.01, and 0.002, respectively. In CLARA, damage is calculated deterministically, so flood depths at these exceedances are used as inputs to calculate the corresponding 50-year, 100-year, and 500-year damage exceedances in each census block.

For diagnostic purposes, flood exceedances are also calculated at the 400- and 1,000-year level, as well as ten-year intervals from the 50-year to 150-year levels.

Assessing Economic Value, Growth, and Flood Damage

Overview

CLARA estimates the direct economic impacts of flooding by census block at several years between 2011 and 2061. The model employs methods that closely parallel those used by the LACPR (USACE, 2009b) and FEMA Hazus-MH MR4 flood risk models (FEMA, 2009). Damage is estimated for the following categories of assets:

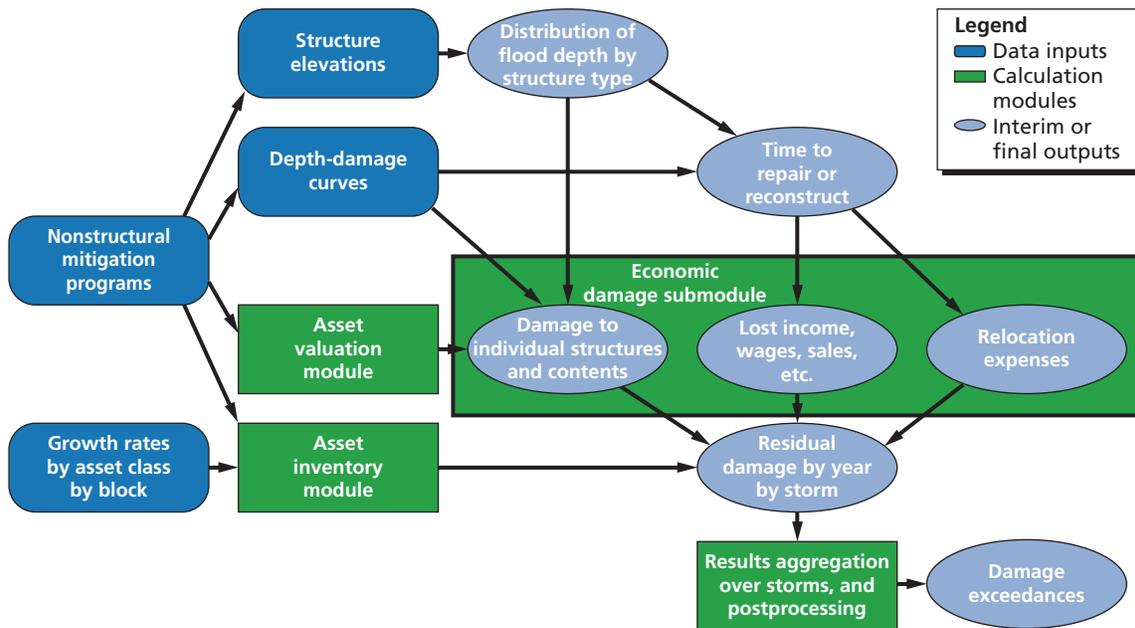
- single-family residences
- manufactured homes
- small multifamily residences (e.g., duplex, triplex)
- large multifamily residences (e.g., apartment building, condominium complex)
- commercial
- industrial
- public facilities
- transport infrastructure (e.g., roads, bridges, rail)
- vehicles
- agriculture structures and properties
- agricultural crops.

A summary of the economic module calculation steps is shown in Figure 7.1. For these asset classes, damage is estimated by starting with an inventory of assets (e.g., number of structures, miles of roads) for each asset class by census block. Assumptions about the average value of an individual asset yield an estimate of the total exposed value of that asset type in each census block; where more data are available, assets are stratified across characteristics, such as number of stories, square footage, and construction type, to obtain a more nuanced valuation.

Depth-damage curves give the percentage of an asset class's value that is damaged by flooding as a function of flood depth, and this provides the final estimate of direct damage to each asset class, which can be interpreted as the full cost of repairs or replacement. Additional direct economic impacts, such as lost income, lost sales, lost rents, and relocation expenses, are computed based on the length of time estimated to be required for repairs or reconstruction.

Projections of how assets in each census block grow over time are based on available data about pre- and post-Katrina and -Rita population change and economic activity. Reconstruction efforts in response to Hurricanes Katrina and Rita in 2005 are still ongoing; any estimates of future growth should be treated as speculative at best. To compensate for this uncertainty, the economic module calculations are run using a range of different growth scenarios, which we explore in the analysis.

Figure 7.1
Summary of Economic Module Calculations



RAND TR1259-7.5

Indirect economic consequences, such as regional economic spillover effects or losses due to temporary unemployment, are not included in this analysis because of time and data constraints. Estimating these types of consequences necessitates a much broader and more detailed general equilibrium-based economic model that allows for consideration of regional and national changes due to a large flooding event and further requires many more assumptions regarding the state of the national economy throughout the period of analysis (2011–2061). Given the level of complexity and lack of available examples on which to draw, we determined that these indirect consequences were outside the scope of the initial CLARA analysis.

Although we attempt to distinguish between (1) direct economic impacts associated with structures and the individuals associated with those structures and (2) indirect impacts—economic disruptions—associated with structural damage and population relocation, such distinctions can be unclear. In some cases, the ultimate decision to exclude some impacts was based on a lack of available data during the model development phase.

Input Data

When several sources of economic data are available, preference is generally given to data that are specific to Louisiana or are the most recent. For example, information about relocation expenses are taken from LACPR rather than Hazus-MH MR4 because LACPR surveyed victims of Hurricane Katrina about the location to which they were evacuated, how often they traveled back to Louisiana during the rebuilding process, and what the average costs of hotels and meal expenses were. In this section, we briefly describe the specific sources of data for the

asset inventory, valuation, and economic damage submodules; these are also summarized by order of precedence in Tables 7.1, 7.2, and 7.3, respectively.

Asset Inventory Module

Baseline counts of residential structures are from the LACPR economics database, which was originally sourced from Hazus-MH MR2 (FEMA, 2005) and updated by Calthorpe Associates to represent second-quarter 2005 (pre-Katrina) economic conditions (Calthorpe Associates and USACE, 2008). When doing so was justified by additional data, we further adjust the LACPR asset counts using additional data sources, including a database of residences receiving mail in seven parishes in and around New Orleans, developed for GNOCDC, and estimates of current population and household unit counts developed by the ACS updates to the U.S. census.¹ In some cases, counts must be interpolated or aggregated to reach the census-block level of analysis. These adjustments are based on assumptions that residential assets are proportional to population and that the percentages of single-family homes, manufactured homes, small multifamily residences, and large multifamily residences remain constant with respect to their pre-Katrina levels within each census block.

Structure inventories for nonresidential assets are taken from the General Building Stock (GBS) inventory in the FEMA Hazus-MH MR4 model, which was developed by Dun and Bradstreet (FEMA, 2009). Because these data reflect pre-Katrina conditions, we develop several scenarios to represent current and future conditions, including scenarios with lower and higher asset inventories. The baseline inventory of nonresidential structures is adjusted at the parish level by applying the percentage growth from 2005 to 2008 as reported by the Census Bureau's CBP database to nonresidential structures. Lacking better and more-reliable data, we

Table 7.1
Data Elements for the Asset Inventory Module

Data Element	Asset Class	Source (by order of precedence)
Number of structures	All residential classes	GNOCDC, ACS, LACPR, Hazus-MH
Number of structures	All nonresidential, structural classes	LACPR, Hazus-MH, Census CBP
Acreage of agricultural crops	Agricultural crops	LACPR (NASS, LSU AgCenter)
Number of vehicles	Vehicles	LACPR (adjusted by ACS)
Inventory of roads, railroad, bridges	Infrastructure	LACPR
Square footage	All structural classes	LACPR, Hazus-MH

NOTE: CBP = County Business Patterns.

¹ We compared projections from LACPR with estimates from GNOCDC and ACS for the post-Katrina period. For most parishes, the estimates of replacement value of structures were similar (i.e., within 10 percent). The discrepancies among the data sets are due largely to assumptions regarding population changes; model users may run different baseline population scenarios based on the values reported in the different databases. Moreover, because the ACS and GNOCDC estimates are similar for parishes where both data sets are available, we were able to use the ACS to develop alternative scenarios for parishes not included in GNOCDC.

assume that the effects of post-hurricane growth to the region and depressed economic conditions more or less counterbalance each other, such that current inventories are similar to 2008 levels (U.S. Census Bureau, 2010).

Inventories of roads and other infrastructure are taken from the LACPR database of economic assets. Private-vehicle counts are estimated based on an average number of privately owned vehicles per household from census data; commercial vehicles are based on the number of commercial licenses reported by the Louisiana Department of Motor Vehicles in October 2006. Agricultural assets are based on a database of crop acreages at the census-block level compiled by LACPR.

Asset Valuation Module

By default, values and damage reported by the model represent replacement and repair costs rather than depreciated exposure figures. Including depreciation in asset values would require making broad and somewhat arbitrary assumptions about the declining value of assets over time, and using replacement costs better matches the actual damage or repair costs reported for other asset types. Replacement costs are expressed in terms of 2010 U.S. dollars, with the implicit assumption that construction costs track inflation.

The values of assets in each census block are dependent on a set of characteristics that varies by asset type. This set is most nuanced for single-family residences, for which data are richest. Here, CLARA uses estimates of replacement costs per square foot stratified by construction class (economy, average, custom, and luxury), number of stories, and the existence of a garage, together with estimates of average square footage per home based on the median household income of residents in each census block.

The replacement value for nonresidential structures is based on the total square footage of structures and the asset class. These data are compiled by census block. The economic module

Table 7.2
Data Elements for the Asset Valuation Module

Data Element	Asset Class	Source (by order of precedence)
Structural characteristics for each asset class	All structural classes	Hazus-MH
Replacement cost per square foot	All structural classes	Hazus-MH
Proportion of structures by construction class (economy, average, custom, luxury)	All residential classes	Hazus-MH
CSVR	All structural classes	LACPR
Value of inventory per square foot	Commercial, industrial	Hazus-MH
Depreciation curves by structure age	All structural classes	Hazus-MH
Repair costs per mile	Infrastructure	LACPR, Hazus-MH
Agriculture valuations	Agricultural crops	LACPR
Proportion of structures by construction method (e.g., wood frame, masonry)	All structural classes	Hazus-MH

uses a census-block average replacement cost per square foot to derive the replacement value for each asset class.

Contents of a structure are defined as furniture, equipment that is not integral to structure, computers, household appliances and goods, and other supplies. These are valued as a proportion of the total value of the structure based on a CSVN developed from field surveys and expert panels conducted by the 1996 Jefferson and Orleans Parishes Feasibility Study and the 2006 Donaldsonville to the Gulf Feasibility Study (FEMA, 2009). LACPR employed these data in its economic analysis.

Goods designated for sale are not classified as contents but are instead considered business inventory and do have a value for some GBS codes of commercial, industrial, and agricultural asset classes. Damage for lost inventory and goods is estimated according to the Hazus-MH methodology, which assumes an average gross sales or production per square foot of space. This includes only inventory in stock at the time of the flood event. For example, value of sales lost due to repair time is estimated separately.

Repair costs for roads, rail, and other infrastructure are derived from the Economic Data Survey for the Mississippi River and Tributaries Protected Area and the Louisiana Department of Transportation and Development Engineering Division, both used by the LACPR team (USACE, 2009a). Some of these data are derived directly from repair costs generated by Hurricanes Katrina and Rita. These values are not construction costs but rather estimates of the average repair costs per mile of infrastructure damaged by floodwater inundation.

Valuations for vehicles are based on an average retail replacement value for both private and commercial vehicles. Although inventories and values are not stratified by vehicle class (e.g., car, truck), aggregation of the inventories to the census-block level should produce relatively unbiased valuations. Costs associated with the post-flood response, such as landscaping repair, debris removal, and other cleanup, are also modeled in accordance with the LACPR methodology.

Other direct economic impacts included in CLARA are due to displacement of people and economic activity. These costs are incurred by displacement from the local area during evacuation and the repair and reconstruction process, up to the point of reoccupation. Examples of these costs include evacuation and subsistence costs for damage to residential assets, as well as lost sales, lost income, lost rents, and relocation costs (e.g., temporary storage) for other structural asset classes. Residential evacuation and subsistence costs are based on LACPR surveys of costs incurred by evacuees from a variety of recent Gulf Coast flood events; nonresidential losses are estimated using average losses per square foot per day of displacement. Restoration times for each structure are dependent on the level of damage incurred to that structure, as well as the overall scale of flooding (USACE, 2009a).

Economic Damage Submodule

After assets have been valued, the damage and losses incurred by a flood event are dependent on the depth of flooding in each census block. The relationship between flood depth and the damage inflicted as a proportion of an asset's value is known as a depth-damage curve. These curves are the basis of damage estimates for most asset categories. The curves for each asset type are taken from whichever one of the Hazus-MH or LACPR inventory and valuation is used, as indicated in Table 7.3, with LACPR damage curves taking precedence. The depth-

Table 7.3
Data Elements for the Economic Damage Submodule

Data Element	Asset Class	Sources (by order of precedence)
Flood elevations	N/A	Calculated by model
Proportion of structures by construction method (e.g., wood frame, masonry)	All structural classes	Hazus-MH
Structural elevation above grade	All structural classes	LACPR
Depth-restoration time curve	All structural classes	Hazus-MH
Depth-damage curves for structure	All structural classes, infrastructure	LACPR, Hazus-MH
Depth-damage curves for contents	All structural classes	Hazus-MH
Depth-damage curves for inventory	Commercial, industrial	Hazus-MH
Costs dependent on displacement time: lost income, lost wages, lost sales, disruption costs, relocation rental costs	All structural classes	LACPR, Hazus-MH
Costs dependent on displacement time: evacuation and subsistence costs	All residential classes	LACPR
Post-flood response costs: landscaping repair, debris removal, other cleanup	All structural classes	LACPR
Depth-velocity-collapse curves	All structural classes	Hazus-MH

damage relationships are derived from expert elicitation and actual insurance claims and can vary by geographic region; where Hazus-MH is used, CLARA takes damage curves drawn from Orleans Parish data.

Flood elevations are taken as calculated by the previous CLARA modules, relative to the average elevation of each census block and the elevation above grade of the structure's foundation. Within a block, ground elevation is assumed to be constant and equal to the mean block elevation. These elevations are added to any structural elevation and then compared with the flood elevation in order to arrive at the flood depth for each structure.

Damage is assumed to be incurred primarily as a result of inundation, particularly if structures are located within an HPS. No additional consideration is made for damage resulting from the velocity of an incoming surge, wind damage, or other force; velocity damage may be more likely in unprotected or semiprotected areas, but CLARA assumes that structures that incur damage from velocity would have received approximately the same level of damage due to the associated inundation. The economic damage submodule of CLARA is nonstochastic: Characteristics of the structure and the level of flooding wholly determine the economic impact, although the result is conditioned on multiple uncertain parameters.

Scenarios of Future Growth

Projections of asset growth are speculative in light of the ongoing reconstruction and resettlement efforts after Hurricanes Katrina and Rita and likely future variations in economic and population growth. CLARA assumes an average growth rate (constant over time) based on pre- and post-Katrina rates for each census block and asset class, adjusted for a variety of fac-

tors discussed in this section. Uncertainty analysis provides estimates for future risk based on a wide range of possible future scenarios.

Between 2005 and 2010, population levels and population growth rates in many areas of coastal Louisiana deviated greatly from the levels and rates that those areas experienced prior to Katrina and Rita. As of 2009, some parishes in the New Orleans area had lower populations than they did in early 2005. Even in areas that have rebounded strongly, we consider long-term sustained growth in population at a rate greater than that from 2000 to 2005 unlikely. Consequently, to construct baseline long-term population growth rates, CLARA uses historical population data (including U.S. census data from 1980 to 2000) and assumes that future growth in population is likely to broadly mirror pre-Katrina/Rita growth trends. The 2011 population levels used as a baseline for future growth are set using the most recent data available from the 2010 U.S. census, GNOCDC, and other sources.

Consequently, in the “nominal” or default economic growth scenario, the population growth rate for the entire study region is set at 0.67 percent year over year, which is approximately equal to the average annual rate of growth in population from 1990 to 2000, representing an assumption that long-term growth may return to pre-Katrina rates. Alternative scenarios range from a “no-growth” scenario, i.e., one in which the population stagnates or growth in one region is balanced by declines in others, to a 1.5-percent rate of growth in population, which is approximately equal to the average annual growth rate for the coastal region from 1950 to 2000.

All asset types except for agricultural structures, agricultural crops, and roads are assumed to grow in proportion with the rate of growth in population. The other asset types are assumed to remain constant.

Urbanization and Other Growth Scenarios

The scenarios described in the previous section all assume that population growth is distributed among census blocks in the same proportion as the baseline inventory. This does not account for the possibility of differential population growth between parishes or between census blocks within the same parish. To address this, a growth dispersion parameter is applied to residential, commercial, and industrial structures. This parameter represents the proportion of the population living in urban versus rural blocks, as defined in the 2000 census. As population growth is projected out to 2061, the populations of urban and rural blocks change such that, in 2061, the total proportion of urban residents is equal to the scenario-dependent dispersion parameter, and the total population reflects an average growth rate equal to the scenario-dependent growth rate.

The dispersion parameter and overall growth rate can be changed independently to model different scenarios of regional population growth.

Nonstructural Mitigation

In addition to evaluating the effect of structural protection and restoration projects on flood risk, we also modeled the effects of various nonstructural policy options developed by the Nonstructural Project Team. *Nonstructural mitigation*, in this context, refers to investments

designed to reduce or prevent damage to individual structures in the floodplain and does not include the various types of restoration projects considered separately in the Master Plan analysis. In general, nonstructural mitigation methods do not affect surge heights or standing flood elevations; instead, they reduce damage by elevating or hardening individual buildings to protect against the effects of floodwaters. These techniques alter the depth-damage curves applied to a structure. Examples include floodproofing, which eliminates or reduces damage from inundation up to the height of protection; reducing the depth of flooding relative to the ground floor by elevating structures; and removing risk in a particular area directly through buyouts or relocation programs. Characteristics of nonstructural mitigation projects and the estimated effect over time on structure inventories and depth-damage curves are provided by the Nonstructural Project Team.

Nonstructural projects are defined by the target community where the policy is active; for example, the NS.ALG.100.1 project is active in all blocks in the Algiers community. The participation rate is assumed to apply equally within each block of the community, and only currently existing assets are affected. The geographic definitions, attributes, and effects of nonstructural mitigation are regarded as data inputs that affect the asset inventory and asset valuation modules and modify other inputs, such as average structure elevation.

Final Residual Risk Calculations

Overview

The final set of calculation steps in the flood depth module produces a probability distribution for each location—either census block or CPRA-defined community target area—that summarizes the annual recurrence of different levels of storm surge flooding for that area for each scenario, project condition, and time period considered. Because economic damage has a one-to-one relationship with flood depths, the 100-year damage in each block is simply the damage resulting from the 100-year flood depths. This enables the calculation of 50-year, 100-year, and 500-year damage exceedances, which are recorded and passed to the Planning Tool. For more information on how the Planning Tool uses these risk estimates, please see Appendix E of the Master Plan (CPRA, 2012b).

Expected Annual Damage

Because of the nonlinear nature of overtopping and system fragility, many projects may provide benefits that are not captured by examining only a small number of exceedances. For example, two projects may provide full protection at the 50- and 100-year exceedances but both may result in complete inundation at the 500-year exceedance. However, the first project might produce no flooding up to the 400-year exceedance, whereas the second might start to see flooding at the 150-year exceedance. In order to understand the benefits of a project across the entire probability distribution of damage, CLARA also calculates an EAD metric.

To estimate EAD in a particular scenario, the flood depths produced by each synthetic storm are aggregated into bins of 1-foot intervals. The probabilities associated with each synthetic storm are summed within each bin in order to calculate the probability of no flooding, flooding between zero and 1 foot, between 1 and 2 feet, and so on, up to the probability of flood depths greater than 20 feet. The mean depths in each bin are used as inputs to the eco-

conomic damage module, and the resulting damage is averaged, weighted by the probability weights associated with each bin.

This produces an expected risk conditional on a storm occurring. This value is then converted to EAD by multiplying by the scenario-dependent overall storm frequency.

Uncertainty in CLARA

Overview

A key objective of risk analysis is to quantify uncertain or random events to support improved planning or decisionmaking. Risk analysis itself is a process of seeking to better understand and describe this uncertainty using the tools of probabilistic analysis and statistics. However, estimates of risk produced using these tools are themselves uncertain, so a distinction should be made between the different types of uncertainty present in any risk analysis. First, the “randomness of nature” that risk analysis directly seeks to quantify—in this instance, uncertainty regarding how frequently different areas of the coast can expect flood damage from storm surge—can be referred to as *aleatory uncertainty*. Aleatory uncertainty can be quantified but is otherwise irreducible (Budnitz et al., 1997; USACE, 2009b).

In contrast, uncertainty surrounding these estimates of risk is referred to as *epistemic uncertainty*. Epistemic uncertainty derives from an incomplete understanding of the system, lack of observed historical data, uncertainty regarding key drivers of the system (e.g., coastal subsidence) and nonstationarity of other inputs (e.g., climate change). Better data or improved understanding of key processes can reduce epistemic uncertainty, although the amount of uncertainty associated with estimates of flood risk in coastal Louisiana suggests that some epistemic uncertainty will always be present.

CLARA uses probabilistic risk analysis to quantify the aleatory uncertainty associated with storm surge flood risk estimates. For example, the 100-year flood damage exceedance is an estimate of the damage level with a 1-percent chance of occurring or being exceeded each year. Statistical approaches can also be used to quantify the epistemic uncertainty surrounding these estimates, by estimating or assuming probability distributions for each of the model inputs and then deriving the resulting variance of the model outputs through calculation or empirical (Monte Carlo) simulation.

Recent efforts to quantify flood risk in New Orleans and throughout coastal Louisiana, including the IPET and LACPR analyses, have included statistical estimates of epistemic uncertainty in this manner. The IPET Risk and Reliability Team, for example, sought to apply probability distributions to all key inputs, including storm surge and wave estimates, protection system reliability, operational uncertainty, and asset valuations, and reported the resulting risk estimates with confidence intervals. IPET was unable to apply probability estimates to the performance of pumps in New Orleans, however, and thus elected to use scenario analysis to separately report flood risk results from bracketing scenarios in which outfall pumps performed at 0 percent, 50 percent, or 100 percent of rated capacity (USACE, 2009b).

LACPR performed similar calculations of epistemic uncertainty. It quantified uncertainty in overtopping rates by using Monte Carlo simulation to randomly vary the surge inputs along different protection system structures and estimate the resulting variation in overtopping volumes. LACPR also used scenario analysis where probabilistic assessment was not possible. Specifically, LACPR produced risk results in 2060 for two possible rates of RSLR and two different scenarios of economic growth along the coast (USACE, 2009a).

CLARA draws substantially from these recent efforts but addresses epistemic uncertainty solely through scenario analysis rather than by combining both probabilistic and scenario-based methods. Specifically, CLARA parameterizes selected key input variables in multiple scenarios designed to span the range of outcomes arising from these uncertainties. Other uncertainties, such as the effect of seasonality and tidal forces on storm surge, are not explicitly parameterized but are taken into account when calculating flood depth return intervals. Given a particular flood depth within a particular scenario, however, damage is calculated deterministically, and specific assumptions are made regarding uncertain inputs not included in the scenario analysis. As a result, CLARA does not produce estimates of parametric uncertainty or probabilistic confidence intervals for damage estimates.

There are several reasons for adopting this scenario approach. First, CLARA is designed to estimate flood risk and damage outcomes to support a master planning effort over a 50-year timespan. Substantial uncertainty is inherent in any such long-range projections; we assume that the level of uncertainty associated with these projections (i.e., those for which there is no information or substantial disagreement regarding the probability distribution) would typically be much greater than the model or relationship uncertainty that could be captured probabilistically. Second, CLARA is intended to provide initial, planning-level estimates of damage reduction benefits from various risk reduction projects (roughly corresponding to a USACE feasibility study). Once promising projects are identified, design-level estimates of project performance would still be required. The more-detailed design analysis would include estimates of probabilistic uncertainty surrounding project performance in order to ensure that a sufficient FOS was achieved in the design. Finally, the CLARA was designed to be consistent with the overall Master Plan analysis, which is described in detail in the main body of the Master Plan (CPRA, 2012a).

Scenario Inputs

The number and choice of scenario variables implemented in the CLARA analysis reflect a balance between a desire to capture the full range of possible surge and flood responses accurately and a need for a computationally manageable experimental design. Some variables were also chosen because of their use by other work groups or because of their use in prior studies from which CLARA draws heavily. The scenario inputs specifically defined for CLARA are summarized in this section. Those denoted with an asterisk were defined as part of the overall 2012 Master Plan analysis and are discussed in detail in Appendix C of the Master Plan (CPRA, 2012b).

Storm Surge and Wave Inputs

Sea-Level Rise*

SLR scenarios are defined by CPRA for all modeling teams and range from 0.27 to 0.79 meters from 2011 to 2061. Specifically, the *moderate future scenario* assumes SLR of 0.12 meters (0.4 feet) by 2036 and 0.27 meters (0.91 feet) by 2061. The *less optimistic scenario*, alternatively, uses a higher rate leading to 0.19 meters (0.62 feet) by 2036 and 0.45 meters (1.48 feet) by 2061. Finally, the *moderate future with high SLR* assumes a rate that produces 0.31 meters (1.03 feet) of SLR by 2036 and 0.79 meters (2.58 feet) by 2061. Surge values provided by the Storm Surge/Wave model already incorporate these increases.

Subsidence Rate*

CPRA also defined subsidence rates using ranges that vary geographically across the coast according to the boundaries of 17 subsidence zones defined by CPRA. Landscape scenarios used by all modeling teams assume that the actual observed subsidence rate is some scenario-dependent fraction of the range. For more information, please see Appendix C of the Master Plan (CPRA, 2012b).

Storm Intensity*

The storm intensity uncertainty represents a plausible future shift in the mean of the probability distribution for tropical storm central pressures due to climate change. The 2011 storm intensity probability distribution mean is estimated from the observed intensity of historical storms making landfall in the study region, as identified in IPET (USACE, 2009b). Scenario values are described as a percentage change from the 2011 value.

Storm Frequency*

The storm frequency uncertainty represents the possibility that climate change might lead to a smaller or greater number of storms making landfall on the Louisiana coast, on average, by 2061. The 2011 storm frequency value is estimated from the observed frequency of historical storms making landfall in the study region as identified in IPET (USACE, 2009b). This uncertain parameter represents a future shift in the overall frequency of Category 3 or greater hurricanes affecting the study area. The parameter is described as a percentage change from 2011 coastwide frequency of approximately 0.052 storms per year.

Flood Depth Module

Protection System Fragility

The probability of failure of the protection system has four plausible levels: no failure, low, medium, and high. For the no-failure case, we assume that the protection system does not fail. For the medium case, we assume that the value of the FOS for seepage and slope stability failures is 1.0. For the low and high cases, we assume values for the factor of safety of 1.1 and 0.9, respectively.

Pumping Effectiveness

This scenario uncertainty reflects the possibility that pumps malfunction or become inoperable during a surge-based flood. Performance of all pumps is adjusted based on this factor to provide bounds on plausible damage levels with and without pumping. The pumping system can operate at three levels: 0, 50, and 100 percent of rated capacity.

Economic Module

Coastwide Population Growth Rate

Assets that can be damaged by flooding across coastal Louisiana expand according to discrete economic development cases. These cases are anchored to population growth trends in Louisiana prior to the 2005 hurricane season. Specifically, this uncertainty represents the annual coastwide population growth rate from 2011 to 2061, starting from a 2010 basis of 2,215,459 people (2010 census estimate). The ranges are derived from a review of historical census data, setting aside 2000–2010 due to the confounding effects of the four major hurricanes that occurred during this time. The lower bound represents no overall growth in population on the coast. The upper bound is approximately 20 percent higher than the average coastwide population growth rate from 1950 to 2000 (1.26 percent) and represents a doubling of the coastal population over the 50-year span. The middle (and nominal) rate is exactly the observed coastal growth rate from 1990 to 2000.

The implied 2061 coastal population using these growth rates is as follows:

- low: 2.21 million persons
- middle: 2.99 million persons
- high: 4.66 million persons.

Fraction of Population Growth in Urban Versus Rural Areas

This uncertain parameter is designed to reflect changes in the distribution of population between concentrated (urban) and distributed (rural) asset areas. This parameter applies both to new growth and existing population along the coast.

Urbanization information for 2011 is drawn from the census, using the “urban areas” definition. According to the 2010 census, 81 percent of the study area population in south Louisiana lives in areas designated as urban.

The lower bound for the scenario uncertainty parameter reflects an urban/rural split more reflective of 1990 conditions (5-percentage-point decline in urbanization), while the upper bound is simply an extrapolation reflecting plausible additional urbanization (5-percentage-point increase in urbanization).

Nonstructural Mitigation Participation Rate*

The effectiveness of nonstructural projects is characterized by level of participation only. Participation rates vary by nonstructural project type—elevation, floodproofing, acquisitions, and easements—and range over four different scenarios representing low, medium, medium-high, and full participation. Specific values for each project type and participation scenario are described in Appendix A of the Master Plan (CPRA, 2012b).

Analysis of Uncertainty

In designing the Master Plan, no particular combination of the above parameters was assumed to be more likely than another; instead, the Planning Tool looked for risk reduction projects that performed well across a range of uncertain scenarios. This section describes how CLARA was used to explore the full space of uncertain futures suggested by the range of uncertainties above. It also describes the sensitivity analysis performed to explore potential bias introduced by using a relatively small set of storms to estimate flood exceedances.

Flood Depth and Economic Module Scenario Analysis

The CLARA team conducted a complete scenario analysis by varying the key uncertain inputs identified above for the flood depth and economic modules (Table 8.1). This analysis was conducted when evaluating the final Master Plan (CPRA, 2012a) and entailed running a full factorial experimental design across all key inputs at the values specified in Table 8.1 except for protection system fragility. For this input, initial testing indicated that results do not vary with different FOS assumptions, so we decided to run only the No Fragility case and a case in which the FOS is equal to 1. In addition, storm frequency and intensity were not included in this design because they are considered in the separate CPRA-defined scenarios.

Running the full experimental design entailed producing six different results from the flood depth module to capture the fragility and pumping uncertainties, and nine results from the economic module. In total, we produced 54 (6×9) scenario results to capture the range of outputs for structural protection projects. When nonstructural projects were considered, one additional uncertain input (nonstructural participation rate) was introduced with four possible levels. For estimates of damage and damage reduction from nonstructural projects in the Master Plan (CPRA, 2012a), then, we produced 216 ($6 \times 9 \times 4$) scenario results.

Storm Selection Sensitivity Analysis

As outlined previously, one key trade-off made to support this analysis was the use of a smaller storm set to generate flood statistics than the 304 storms originally identified during the LACPR study. Basing estimates of synthetic surge and wave characteristics on a condensed set of 40 storms—with no variation in forward velocity or landfall angle—necessarily introduces some uncertain level of bias in model results. The Risk and Damage Team therefore conducted a separate sensitivity analysis to better understand the level of variation that could be introduced in this instance. Results from this sensitivity analysis did not directly alter the final damage estimates, but they nevertheless provided important information regarding the limits of the deterministic, scenario-specific outputs produced by CLARA.

We initially selected the 40 storms in the CPRA storm set by comparing statistics produced from a large number of possible subsets with statistics produced from the full storm set using surge data produced in the LACPR analysis. Results were recorded at LACPR sample

Table 8.1
Summary of Uncertain Model Parameters

Uncertainty	Low	Mid	High	Nominal
Storm intensity (%)	0	10	20	10
Storm frequency (%)	-10	0	5	0
Protection system fragility (FOS)	1.1, or No Fragility scenario	1.0	0.9	1.0
Pumping effectiveness (%)	0	50	100	100
Coastwide population growth rate (% per year)	0	+0.67	+1.5	+0.67
Fraction urban versus rural (%)	76	81	86	81

NOTE: Nominal values listed are the default values used when only one case from the experimental design is considered. When comparing individual protection projects, for example, all uncertainties were set at their nominal values.

points; our testing using these outputs indicated that a relatively small number of storms—four storms from each landfall track that take the central values for forward velocity and landfall angle and vary by central pressure and radius—best balanced a manageable number of storms with estimates of surge exceedances similar to those produced by the full storm set (see the “Statistical Methodology and Experimental Design of Storms” section of Chapter Three).

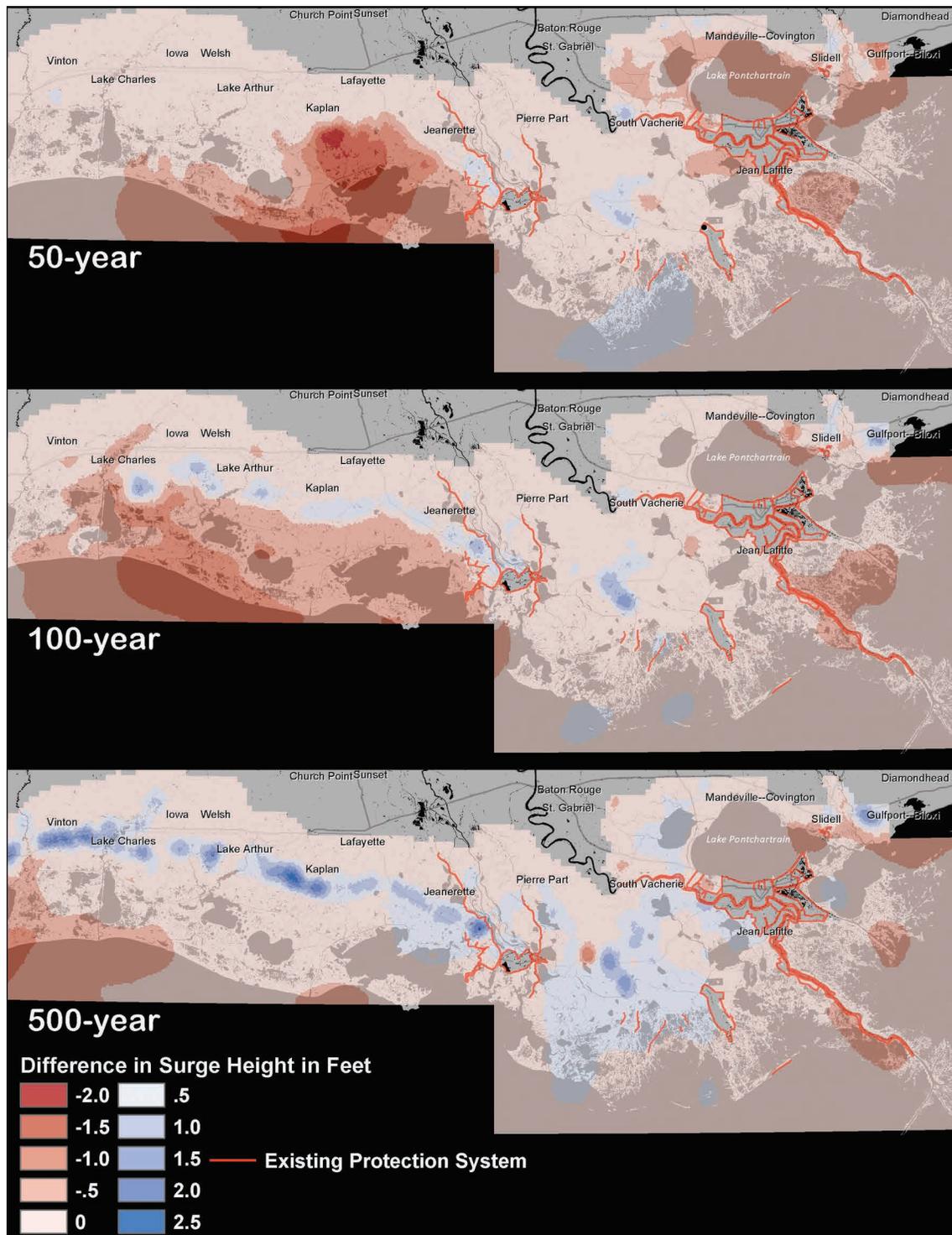
Although CLARA does not explicitly estimate the probabilistic variance in surge associated with the reduced set, we conducted additional sensitivity analysis to investigate the bias using the sample points and storm surge and wave data from the Master Plan analysis. We first identified a larger subset of 154 storms from the complete 304-storm set to use as a basis for comparison. This set is based on the subset used for the eastern half of the state in the IPET analysis (USACE, 2009b) and varies the storms across all key parameters except for forward velocity, for which only storms with the central value (11 knots) were run. The Storm Surge/Wave Team then ran the 154-storm subset for one set of conditions—the FWOA case in the moderate scenario—and provided surge and wave outputs for additional sensitivity analysis. We applied a revised version of the JPM-OS method to these outputs, generating surge exceedances for the more complete 154-storm sample to use as a basis for comparison for the CPRA storm set.

Comparisons of the resulting surge exceedances are shown in Figure 8.1. The values shown on the map are calculated as the 154-storm exceedance minus the 40-storm exceedance, with positive values (shown in blue) indicating that the CPRA storm set underestimates surge values compared with the 154-storm sample, and negative values (shown in red) indicating that the CPRA storm set overestimates the surge exceedance. When we compare these subsets, we see that most areas of the coast see a difference of less than 1 foot between the 40-storm and 154-storm sets.

There are several notable exceptions, however. At the 50-year surge exceedance, estimates in the Vermilion Bay area from the CPRA storm set are 1 to 2 feet greater than the 154-storm estimates. We also note overestimates of 0.5 to 1 foot in the CPRA storm set along the Chenier Plain in the western part of the state in the 100-year and 500-year results, with the bias moving westward at higher exceedances. In the 100-year and 500-year surge exceedances, the CPRA storm set alternatively begins to underestimate surge in the vicinity of Houma area and along the northern boundary of the study region by 1 to 2.5 feet. Except for these areas, however, results from the CPRA storm set are similar to those from the larger set and typically produced more-conservative estimates, meaning that surge was more often slightly overestimated than underestimated.

Minor differences can also manifest at points on the exterior of protected areas—see, for example, the 0.5- to 1-foot differences in the vicinity of Lake Pontchartrain. To test the performance of the CPRA storm set in these areas, we generated a full set of synthetic storms based on the 154-storm set, evaluated those storms using the flood depth and economic modules, and compared them with results from the CPRA storm set. The resulting depths differed by less than 1 foot at each exceedance in protected areas, including Larose, Slidell, and Morgan City (not shown). In selected portions of the Greater New Orleans system, minor differences in exterior surge heights between the smaller and larger storm sets led to levee or floodwall failures with either slightly higher or slightly lower frequencies, depending on location. This variation changed the 500-year surge exceedance estimates in several BHUs (not shown) but did not notably shift the flood depth probability distributions as a whole for these areas.

Figure 8.1
Comparison of Storm Surge Exceedances from the 154-Storm and 40-Storm Subsets at the 50-Year, 100-Year, and 500-Year Exceedances



Supporting Master Plan Development with CLARA

CLARA was built to flexibly evaluate flood risk reduction from a wide range of protection projects. CPRA identified a set of 34 structural protection projects to evaluate for the Master Plan, with the goal of identifying a high-performing combination of projects for implementation over the next 50 years. For detailed descriptions of the projects considered, please see Appendix A of the Master Plan (CPRA, 2012b). However, testing the effect of different combinations of projects in order to identify the best possible combination would require testing many thousands of possible combinations; including the 112 candidate nonstructural protection projects and 238 restoration projects would expand the set of possibilities even further.

To simplify the evaluation process, CPRA made an assumption that, for initial screening purposes, the effects of each project on damage reduction would be treated as independent and additive when combined. Even though this does not represent the actual outcomes if two projects were implemented in the same community, the Planning Tool used this approximation to assemble the final set of Master Plan projects (CPRA, 2012a).

To provide an estimate of risk reduction from each of the 34 structural protection projects and 112 nonstructural protection projects, we worked in conjunction with the Storm Surge/Wave Team to create eight different “grids” of protection projects to model. The first grid, representing the FWOA, modeled a future landscape in which no changes to the protection system are made. The other seven grids each included a set of four to seven projects located far enough apart that they were judged to have no impact on each other’s performance, so that every independent project affects a distinct geographic area. A full list of the structural protection projects considered, along with associated facts, assumptions and estimated effects on risk reduction, is available in Appendix A of the Master Plan (CPRA, 2012b). It also includes a description of other alternatives and the screening rationale used to develop the set of candidate structural protection projects from a larger set of project concepts. The eight grids are referred to as the *FWP grids*, and the process of evaluating the effect of each individual candidate project is referred to as the *FWP analysis*. Each FWP grid was run through CLARA in conjunction with the moderate and less optimistic future scenarios. For each scenario and project grid, we estimated flood exceedances in 2061 under two cases related to system performance:

- (1) All pumping systems in areas protected from hurricanes are working and (2) potential failures of the HPS are not considered.
- (1) All pumping systems in areas protected from hurricanes are working and (2) potential failures of the HPS are considered with the nominal degree of fragility.

A broader set of pumping and fragility cases, described in the next chapter, was used when evaluating the Master Plan alternatives, but the above two cases, representing nominal system performance as well as allowing for system failures, were judged sufficient for comparing individual project effects. For each scenario, set of protection projects, and case, the modeling team produced outputs of the storm surge elevation and flood depths representing 50-, 100-, 400-, 500-, and 1,000-year flood exceedances. The 50-, 100- and 500-year exceedances were reported for use by the Planning Tool, while the 400- and 1,000-year exceedances were also calculated for comparison with results from the previous IPET and LACPR studies.

For each FWP grid, the coastline was divided into pieces such that storm surge in each piece is affected by only one project in the grid. For example, Figure 9.1 illustrates the project effects regions for one of the FWP grids, where the five candidate projects are shown with red lines alongside the existing protection systems in brown, and the colored regions represent the individual project effects regions. In some cases, these regions were adjusted iteratively after comparing surge elevations in an FWP grid to elevations in the FWOA grid. At the boundaries between regions, the difference in surge for individual storms between FWP and FWOA should be negligible, indicating that no project has an effect near the boundary. In other cases, the regions were adjusted to avoid including spurious effects that the Storm Surge/Wave Team judged to be noise or anomalous surge results.

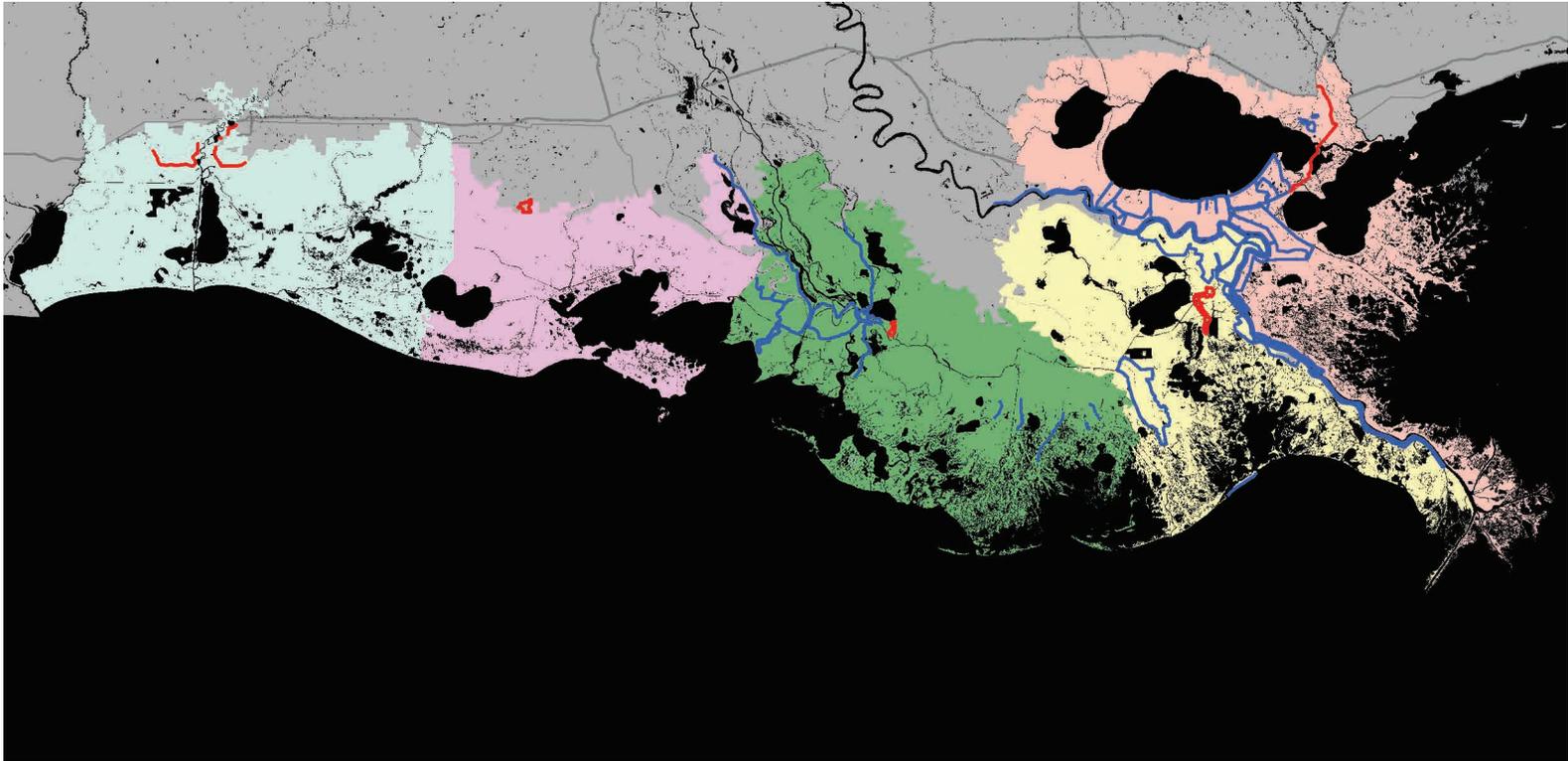
Once the modeling runs were complete, a series of maps was created for the purposes of reviewing output. Table 9.1 lists the maps that were created to facilitate the QA review process. These maps were used to identify the extent of project effects and any areas with anomalous or unexpected surge results and to adjust the project effects regions accordingly as described above. The data contained in the maps and damage estimates were also posted in tabular format by census block and by BHU, facilitating quantitative review where necessary.

When the map sets were being reviewed, a variety of questions were considered for QA purposes. The following key considerations were taken into account:

- Are the surge heights consistent with other published results? Are they self-consistent—for example, are inland surges lower than surges near the coast? Is the 50-year surge lower than the 100-year surge; is the 100-year surge lower than the 500-year surge?
- Is the difference in surges when including protection system projects consistent? For example, restoration projects are intended to attenuate the incoming surge, lowering inland surge heights. Alternatively, elements of protection systems, such as floodwalls, may divert the surge elsewhere. For areas in which the surge increases when protection system elements are included, are the results readily explainable?
- Are the differences in flood heights within protected areas consistent when considering HPS measures? For all areas in which flood heights increase, specific explanations were to be given and anomalies noted.
- Are the differences in flood heights within protected areas consistent when considering the fragility of the protection system? For all areas in which flood heights increase, specific explanations were to be given and anomalies noted.

Once reviewers were satisfied with the flood depth module results, each set of resulting flood exceedances was run through the economic module to produce corresponding damage exceedances as well as estimates of EAD. The damage reduction effect of each project was then calculated to be the difference in damage between the project's grid and the FWOA grid,

Figure 9.1
Division of Study Area into G91 Project Effects Regions



RAND TR1259-9.1

Table 9.1
Listing of Maps Created for Review Prior to Posting to the Coastal Protection and Restoration Authority of Louisiana Server

Map Set Number	Number of Maps	Type of Map	Description of Map	Exceedances (years)
1	3	Absolute surge	The storm surge that results when the HPS measures under consideration are in place	50, 100, 500
2	3	Difference between surges	Difference in the surges that result when no changes to the protection system are in place compared with those that result when the protection measures under consideration are in place	50, 100, 500
3	6	Absolute flood depths	The flooding that results for each pumping/fragility case under each future scenario	50, 100, 500
4	3	Difference between flood depths	Difference in the flood height that results in protected areas with no changes to the protection system compared with those having the protection system measures under consideration in place	50, 100, 500
5	3	Difference between flood depths	Differences in the flood height in each pumping/fragility case	50, 100, 500

NOTE: The same set of maps was created for each scenario of the future Louisiana coast. Map sets 2, 4, and 5 considered surge and flood differences for the case of full pumping and assuming a fragile protection system. For map set 5, the comparison was between flood heights within a given set of protection system projects.

summed over every census block in that project's effects region. This was estimated for each exceedance interval and for EAD.

For the Planning Tool to evaluate the effectiveness of each project, the damage resulting from each project was tallied for each community coastwide. Damage was aggregated to the community level from the census-block level; for each project, the damage from blocks in the project effects region was taken to be the damage in the FWP grid, and damage from blocks outside the project effects regions was reported as the damage in the corresponding FWOA case.

Figure 9.2 shows an illustrative example of the project effects output provided to the Planning Tool for one FWP grid.¹ Results are for the Slidell community (SLI.100) in the moderate scenario (referred to internally as S12) under the Full Pumping with Fragility case. Frequency identification numbers 1 through 4 represent 50-, 100-, and 500-year damage exceedances and EAD, respectively. One of the projects modeled, the Lake Pontchartrain >100-year Alignment (Master Plan Project ID 001.HP.07), provides substantial risk reduction to the Slidell community relative to the FWOA case. The values shown for the other projects in the figure equal the FWOA damage estimate because they do not contain Slidell in their project effects regions.

The FWOA grid was also used by the economic module to evaluate the effect on risk reduction of the candidate nonstructural protection projects. These projects were defined by community and by protection standard, resulting in 56 projects based on a base flood elevation (BFE) plus 1 foot (BFE+1) standard and 56 projects based on protecting to a standard of

¹ Results are shown as calculated by the economic module, but the number of significant figures presented is not indicative of the actual precision of the model.

Figure 9.2
Example Project Effects Output Provided to the Planning Tool

Scenario	Pumping	Fragility	Project	Frequency	Community ID	FWP_Value
S12	3	2	001.HP.07	1	SLI.100	\$ 808,573,867
S12	3	2	002.HP.07	1	SLI.100	\$14,926,463,957
S12	3	2	004.HP.05	1	SLI.100	\$14,926,463,957
S12	3	2	004.HP.11	1	SLI.100	\$14,926,463,957
S12	3	2	03B.HP.07	1	SLI.100	\$14,926,463,957
S12	3	2	001.HP.07	2	SLI.100	\$ 1,353,657,961
S12	3	2	002.HP.07	2	SLI.100	\$24,912,739,120
S12	3	2	004.HP.05	2	SLI.100	\$24,912,739,120
S12	3	2	004.HP.11	2	SLI.100	\$24,912,739,120
S12	3	2	03B.HP.07	2	SLI.100	\$24,912,739,120
S12	3	2	001.HP.07	3	SLI.100	\$ 2,157,199,012
S12	3	2	002.HP.07	3	SLI.100	\$47,082,895,686
S12	3	2	004.HP.05	3	SLI.100	\$47,082,895,686
S12	3	2	004.HP.11	3	SLI.100	\$47,082,895,686
S12	3	2	03B.HP.07	3	SLI.100	\$47,082,895,686
S12	3	2	001.HP.07	4	SLI.100	\$ 40,682,238
S12	3	2	002.HP.07	4	SLI.100	\$ 694,343,829
S12	3	2	004.HP.05	4	SLI.100	\$ 694,343,829
S12	3	2	004.HP.11	4	SLI.100	\$ 694,343,829
S12	3	2	03B.HP.07	4	SLI.100	\$ 694,343,829

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BFE plus 4 feet (BFE+4). Nonstructural projects involve only hardening individual buildings against flooding and do not impact flood elevations themselves, neither in their own communities nor in any other. Thus, the implementation of any nonstructural project does not have an effect on damage reduction in any community outside of its own, and the BFE+1 and BFE+4 projects in the same community are mutually exclusive.

The full set of BFE+1 projects and the full set of BFE+4 projects were run through the economic module using the FWOA flood depths, assuming the medium-high participation rates defined by CPRA. The effect on risk reduction, cost, and duration for implementation of each project were calculated, and these data were provided to the Planning Tool Team for use in selecting the set of projects for the Master Plan. Additional data, such as flood depths by block, were provided to other modeling teams to inform other decision metrics, such as the inundation of strategic and historic assets.

Results from the Final Master Plan Analysis

Introduction

CPRA developed a final version of Louisiana’s 2012 Master Plan in March 2012. Subsequent to finalizing the plan, CPRA asked the RAND team to evaluate the benefits of reducing flood damage from storm surge and waves to property and other physical assets in coastal Louisiana from the proposed coastwide projects. This chapter presents results from CLARA regarding potential changes in storm surge and flood damage over the 50-year span 2012–2061 with or without the 2012 Coastal Master Plan in place. In contrast to the initial analysis conducted to help compare and rank projects for inclusion in the plan (*project-level analysis*) described in Chapter Nine, the results presented below for the 2012 Master Plan reflect the combined damage reduction benefits from Master Plan investments in new or upgraded protection structures, nonstructural risk reduction projects, and coastal restoration.

We first provide summary, coastwide flood depth, and storm surge flood damage results from an evaluation of the FWOA and then with the final Master Plan in place. Results are presented for current conditions (2012), as well as in two future time periods: 2036 (25 years from the present) and 2061 (50 years from the present). We describe results from three Master Plan scenarios used across the entire modeling effort: the *moderate*, *moderate with high SLR*, and the *less optimistic* future scenarios. These scenarios are described in detail in Appendix C of the Master Plan (CPRA, 2012b).

Next, we highlight key outcomes both in the FWOA and with the Master Plan in place, focusing on selected geographic areas and different types of risk reduction investments. This discussion focuses on the less optimistic scenario only. In select instances, however, we also present additional results from the uncertainty analysis focused on characterizing the remaining uncertainty about protection system performance (e.g., fragility and pumping) and future economic growth (e.g., future population growth and dispersion patterns).

This chapter includes a subset of the mapping and damage output produced for the final Master Plan analysis. More-complete results are provided in the appendix to this document, available online. Also see the appendix for a complete list of additional maps.

Modifications to CLARA for the Analysis of the Master Plan

The Master Plan analysis differs from the initial project-level analysis in several ways. First, we considered only two grids, or combinations of structural and nonstructural risk reduction

projects and coastal restoration projects across the coast: one representing a revised¹ projection of the FWOA grid, in which only currently built or authorized projects are included, and another to which we refer as *with Master Plan in place*, in which the Master Plan projects are also included as a suite of coastal improvements. In this analysis, we also estimated outcomes with CLARA at two future points in time—2036 and 2061, corresponding to year 25 and year 50 of the analysis—whereas, in the project-level analysis, only results in 2061 were estimated. In addition, we estimated outcomes for a new CPRA-defined planning scenario, termed the *moderate future with high SLR*, in addition to the existing *moderate future* and *less optimistic* scenarios considered in the project-level analysis. We refer to these planning scenarios below as *Master Plan scenarios*.

Finally, we performed a more complete uncertainty analysis and considered variation across the protection system and uncertain economic growth inputs listed in Table 8.1 in Chapter Eight. This is in contrast to the project-level analysis, in which we provided results using single point estimate assumptions regarding the uncertain performance of the protection system or economic growth over time. The “nominal” assumptions used in the project-level analysis are also defined in Table 8.1 in Chapter Eight.

For the more complete uncertainty analysis, we varied the protection system fragility assumption (With Fragility or No Fragility). As a reminder, With Fragility means that a nonzero probability of failure is estimated for each reach segment and transition of enclosed protection systems. CLARA uses these probabilities to estimate average flooding that might result. No Fragility, in contrast, sets the probability of failure to zero and allows floodwaters to reach enclosed protection systems through rainfall, wave overtopping, or surge overtopping of the protection structures. We also considered uncertainty regarding the performance of pump systems to remove floodwaters, setting the pumping effectiveness assumption to 0, 50, or 100 percent of rated capacity for all areas with pumps. Combined with the fragility scenarios, this produced a total of six flood depth outputs for each combination of grid, year, and Master Plan scenario.

In the damage calculations, we also considered three plausible coastwide population growth rates (0-, 0.67-, or 1.5-percent increase per year) and three fractions of the future coastal population living in urban areas (76, 81, or 86 percent).² This produced a total of nine additional uncertainty assumptions related to damage outcomes. The combined additional depth and damage scenarios considered produced a total of 54 outputs for the damage metrics for each grid, year, and Master Plan scenario, or 648 cases in total (Table 10.1).

Additional uncertainty analysis outcomes are used to highlight or clarify results in several instances below. Except where noted, however, results shown in this discussion generally reflect the nominal uncertainty assumptions made for the project-level analysis.

Another change from the project-level analysis addresses the nonstructural projects considered for each CPRA-defined community. In the project-level analysis, one set of nonstructural projects was modeled that elevated or floodproofed structures to the FEMA-defined BFE+1;

¹ Some of the models used as inputs to create the FWOA grid were modified after the project-level analysis because of changed assumptions or bug fixes, resulting in a new FWOA grid that differs from the FWOA grid used in the project-level analysis.

² Note that we did not consider alternative assumptions regarding nonstructural program participation rates with the plan in place. All participation rates were set at the values used for the with-project analysis, which are the “medium-high” rates defined in Table 9 of Appendix A to the Master Plan (CPRA, 2012b).

Table 10.1
Summary of Experimental Design for the Uncertainty Analysis

Grids		Future Years		Master Plan Scenarios		Flood Module Scenarios		Economic Module Scenarios		Total Cases
2	×	2	×	3	×	6	×	9	=	648

another set of projects raised the protection level to BFE+4. The costs and risk reduction benefits of both sets of projects were considered when choosing communities for nonstructural mitigation measures. In the final analysis of the Master Plan projects, however, CPRA instead decided to model all communities selected for nonstructural mitigation at just the BFE+1 level.

The last change of note between the project-level and final Master Plan analyses occurred “upstream” of CLARA, in the landscape and surge analyses. In general, the new FWOA landscape used in this analysis yields lower surge heights than those observed in the FWOA for the project-level analysis). In turn, this yields a lower coastwide damage level than estimated in the previous FWOA analysis.

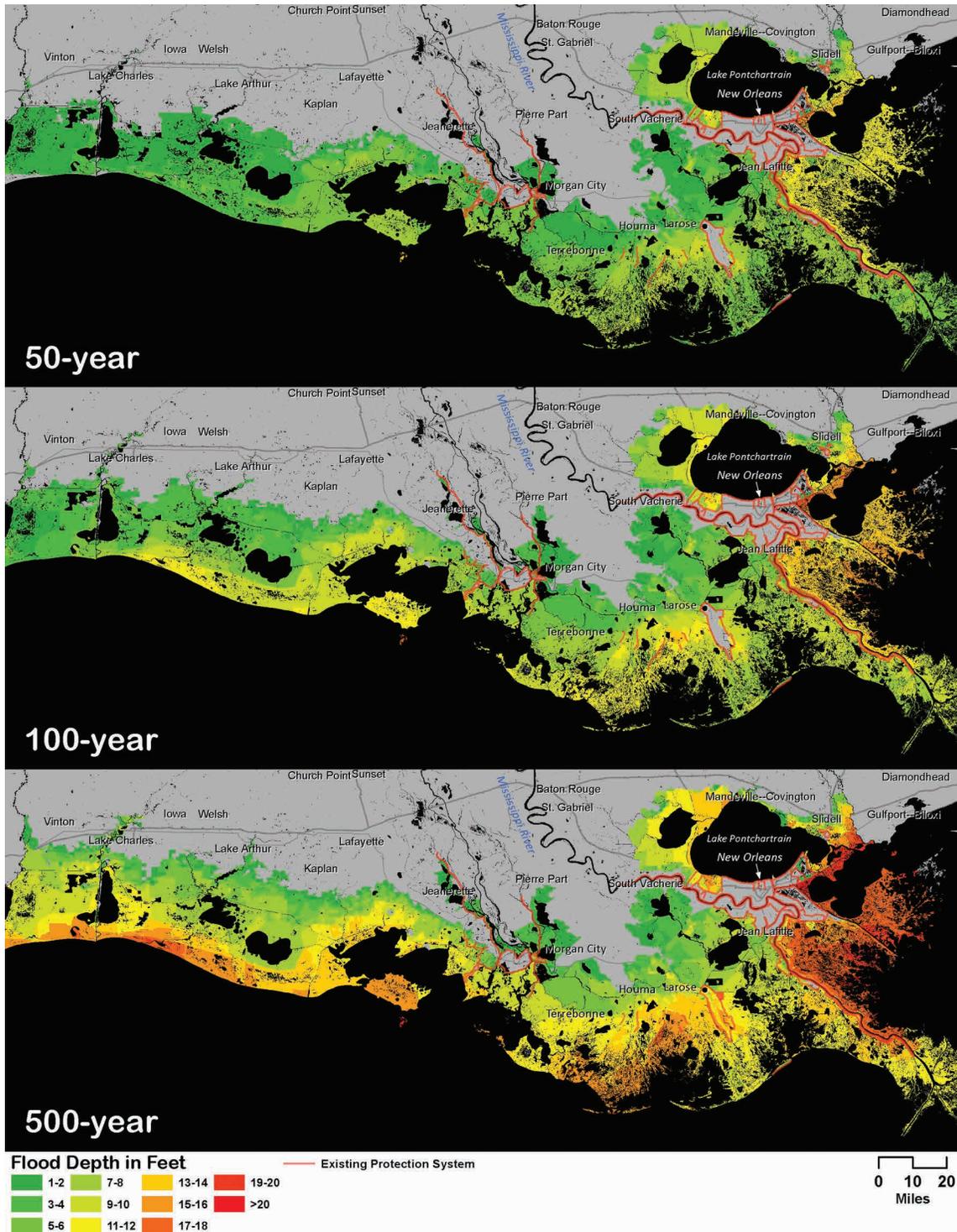
Coastwide Outcomes in the Future Without Action: Flood Depths

In this section, we discuss summary coastwide results from the CLARA analysis of current and future flood depths in coastal Louisiana. We first describe results from the analysis of current conditions and then discuss outcomes in two future time periods (2036 and 2061) across three Master Plan scenarios. Other than considering three Master Plan scenarios to understand uncertainties, results in this section use the same set of nominal assumptions for system fragility, pumping, and future population growth and dispersion made during the project-level analysis to help construct the Master Plan. Exemplar maps and selected damage results are presented below. Flood depth results are presented and described in terms of *flood exceedances*, which are statistical summaries of flooding at different frequencies of occurrence. For example, the 2-percent flood exceedance is the flood depth with a 2-percent chance of occurring or being exceeded in each year. This is referred to in this document as the *1-in-50* or *50-year flood exceedance*. We also present results at the *100-year flood exceedance* and *500-year flood exceedance*, which are, respectively, the flood depth levels with a 1-percent or 0.5-percent annual chance.

These results represent most likely values. CLARA does not generate confidence intervals for each exceedance, and the actual precision of estimates likely varies by geographic location; between protected, semiprotected, and unprotected areas; and by scenario. The precision of damage estimates may also vary by asset type. This is due to many sources of uncertainty propagated through the model, including uncertainty in model inputs provided by other teams, such as confidence in the effect of restoration projects or in the precision of storm surge estimates. Identifying consistent trends across multiple scenarios helps to provide confidence in the significance of results, so this document focuses on describing these overall patterns where they exist and noting differences between scenarios where they do not.

The maps show, in turn, flood depth levels by census block in 2-foot increments for different year and scenario outcomes (see Figure 10.1, for example), and flood depth changes by census block in 1-foot increments (see Figure 10.2, for example). Maps presenting the change

Figure 10.1
Estimated Flood Depth Under Current Conditions in 2012, by Census Block, for Coastal Louisiana at the 50-Year, 100-Year, and 500-Year Flood Exceedances



in flood depth show either the difference over time in the FWOA or between the FWOA and with Master Plan grids in a given year.

A more complete set of maps, as referenced in the discussion below, can be found in the appendix to this document, available online.

Current Conditions

For a comparative baseline, we first ran CLARA to evaluate the recurrence of storm surge flood depths in coastal Louisiana under current (January 1, 2012) landscape conditions. Figure 10.1 shows the resulting flood depths by census block at each reported flood exceedance. These results show that, at present, most unprotected areas of the coast will incur at least 1 to 2 feet of surge and wave flooding with a 2-percent chance each year (50-year flood exceedance). Most areas with enclosed protection, with the exception of selected portions of the New Orleans to Venice (Plaquemines Parish) protection system, show no flooding at the 50-year flood exceedance, and the Larose to Golden Meadow protection system prevents flooding at the 100-year flood exceedance under current conditions using nominal assumptions. In addition, the results suggest that the upgraded Greater New Orleans HSDRRS currently prevents most flooding at both the 100- and 500-year flood exceedances. The flood depth reduction at the 500-year flood exceedance provided by the HSDRRS that is estimated in CLARA meets or exceeds the USACE's risk reduction goals for the city. This is likely due to the large margin of safety included by the USACE during the recent large-scale upgrades to the protection system.

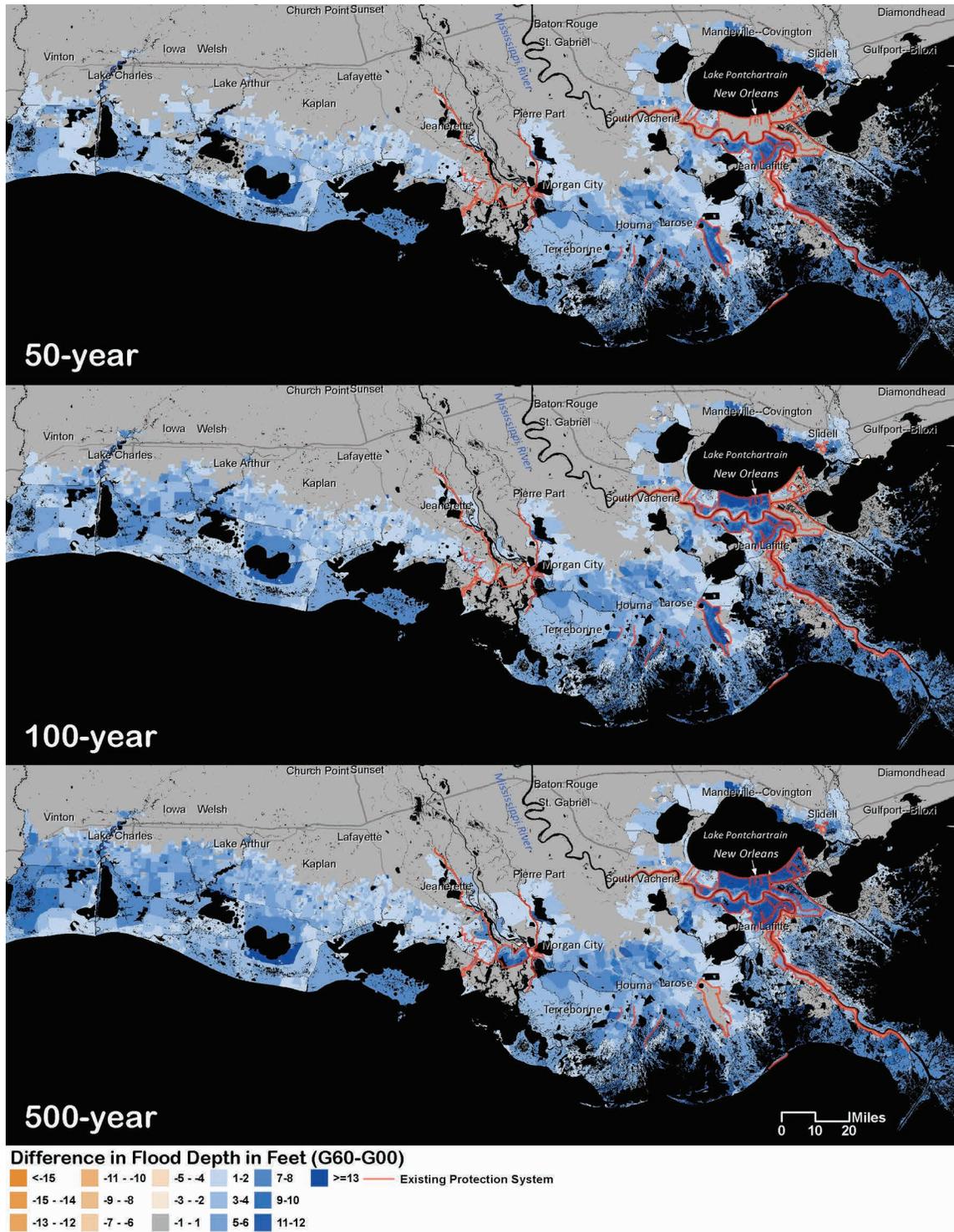
2036 (Year 25) Conditions

Using the *moderate future scenario* defined by CPRA to estimate outcomes in 2036, we note changes in flood exceedances emerging in different areas of the coast. All three flood exceedances increase in different areas of the coast, most often in the range of 0.5 to 2 feet (Figures A.2 and A.3 in the appendix). Selected areas, including portions of the north shore of Lake Pontchartrain and the Terrebonne vicinity south of Houma, show greater increases in this scenario in 2036. In the former, these changes are upward of 5 to 10 feet, depending on the flood exceedance; in the latter, the increases are closer to 3 to 6 feet relative to the baseline. In total, flood depths on the north shore of Lake Pontchartrain range from 5 to 10 feet at the 50-year flood exceedance interval to upward of 15 feet at the 500-year flood exceedance, while depths in Terrebonne range from 5 to 10 feet (50-year) to 15 to 20 feet (500-year).

For areas with HPSs, one notable change is the substantial increase in flood depths in Larose to Golden Meadow at the 50- and 100-year flood exceedances. With the nominal fragility assumptions, for example, the Larose system is inundated by upward of 8 to 10 feet of water at the 50-year flood exceedance (Figure A.2 in the appendix). In the central part of the coast and Atchafalaya region, positive flood elevations also emerge in Morgan City and in the protected area south of Franklin at the 50-year level.

Similar patterns emerge in the *moderate future with high SLR scenario* defined by CPRA (Figures A.4 and A.5 in the appendix) in 2036. Additional areas of the coast show flood depth increases in this scenario, with notable increases of 1 to 4 feet occurring relative to the 2012 baseline in the western portion of the state (e.g., Cameron Parish). The Terrebonne/Barataria vicinity is also adversely affected by the higher SLR rate, with 500-year flood depths upward of 10 to 20 feet for many census blocks in these areas. Once again, Larose and Morgan City show positive depths at the 50-year flood exceedance.

Figure 10.2
Estimated Change in Flood Depth, 2012–2061, by Census Block, for Coastal Louisiana (Less Optimistic Scenario)



The *less optimistic scenario* defined by CPRA (Figures A.6 and A.7 in the appendix) also shows notable depth increases 25 years from now, driven both by SLR and higher subsidence rates than those considered in the other Master Plan scenarios. Depth increases are similar to the moderate scenario with high SLR in many areas without HPSs. However, one notable change is that portions of the HSDRRS on the east bank of the Mississippi River, including Central New Orleans, Kenner, Metairie, and St. Charles, no longer maintain 500-year risk reduction in this scenario in 2036. Instead, subsidence of the protection structures on the south shore of Lake Pontchartrain leads to system failures emerging at this flood exceedance, which in turn leads to high levels of flooding as estimated by CLARA.

2061 (Year 50) Conditions

Flood depth projections of the FWOA at 50 years show further increases in flood depths at all three flood exceedances considered. Nearly all areas of the coast show depth increases in the moderate scenario (Figures A.9 and A.10 in the appendix), with notable increases in the 50-year flood exceedances in Terrebonne and on the north shore of Lake Pontchartrain. As with the less optimistic scenario in 2036, by 2061, most of the east bank of the New Orleans HSDRRS is flooded at the 500-year flood exceedance.

Notably higher flood depths are shown in the moderate future with high SLR (Figures A.10 and A.11 in the appendix) and less optimistic scenarios (Figures A.12 and A.13 in the appendix and Figure 10.2 here) in 2061 if no further action is taken. In both instances, flood depths increase in most areas of the coast by at least 3 to 6 feet at all flood exceedances, yielding deep floods in 2061. For instance, 500-year flood depths in many areas exceed 15 to 20 feet in the less optimistic scenario. Once again, we see substantial increases in flood depth in the vicinity of Houma and Terrebonne, but similar adverse outcomes occur in many other unprotected or semi-protected areas of the coast.

Protected areas also see substantial flooding in the moderate future with high SLR and less optimistic scenarios by 2061. In particular, Greater New Orleans no longer maintains risk reduction at the 100-year flood exceedance (Figure 10.2). Most of the New Orleans HSDRRS, including areas on both the east and west banks of the Mississippi River, is flooded at the 100-year flood exceedance in the moderate with high SLR scenario. Furthermore, in the less optimistic scenario, the west bank floods at the 50-year flood exceedance and the entire HSDRRS is flooded at the 500-year level. The simplifying assumptions used to develop CLARA likely lead to an overestimate of flood depths for Greater New Orleans when portions of the system fail during extreme events. Nevertheless, this analysis suggests that Greater New Orleans could experience substantial flooding by 2061 due to breach flooding even when using more-moderate assumptions about the flood volumes entering the system in the event of a failure.

Figure 10.2 shows the change in flood depth from 2012 to 2061 in the less optimistic scenario and is provided as an example of maps indicating the change in depth from one scenario to the next. Figure 10.2 shows what is, for most coastal census blocks, the most adverse case for the Master Plan analysis.

Comparison of CLARA Flood Elevations with Other Recent Estimates

Comparisons Are Challenging Because CLARA Differs from Previous Efforts

As we discuss earlier in this report, the CLARA model is based in large part on recent investigations of hurricane storm surge flood risk conducted by the IPET and LACPR teams. With similar model structure and data sources, a natural question is how our estimates of flood and

damage exceedances compare with these earlier efforts. This is not, however, a straightforward question to answer. Although the methods are similar, the IPET and LACPR teams in some cases used very different data sources and assumptions and addressed alternative research questions.

For instance, both LACPR and IPET used representations of the New Orleans HSDRRS that were developed in 2007–2008 as the system was still being designed and during early phases of construction. In contrast, the protection structures included in CLARA represent the final iteration of the system as presently constructed, and, in some areas, there are notable differences in the respective modeled systems. For example, IPET modeled levee heights of 15–18 feet on the eastern edge of the HSDRRS, running from Lake Pontchartrain southeast to Lake Borgne in New Orleans East. CLARA modeled these levees as 22 feet high, representing the upgraded 2012 system. This change considerably bolsters the defenses adjacent to New Orleans East, which is borne out in the modeled results. Similar differences of 2–5 feet exist in several reaches of the Orleans Main Basin part of the HSDRRS; the 2012 system modeled by CLARA is sometimes lower and sometimes higher than the 2011 IPET system.

Another key difference is the set of storms used to estimate the exceedance probabilities. As previously discussed, CLARA uses a set of 40 storms to provide estimates of flood exceedances across many projects and scenarios. By contrast, the LACPR effort estimated flood exceedances under “current” (2010) conditions using 152 storms for each half of the coast, or 304 storms coastwide. Then, in order to estimate results in future years or with new projects in place, the LACPR team selected smaller subsets of storms to run with ADCIRC and used regression analysis to interpolate results from storms not run.

For Greater New Orleans, the IPET team alternatively used a set of 77 storms focused on the eastern half of the state. IPET made no attempt, however, to estimate future flood exceedances, and all results refer to “current” (2011) conditions or the recent past (pre-Katrina or June 2007 versions of the HSDRRS) (USACE, 2009b). In both LACPR and IPET, earlier versions of ADCIRC, depending on older landscape data sets, were utilized to estimate surge from each storm. These efforts also used different wave models (Steady State Spectral Wave [STWAVE] rather than Simulating Waves Nearshore [SWAN]) and different surge and wave modeling assumptions.³

The difference in modeling assumptions and methodological choices is also notable. LACPR did not consider system fragility in its interior flood elevation calculations, for instance, and reported only results comparable with our No Fragility scenario output. In addition, the interior flood exceedances reported in the LACPR report represent the 90th percentile of the distribution created using LACPR’s Monte Carlo simulation of varying overtopping rates (USACE, 2009a). IPET also reports results from a probabilistic distribution, including a full analysis of uncertainty with derived or assumed probability distributions for many or most of the model parameters (USACE, 2009b). By contrast, CLARA uses a scenario framework to consider key uncertainties for the CPRA planning effort but otherwise uses point estimate parameter assumptions and does not attempt to further quantify uncertainty using probability distributions. As a result, CLARA results can be considered representative values but are not directly equivalent to LACPR or IPET results.

³ For example, LACPR used the STWAVE model without considering friction from vegetation, which tended toward larger significant wave heights in that analysis (USACE, 2009a).

Comparisons in Selected Locations Show Patterns of Similar and Differing Results

Because of these differences in data, assumptions, and methods, LACPR and IPET outputs cannot be used directly to verify CLARA flood exceedances. Nevertheless, there is value in comparing the results from each investigation in order to identify patterns of similarity or difference in flood exceedances. In particular, differences could show areas in which biasing could be occurring in one or more of the analyses, which in turn would suggest where additional investigation is needed.

Below, we compare results from CLARA with the LACPR and IPET analyses in selected locations that are illustrative of some of the discrepancies discussed above. We focus on enclosed protected areas in which overtopping, fragility, rainfall, pumping, and interior drainage are calculated in CLARA. To the extent possible, we have also selected results that reflect similar assumptions among our analysis and previous efforts regarding future scenario uncertainties, pumping, and levee fragility. Figure 10.3 illustrates the location of the BHUs chosen for comparison, which, in the New Orleans HSDRRS, coincide directly with the IPET subbasins. Larose is not pictured because it is outside of the Greater New Orleans area.

Table 10.2 shows results from CLARA (right column) compared with results from the LACPR analysis (left column) in selected enclosed protected locations. In all cases, the results shown are *flood elevation* rather than *flood depth* exceedances. The flood elevation exceedances produced by CLARA are summarized by BHU and provide an estimate of flooding relative to a fixed vertical elevation (the vertical datum NAVD88) rather than a flood depth relative to an average ground elevation. This allows for summary comparisons of flooding by BHU. In contrast, flood depth exceedances will vary by census block because of variation in ground elevation. Note that flood elevation exceedances from CLARA are shown at the 400-year and 1,000-year intervals in order to provide a direct comparison to the LACPR results reported at these intervals. These exceedances were produced for review and comparison purposes during our analysis but were not otherwise used during Master Plan development and are not discussed elsewhere in this report.

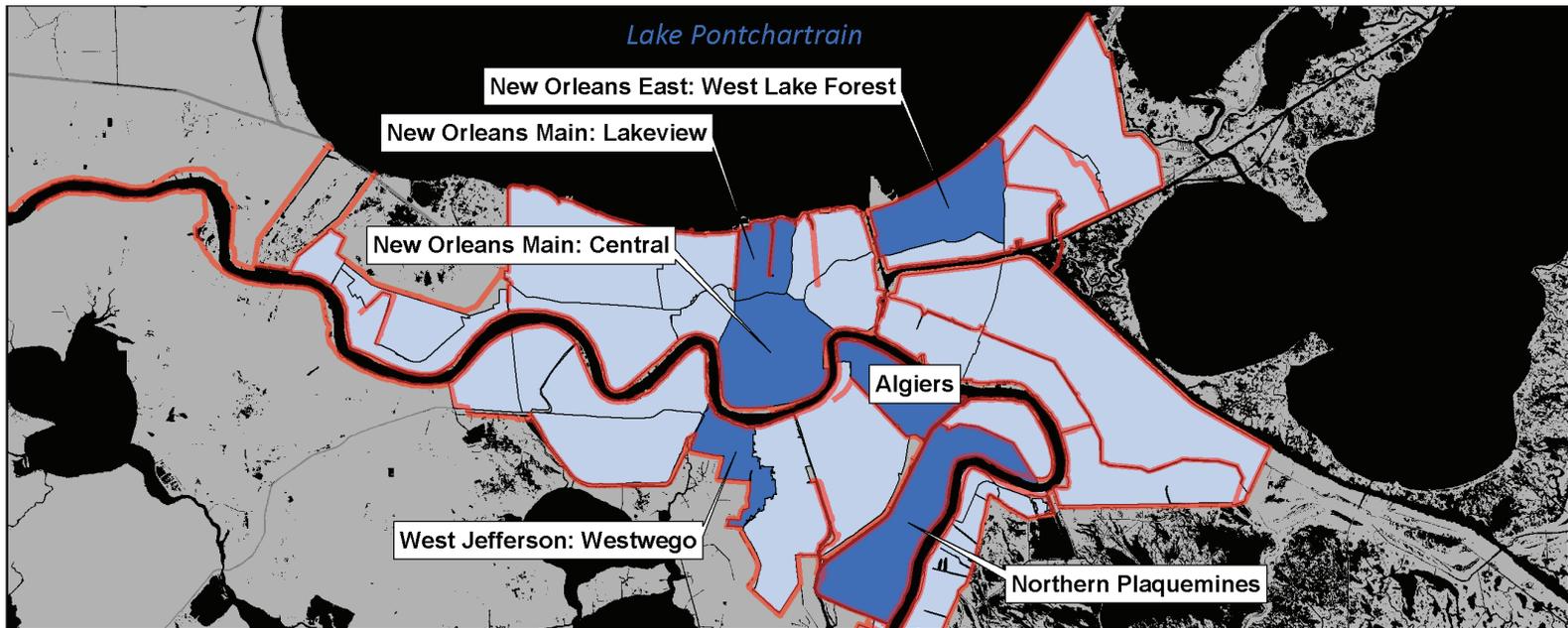
Results from the CLARA analysis compared with LACPR results include current conditions (top panel) and results from one Master Plan scenario in 2061 with similar RSLR assumptions (bottom panel).⁴ LACPR did not consider the possibility of system failure in its analysis, so we present the corresponding No Fragility results from CLARA.

A similar comparison between flood elevation exceedances produced by IPET (left column) and CLARA (right column) is shown in Table 10.3. Only current conditions are shown, because the IPET Risk and Reliability analysis did not project flood estimates for future conditions. IPET did consider fragility, so the With Fragility results from CLARA are included for comparison. The table shows results from the 50-, 100-, and 500-year flood elevation exceedances in a similar set of locations, including one extra protected BHU (New Orleans Main: Lakeview/City Park) and omitting Larose, which was not included in IPET's scope. The top panel compares results from the 100-percent pumping scenario from each analysis, while the bottom panel shows the 0-percent pumping scenario.

The LACPR estimates of current flood elevation exceedances are generally much higher than both the CLARA and IPET estimates. LACPR's flood elevations in New Orleans Main are similar to CLARA's, but, in other polders, such as New Orleans East and on the west bank,

⁴ RSLR is defined as the sum of SLR and subsidence effects.

Figure 10.3
Map of BHUs Selected for Comparison in the New Orleans HSDRRS



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Table 10.2
Comparison of Flood Elevation Exceedances from LACPR and CLARA (in Feet Above NAVD88) at Selected Locations

	LACPR Results: Current Conditions			CLARA Results: Current Conditions (No Fragility, 100% Pumping)		
	100-Year	400-Year	1,000-Year	100-Year	400-Year	1,000-Year
New Orleans Main: Central	-5.1	-4.8	-3.0	-7.5	-7.0	-6.5
New Orleans East: West Lake Forest	-5.8	0.5	10.9	-12.5	-11.5	-11.0
Algiers	-3.8	10.7	12.1	-16.0	-16.0	-16.0
West Jefferson: Westwego	-1.5	11.0	11.3	-11.5	-3.5	-3.5
Larose	-2.5	9.0	12.0	-5.5	-1.5	0.0
	LACPR Flood Elevations: Future Conditions (2060; RSLR 2.6 feet)			CLARA Flood Elevations: Future Conditions (2061; Moderate Scenario with High SLR; RLSR in Pontchartrain = 4.12 feet; No Fragility, 100% Pumping)		
	100-Year	400-Year	1,000-Year	100-Year	400-Year	1,000-Year
New Orleans Main: Central	-5.0	16.0	16.0	-7.5	-6.0	-5.0
New Orleans East: West Lake Forest	-0.1	16.0	16.0	-5.5	-1.0	1.0
Algiers	12.9	16.3	17.9	-16.0	-16.0	-16.0
West Jefferson: Westwego	11.6	14.3	15.8	-3.5	-3.5	-3.5
Larose	15.0	15.0	15.0	8.0	8.5	8.5

SOURCE: USACE, 2009a.

including Algiers and Westwego, LACPR reports much greater elevations. In several locations, the 100- and 400-year flood elevation exceedances from LACPR, which do not account for system fragility, are significantly greater than the corresponding 100- and 500-year elevations in IPET and CLARA for the cases that do consider fragility. LACPR also reports greater current flood risk in Larose than CLARA does. These differences are partially due to the different protection systems modeled, but the general upward bias may also be due to methodology differences, such as reporting 90th-percentile values from Monte Carlo simulations of overtopping. Similar differences appear in the projections of future flood elevation exceedances.

With these comparisons, however, it should be noted that very often, differences in flood elevations are still quite small when considering the volume of water they represent and the actual flood depths that would result in each case. This is because a small amount of water can lead to a large change in flood elevation relative to NAVD88 when flood elevations are low or negative. For instance, filling a drainage culvert that lies below NAVD88 with a small amount of floodwater might lead to several feet of flood elevation change relative to the NAVD88 reference. In addition, ground elevations vary across each BHU, so low or negative flood elevations might lead to damage in only a small number of census blocks.

For example, consider the comparison of current conditions between CLARA and IPET. In the central area of the New Orleans Main BHU, only one census block out of 4,425 has a mean elevation below CLARA's estimated 100-year flood elevation exceedance of -7.5 feet;

Table 10.3
Comparison of Flood Elevation Exceedances from IPET and CLARA (in Feet Above NAVD88) in Selected BHUs

	IPET Results: Current Conditions (100% Pumping)			CLARA Results: Current Conditions, (100% Pumping, with Fragility)		
	50-Year	100-Year	500-Year	50-Year	100-Year	500-Year
New Orleans Main: Central	-12.0	-12.0	-2.0	-8.5	-7.5	-7.0
New Orleans Main: Lakeview/ City Park	-12.0	-12.0	-12.0	-8.5	-8.0	-7.0
New Orleans East: West Lake Forest	-11.0	-9.0	-6.0	-13.0	-12.5	-11.0
Algiers	-3.0	-2.0	0.0	-16.0	-16.0	-16.0
West Jefferson: Westwego	-12.0	-2.0	0.0	-11.5	-11.5	-3.5
Northern Plaquemines	-12.0	-12.0	-5.0	-20	-20	-20
	IPET Results: Current Conditions (0% Pumping)			CLARA Results: Current Conditions (0% Pumping, with Fragility)		
	50-Year	100-Year	500-Year	50-Year	100-Year	500-Year
West Jefferson: Westwego	-2.0	-2.0	0.0	-4.5	-3.5	-3.5
Northern Plaquemines	-2.0	-2.0	1.0	-6.5	-6.0	-4.5

SOURCE: USACE, 2009c.

based on the CLARA stage-storage curves, the difference between CLARA and IPET's prediction of -12 feet represents only about 35 acre-feet of water, a negligible amount for a BHU of more than 11,000 acres in area. Thus, the apparent difference in flood elevations becomes much less significant when examining the resulting extent of flooding or damage. A similar effect exists in Lakeview, where the difference between the 50-year elevations of -12 and -8.5 feet represents only about 4 acre-feet.

In Northern Plaquemines and Westwego, the relative differences in flood elevations between the 0- and 100-percent pumping cases are shown in Table 10.3. Both CLARA and IPET show no flooding in Northern Plaquemines at the 50- and 100-year levels (the difference between -20 and -12 feet represents less than 0.5 acre-feet of water), but IPET shows significantly more flooding in the case without pumping than CLARA does: The difference between the 50-year levels in this case is more than 9,000 acre-feet. This relative shift is likely driven by differences in the pumping capacities assumed by the two models for the newly upgraded West Closure Complex pumping stations. The same phenomenon appears to occur in Westwego; CLARA generally shows less flooding, but the relative difference is much greater in the case assuming full pumping, indicating that greater pumping capacities are likely included.

A More Comprehensive Reconciliation of Modeling Approaches Is Needed

The CLARA, IPET, and LACPR models adopt a variety of different assumptions and methodologies that can produce differences in their estimates of flood elevation exceedances. In some cases, the source of discrepancies is obvious. In others, however, we can only make informed guesses about the factors causing results to diverge. However, an in-depth examination of each study's methods and findings was infeasible during the Master Plan analysis given the

time constraints, and this leaves uncertainty regarding the differences among studies. A more detailed reconciling of storm surge modeling approaches applied for coastal Louisiana, with a focus on data sources, assumptions, and methods, would provide more information about the strengths and weaknesses of each approach. This would also lend more confidence to CLARA's results while identifying areas for future improvement.

Coastwide Outcomes in the Future Without Action: Flood Damage

Flood depth outcomes by census block are an interim output produced to better understand where damage might occur or how changes in flooding recurrence and severity will propagate over time. However, the primary outputs produced by CLARA are estimates of direct damage to property and other physical assets from storm surge flooding over the next 50 years, with or without the Master Plan implemented. Direct and local economic impacts of the damage, such as lost wages and sales while reconstruction occurs, are also included; a complete list of impacts modeled is given in Chapter Seven. As previously described, these estimates were provided as the damage associated with flood exceedances at three frequencies—50, 100, and 500 years—as well as in terms of EAD.

The Master Plan Development Team used EAD reduction as the primary metric to evaluate damage reduction benefits, estimate project cost-effectiveness, and rank projects for inclusion in the Master Plan. As a result, we present damage results in the FWOA estimated at three damage exceedances and in terms of EAD. These results are summed values for the entire Louisiana coast, with selected locations highlighted in Chapter Seven. All results in this section use the same nominal assumptions regarding system performance and uncertainty in economic growth as were applied when comparing projects for inclusion in the 2012 Coastal Master Plan.

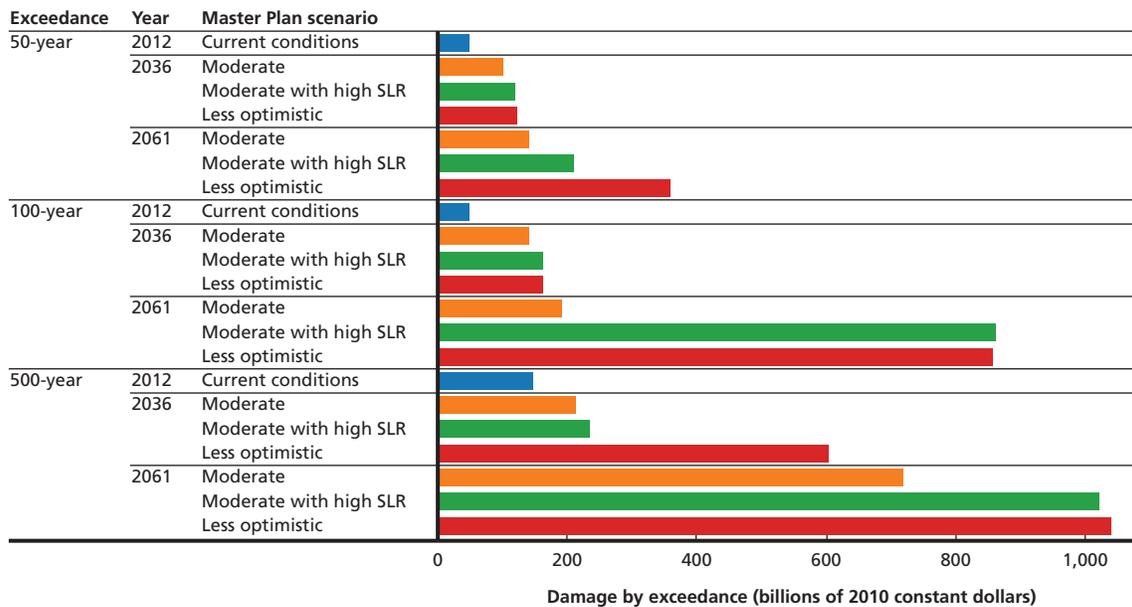
Damage by Exceedance

Figure 10.4 shows the sum of coastwide storm surge flood damage for each damage exceedance, year, and Master Plan scenario, respectively. For example, the damage associated with the 50-year flood exceedance, or damage exceedance (top panel)—which can be interpreted as the damage level associated with storm surge flooding with a 2-percent (1-in-50) chance of being met or exceeded in a given year—is \$47 billion in 2012. In the less optimistic scenario, this 50-year damage exceedance increases to \$122 billion by 2036, or \$358 billion by 2061. All damage values presented are in terms of 2010 constant dollars. In general, these coastwide results show flood damage levels increasing over time across all Master Plan scenarios, with substantial increases noted in some cases. Scenario results are ordered by the amounts of coastwide damage. The results show that the moderate scenario produces the lowest increase relative to current conditions, followed by the moderate future with high SLR and less optimistic scenarios, respectively.

In unprotected, more rural areas, damage increases gradually but steadily over time, corresponding to the gradual increases in projected flood exceedances. In Terrebonne, for example, the 100-year damage exceedance of \$6 billion in 2012 grows to \$12 billion in 2036 and \$18 billion by 2061.

The substantial nonlinear jumps in damage coastwide are driven by increased damage in urban areas as some protection systems cease to provide protection at the 50-, 100- or 500-year

Figure 10.4
Estimated Storm Surge Flood Damage in the Future Without Action, by Year, Master Plan Scenario, and Damage Exceedance



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flood exceedance in future years. As noted before, New Orleans East currently does not flood at the 500-year flood exceedance but is largely flooded at this exceedance by 2061; this leads to a 500-year damage exceedance of \$39 billion in 2061, compared with only \$9 million in 2012 and 2036. Similarly, the Larose to Golden Meadow area currently receives protection up to the 100-year flood exceedance, but by 2036, it no longer receives even 50-year risk reduction, leading to a jump at the 100-year damage exceedance from \$0.6 billion in 2012 to \$11 billion in 2036. This increases only to \$12 billion by 2061, primarily from economic growth rather than due to increases in flood exceedances.

Expected Annual Damage

In general, damage levels increase over time as a result of the increasing flood exceedances that are projected in every Master Plan scenario. However, the value of assets at risk also increases over time in the nominal economic growth scenario (0.67-percent annual population increase; see Table 8.1 in Chapter Eight), creating a larger potential for damage at comparable flood levels. Using the nominal economic growth assumption of 0.67 percent per year, EAD grows tenfold, from \$2 billion in 2012 to \$21 billion by 2061, in the less optimistic scenario. However, assuming 0-percent annual growth coastwide, EAD in 2061 is projected to be \$16 billion; thus, approximately 25 percent of the increase in EAD by 2061 in the less optimistic scenario is due to economic growth.

As Figure 10.5 illustrates, EAD in the other Master Plan scenarios is not as large as in the less optimistic scenario, reaching \$7 billion in the moderate scenario and \$16 billion by 2061 in the moderate scenario with high SLR. In Greater New Orleans, 2061 EAD in the moderate scenario is \$1.5 billion, compared with \$6.9 billion in the moderate with high SLR scenario and \$12.4 billion in the less optimistic scenario. That means that the performance

of the Greater New Orleans HSDRRS is responsible for about 78 percent of the difference in EAD between the moderate and less optimistic scenarios. The dramatic increase in EAD is thus driven by the impact of higher SLR and land subsidence on the fragility of existing protection systems; less severe, more frequent storms become more likely to cause catastrophic levee failures in protected areas with highly concentrated assets than in the moderate scenario.

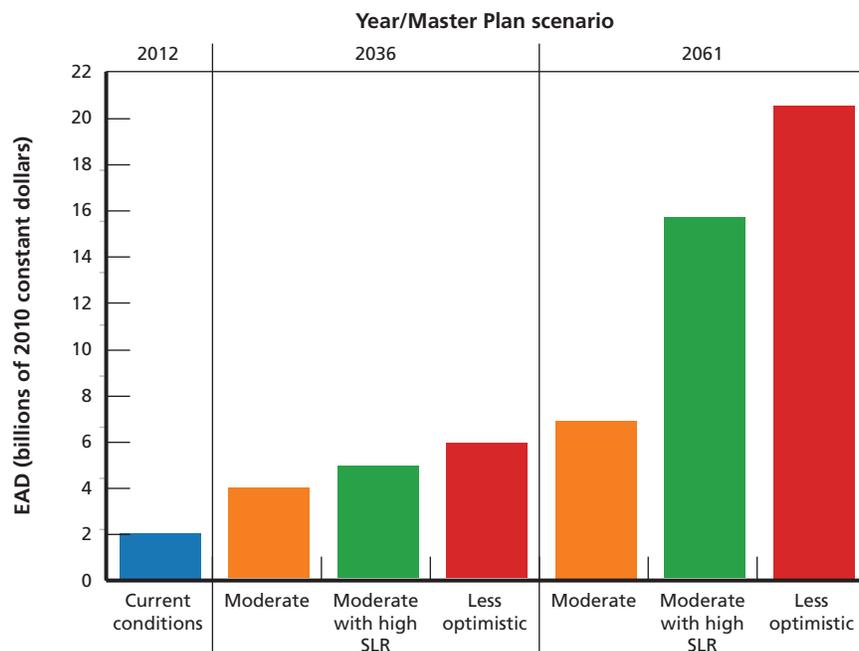
Projected Coastwide Outcomes from the Master Plan: Flood Depth Reduction

2036 (Year 25) Conditions

With the Master Plan in place, new project investments in the first 25 years provide new protection to Abbeville, Iberville Parish, and Vermilion Parish by extending the Franklin levee system; to Amelia by extending the St. Mary and Berwick system; to Laplace through an extension of the HSDRRS; to Terrebonne and Houma through the Morganza to the Gulf project; and to Lafitte by building a new ring levee around the town. Maintenance is provided to the Larose and West Bank New Orleans protection systems, and new levees connect existing ring levees in the Slidell and Oak Harbor areas.

These projects are designed to offset deterioration over time due to SLR, subsidence, and other landscape changes; provide additional protection across the eastern and central portions of the coastline; and boost the coastal defenses against possible future increases in hurricane intensity and frequency. At the 50-year flood exceedance, affected areas see depth reductions of 2 to 10 feet in the moderate scenario (Figure A.15 in the appendix), with the greatest depth

Figure 10.5
Estimated Expected Annual Storm Surge Flood Damage in the Future Without Action, by Year and Master Plan Scenario



reduction seen in the Larose and Golden Meadow system. Depths are unchanged within the Larose system at the 100-year level, however, and the 500-year depth is 1 to 3 feet greater there than in the FWOA case.⁵ The reductions in flood depth are consistent across the 50-, 100- and 500-year flood exceedances in the other affected areas. Unprotected portions of Plaquemines Parish also see modest reductions of 1 to 3 feet at all flood exceedances because of the effect of restoration projects.

Newly established projects near Vermilion Bay and Terrebonne Bay reduce flooding in upland areas but yield additional flood depths of 1 to 4 feet at the 100- and 500-year levels outside (south) of the protection structures.

The general pattern of flood depth reduction in 2036 is much the same in the moderate with high SLR scenario (Figure A.17 in the appendix), with the exception that the 100-year flood depths in Larose are 1 to 2 feet higher in the high SLR scenario than in the moderate scenario. (The area does not have 100-year protection in either case.) Also, parts of Laplace see 3 to 8 feet greater 500-year flood depths than in the FWOA case, in contrast to the reduction seen in the moderate scenario. In the less optimistic scenario (Figure A.19 in the appendix), these same areas are unchanged relative to the FWOA at the 500-year level. Otherwise, the difference in flood depths between the FWOA and the Master Plan is generally similar in the less optimistic scenario to the other scenarios in year 25 of the analysis.

2061 (Year 50) Conditions

In year 50, the full range of Master Plan projects are implemented. With regard to structural protection, the previously implemented Franklin and St. Mary systems are upgraded, adding the Greater New Orleans High Level Plan alignment upgrades and building a proposed new semi-enclosed alignment designed to reduce flooding in the Lake Charles area.

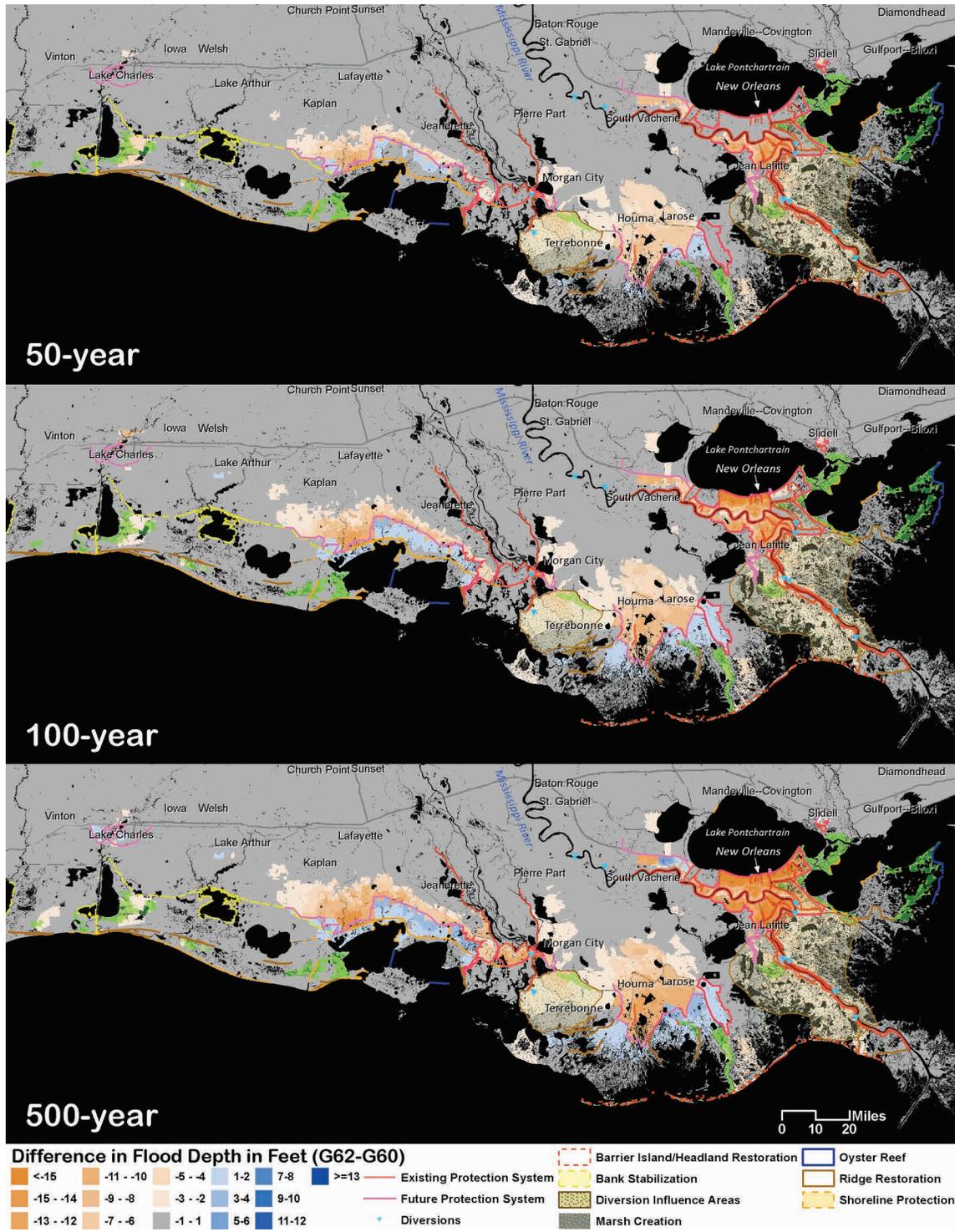
When results from each Master Plan scenario are compared, the difference in flooding between FWOA and the Master Plan is very similar in 2061 to the 2036 outcomes. Overall flood levels are still greater than in 2036 because of continued landscape change over time, but the impacts of the initial set of projects are largely the same as when first implemented.

Of the new projects implemented, the Greater New Orleans High Level Plan upgrade and West Bank and Vicinity maintenance produce 500-year protection in Greater New Orleans and West Bank and Vicinity in all scenarios modeled, representing substantial reductions in flood depths at the 500-year flood exceedance, as well as at the 100- and 50-year flood exceedances for some areas in selected scenarios. The same protection and corresponding depth reductions are provided to the Franklin and Morgan City areas and to protected areas of St. Mary Parish in all scenarios.

The Lake Charles area sees little impact at any level in the moderate scenario due to the low levels of baseline flooding. However, in the less optimistic scenario, flood depths are reduced as the new alignment provides 500-year protection (Figure 10.6). In the moderate with high SLR scenario (Figure A.23 in the appendix), this level of risk reduction is not attained, so flood depth is substantially reduced only at the 50- and 100-year flood exceedances.

⁵ The depth increase with increased protection is caused by a “bowl effect,” in which substantial flood volumes caused by surge and wave overtopping or breaches from extreme storms are able to fill up a deeper bowl once the crown heights of the levees are raised.

Figure 10.6
Estimated Change in Flood Depth in 2061 with the Master Plan in Place, by Census Block, for Coastal Louisiana (Less Optimistic Scenario)



Projected Coastwide Outcomes from the 2012 Master Plan: Flood Damage Reduction

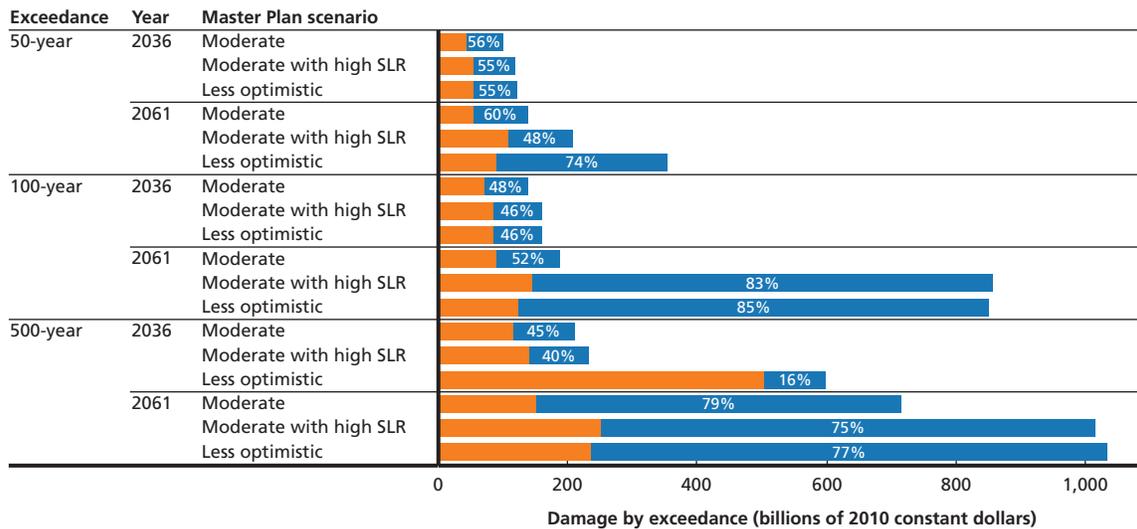
Damage by Exceedance

According to FEMA and USACE estimates for coastal Louisiana applied in CLARA, most of the potential damage to individual structures is done by the first foot or two of flooding. In terms of damage outcomes, then, there is a much greater difference between 0 and 2 feet of flooding than there is between 2 and 4 feet of flooding. As a result, most of the damage reduction at any damage exceedance is provided by Master Plan projects that reduce flood depths to zero at that interval.

Figure 10.7 summarizes the damage reduction produced by the Master Plan projects at each damage exceedance and each landscape scenario; all the figures in this chapter use the default assumptions previously defined for protection system performance and uncertainty in economic growth. The orange bars represent the remaining damage with the Master Plan projects implemented. The sum of the orange and blue bars indicates the FWOA damage, and the blue section by itself represents the amount of FWOA damage that is reduced by the Master Plan. The proportion of FWOA damage reduced with the Master Plan in place is also indicated by the percentage values accompanying each blue bar.

Most protection systems currently in place provide at least 50-year risk reduction in 2061 under the majority of scenarios. As a result, the reduction in 50-year damage shown in Figure 10.7 comes primarily from newly protected areas, such as Vermilion Parish, where 50-year damage in 2036 is reduced by 73 to 78 percent in 2036 from a baseline of \$2 billion to \$3 billion. Growth in the parish, along with future subsidence and SLR, contributes to greater damage in 2061, but the Master Plan’s reduction compared with the FWOA case remains proportional, lowering damage from \$3 billion to \$5 billion to approximately \$0.8 billion to \$1.4 billion, depending on the scenario.

Figure 10.7
Estimated Remaining Flood Damage and Reduction in Flood Damage with the Master Plan in Place, by Year, Master Plan Scenario, and Damage Exceedance



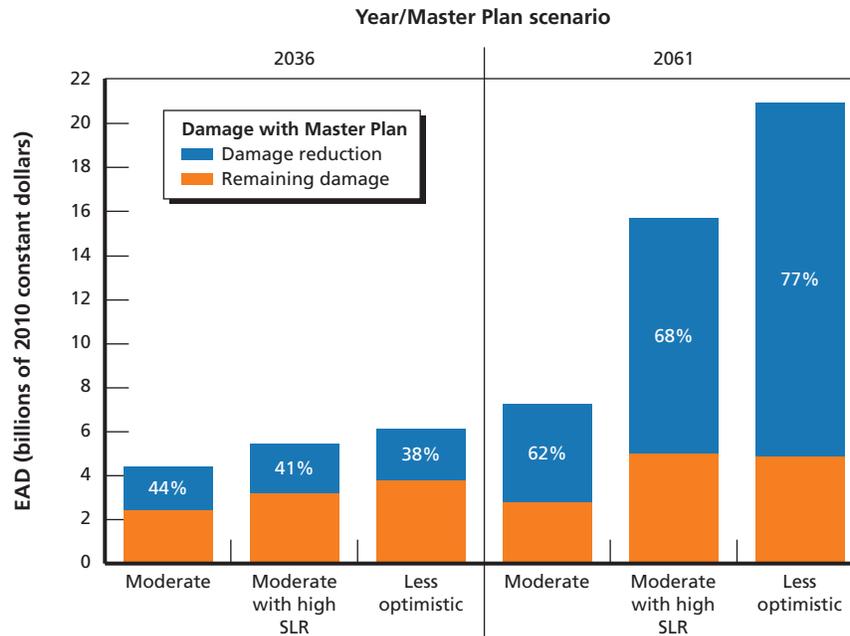
In Vermilion, these benefits extend to the 100- and 500-year damage levels; even the 500-year damage in 2061 is reduced by 64 to 81 percent across the various scenarios modeled. However, in terms of absolute dollars, most of the damage reduction at the 100- and 500-year levels is driven by the improvements to the New Orleans system, where the majority of assets are concentrated. The New Orleans community maintains roughly 500-year risk reduction, similar to the risk reduction provided by the current system in 2012, and, in 2061, 500-year damage is reduced from more than \$200 billion to \$400 million. Similar near-total reductions in damage occur at the 100- and 500-year levels in other areas, such as Algiers and the parts of Jefferson Parish within the west bank portion of the HSDRRS.

Expected Annual Damage

As summarized in Figure 10.8, the Master Plan provides substantial coastwide risk reduction when measured using EAD, with the greatest proportional reductions coming in more-severe Master Plan scenarios. In the less optimistic scenario, overall EAD is reduced from \$21 billion in 2061 to \$4.9 billion. Of the \$16.1 billion in damage reduction, \$12 billion comes from the Greater New Orleans area and another \$1.4 billion is from Houma.

In the moderate scenario, the Greater New Orleans area has 500-year protection in the FWOA case, so overall EAD is much lower than in the FWOA. As a result, there is lower potential for damage reduction, and this is borne out by the results. Of the \$4 billion in damage reduction, in this case only \$1.4 billion comes from Greater New Orleans; Houma sees a reduction of \$0.9 billion.

Figure 10.8
Estimated Remaining Expected Annual Damage and Reduction in Expected Annual Damage with the Master Plan in Place, by Year and Master Plan Scenario



In 2036, the Greater New Orleans High Level Plan upgrades to the HSDRRS have not yet been constructed, so EAD in the Greater New Orleans area actually increases because of levee subsidence and SLR over time in the absence of improvements. In other areas of the coast, reductions are roughly half of the total reductions described above in 2061.

Key Insights from Selected Coastal Areas

We highlight a sample of notable outcomes from the final Master Plan analysis, with a focus on areas of the coast experiencing either significant deterioration in the FWOA or substantial improvement with the Master Plan in place. These are not the only story lines from this analysis but instead are results of interest to Louisiana planners and stakeholders in key areas of focus along the coast based on the projects specified in the Master Plan. Future discussions and follow-on analyses could focus attention on other areas where key changes are occurring.

We describe the story lines using estimated damage outcomes in 2061 in the less optimistic scenario (the most adverse case considered). First, we describe key changes occurring in the FWOA and then show how new projects selected in the Master Plan for these areas could help to reduce storm surge flood damage. We also highlight several areas where currently selected projects do not provide substantial damage reduction. In the discussion below, we describe outcomes using the nominal assumptions made when estimating individual project benefits but in some cases also show outcomes from additional scenarios that introduce additional uncertainty related to the performance of the protection system or economic growth over time.

Notable Changes in the Future Without Action

A Substantial Fraction of the Increase in Damage by 2061 Occurs in Greater New Orleans

As discussed earlier in this chapter, the Master Plan analysis suggests that, in the absence of new actions, coastal Louisiana will experience a dramatic increase in storm surge flood damage over the next 50 years, particularly in the less optimistic scenario. Figure 10.8 shows, for instance, that coastwide EAD is estimated to increase tenfold from 2012 to 2061 in the less optimistic scenario, from \$2 billion to \$21 billion in constant 2010 dollars. This represents a significant increase in damage relative to earlier time periods, as well as when compared with 2061 EAD outcomes from the moderate (\$7 billion) and moderate with high SLR (\$16 billion) scenarios.

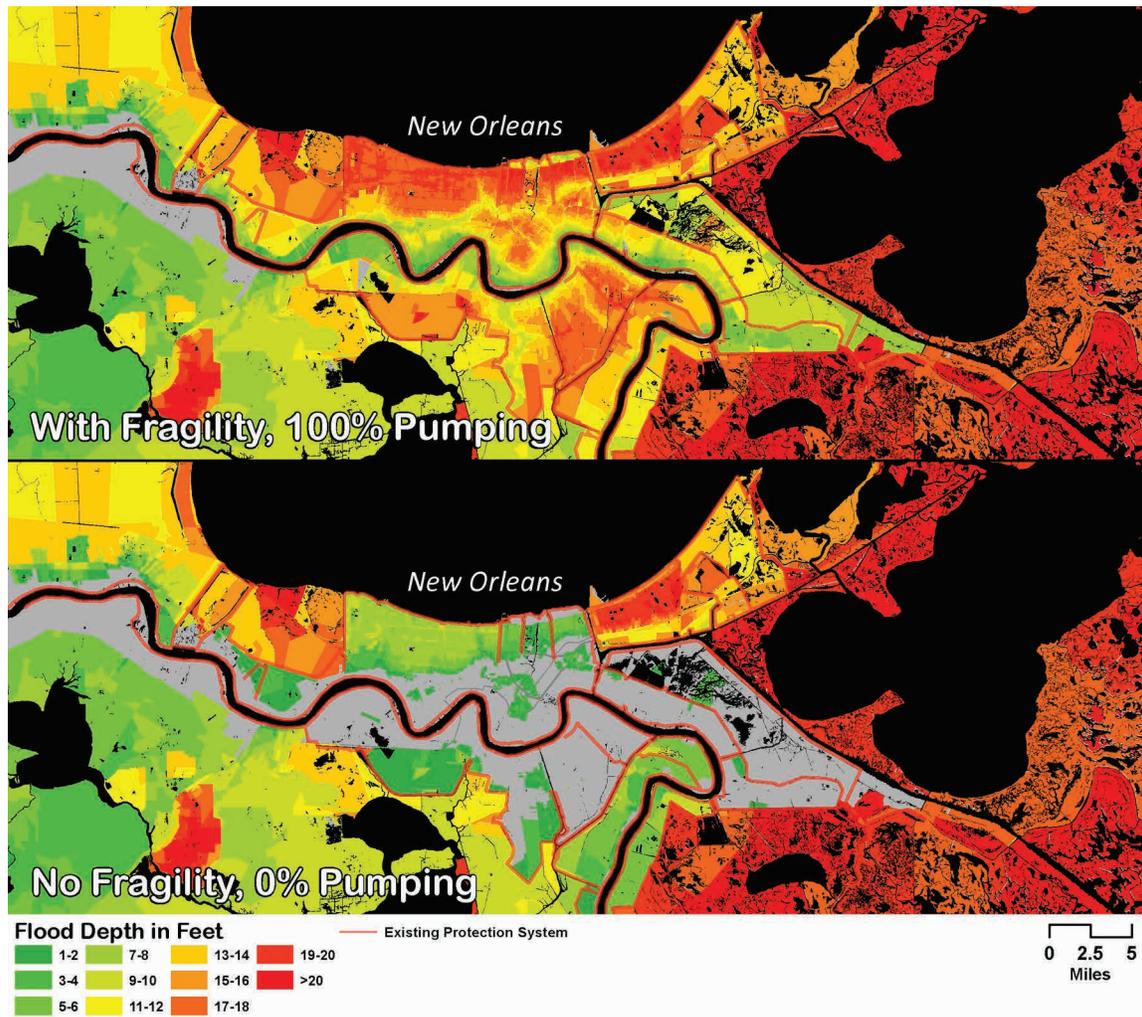
Additional investigation shows that these results are driven primarily by a rise in the number of system failures of existing structures from higher-probability surge events occurring in Greater New Orleans, on both the east and west banks of the New Orleans HSDRRS. In other words, the combined effect of SLR, which raises the surge water level at all points surrounding the system, and subsidence, which reduces the effective heights of the levees and other protection structures, is to make failures increasingly likely in the HSDRRS over time and in more-extreme SLR and subsidence scenarios.

CLARA relies on a key simplifying assumption that the interior flood elevation equalizes to the peak exterior surge elevation at the location of the breach. The consequence of this assumption is that, by instantaneously equalizing exterior and interior water levels, the model does not take into account the movement of water over time or limits in water flow rate through a levee breach. As a result, CLARA almost certainly overestimates the resulting damage when a failure occurs.

The Risk and Damage Team considered this possibility when initially developing the model. To better understand the range of uncertainty regarding system fragility, the team elected to include a scenario in which the possibility of levee breaching was turned off (the No Fragility scenario). In this scenario, water could reach the interior of a protected area only via storm surge overtopping, wave overtopping, or rainfall. For protected areas such as New Orleans, the No Fragility assumption provides a lower bound on future flood damage. Combined together, the With Fragility and No Fragility assumptions provide a bounding range for actual damage levels for protected areas.

Figure 10.9 shows depths at the 500-year flood exceedance in Greater New Orleans for a scenario with (top) or without (bottom) fragility turned on. The top panel shows the nominal Master Plan assumptions (With Fragility, Full Pumping), while the bottom panel further subdivides and shows No Fragility results with no pumping in effect—in essence, the worst case for New Orleans in the event no breaching occurs. The With Fragility map shows that

Figure 10.9
Estimated Flood Depths at the 500-Year Flood Exceedance in Greater New Orleans in 2061 (Less Optimistic Scenario)

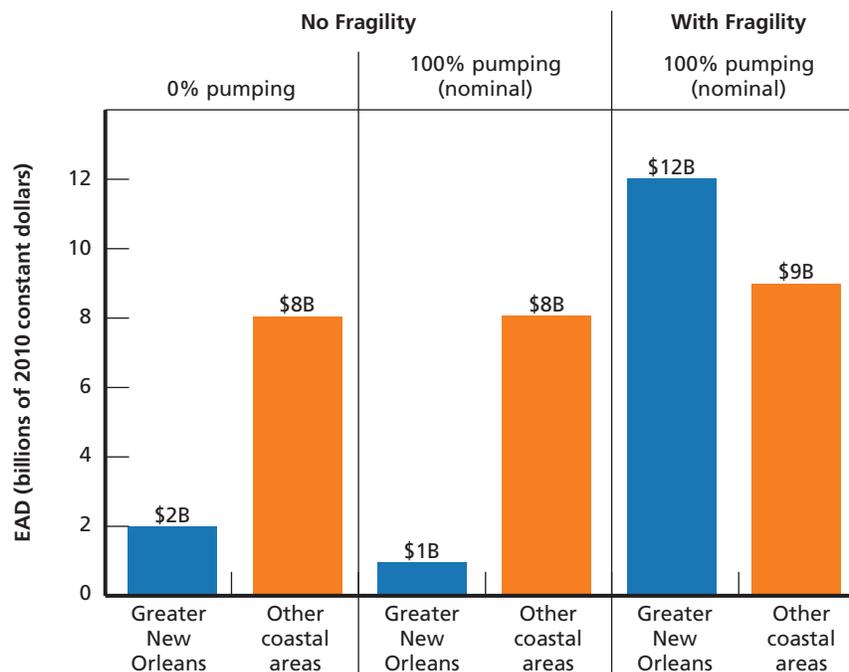


CLARA predicts high flood depths for all of Greater New Orleans at the 500-year flood exceedance with fragility in place, with all areas receiving at least 1 to 2 feet of flooding and 10 feet or more of flooding in the majority of census blocks in the broader metropolitan area. In contrast, the No Fragility, No Pumping outcome generally shows lower flood depths for many areas of the city except for New Orleans East and other low-lying areas. Without fragility, flood depths inside the HSDRRS are generally much lower, though still positive in many areas of the city if pumping fails to operate as expected.

The high flood depths in Greater New Orleans with fragility in place translate to very high damage estimates as sea levels rise and protection structures subside. For instance, Figure 10.10 shows coastwide EAD in the less optimistic scenario in 2061, subdivided into two groups: Greater New Orleans and all other coastal areas. Three system cases are shown: With Fragility, Full Pumping (right panel); No Fragility, No Pumping (left panel); and No Fragility, Full Pumping (middle panel). This figure shows that a large majority of the coastwide EAD estimated by CLARA in 2061 in the less optimistic scenario—\$12 billion, or 57 percent of the \$21 billion total—comes from Greater New Orleans, and is contingent on the With Fragility scenario being active. By comparison, the No Fragility scenarios show EAD between \$1 billion (Full Pumping) and \$2 billion for Greater New Orleans, a small fraction of the With Fragility total.

In contrast, EAD estimates in other coastal areas do not vary as substantially with the fragility assumption, ranging from \$8 billion in No Fragility to \$9 billion in With Fragility. This is consistent with our interpretation of the flood depth results in other protected areas. In protection systems that, like Larose to Golden Meadow or New Orleans to Venice (Plaquemines),

Figure 10.10
Estimated Expected Annual Damage in Greater New Orleans Versus the Remainder of the Coast in 2061 (Less Optimistic Scenario)



have large amounts of wave and surge overtopping, flood depths and damage levels in the No Fragility case are much closer to the With Fragility estimates and tend to converge in later time periods and more-adverse Master Plan scenarios as SLR and subsidence effects progress (not shown).

These results suggest that the simplifying assumptions made regarding interior flood elevations from a breach overestimate damage in the With Fragility case and further show that most of the biasing occurs in Greater New Orleans. This overestimate biases upward the less optimistic scenario results in both 2036 and 2061 and also affects the moderate and moderate with high SLR scenarios in 2061. The No Fragility results instead suggest that the lower bound of FWOA coastwide EAD in the less optimistic scenario is \$8 billion to \$9 billion, and a less biased estimate likely lies somewhere between the lower and upper bounds discussed. *As a result, the FWOA and with–Master Plan analysis results for Greater New Orleans should be used with caution. Further analysis is needed to improve the interior flood and damage estimates in alternative future conditions for this important metropolitan area.* However, it is important to note that the coastwide FWOA EAD of \$8 billion to \$9 billion (No Fragility, less optimistic scenario) nevertheless represents a four- to fivefold increase in flood damage compared with current conditions and still shows notably deteriorating conditions over time even without system fragility represented for the New Orleans HSDRRS.

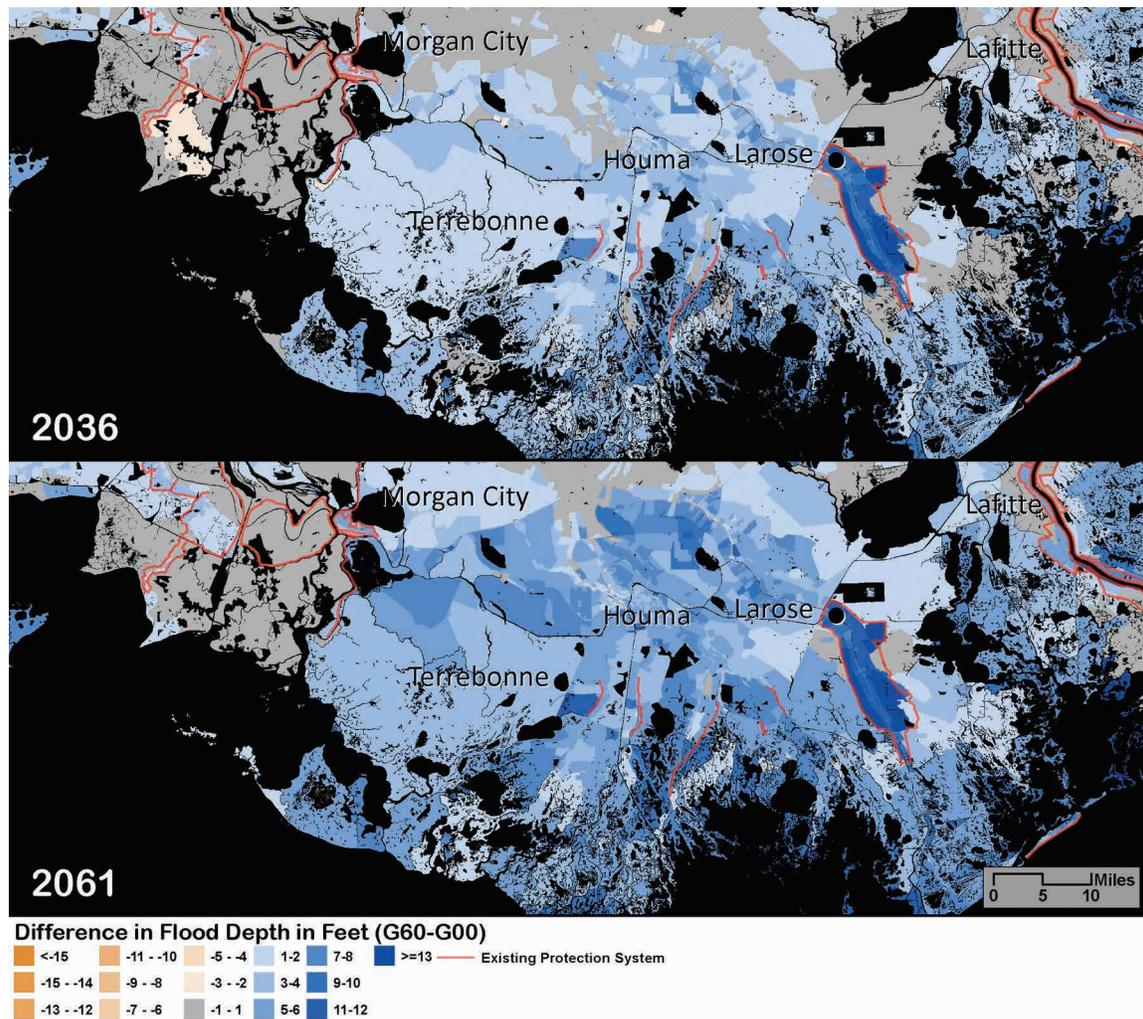
SLR and Subsidence Lead to Substantial Deterioration in the Terrebonne Vicinity

Building on the previous discussion, the Master Plan results suggest that some areas of the coast will experience increases in storm surge flood damage over time as conditions worsen. This deterioration is particularly notable in the central portion of the coast spanning Terrebonne Parish, the city of Houma, and Bayou Lafourche, including Larose and Golden Meadow. Of these areas, Larose and Golden Meadow currently have an enclosed protection system, while Houma and other more densely populated communities in Terrebonne currently have essentially no protection from hurricane storm surge.

Figure 10.11 provides a zoom on these areas and shows the change in 100-year flood depth from 2012–2036 (top) and 2012–2061 (bottom) estimated using CLARA in the less optimistic future scenario. Nominal assumptions (With Fragility, Full Pumping) are shown. These maps show that, for the currently unprotected areas, 100-year flood depths increase from a baseline of 1 to 8 feet in 2012 by an additional 1 to 6 feet by 2036 and 3 to 10 feet by 2061. In addition, the Larose to Golden Meadow protection system no longer maintains 100-year risk reduction by 2036 and shows substantial depth increases of more than 10 feet in both time periods.

Sea levels are projected to increase by approximately 1.5 feet over the 50-year period of analysis in the less optimistic scenario, while subsidence in the Terrebonne region is assumed to increase by 2.1 feet during that time. Thus, a simple linear increase in surge heights in the unprotected areas based on the sum of SLR and subsidence in the less optimistic scenario would suggest a depth increase of approximately 3.6 feet for this area by 2061. Figure 10.11 shows that 100-year flood depths in many census blocks do increase by 3 to 4 feet, but, in other blocks, flood depths increase more than linearly with SLR and subsidence, with depth increases of 5 to 10 feet or more in some locations. The reasons for these large increases are changes to the landscape and vegetation and are described in a separate report by the Storm Surge/Wave Team.

Figure 10.11
Change in 100-Year Flood Depth over Time, 2012–2036 and 2012–2061, Terrebonne/Houma Area
(Less Optimistic Scenario)

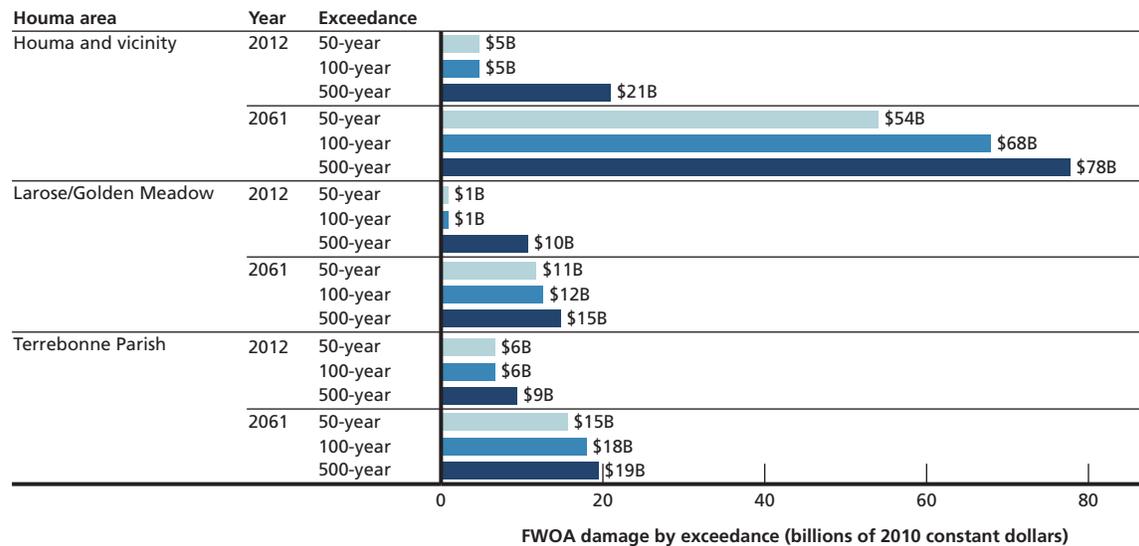


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The substantial depth increases noted in this area also translate to increasing damage associated with flooding at all three flood exceedances. Figure 10.12 shows the CLARA predictions for FWOA storm flood damage (less optimistic scenario) in 2012 and 2061 for Houma and the surrounding communities, Larose and Golden Meadow, and the remainder of Terrebonne Parish, respectively. In each location and across the three damage exceedances, damage increases substantially. For instance, CLARA estimates that damage associated with the 50-year flood depths in Terrebonne Parish will increase from \$6 billion in 2012 to \$15 billion in 2061, more than doubling over the 50-year span.

Houma and the surrounding communities are strongly affected in the less optimistic scenario. Fifty-year damage increases from \$5 billion in 2012 to \$54 billion in 2061, a tenfold increase, and an even larger increase is noted at the 100-year damage exceedance (\$5 billion to \$68 billion). These areas currently have no enclosed hurricane protection or continuous storm surge barrier, so these figures are unaffected by the fragility assumptions noted earlier. Instead,

Figure 10.12
Increase in Damage over Time in the FWOA for the Terrebonne/Houma Area, by Damage Exceedance (Less Optimistic Scenario)



NOTE: Houma and vicinity includes the CPRA-defined communities of Houma, Bayou Blue, Mathews/Lockport, and Raceland.

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these increases are driven primarily by changes in surge and wave levels due to SLR, subsidence, and the other landscape assumptions made for the Master Plan scenarios.

Finally, Larose and Golden Meadow also experience damage increases in this scenario. These areas do have enclosed protection and are influenced by the fragility assumptions. However, as indicated earlier, damage for these areas is anticipated to increase irrespective of whether the CLARA fragility assumptions are used or not. In the No Fragility system scenario, for instance, 50- and 100-year damage for Larose and Golden Meadow is estimated to be approximately \$10 billion. This tenfold increase from current conditions is caused by substantial surge and wave overtopping of the enclosed protection system as exterior conditions worsen.

Master Plan Benefits for Selected Areas

Upgrades to the Greater New Orleans Protection System Reduce Likelihood of Overtopping and Subsequent Breaching

In the previous section, we described the substantial increases in FWOA flood damage estimated for Greater New Orleans in the less optimistic scenario with the simplified CLARA assumptions regarding flood levels if and when a breach occurs. Informed by the project-level analysis, the state selected two Master Plan projects intended to reduce future flood damage in metropolitan New Orleans. The Greater New Orleans High Level Plan project, adapted from the USACE LACPR analysis, raises levees and other protection structures on the east bank of the HSDRRS to a height of 15 to 35 feet. This project was initially selected for construction starting in 2032 and thus does not provide any benefits by year 25 of the analysis (2036). The Master Plan also proposes a project to maintain the existing West Bank and Vicinity project levees to offset the effects of SLR and subsidence.

Analysis with CLARA shows that these projects together could substantially reduce the likelihood of breaching from surge events considered in this analysis. The CLARA modeling shows that, in the With Fragility system scenario, these projects prevent catastrophic flooding due to breaching from occurring and help to maintain 500-year risk reduction on both the east and west banks of the HSDRRS in the less optimistic scenario in 2061 (Figure 10.13, top panel). By contrast, breach flooding begins to occur at the 50-year flood exceedance on the west bank by 2061 in the FWOA and at the 100-year flood exceedance on the east bank. In addition, these projects also provide benefits by preventing surge and wave overtopping from occurring in the No Fragility scenario (Figure 10.13, bottom panel).

As expected, CLARA also estimates substantial damage reduction for Greater New Orleans with the Master Plan in place. Figure 10.14 shows the damage reduction in 2061 for this area versus the remainder of the coast in terms of EAD. The plot provides damage reduction results separated across several different scenario uncertainties, with the columns showing

Figure 10.13
Reduction in Flood Depth at the 500-Year Flood Exceedance in Greater New Orleans in 2061 with the Master Plan in Place (Less Optimistic Scenario)

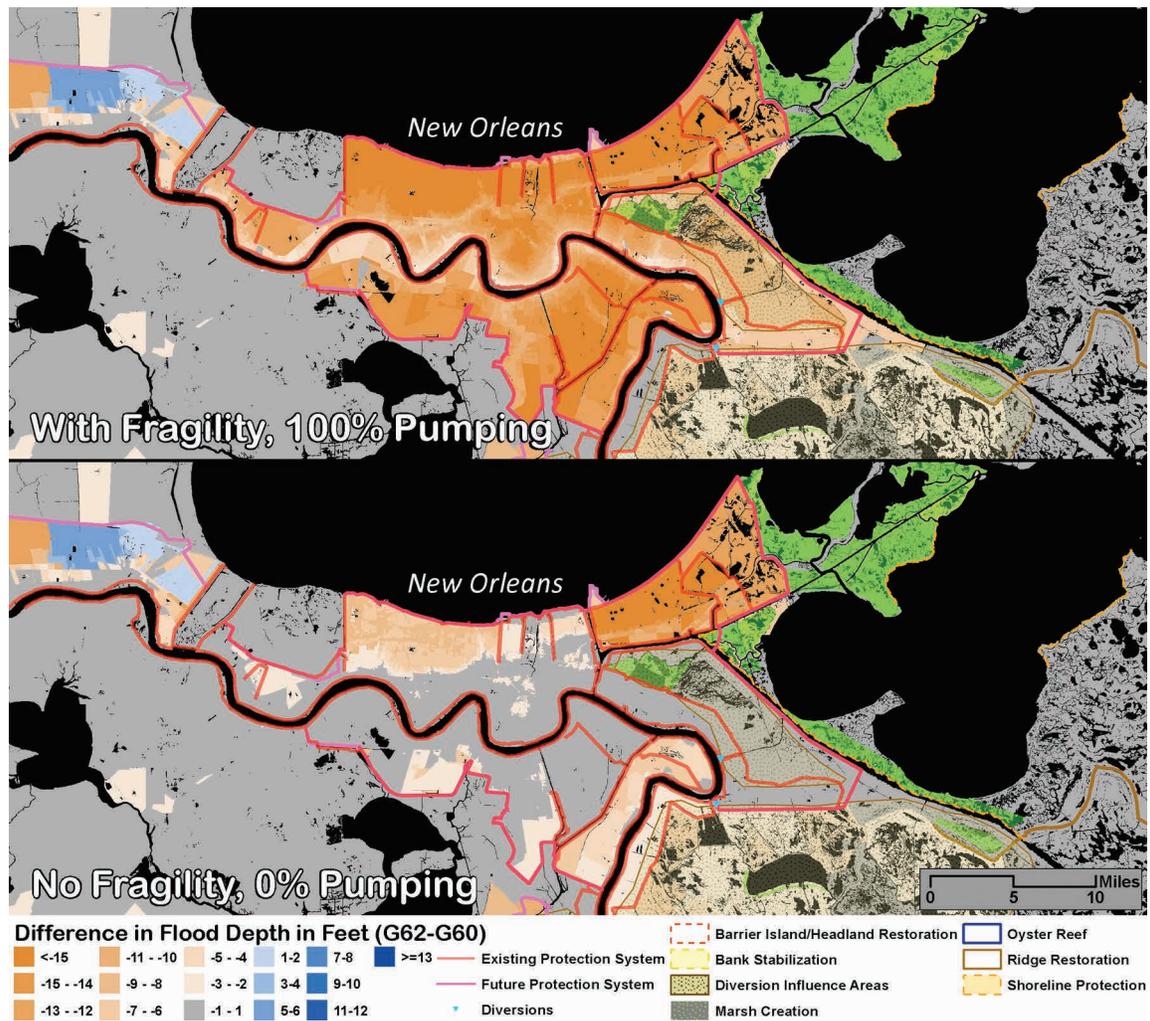
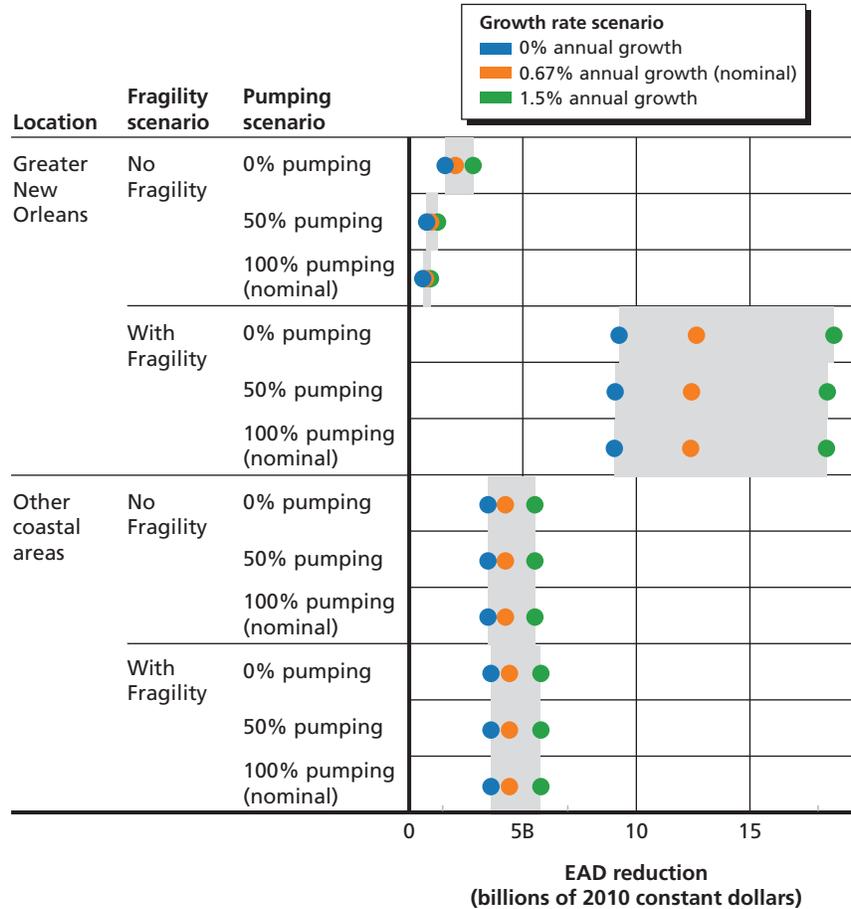


Figure 10.14
Expected Annual Damage Reduction in 2061 in Greater New Orleans
Across Fragility and Pumping Assumptions and Population Growth Rate
Assumptions (Less Optimistic Scenario)



NOTE: Each colored point shows one scenario outcome.
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the fragility and pumping scenarios, respectively, while the population growth rate is indicated with colored symbols. Each symbol represents the damage reduction from one combination of scenario inputs. The grey bars indicate the range for each subset presented.

Damage reduction in Greater New Orleans, according to Figure 10.14, varies substantially depending on the fragility, growth rate, and pumping scenarios, while much less variation is noted in other coastal areas across these scenario uncertainties. Specifically, there is the expected wide gap in damage reduction between EAD reduction in the No Fragility (\$625 million to \$2.6 billion in EAD reduction) and With Fragility (\$8.9 billion to \$18 billion) scenarios, mirroring the gap in FWOA damage previously noted. Within the No Fragility scenario in Greater New Orleans, pumping uncertainty plays an important role, with lower effective pumping rates translating to greater amounts of EAD reduction from the new system upgrades.

Conversely, in the With Fragility scenario, the range of results depends almost entirely on the population growth rate. This result is expected for two reasons. First, CLARA assumes

that pumping is inoperable during a breaching event (per the simplifying assumptions), and thus we would expect less variation by pumping scenario. Second, given the high proportion of assets that are considered flooded during a breach event in New Orleans as modeled in CLARA, additional population and asset growth over a 50-year span will necessarily translate to a substantial increase in damage if most of these new assets are also damaged or destroyed. By contrast, results using alternative assumptions about pumping effectiveness (50 percent or 0 percent of rated capacity) for the remainder of the coast show much less variation, with very similar results with or without fragility, essentially no variation by pumping scenario, and a narrower range (\$3 billion to \$6 billion) across the population growth scenarios considered.

As with the FWOA damage results, however, damage reduction benefit results in Greater New Orleans from the Master Plan should be used with caution, as the nominal With Fragility results very likely overestimate benefits from the two projects selected for this area. If other assumptions in the model are correct, the true benefits are more likely bracketed by the widely ranging scenario results presented above. However, we note that even the lowest estimate of EAD reduction for New Orleans (No Fragility, 100-percent pumping, 0-percent growth rate) of \$625 million represents a substantial amount of annual damage reduction when compared with benefits for the remainder of the coast from the Master Plan.

Benefits from a New Structural Alignment: Morganza to the Gulf

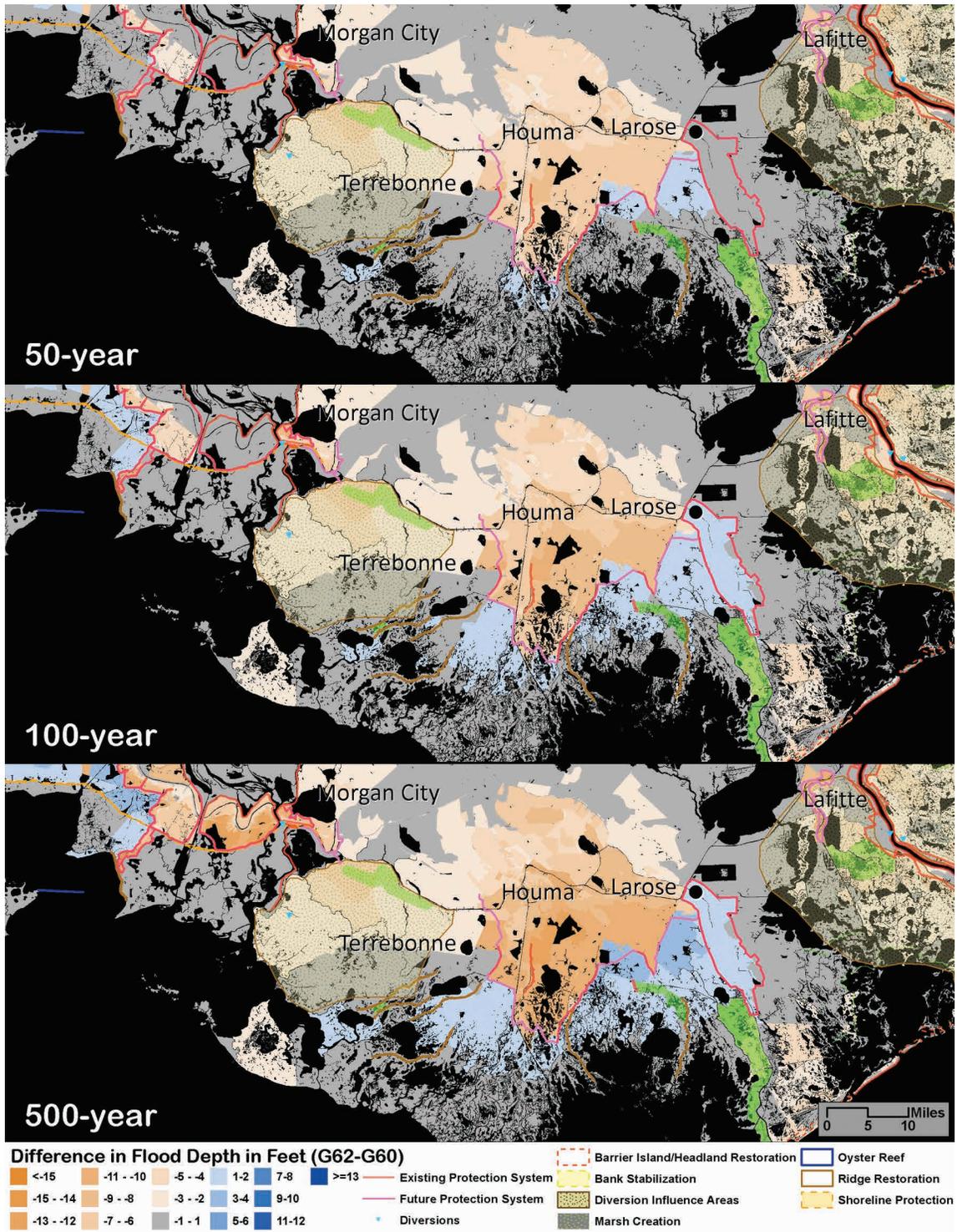
Turning to other areas of the coast, we previously described the substantial increase in storm surge flood damage projected to occur for the Houma vicinity under the less optimistic scenario in the FWOA. To address this growing threat, the Master Plan includes a major new protection investment: the Morganza to the Gulf barrier alignment, built to an elevation of 20 to 37 feet. This new levee is unenclosed, yielding a semiprotected area behind, and interconnects with the Larose to Golden Meadow system.

The final Master Plan analysis shows that the new alignment could provide substantial risk reduction benefits to Houma and the surrounding Terrebonne Ridge communities. Analysis with CLARA shows that Morganza to the Gulf could reduce depths across all three flood exceedances considered (Figure 10.15), with depth reduction of 2 to 5 feet (50 years, top panel), 2 to 7 feet (100 years, middle panel), and 2 to 11 feet (500 years, bottom panel), respectively. Depth reduction extends for a large area of the coast behind the new alignment, including other portions of Terrebonne Parish and some upland areas. In addition, this figure shows that the combination of restoration projects to the west of the Morganza alignment—a combination of ridge restoration, marsh creation, and a new diversion from the Atchafalaya River, specifically—reduces flood depths in other portions of Terrebonne Parish, in the range of 1 to 3 feet.

However, the Morganza to the Gulf alignment also displaces surge that previously flooded areas to the north leading to an increase in surge heights and flood depths for areas exterior to the levee system (blue shading). In addition, a notable result is that the new alignment displaces surge onto the existing Larose to Golden Meadow system, leading to induced flooding on the interior.

The Master Plan separately specifies a project to maintain levee heights for Larose to Golden Meadow; however, our analysis suggests that this project does not notably reduce flood depths for the interior area in the less optimistic scenario by 2061 when combined with new Morganza alignment. Instead, the results show a slight increase in interior flood depths for Larose to Golden Meadow due to additional induced surge on the southwest portion of

Figure 10.15
Estimated Change in Flood Depth in 2061 with the Master Plan in Place, by Census Block, for Houma and Terrebonne (Less Optimistic Scenario)

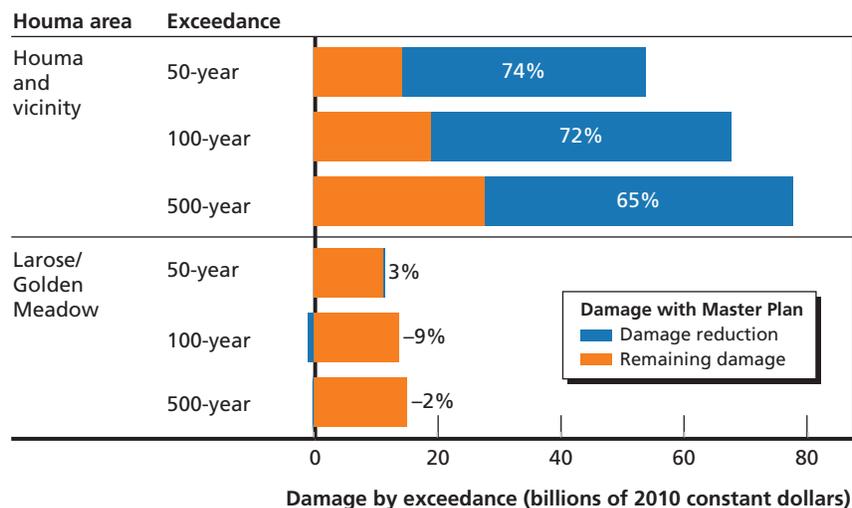


the system. Furthermore, crown elevations for the new Morganza alignment are approximately 30.5 feet where the barrier interconnects with the Larose to Golden Meadow, while the enclosed protection system has levee heights of 10 to 12 feet in this region. This disparity indicates that additional levee upgrades will be needed for the Larose to Golden Meadow system to keep pace with the Morganza alignment and prevent induced flooding events.

Nevertheless, the Master Plan provides substantial damage reduction for Houma and the surrounding communities (Figure 10.16, top panel). In the less optimistic scenario, for instance, damage levels are reduced by 74 percent, 72 percent, and 65 percent at the 50-, 100-, and 500-year damage exceedances, respectively. Damage still occurs in these areas at all intervals due to a combination of levee overtopping and surge “run-around” (surge water infilling from behind, due to the lack of a protection system enclosure). In addition, the damage results show that the Master Plan provides either zero or slightly negative damage reduction benefits to Larose and Golden Meadow due to the induced flooding described above (Figure 10.16, bottom panel).

We note one important caveat regarding the damage reduction benefits from the new Morganza to the Gulf alignment. This is a barrier that produces a new semiprotected area. Recall that the simplified CLARA analysis does not consider the possibility of wave overtopping or levee fragility for the new barrier but instead includes only surge overtopping and run-around as estimated in the ADCIRC model. As a result, this analysis likely underpredicts damage with the new barrier in place and subsequently overestimates the benefits provided. Any bias introduced is almost certainly strongest in a local area relatively near the barrier, but the extent to which the bias tails off as distance inland increases is unknown. The amount of bias is also unknown, but we expect that the alignment would have a low probability of failing at least to the 100-year exterior surge exceedance based on a comparison of the modeled surge exceedances and the alignment’s design heights. *A more detailed follow-on analysis that*

Figure 10.16
Estimated Remaining Damage and Damage Reduction for Houma and Vicinity and Larose/Golden Meadow, in 2061, by Damage Exceedance (Less Optimistic Scenario)



takes into account wave overtopping and potential breach flooding from extreme events is needed to improve damage reduction estimates for Morganza to the Gulf.

Nonstructural Risk Reduction: Community of Mandeville

Although the Master Plan includes a series of projects to upgrade or provide new structural protection to different areas of the coast, structural investments are not made for all communities. Instead, the Master Plan relies on a combination of restoration and nonstructural risk reduction projects to help reduce future flood damage in these areas. The nonstructural projects considered are described in detail elsewhere (see Master Plan, Appendix A, CPRA, 2012b), but in general represent a limited set of options implemented at a broad level without taking into account the particular planning circumstances in individual communities.

As a result, in some areas, nonstructural risk reduction investments provide only limited risk reduction relative to the FWOA baseline. For example, the town of Mandeville on the north shore of Lake Pontchartrain is a community that would see 100-year flood depths increase for most near-coast areas from 1 to 8 feet in 2012 (not shown) to 4 to 12 feet in 2061 in the less optimistic scenario (Figure 10.17). EAD is also projected to increase from \$138 million in 2012 to \$415 million in the less optimistic scenario by 2061 (Figure 10.18).

The Master Plan specifies a nonstructural risk reduction project for Mandeville, using the FEMA-defined BFE+1 foot of freeboard as an elevation target for structure raising and flood-proofing. However, as Figure 10.18 shows, the nonstructural investment yields EAD reduction of less than 12 percent of overall damage in all years and Master Plan scenarios, leaving a substantial amount of damage in the future as conditions worsen.

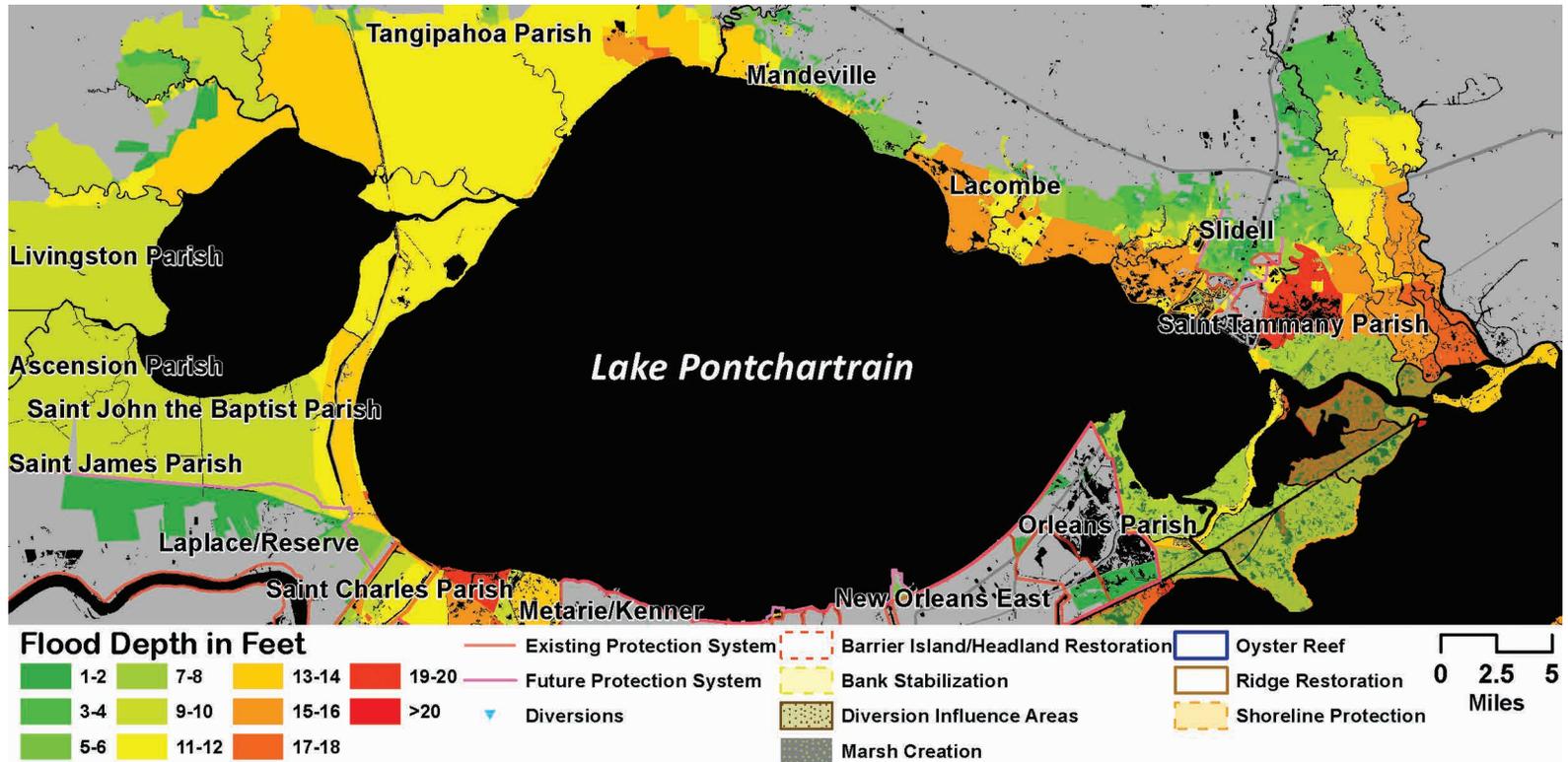
The reason for this disparity is that BFE is less than the mean block elevation in 40 percent of census blocks in the Mandeville community, and 63 percent are less than 1 foot above the mean block elevation. As a result, only a small number of structures are elevated when a BFE+1 standard is applied; for those that do undergo mitigation, protection is provided for only a small amount of additional elevation, so the impact on EAD is correspondingly small. The results for Mandeville highlight that additional analysis is needed to consider a broader range of options for some communities where risk remains relatively high with the Master Plan in place.

The broader range of options could include additional nonstructural options or, in some cases, could include structural protection alignments previously omitted from the 2012 Coastal Master Plan. For Mandeville and other north shore communities, for example, CPRA could reconsider a barrier across the mouth of Lake Pontchartrain as a possible structural project, assuming that other important planning considerations (e.g., surge effects on neighboring Mississippi, effects on the Lake Pontchartrain ecosystem) could be better addressed through a detailed follow-on analysis.

Summary

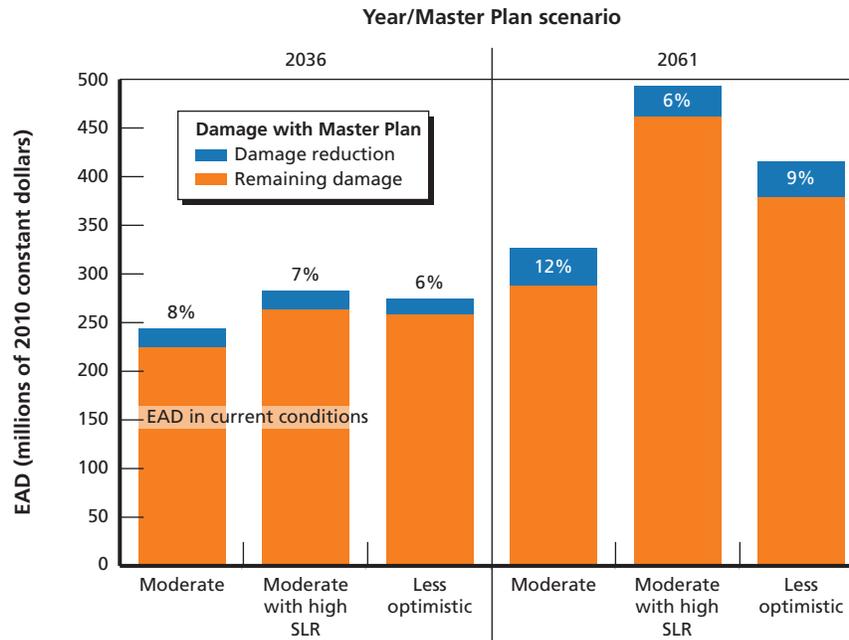
Risk and damage results from the final Master Plan analysis show that storm surge flood damage represents a major threat to coastal Louisiana and, if no action is taken, is expected to grow substantially in the future as coastal conditions worsen. Flood depth and damage outcomes both worsen over time in the FWOA, with the amount of increased flood damage varying substantially by Master Plan scenario and with the assumed structural reliability of the

Figure 10.17
Estimated Flood Depth at the 100-Year Flood Exceedance, in 2061 with the Master Plan in Place for Mandeville and Surrounding Lake Pontchartrain Communities (Less Optimistic Scenario)



RAND TR1259-10.17

Figure 10.18
Estimated Remaining Expected Annual Damage and Expected Annual
Damage for Mandeville in 2061, by Master Plan Scenario



RAND TR1259-10.18

New Orleans HSDRRS in future years. In particular, considering the possibility that elements of the protection system might fail during extreme events dramatically increases damage estimates for New Orleans in some Master Plan scenarios, with the likelihood of failure increasing with higher SLR and land subsidence. Results produced in the CLARA analysis may overstate this damage due to simplifying assumptions, but results nevertheless indicate that considering system fragility is critical to understanding the potential benefits and trade-offs associated with future protection system investments.

According to this analysis, the 2012 Coastal Master Plan helps to reduce flood damage in many areas of the coast through a combination of structural and nonstructural risk reduction investments and a series of coastal restoration projects. Flood depth and damage reduction are notable across all three state-defined Master Plan scenarios. In 2061, EAD is projected to increase to between \$7 billion and \$21 billion in the FWOA, depending on the Master Plan scenario, for instance, but, with the Master Plan in place, this damage level is reduced to between \$3 billion and \$5 billion. This corresponds to a reduction of approximately 60 to 80 percent compared with the FWOA flood damage level.

Different story lines emerge from different areas of the coast. For instance, a large proportion of the coastwide damage reduction occurs in Greater New Orleans after 2032, and emerges from new investments that reduce the likelihood of the protection system being breached by waves or storm surges. The new Morganza to the Gulf surge barrier provides substantial flood depth reduction and consequent damage reduction in the vicinity of Houma and Terrebonne but also leads to induced flooding in the Larose to Golden Meadow enclosed protection system. Finally, some areas receiving nonstructural investments in the Master Plan, such as the community of Mandeville on the north shore of Lake Pontchartrain, see very lim-

ited flood damage reduction from the Master Plan due to the limited range of nonstructural projects considered in this analysis. For these areas, a wider range of options may need to be considered to reduce vulnerability to damage from future storm surge events.

Conclusion

CLARA was designed to support the flexible exploration of a large set of risk reduction projects for coastal Louisiana across a range of scenarios representing uncertainty about future coastal conditions. Achieving this flexibility required some trade-offs with regard to model complexity and the size of data inputs. Its development and use as part of the Master Plan process illustrated the relative importance of different dimensions of uncertainty, produced new methods for estimating interior flood exceedances, and prompted many new questions for further inquiry. This chapter highlights some of the key insights drawn from CLARA, next steps for future research, and remaining challenges to be resolved.

Insights from the Master Plan Analysis

As detailed in the summary at the end of the previous section, Louisiana faces a growing threat from increased future flood risk, but the 2012 Master Plan takes an important step toward protecting the state's vibrant cultural history and economic livelihood for years to come. CLARA establishes the capability to perform comparative evaluations of many options to reduce flood risk in a rigorous manner over a wide range of potential futures.

Across all Master Plan scenarios, the projects implemented over the next 50 years are projected to reduce EAD by 60 to 80 percent compared with the FWOA case. Upgrades to existing systems, such as the Greater New Orleans HSDRRS, are responsible for much of this benefit, but large new projects also extend surge reductions to areas that, like Houma, have heretofore been unprotected.

Previous studies have considered system fragility (IPET) and uncertain future scenarios (LACPR); CLARA incorporates both to present a thorough analysis of future risk. The differences in SLR, subsidence, and storm characteristics between the moderate and less optimistic scenarios create greater contrast in future flood depths when fragility is considered than when protection systems are assumed not to fail. This contrast illustrates the importance of characterizing uncertainty in both threat and vulnerability.

As part of the Master Plan development, CLARA provided estimates of benefits from nonstructural projects that reduce vulnerability without affecting the threat of future flooding. Basing nonstructural mitigation standards on existing base flood elevations gave the Planning Tool data to approximate the relative value of nonstructural and structural projects, but opportunity exists to implement nonstructural measures more efficiently than how they were modeled. This can further enhance risk reduction in unprotected areas, such as Mandeville.

Improvements to CLARA

CLARA was developed to provide analytic results for the Master Plan on a rapid time line. As such, the model makes a number of simplifying assumptions that limit the strength of any conclusions drawn from its results. Primary among these limits is the lack of statistical confidence intervals around flood or damage exceedance estimates. Confidence in the relative performance of candidate protection projects is derived from identifying general trends across the many scenarios analyzed. Ultimately, the large number of uncertainties introduced at each step of the model suggests a more thorough sensitivity analysis than was possible in development of the Master Plan. CLARA's complexity makes it difficult to identify which data and parameter values drive uncertainty in the results; further, the limited sample of historical storms and limited resources for data collection result in data quality issues where systematic bias or confidence intervals on model parameters may be difficult or impossible to estimate.

In particular, the process of selecting the CPRA storm set, along with the comparative analysis of 40 storms versus 154 storms, presents a number of questions for future investigation. In comparing the performance of many different subsets of the original LACPR storm set, we identified a general trade-off between bias and the number of storms in a subset. However, it was not always apparent why some subsets performed better than others with the same number of storms or why some geographic points were generally more biased than other points along the coast. Better identification of the sources of bias could lead to improved storm selection in future studies or allow for credible bias correction. A useful related study would involve a more detailed analysis of JPM-OS and other methods for estimating flood exceedances that might produce a better understanding of the value of developing completely new storm sets for estimating the risk to coastal Louisiana from catastrophic storms.

In addition, CLARA's handling of system fragility was designed to bracket possible behavior by examining two extreme cases: one in which protection systems never fail (as assumed by LACPR) and one in which breaches result in interior inundation up to the level of surge that initiated the breach. As discussed previously, this likely overstates interior flood depths in the With Fragility case, which in turn likely overestimates the benefit of nonstructural risk reduction measures in protected areas. The existing fragility assumptions were sufficient for a comparative planning study, such as the Master Plan, but development of a more realistic breaching model is essential to producing more-accurate cost-benefit analysis for the final plan. This will also enable better evaluations of options for implementation of nonstructural mitigation strategies. The system fragility module in CLARA should also be expanded to estimate failures and potential breach flooding for unenclosed levee alignments, such as the Morganza to the Gulf alignment.

Many decisions made regarding model structure and data sources were guided by time constraints, and the current version of the model includes some simplifications and assumptions that could be improved on in subsequent development cycles. Fortunately, by dividing the model into a series of independently developed modules and a separate supportive database, the Risk and Damage Team deliberately structured CLARA so that iterative improvements could be made while retaining the basic functionality of the model. Below are examples of potential improvements and extensions that could be made to CLARA to better support future coastal planning. Some are intended to address the limitations discussed previously in this document; others are general improvements.

Overall Model Changes

Improvements to Existing Functionality

- Increase the number of storms used in the modified JPM-OS methodology to improve estimates of surge and wave characteristics.
- Create a better-structured code base and general functions to more easily port the model functionality to other geographic locations.
- Include additional exceedances, and use them to estimate the level of protection afforded to a given protected area (i.e., “350-year protection”).
- Expand the geographic scope of the model to consider additional census blocks to the north of the current study boundary.
- Expand the geographic scope of the model to consider induced flooding effects from selected protection projects in coastal Mississippi.

New Extensions

- Develop a parametric uncertainty methodology to estimate flood depth and damage confidence intervals for each scenario.
- Compare data sources, assumptions, and methods applied to estimate storm surge flood depth and damage in coastal Louisiana in recent studies, identify strengths and weaknesses of different approaches, and modify CLARA where improvements are indicated.

Flood Depth Module

Improvements to Existing Functionality

- Add scenarios to better represent uncertainty surrounding the probability of failure from overtopping.

New Extensions

- Improve assumptions about the consequences of system failures by incorporating breach volumes rather than assuming that flooding reaches the elevation of peak surge at the point of failure.
- Consider additional modes of structure failure (e.g., erosion of the protected side due to wave overtopping).
- Improve treatment of levee run-around and include wave overtopping estimates for semi-protected areas (e.g., Morganza to the Gulf).
- Consider the additional risk introduced by operational failures (e.g., not all gates closed during a storm).
- Improve the fragility methodology to incorporate estimates of local effects of failure in semiprotected areas (e.g., Morganza to the Gulf).
- Add functionality for the flooding results from a structure failure that leads either to a surge elevation below the peak surge height or to a discrete volume of water entering through the breach. These additional cases could then be incorporated into the scenario analysis.
- Augment or replace the interior drainage module to represent flows of water in the system over time.

Economic Module

Improvements to Existing Functionality

- Include additional asset classes to address damage to critical infrastructure and strategic assets.
- To improve damage estimates, incorporate additional 2010 census data (e.g., median household income).

New Extensions

- Consider the impact of damage from other sources, such as surge velocity and wind, following FEMA methodologies used in the FEMA Hazus-MH MR4 model.
- Augment FEMA Hazus-MH asset valuation methodology with local data on asset values (e.g., from real estate sales data).
- Add a module to consider the effects of flooding on human health and safety.
- Add a module to consider the secondary economic effects of flooding on regional or national economic output, employment, or other aggregate changes.

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