**Model Name:** Coastal Louisiana Risk Assessment (CLARA) Model

**Functional Area:** Storm Damage and Risk Assessment

**Model Proponents:** Coastal Protection and Restoration Authority of Louisiana (CPRA)

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## Abbreviations

| | |
|---|---|
| ACS | American Community Survey |
| 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 |
| 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 |
| JPM-OS | Joint Probability Method with Optimal Sampling |
| LACPR | Louisiana Coastal Protection and Restoration |
| LA DOTD | Louisiana Department of Transportation and Development |
| 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 |

| | |
|---|---|
| QR | quality review |
| RGSPI | RAND Gulf States Policy Institute |
| RMSE | root mean squared error |
| RSLR | relative sea-level rise |
| SWP | surge and wave point |
| TRMM | Tropical Rainfall Measuring Mission |
| USACE | U.S. Army Corps of Engineers |
| USGS | U.S. Geological Survey |

## Section 1: Background

### a. Purpose of Model

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 has responded to the threat of catastrophic hurricanes by engaging in a new planning process to support the development of Louisiana's *2012 Coastal Master Plan.* The master plan proposes a range of coastal restoration and structural protection projects to reduce storm surge flood risks to coastal communities and to 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 group of modeling teams to provide analytical support and help improve its 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 (RGSPI) to develop a hurricane flood risk model to assess how proposed restoration and protection projects reduce damage in the next 50 years. In response, our team developed the Coastal Louisiana Risk Assessment (CLARA) model to systematically evaluate proposed flood risk reduction projects on the basis of how well they reduce damage in Louisiana's coastal region.

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 protective 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.

This document is a technical appendix that describes how CLARA works. 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. The modeling approach we describe draws heavily from previous analytical efforts, including the *Louisiana Coastal Protection and Restoration (LACPR) Final Report* (U.S. Army Corps of Engineers [USACE], 2009a), *Interagency Performance Evaluation Team (IPET) Engineering and Operational Risk and Reliability Analysis* (USACE, 2009b), the Federal Emergency Management Agency (FEMA) Hazus® MH MR4 model (FEMA, 2009), and ongoing RAND research funded by the National Oceanic and Atmospheric Administration (NOAA) (Fischbach, 2010).[1]

[1] NOAA Award NA09OAR4310157.

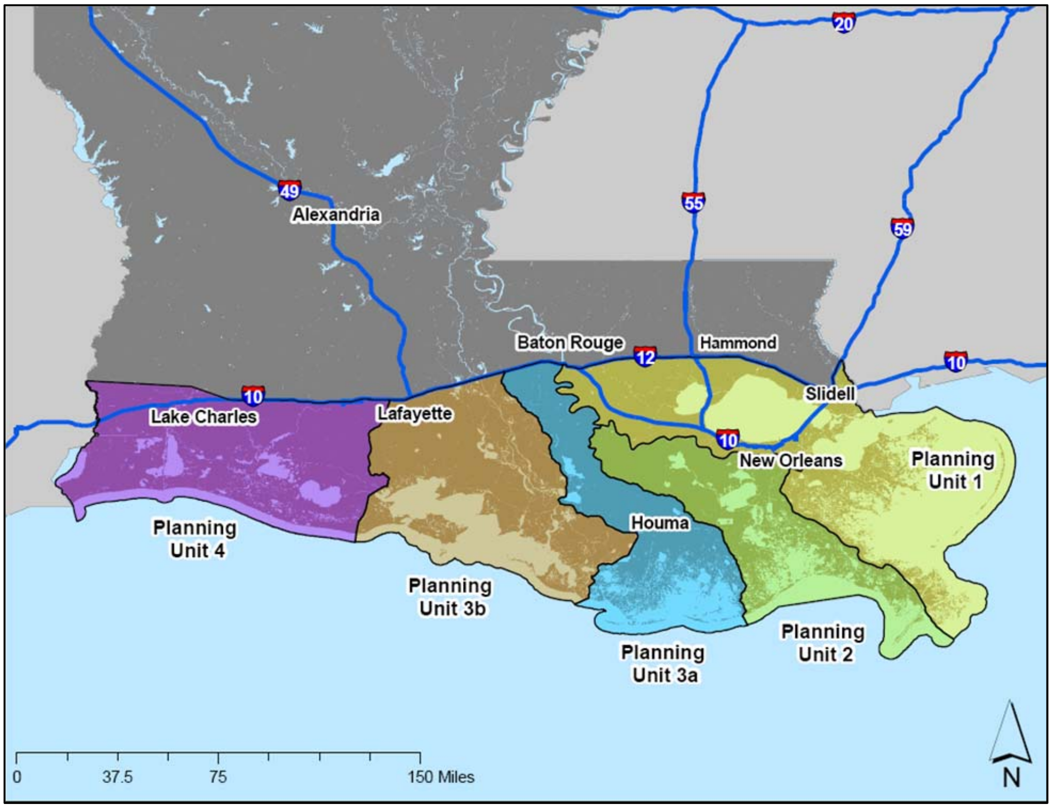
CLARA is only one piece of the broader analytical effort that supports the development of the master plan, and the model uses inputs from several CPRA modeling teams. CLARA in itself is not a decision support tool, but provides inputs to the broader process of updating the master plan. The Storm Surge/Wave modeling team, led by Arcadis, provides 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 provides 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, have been provided to RAND by CPRA, the USACE, and other CPRA modeling teams.

For more information on how the models work together to project future coastal conditions and estimate project performance, please see the main text of Appendix D of the 2012 Coastal Master Plan. In addition, outputs from this model feed into a separate quantitative tool, called the Planning Tool, which uses the information to assess the overall benefits and costs of proposed protection and restoration projects and provides project rankings across different objectives. Outputs from CLARA to the Planning Tool are noted in the remainder of this appendix. For more information on the Planning Tool, please see Appendix E of the 2012 Coastal Master Plan.

## b. Model Description and Depiction

### *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 Louisiana Coastal Protection and Restoration (LACPR) analysis, which divided the coast into a series of five Planning Units (Figure 1) and approximately 1,000 Planning Subunits (USACE, 2009a). LACPR developed the northern extent of this study area using its estimate of the 1,000-year surge flooding extent.




SOURCE: USACE, 2009a.

**Figure 1: Louisiana Coastal Protection and Restoration Planning Units and Study Area Extent**

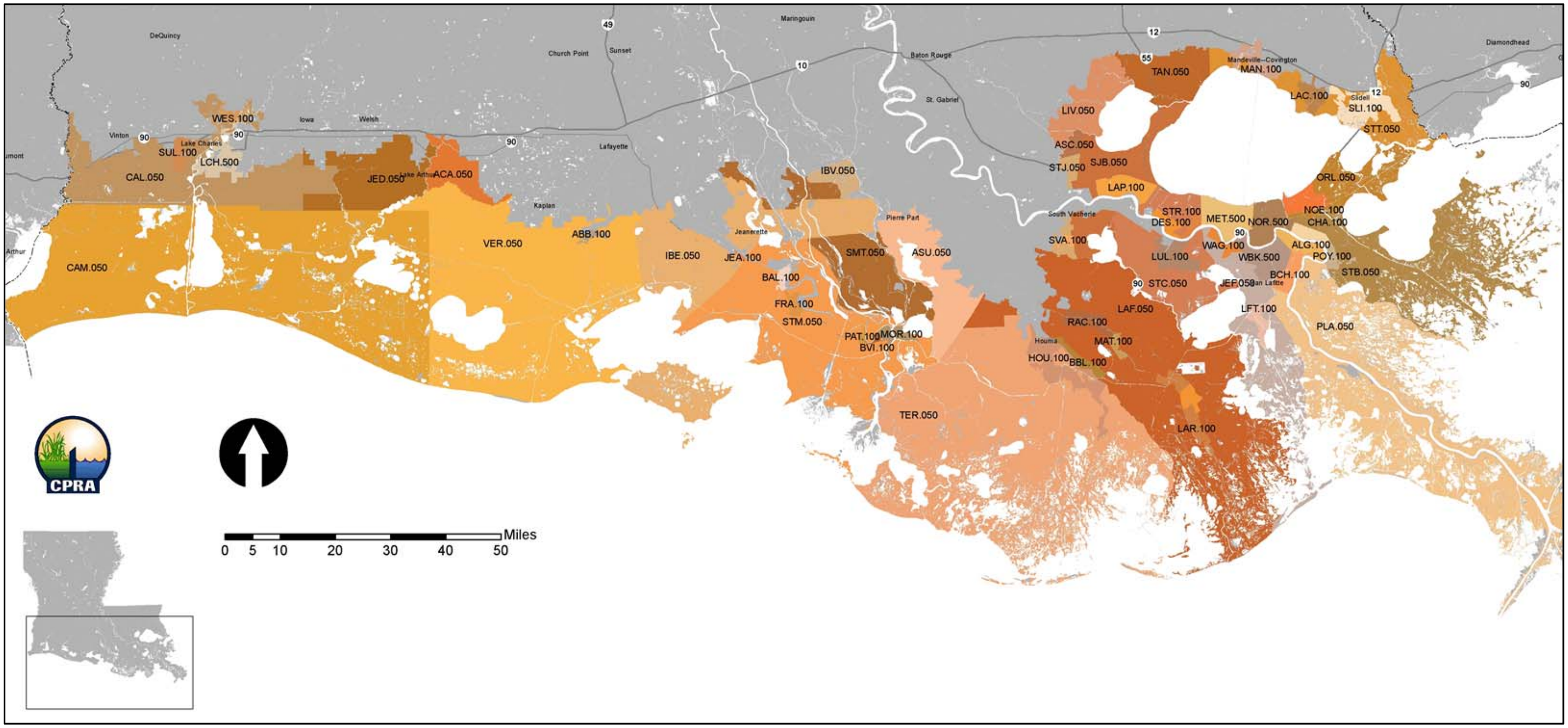
CLARA adopts the LACPR Planning Subunits as the basic spatial unit of analysis to determine flood elevations in protected areas. Hereafter, these subunits are referred to as basic hydrologic units (BHUs). CLARA labels each BHU as one of three types of areas: unprotected, semiprotected, and protected (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 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.[2] Flood

[2] 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 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.

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). Damage at the target-community level are reported to the Planning Tool for use in comparing the effects of different structural and nonstructural risk reduction projects.




SOURCE: CPRA. Colored areas on the map represent different target communities specified by CPRA.

**Figure 2: Coastal Protection and Restoration Authority of Louisiana Target Communities**

### *Risk and Damage Metrics*

The CLARA model 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 once 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 storm surge flooding events of all sizes in each year. 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 2060), as requested by CPRA.

These damage results are summed for each coastal community—as defined by CPRA—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 has identified a target level of risk reduction for each coastal community that corresponds to the 50-, 100-, or 500-year flood 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 depth 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 2012 Coastal Master Plan.

### *Treatment of Uncertainty*

The Planning Tool is designed to incorporate the substantial uncertainty that complicates planning for coastal restoration and protection into the process for developing the 2012 Coastal 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 2012 Coastal Master Plan, CLARA has been 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 an 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 and 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.

### *Coastal Louisiana Risk Assessment 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 section. These steps are split across three primary model components:

- The preprocessing module parses certain data inputs for later use and generates flood exceedances in unprotected and semiprotected areas. Steps 1–4 are calculated in the 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 the next section, is calculated in the economic module.

Figure 3 illustrates the basic structure of the model, flow of calculations, and primary submodules. Following the figure are the steps taken in making the calculation.

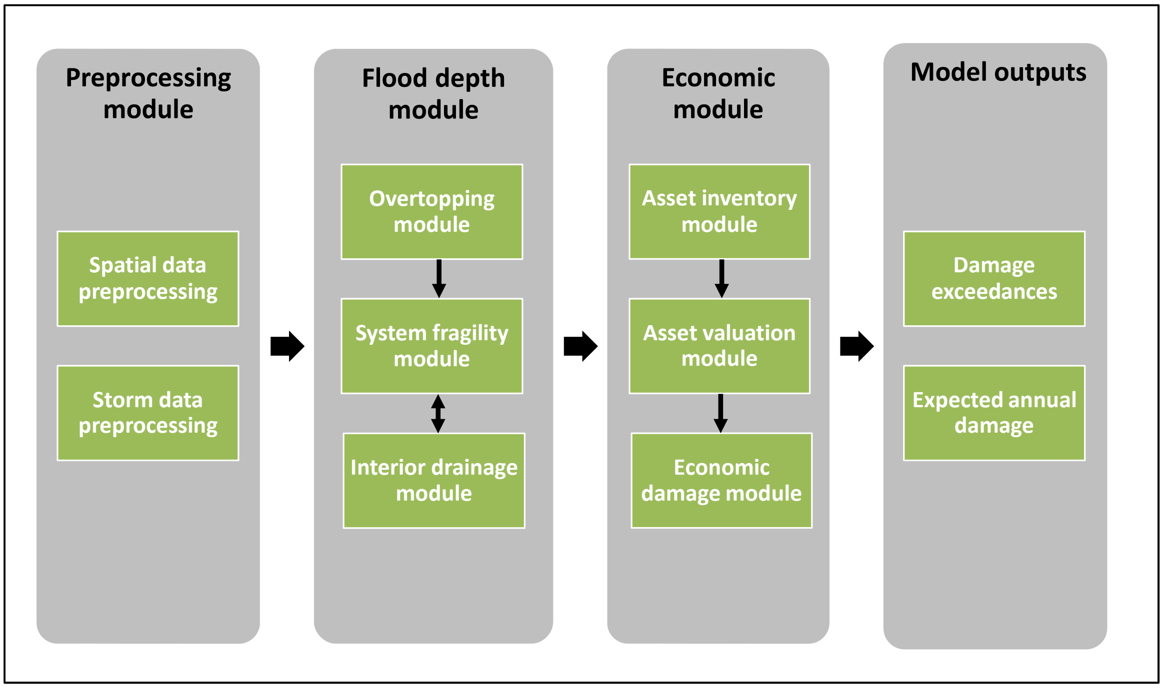



**Figure 3: Coastal Louisiana Risk Assessment Model Structure and Primary Submodules**

*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 point sets 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.

*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 floodwall protection. Using a modified version of the Joint Probability Method with Optimal Sampling statistics approach (JPM-OS; see "Storm Data Preprocessing" in Section 2) applied by the USACE (USACE, 2009b), CLARA then estimates a cumulative distribution function for surge and wave elevations in each block and 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 semiprotected areas are calculated as part of the storm data preprocessing because they do not need to run through the flood depth module because 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, and 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 Interagency Performance Evaluation Task Force (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.[3]

- 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 due to 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.

[3] 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 on 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.

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 armoring, 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 is used to translate a two-dimensional estimate of fragility to a three-dimensional estimate; the geotechnical characteristics are parameters used to estimate the factor of safety that underlies the estimation of slope stability and seepage failures.

The dominant failure mode in our analysis is overtopping. 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 in between them. The minimum connecting elevation is known as the *interflow elevation*. These interflows and 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 modeling 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 employ 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 damage that results.

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).[4] Damage depends on the inventory of assets in each block. This inventory includes homes

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

and dwellings; commercial, industrial, and public-sector properties; and roads, highways, and agricultural buildings and crops. Inventories in 2011 are 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 2060 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.

**c. Contribution to Planning Effort**

The risk assessment model described here is an input to the Planning Tool that CPRA uses to assist in the development of the 2012 Coastal Master Plan 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.
- Accommodate alternative risk reduction measures that may be considered as part of 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 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, the CLARA model 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.

**d. Description of Input Data**

Inputs to the flooding and risk assessment model 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 1 and 2.

**Table 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. | |

**Table 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, 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 | LACPR, Hazus |

| Subset | Data Element | Asset Class | Source (in order of precedence) |
|---|---|---|---|
| | | classes | |
| Valuation | Structural characteristics for each asset class | All structural classes | Hazus |
| | Replacement cost per square foot | All structural classes | Hazus |
| | Proportion of structures by construction class (economy, average, custom, luxury) | All residential classes | Hazus |
| | CSVR | All structural classes | LACPR |
| | Value of inventory per square foot | Commercial, industrial | Hazus |
| | Repair costs per mile | Infrastructure | LACPR, Hazus |
| | Agriculture valuations | Agricultural crops | LACPR |
| | Proportion of structures by construction method (e.g., wood frame, masonry) | All structural classes | Hazus |
| | Flood elevations | N/A | Calculated by model |
| Damage | Structural elevation above grade | All structural classes | LACPR, Road Home, HMGP |
| | Depth-restoration time curve | All structural classes | Hazus |
| | Depth-damage curves for structure | All structural classes, infrastructure | Hazus |
| | Depth-damage curves for contents | All structural classes | Hazus |
| | Depth-damage curves for inventory | Commercial, Industrial | Hazus |
| | Costs dependent on displacement time: lost income, lost wages, lost sales, disruption costs, relocation rental costs | All structural classes | LACPR, Hazus |
| | Costs dependent on displacement time: | All residential classes | LACPR |

| Subset | Data Element | Asset Class | Source (in order of precedence) |
|---|---|---|---|
| | evacuation and subsistence costs | | |
| | Post-flood response costs: landscaping repair, debris removal, other cleanup | All structural classes | LACPR |

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

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

### e. 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 4, and a screenshot showing example damage output data by community is shown in Figure 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.

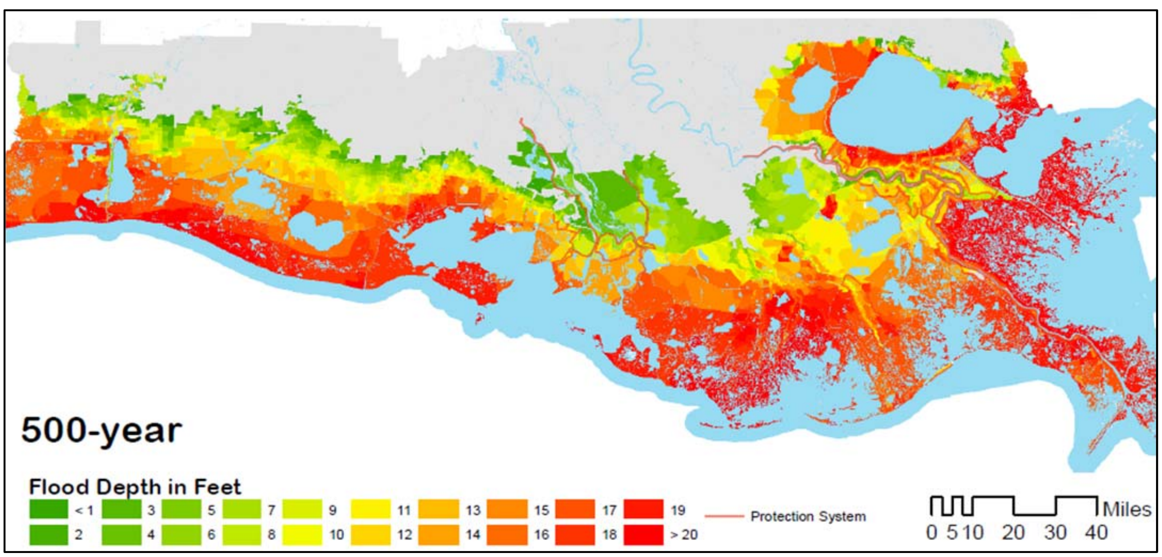



**Figure 4: Example Flood Depth Map (500-year flood depth exceedance)**

| | A | B | C | D | E |
|---|---|---|---|---|---|
| 1 | Community_ids | 50yr | 100yr | 500yr | EAD |
| 2 | ABB.100 | 1.05E+08 | 6.46E+08 | 2.98E+09 | 17679309 |
| 3 | ACA.050 | 447087.2 | 53853983 | 2.37E+08 | 1371591 |
| 4 | ALG.100 | 0 | 0 | 0 | 10038012 |
| 5 | ASC.050 | 873086.8 | 873086.8 | 873086.8 | 45800.04 |
| 6 | ASU.050 | 1.04E+09 | 1.52E+09 | 2.44E+09 | 35242395 |
| 7 | BAL.100 | 33607284 | 69093028 | 2.08E+08 | 1691730 |
| 8 | BBL.100 | 1.33E+09 | 1.79E+09 | 2.1E+09 | 45967154 |
| 9 | BCH.100 | 1330606 | 1760569 | 2028339 | 2562642 |
| 10 | BVI.100 | 0 | 0 | 0 | 3716751 |
| 11 | CAL.050 | 2.41E+08 | 1.36E+09 | 7.43E+09 | 47440657 |
| 12 | CAM.050 | 2.51E+09 | 3.64E+09 | 6.65E+09 | 1.08E+08 |
| 13 | CHA.100 | 556.8529 | 556.8529 | 1.98E+10 | 48947505 |
| 14 | DES.100 | 0 | 0 | 8.92E+09 | 45389043 |
| 15 | FRA.100 | 79834561 | 7.65E+08 | 2.6E+09 | 18237875 |
| 16 | HOU.100 | 2.04E+10 | 3.06E+10 | 4.6E+10 | 7.42E+08 |
| 17 | IBE.050 | 2.51E+09 | 4.65E+09 | 8.87E+09 | 99419731 |
| 18 | IBV.050 | 0 | 0 | 0 | 0 |
| 19 | JEA.100 | 0 | 0 | 0 | 2509.164 |
| 20 | JED.050 | 12681131 | 1.16E+08 | 1.26E+09 | 6294960 |
| 21 | JEF.050 | 1.8E+09 | 2.26E+09 | 2.57E+09 | 73327550 |

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

**Figure 5: Example Damage Results by Coastal Protection and Restoration Authority of Louisiana Target Community**

## Section 2: Technical Quality

### a. Theory

The CLARA model 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, $\Pr(storm)$ (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 JPM-OS methodology. Detailed methods are described in “Storm Data Preprocessing” later in this section.
- *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 $\Pr(flood \mid storm)$. 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 due to the complexity of engineered systems and 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 “Flood depth module” later in this section. Unprotected or semiprotected areas are addressed separately with simplifying assumptions; see “Storm Data Preprocessing” later in this section.
- *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 $E(damage \mid flood)$. 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 LACPR models and are described in detail in “Economic Module” later in this section.

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

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

or

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

Note that these equations describe the flood risk for a particular storm event. 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 the next section, "Analytical Requirements."

## b. Analytical Requirements

### *Software and Hardware Configuration*

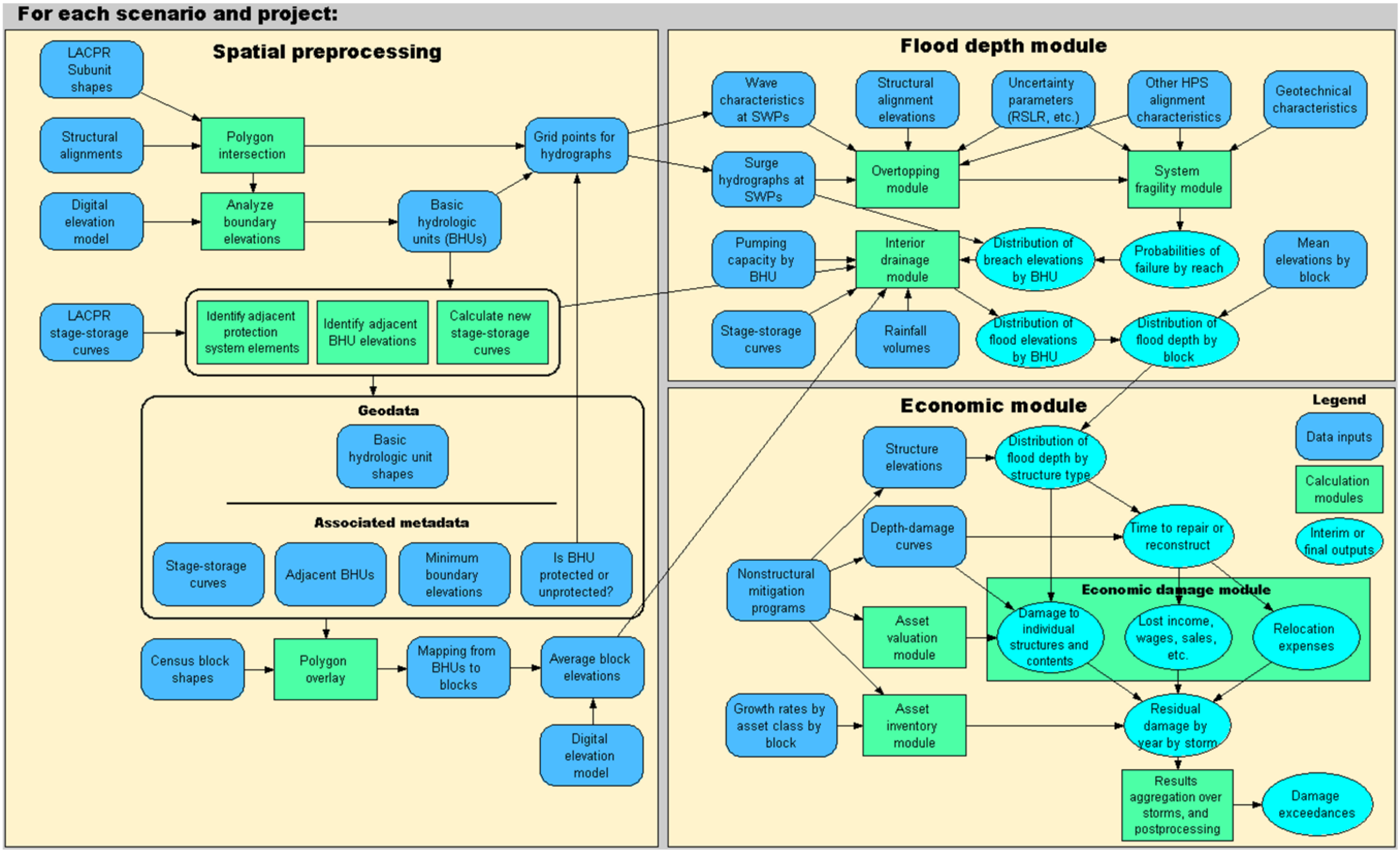
The CLARA model consists of several interdependent modules that exchange data and intermediate calculations through a central database. Splitting model development into independent subtasks simplifies development and quality assurance, while the central database allows for changes and updates to data sets. When possible, spatial data are preprocessed and stored in the database to reduce model run time, thus enabling rapid comparison of alternative measures. This is done to reduce computational demand during run time and to integrate observed data from real flood events when available.

The model is divided into three primary components: the central database, in which preprocessing occurs; the flood depth module; and the economic module. A more detailed view of the logical flow of model calculations is shown in Figure 6. The modular approach to model development also facilitates the use and integration of several software packages.

The data structures used by the risk assessment model are designed to facilitate communication among the modules, as well as with the CPRA Planning Tool. The primary components are a geodatabase of shapes for each geographic unit of analysis (i.e., hydrologic subunits and census blocks) and structural alignments, with layers for characteristics, such as crown or top-of-wall elevation, geotechnical characteristics (i.e., the type of soil, the presence of armoring and design characteristics), and floodwall heights. This is paired with a relational database that houses the economic data needed to translate the calculated flood elevations into estimates of economic damage. Individual data inputs and outputs are described in further detail in subsequent sections.

### *Hydrologic and Economic Spatial Definitions*

The hydrologic spatial units of analysis begin with the Planning Subunits defined in the LACPR analysis (USACE, 2009a), which were chosen to represent hydrologically distinct areas with boundaries made up largely of natural or built elevation features. As necessary, we subdivide these units when proposed structural alignments intersect existing units. Throughout this document, we refer to these units as BHUs. Average elevations and stage-storage curves (the relationship between water volumes and flood elevations) of subdivided subbasins are recalculated for the partitioned basins during the data preprocessing by referencing a high-resolution DEM.




NOTE: SWP = surge and wave point. RSLR = relative sea-level rise. HPS = hurricane protection system.

**Figure 6: Outline of Risk Assessment Model Logic**

Census blocks are the base spatial units of economic analysis. When a census block is subdivided by a new project, we assume that economic assets in that census block are located entirely within the newly protected area. Results of the model are reported at the census-block level and include mappings that allow easy aggregation to the BHU, parish, CPRA target community, or Planning Unit level.

***Spatial Data Preprocessing***

The supporting data for the flood elevations portion of the model is composed of data sets describing the coastal protection system assumed to be in place at the beginning of the period of analysis. These data are referred to as the *future without action*, or FWOA. We assume they remain unchanged into the future. The supporting data also include information describing individual protection projects to be evaluated in this analysis. These data are provided by the State of Louisiana and USACE and are discussed in detail in the next section.

Before the data can be used in the flood depth module, a set of preprocessing steps is required to develop the appropriate inputs. These preprocessing steps are performed on both the FWOA and “with-project” coastal conditions and can be summarized as follows.

*Polygon Manipulation Within the System*

These steps include subdividing Planning Subunits into separate BHUs in cases in which new structural protection elements cut through them, assigning census blocks to interior BHUs in cases in which a census block might be split, calculating new stage-storage curves for interior BHUs, and determining minimum connecting elevations between BHUs for the interior drainage module.

In areas protected by an existing HPS, BHU boundaries were originally chosen to divide the region into hydrologically distinct polders separated by built or natural elevation features. Some potential future protection projects split the LACPR subunits into pieces. In this case, CLARA defines new BHUs by assembling the census blocks on the protected and unprotected sides of the project. Best judgment is used when deciding whether to include census blocks that are split in two by a proposed project, with a block typically being considered protected if a significant portion of its geography falls on the protected side. When this occurs, CLARA assumes that any economic assets in the block are located on the protected side.

*Defining Specific Levee and Floodwall Reaches and Individual Structures*

These steps are designed to identify individual segments of the system with common characteristics (e.g., elevation) that can be used as separate units of analysis for overtopping and fragility calculations. Steps include defining reach segments based on automated processing criteria (e.g., treating lengths on each side of a bend or corner as separate reaches), identifying a set of points 200 meters from the system center lines for sampling surge and wave characteristics, and locating system end points and the boundaries between unprotected, semiprotected, and protected areas.

Preprocessing is performed on the ArcGIS 10 platform. Specific tasks are scripted to allow for repetition when new projects are introduced.

### ***Storm Data Preprocessing***

*Statistical Methodology and Experimental Design of Storms*

The statistical methodology that produces estimates of damage at different flood depth 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 2012 Coastal 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 8 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 7 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. After reviewing this output with CPRA and the Storm Surge/Wave modeling team, we determined that the selected 40-storm subset would be sufficient for the initial protection project comparisons.

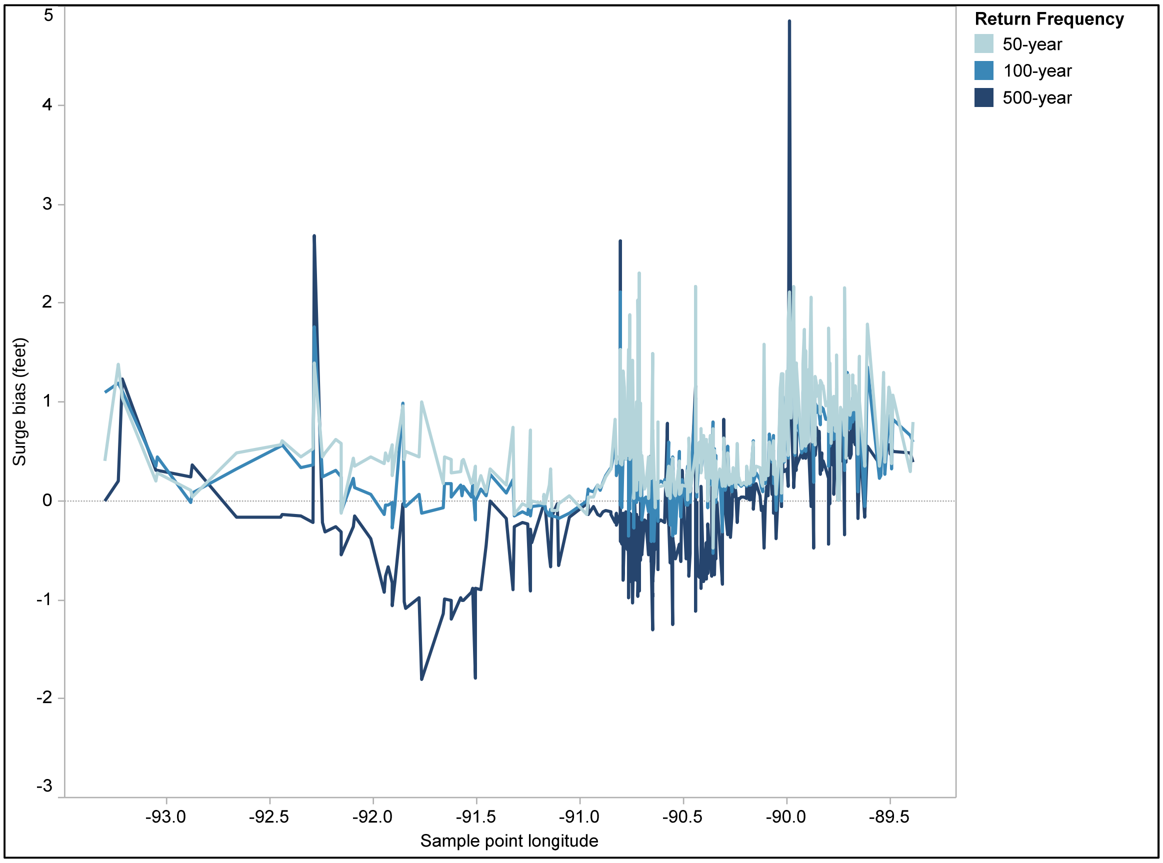



**Figure 7: Difference in Predicted Surge (Bias) Between 40-Storm and 154-Storm Sample at Louisiana Coastal Protection and Restoration Surge Sample Points**

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 radii to max 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 modeling team contains data on peak wave heights, 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 2012 Coastal Master Plan Appendix C). Scenario-dependent values for sea-level rise 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,[5] and then the significant wave height is converted to a free wave crest height by multiplying by a factor of 0.7 (FEMA, 2009). Because the free wave crest height is the height of the wave above the mean still-water level, it is the appropriate height to add to the still-water depth to calculate the total depth of inundation relevant for damage calculations.

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 are summarized in Figure 8.

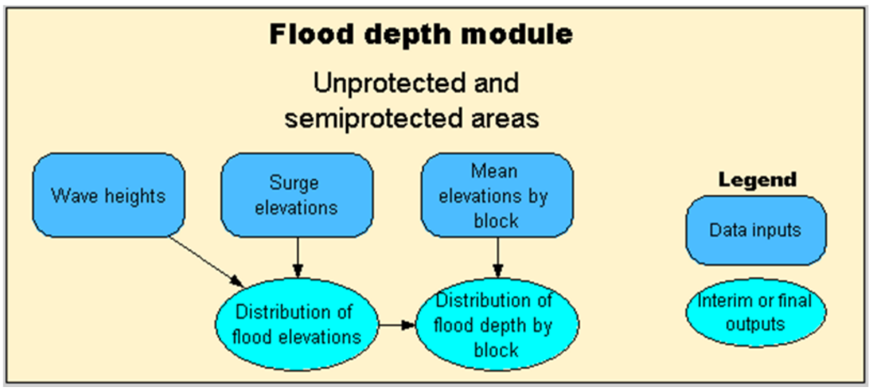



**Figure 8: Flood Depth Calculations in Unprotected and Semiprotected Areas**

*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 function 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

[5] Shan Zou, Arcadis, personal communication, June 9, 2011.

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, and 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 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 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 ($\sigma_l$) and the right-hand side where it falls ($\sigma_r$).

This yields values for $\sigma_l$ and $\sigma_r$ 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 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 consequences module via the central database.

A summary of the flood depth calculation steps is shown in Figure 9; each step is described in detail in the subsections that follow. In the figure, green rectangles represent major modeling modules, which are described in the next three subsections of this document, respectively; the blue, rounded-corner rectangles represent data inputs; and the teal ovals represent interim and final outputs.

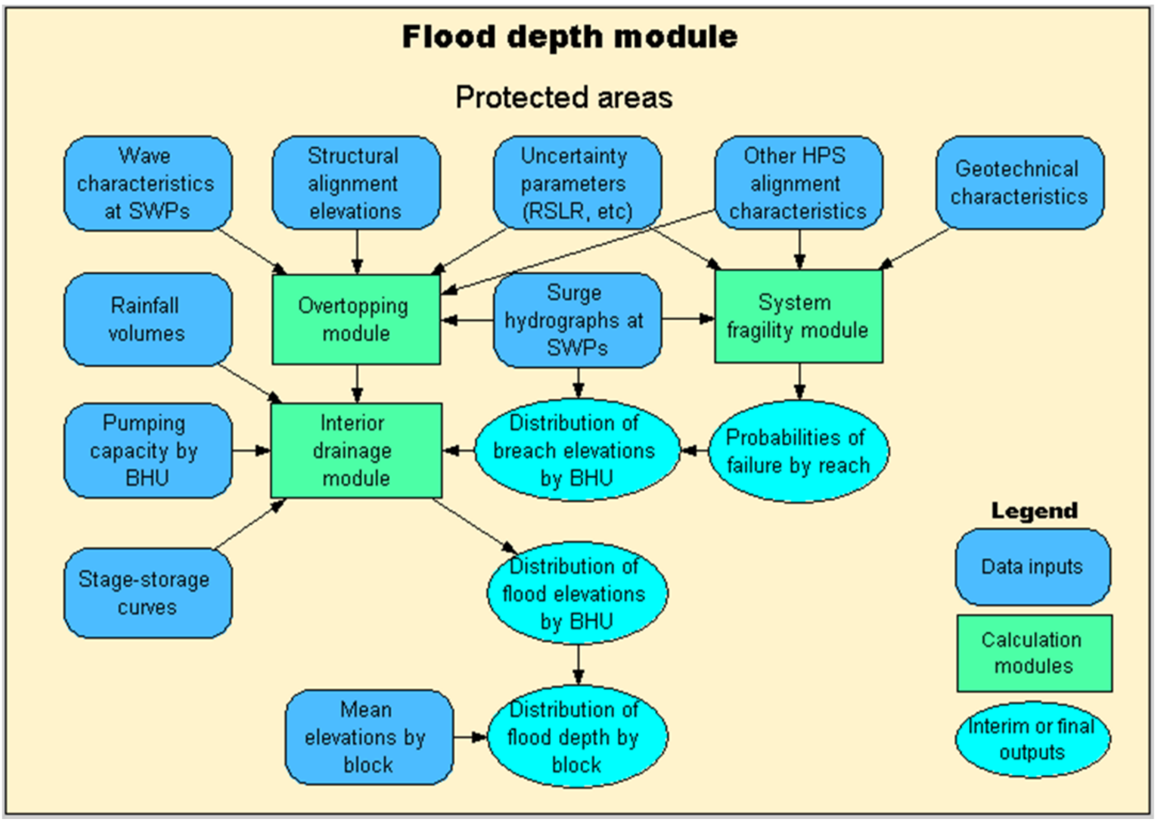



**Figure 9: Flood Depth Calculations in Protected Areas**

*Overtopping Module Calculations*

**Overview**

This section describes the calculations performed in the Overtopping module shown in Figure 9. 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 modeling 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 wave 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.[6] 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 semiprotected 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. For unprotected and semiprotected areas, only the peak surge elevations are used.

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.

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, undated), and then are adjusted based on the geometry of the structure, as explained later in this section. 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 3). 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.

[6] 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.

**Table 3: Data Used in the Overtopping Module**

| 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 | |

**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 section. We discuss pre-overtopping calculations, calculations for levees, and calculations for floodwalls.

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 ($H_s$):

$$H_s = \gamma(H_{200} - z_{\text{toe}}),$$

where

$H_s$ = significant wave height, adjusted for break, in meters

$\gamma$ = wave breaking parameter = 0.4 (default for Louisiana coast),

$H_{200}$ = significant wave height at 200 meters (660 feet), in meters

$z_{toe}$ = elevation of toe of structure (assumed to be 0), in meters.[7]

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

According to LACPR, $z_{toe}$ was assumed to be zero, so $\gamma$ acts as a scaling parameter on $H_{200}$.

To calculate wave overtopping for levees, one must first calculate the surf similarity parameter, $\xi_0$ (Meer, 2002). The surf similarity parameter is

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

where

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

and

- $s_0$ = wave steepness,
- $T_{m-1,0}$ = spectral wave period, in seconds
- g = gravitational acceleration = 9.81, in 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.

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 ($m^3/s/m$)
- g = gravitational acceleration = 9.81 ($m/s^2$)
- $H_s$ = significant wave height at toe of structure (m)
- $\xi_0$ = surf similarity parameter,
- $\tan\alpha$ = slope,
- $R_c$ = free crest height above still water level (m)
- $\gamma$ = influence parameters ([0,1], 0 = total influence, 1 = no influence)
- b = berm influence
- f = friction
- $\beta$ = 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 $\gamma_b$ 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 $\gamma_f$ 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 $\gamma_\beta$, which is the angle of wave attack with respect to the protection structure, essentially assuming a perpendicular angle of wave attack.

Finally, $\gamma_v$ 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 rate of overtopping estimated 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 $\xi_0$ 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 ($m^3$/s/m). 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 $\gamma_s$ is the influence parameter for floodwall geometry.

Here, we adopt the IPET (USACE, 2009b) assumption that $\gamma_s$ equals 1 (no influence) and that $\gamma_\beta$ 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 the protection structure crest acts as a rectangular weir, then the following defines the volume of water that flows over it:

$$Q = C_w L H^{3/2},$$

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:

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

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 above accounts for surge overtopping, and the right term accounts for wave overtopping.

*System Fragility Module Calculations*

**Overview**

This section describes the calculation steps in the System Fragility module shown in Figure 3. 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 full-scale quantitative model to capture the full range of failure mechanisms for hurricane protection structures, but, in reality, there are parameters for which empirical measurement would be difficult, if not impossible. 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 due to 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. Because failures are probabilistic events, we run our model 100 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 storm surge.

**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 a set of 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 the three dimensions to estimate the probability of failure for the actual reach. Each reach is divided into characteristic lengths, which are 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.

**Levee and Floodwall Failure Modes**

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 will likely underestimate 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.[8]

**Point Structure (Transitions and Gates) Failure Modes**

Some parts of the HPSs 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 Station Failure Modes**

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 through three scenarios: 100 percent of pumping capacity, 50 percent of pumping capacity, and no pumping. These are estimated by scenarios and are discussed later.

*Input Data*

In general, input data fall into one of three categories: characteristics of the HPS, geotechnical (i.e., soil and subsurface) characteristics, and uncertain scenario parameters. 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 elements of the protection system, where 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 this section. Table 4 lists the input parameters and source for each element, while Table 5 shows the default parameter assumptions used for different soil types.

[8] 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.

**Table 4: Input Parameters for System Fragility Module**

| Parameter | Unit | Failure Mode | Source |
|---|---|---|---|
| Geotechnical | | | |
| Substratum permeability, $k_f$ | cm/sec<br>ft./sec | Seepage | Technical Manual (TM) 3-424; D10 grain size from boring logs |
| Top blanket permeability, $k_b$ | cm/sec<br>ft./sec | 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, $\phi_{emb}$ | degree | Slope stability | Boring logs, penetration test correlations |
| Unit weight of soil, $\gamma$ | $kg/m^3$<br>$lb./ft^3$ | 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, $\phi_{found}$ | 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 |

[1] See California Department of Transportation, 2000.

**Table 5: 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/sec) | Permeability SD |
|---|---|---|---|---|---|---|---|---|---|
| GW | Well-graded gravel, fine to coarse gravel | 140.50 | 21.92 | 0 | 0 | 40.00 | 4.00 | 2.78E-01 | 4.84E-01 |
| GP | Poorly graded gravel | 133.00 | 25.46 | 0 | 0 | 37.50 | 3.75 | 3.70E+01 | 5.47E+01 |
| GM | Silty gravel | 122.50 | 45.96 | — | — | 42.50 | 4.25 | 2.78E-01 | 4.84E-01 |
| GC | Clayey gravel | 133.00 | 25.46 | — | — | 32.50 | 3.25 | 2.78E-01 | 4.84E-01 |
| SW | Well-graded sand, fine to coarse sand | 117.00 | 43.84 | — | — | 35.00 | 3.50 | 2.22E-04 | 4.37E-04 |
| SP | Poorly graded sand | 110.00 | 36.77 | — | — | 27.50 | 2.75 | 2.22E-04 | 4.37E-04 |
| SM | Silty sand | 115.00 | 38.18 | 1,050 | 315 | 32.50 | 3.25 | 2.22E-04 | 4.37E-04 |
| SC | Clayey sand | 123.50 | 33.23 | 1,050 | 315 | 7.50 | 0.75 | 2.22E-04 | 4.37E-04 |
| ML | Silt | 108.50 | 38.89 | 1,350 | 405 | 32.50 | 3.25 | 2.22E-04 | 4.37E-04 |
| CL | Clay | 113.50 | 27.58 | 1,800 | 540 | 7.50 | 0.75 | 2.78E-09 | 4.84E-09 |
| OL | Organic silt, organic clay | 109.00 | 31.11 | 800 | 240 | 7.50 | 0.75 | 2.78E-05 | 4.84E-05 |
| MH | Silt of high plasticity, elastic silt | 108.50 | 38.89 | 1,500 | 450 | 7.50 | 0.75 | 2.22E-04 | 4.37E-04 |
| CH | Clay of high plasticity, fat clay | 99.50 | 40.31 | 2,150 | 645 | 7.50 | 0.75 | 2.78E-05 | 4.84E-05 |
| OH | Organic clay, organic silt | 103.00 | 31.11 | — | — | 7.50 | 0.75 | 2.78E-05 | 4.84E-05 |
| Pt | Peat | 97.50 | 38.89 | — | — | 5.00 | 0.50 | 3.70E-03 | 5.47E-03 |

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

*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 summarize them in more detail below:

1. Solve for the exit gradient[9] using methods from 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.
5. 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 expected values for all parameters calculate the effective exit distance $x_3$, where

$$x_3 = \sqrt{k_f / k_b \, zd}.$$

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.

[9] 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.

Finally, the landside toe exit gradient, *i*, is calculated as $i = h_0/z$.

Step 2: Repeat calculation of exit gradient for each combination of input parameters in 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 $var(i)$. 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 $(\ln i > 0)$.

Finally, using the cumulative normal distribution function, we calculate

$$p_s(h) = 1 - \mathrm{F}_{\text{normal}}\left(\frac{\ln i_{\text{crit}} - E[\ln i]}{\sigma_{\ln i}}\right),$$

where $\mathrm{F}_{\text{normal}}$ is the cumulative normal distribution function and E [.] is the expected value function.

**Slope Stability**

Slope stability is compromised when the forces exerted by the floodwater elevation are greater than what 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 sufficient 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.[10]

[10] *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.

The FOS represents the multiple of 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, which are similar to the steps for calculating the probability of a seepage failure:

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 and 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 4 and 5.

#### 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 6 lists the probabilities of failure for overtopping, $p_{OT}$.

**Table 6: Empirical Probability of Failure Due to Overtopping**

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

*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 following failure modes are independent and uncorrelated: seepage, slope stability, and overtopping. Correlations between 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 land-side 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:

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

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 section 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 that for the highest surge height during the storm. IPET makes the same simplifying assumption (USACE, 2009b).

*Interior Drainage Module Calculations*

**Overview**

This section describes the calculation steps for the Interior Drainage Module shown in Figure 6. 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 risk model. These data are summarized in Table 7; where necessary, we discuss them in greater detail in the algorithm and uncertainty sections.

**Table 7: 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 | Provided as pump locations and | Sewerage and Water Board |

| Data Name | Description | Source |
|---|---|---|
| BHU | capacities | 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 the each storm | Distribution of rainfall predicted by regression model, capped at a maximum of 6.5 inches per 6 hours |

**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 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 further approximation of a relationships 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 ($\Delta P$) inside the radius to maximum wind speed ($R_{max}$) and to exponentially decay with distance beyond $R_{max}$. Specifically, it takes the form

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

or

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

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

Rainfall rates also depend on the quadrant of the storm in which a given point is located at different points in time 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 square error (RMSE) across all interior BHUs:

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

where $\theta$ indexes the ten storm tracks and $\alpha$ 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 model 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 primarily designed 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 where 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 over all points of 94 hours. 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, with the overtopping and fragility algorithm illustrated in Figure 10 and the interior drainage algorithm in Figure 11.

#### Overtopping and Fragility Algorithm

**Step 1: Calculate elevations under the assumption of overtopping only, with no breaches.**

1a: Initialize boundary BHUs with the overtopping volumes on adjacent reaches, add rainfall, and subtract off any pumping capacity that is effective in the given pumping scenario. These 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.

1b: For each boundary BHU with nonzero water volumes, apply the interior drainage algorithm 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.**

2a: Identify which, if any, reaches failed in that particular run.

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).

2c: Within a single protected area, identify the maximum surge elevation associated with any breach on the boundaries of the protected region.

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.

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.

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 (100) produces stable results in the final exceedance calculations. This is likely due to the exceedances being based on 720 synthetic storms because each storm affects thousands of points along protected areas with highly correlated surge heights. Figure 10 depicts the process for aggregating calculations from the fragility and overtopping modules in the interior drainage module

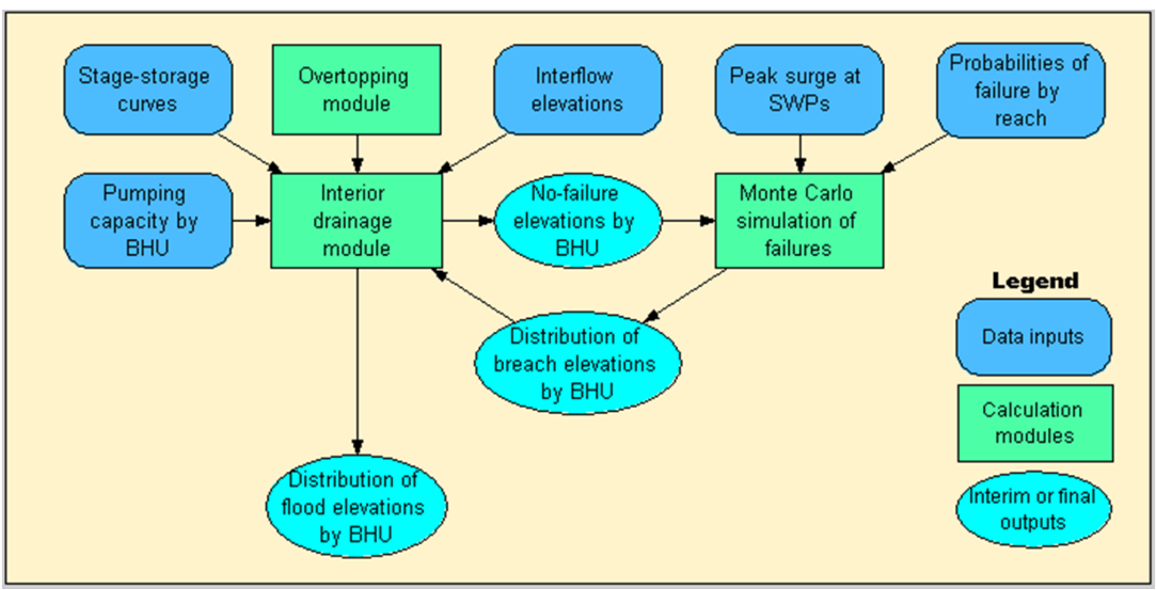



**Figure 10: Integration of Overtopping and Fragility Modules to Yield Flood Elevation Distributions**

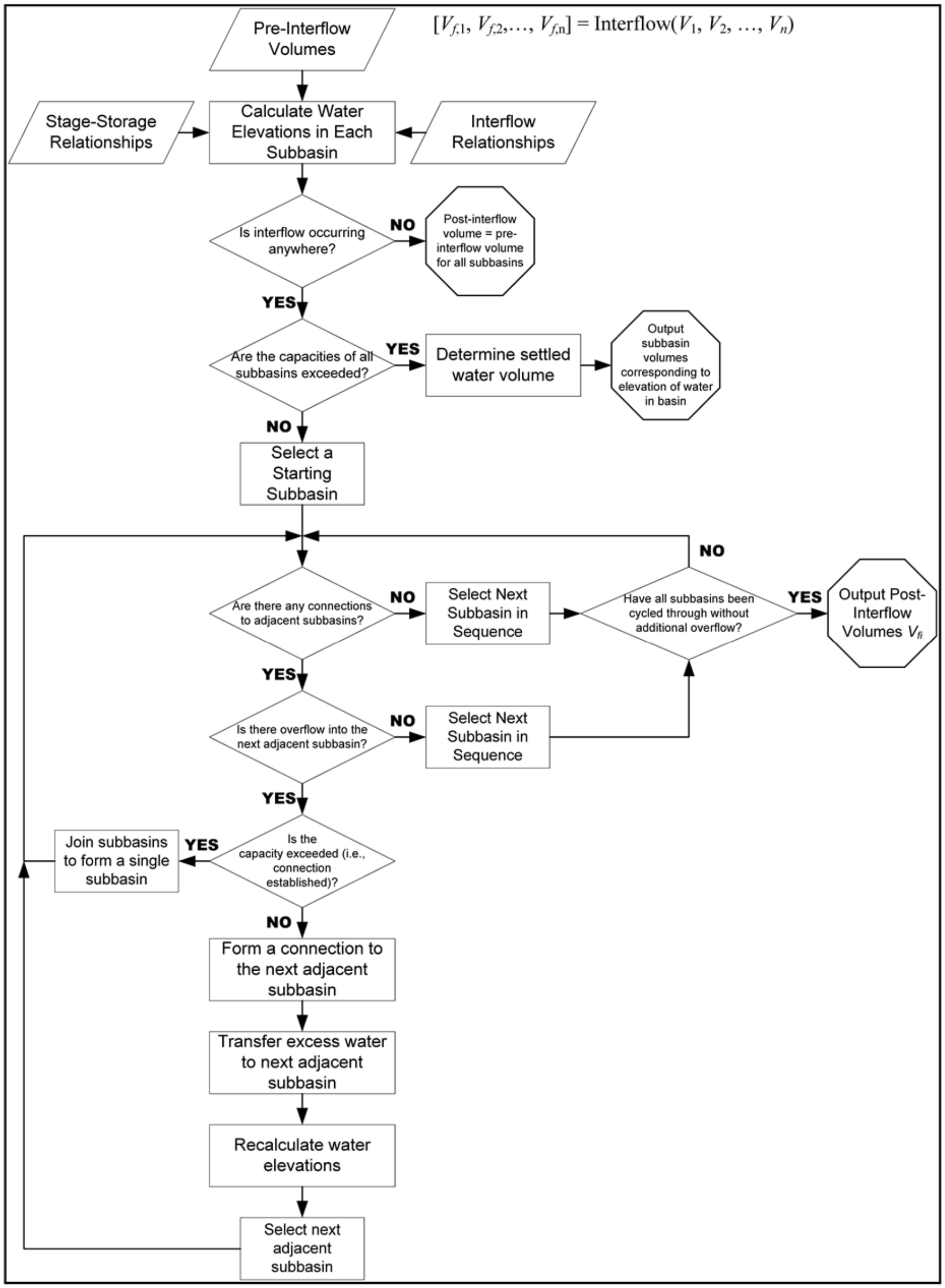
**Interior Drainage Algorithm**

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.

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 11.




SOURCE: IPET (USACE, 2009b).

**Figure 11: Algorithm for Calculating Equilibrium Flood Elevation**

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 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 these 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 interconnection, the basins are treated as joined, and 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 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 depth exceedances, which are used to calculate final damage exceedances in the economic module as described in the next section. The flood depth module also produces an empirical distribution of flood depths used to calculate expected annual damage.

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). 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 2060.

Taking a sum of the synthetic flood depths weighted by the probability masses assigned to each synthetic storm yields an empirical cumulative distribution function (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 depth 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 flood damage levels in each census block.

Surge and flood depth 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, for diagnostic purposes.

### *Economic Module*

*Overview*

The CLARA model estimates the direct economic impacts of flooding by census block at several years between 2011 and 2060. 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 12. 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.

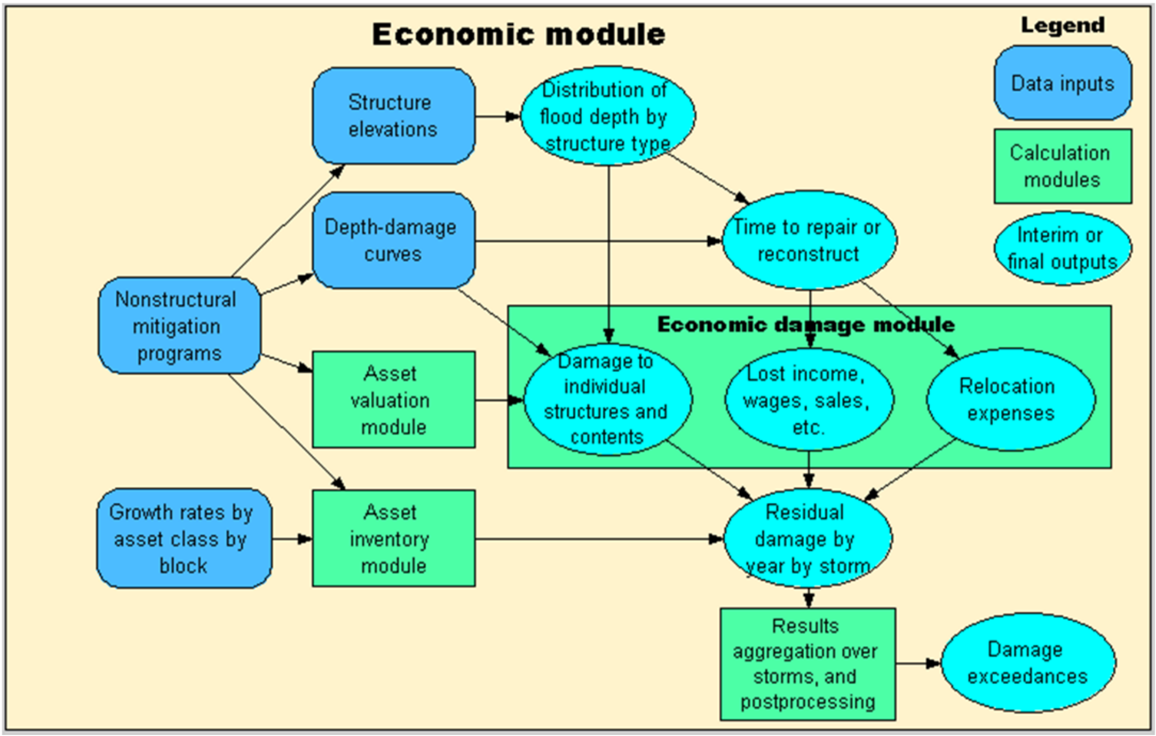



**Figure 12: Summary of Economic Module Calculations**

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 model is run using a range of different growth scenarios, which we explore in the analysis.

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 module 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 (2011–2060). 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*

In general, when several sources of economic data are available, preference is 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 modules; these are also summarized in Table 8, Table 9, and Table 10, 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 to represent second-quarter 2005 (pre-Katrina) economic conditions by Calthorpe Associates (USACE, 2009a). 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.[11] 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.

**Table 8: Data Elements for the Asset Inventory Module**

| Data Element | Asset Class | Source (by order of precedence) |
|---|---|---|
| Number of structures | All residential | GNOCDC, ACS, |

[11] 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.

| Data Element | Asset Class | Source (by order of precedence) |
|---|---|---|
| | classes | LACPR, Hazus |
| Number of structures | All nonresidential, structural classes | LACPR, Hazus, 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 |
| NOTE: CBP = County Business Patterns. | | |

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 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.

**Table 9: 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 |
| Replacement cost per square foot | All structural classes | Hazus |
| Proportion of structures by construction class (economy, average, custom, luxury) | All residential classes | Hazus |
| CSVR | All structural classes | LACPR |
| Value of inventory per square foot | Commercial, industrial | Hazus |
| Depreciation curves by structure age | All structural classes | Hazus |
| Repair costs per mile | Infrastructure | LACPR, Hazus |
| Agriculture valuations | Agricultural crops | LACPR |
| Proportion of structures by construction method (e.g., wood frame, masonry) | All structural classes | Hazus |

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 model 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 contents-to-structure value ratio (CSVR) 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 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 (LA DOTD) 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 postflood response, such as landscaping repair, debris removal, and other cleanup are also modeled in accordance with the LACPR methodology.

Other direct economic impacts that we include in our model 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 Module*

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 of the Hazus or LACPR inventory and valuation is used, as indicated in Table 10, with LACPR damage curves taking precedence. The depth-damage relationships are derived from expert elicitation and actual insurance claims and can vary by geographic region; where Hazus is used, the risk assessment model takes damage curves drawn from Orleans Parish data.

**Table 10: Data Elements for Economic Damage Module**

| 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 |
| Structural elevation above grade | All structural classes | LACPR |
| Depth-restoration time curve | All structural classes | Hazus |
| Depth-damage curves for structure | All structural classes, infrastructure | LACPR, Hazus |
| Depth-damage curves for contents | All structural classes | Hazus |
| Depth-damage curves for inventory | Commercial, industrial | Hazus |
| Costs dependent on displacement time: lost income, lost wages, lost sales, disruption costs, relocation rental costs | All structural classes | LACPR, Hazus |
| Costs dependent on displacement time: evacuation and subsistence costs | All residential classes | LACPR |
| Postflood response costs: landscaping repair, debris removal, other cleanup | All structural classes | LACPR |
| Depth-velocity-collapse curves | All structural classes | Hazus |

Flood elevations are taken as calculated by the previous modules of the risk assessment model, 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 damage module 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. The risk assessment model 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 factors 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 recent 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. These 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 2060, the populations of urban and rural blocks change such that, in 2060, 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. 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 elevations.

***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.

*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 result in complete inundation at the 500-year exceedance. However, one might produce no flooding up to the 400-year exceedance, whereas another 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 one-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 one foot, between one and two 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 economic 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.

### c. Assumptions

The methods used for estimating flood depth probabilities, calculating overtopping volumes, estimating the likelihood and consequences of system failure, and valuing assets at risk and the damage caused by various flood depths all leverage the greater resources and products of previous models, such as LACPR, IPET, and Hazus. This means that CLARA represents the latest scientific and economic understanding of these processes that can be brought to bear. However, in order to model the complex interactions necessary to represent the underlying risk of catastrophic flooding and the resulting losses that result 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 section. 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 section, sorted by CLARA module.

#### ***Storm Surge Inputs and Storm Preprocessing Assumptions***

- *Storm intensity is characterized by the central pressure*. Exceedances are based on observed characteristics of historical storms as used by IPET.
- The set of 40 storms used to generate the surge and wave data with ADCIRC adequately captures the range of possible storm surge and wave effects anticipated to affect the Louisiana coast over the next 50 years.
- *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 Model Assumptions***

*Overtopping Module*

- *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 SI units are used (USACE, 2009b). The application of the weir coefficient is described in Section 2b.
- *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).
- *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 height for every four feet 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.
- *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.

*System Fragility Module*

- *Operational failures are not considered*. All gates, locks, and other closures are assumed to be closed properly prior to any storm surge event.
- 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.”
- *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 (984.25 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.

- *Failures of levees depend only on the maximum surge*, not the time history of the storm surge or waves against the levee.[12]
- The three failure modes are slope stability, seepage, and overtopping causing erosion and failure on the protected side.

*Interior Drainage Module*

- *Time dynamics are not accounted for*. CLARA's interior drainage model does not explicitly account for the time required for floodwaters to move from one BHU to another, relying 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.
- *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 equal to the maximum surge height.

***Economic Model Assumptions***

- Land-use patterns remain constant over the next 50 years.
- Assets at risk from flooding grow in proportion with population growth, except for certain categories, such as roads.
- Population growth rates from 2011 to 2060 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.

[12] The implication of this assumption is that we consider only the maximum static load on the levee when calculating its probability of failure. We are also ignoring the effects of wave action, which can erode a levee over time.

- 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 2060 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 2060.
- The effectiveness of nonstructural projects is characterized by level of participation only. Participation rates vary by nonstructural project type—elevation, flood-proofing, 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.

***Other Capabilities and Limitations***

- CLARA's 720 synthetic storms are based on ADCIRC and SWAN simulations of a limited number of storms (40) to represent the surge and wave hazards that lead to flooding and damage.
- CLARA does not consider noneconomic damage or effects, and dollar losses are calculated for some asset types (e.g., oil and gas infrastructure).
- CLARA uses scenario analysis to evaluate uncertainty in risk estimates and does not produce statistical confidence intervals.

## Section 3: System Quality

### a. Description and Rationale for Selection of Supporting Software Tool, Programming Language, and Hardware Platform

The selection of software and hardware used by the CLARA model was guided primarily by the demands of model functionality, with an emphasis placed on user-friendly, modular development tools and the use of free or open-source packages and file formats where possible. Detailed information about the software and hardware configuration is provided earlier in "Analytical Requirements" in Section 2 of this document.

Preprocessing of the geospatial data that defines each potential structural alignment is accomplished largely in ArcGIS 10, with the final geodatabase exported to the open-source PostGIS format. The PostGIS geodatabase is the primary input to the overtopping and system fragility modules, which utilize R, an open-source statistical software package that can be integrated with PostGIS and PostgreSQL. Surge and wave characteristics that are fed into R are initially stored as comma-delimited text files (.csv files). The R module produces flood elevations by census block and stores them in .csv format for use by the economic module; other economic input data are housed in PostgreSQL. The economic consequences are calculated using Analytica, an object-oriented modeling environment developed by Lumina. CLARA produces results exported to a flat-file database structure suitable for use by the CPRA Planning Tool.

A summary of the data requirements and software packages for each component of the model is provided in Table 11.

**Table 11: Data and Software Requirements**

| | | Software Package Used | | |
|---|---|---|---|---|
| **Module** | **Primary Data Elements** | **Inputs** | **Calculations** | **Outputs** |
| Spatial and Storm Preprocessing | Geospatial data, scenario uncertainty parameters | ArcGIS | ArcGIS | PostGIS |
| Overtopping | Protection system heights, DEMs, surge and wave heights | PostGIS | R | R, PostgreSQL |
| System Fragility | Protection system characteristics, surge heights | PostGIS | R | R, PostgreSQL |
| Interior Drainage | Stage-storage curves, breach and overtopping volumes | R, PostgreSQL | R | PostgreSQL |
| Economic | Flood depths, economic database | PostgreSQL | Analytica | Text file (.csv) |

### b. Proof That Programming Was Done Correctly

The development team employed a multistep process for developing CLARA. First, working closely with the other teams involved in the CPRA modeling exercise and the planning team, we documented the requirements for CLARA. The development team then prepared specification documents describing the functionality required by the different modules in CLARA, including overtopping, system fragility, interior drainage, and economic damage. These documents guided the development of the code and have been revised. They are not part of this technical appendix. The requirements were validated in discussions among the CPRA modeling teams and CPRA.

The code development process included checks to ensure that the code as developed conformed to the design as documented. As the model was being developed, the team members reviewed the model code. The developer first developed a method to perform a certain function, performing a first check for potential errors. Then a different developer reviewed the method as he incorporated it into a broader module. Finally, the lead developer reviewed both the code underlying the methods and modules as he integrated these into the CLARA system. Therefore, prior to being tested as part of a complete unit, each code segment received at least three reviews. For example, the code developed in the R statistical software to perform overtopping calculations was first developed by one team member, then passed to another for review and incorporation into the flood elevation code, and finally passed to the lead code developer for another round of review and final incorporation into CLARA.

The model itself 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 many 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. Manual verification of the calculations with actual input data from CPRA indicate that no errors occur throughout the many unit conversions performed by the model or in intermediate steps, such as using the stage-storage curves to convert water volumes to flood elevations.

Model outputs, including flood depths and damage at each exceedance and EAD, were also subjected to multiple-step quality assurance (QA) process. After outputs were produced, the model technical lead (Jordan Fischbach) reviewed all results and discussed any problems or issues with the lead developer (David Johnson). Once any issues identified were resolved at this level, output summaries (in map and tabular form) were provided to the flood module QA manager (David Ortiz) or damage module QA manager (David Groves), respectively, for additional review. Questions were once again passed to Fischbach and Johnson for clarification. 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.

Through this QA process, we occasionally found issues that required troubleshooting either in the model code or in the geospatial or storm data inputs used by the model. These issues were tracked down and resolved, resulting in a model in which all results have clear and understandable justifications and no unexplained problems are evident.

### c. Availability of Software and Hardware Required by Model

Currently, because of the model’s demands on processing power and memory and the use of software available only for Windows, the CLARA model is operable only on a Windows-based server. For example, running the economic risk module in Analytica requires a 64-bit machine with more than 20 GB of available RAM. The model was developed in an environment that did not impose processing or memory constraints; it may be possible to substantially reduce these requirements through future optimization. CLARA could be transferred to run on a different machine, provided that it has commensurate processing and memory available, as well as the required software licenses.

However, in addition to the results provided to the Planning Tool, efforts have been made to develop a series of mapped outputs using the ArcMap platform that visually display the value of assets at risk and return intervals for surge elevations, flood depths, and damage for each grid and scenario modeled. These have been provided to various work groups for review and comment.

**d. Description of Process Used to Test and Validate the Model**

Substantial portions of the methodologies used by CLARA borrow from methods used by IPET, LACPR, or 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.

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 FWOA scenario have been compared with LACPR flood depths and subjected to expert review to determine that results are plausible 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.

Maps of surge and flood results have been distributed among the various project work groups for QA, to solicit feedback or identify any obvious bugs or errors in the output data. This has resulted in significant improvement through successive iterations.

**e. Interoperability**

CLARA utilizes a large set of input data that can be broken into three main categories:

- geolocated data describing land elevations, protection system characteristics and other features stored as layers in a geodatabase based in the PostgreSQL database system (an open-source platform) and manipulated in ArcGIS
- data describing storm surge and wave characteristics that are provided by the team as a series of text files. These data are processed to create the data set of synthetic-storm characteristics used by the flood module, which are also stored as text files.
- data describing economic assets and the relationships used to determine economic damage as a function of flood depths. These are also stored in the PostgreSQL database.

Outputs from CLARA consist of the following:

- damage results by census block and by target community for each project alignment and scenario. These are provided as comma-delimited text files and formatted both with a variety of identifiers and codes for the Planning Tool and in a more human-readable format for other work groups.
- maps of return exceedances for flood depths, surge elevations, and damage by census block. These are generated in ArcGIS and exported as .pdf files viewable using free software.

## Section 4: Usability

### a. Availability of Input Data Necessary to Support the Model

General information about the source of geospatial, storm, and economic data has been outlined in table format in previous sections. Storm inputs produced by the Storm Surge/Wave model are available on the CPRA FTP site for review or use by other teams. Geospatial and economic data have been subjected to calculations and manipulations and are generally altered from the original source format. The final form of these data when provided as inputs into the CLARA model is stored in the PostgreSQL database described earlier in this document. Although this database is inaccessible to external users, it could be backed up and exported for external review or use.

### b. Formatting of Output in an Understandable Manner

Outputs from the CLARA risk module are provided in a proprietary tabular comma-delimited format for use by the Planning Tool team. Flood outputs are mapped for visual review and summarized by block and by BHU in .csv format. Some flood and risk outputs are also produced as .csv files and provided to other groups for use by the strategic and historical asset decision criteria and to produce summary materials describing the effectiveness of nonstructural mitigation.

### c. Usefulness of Results to Support Project Analysis

Outputs from CLARA, including EAD estimates and 50-, 100-, and 500-year damage exceedance calculations, allow for the direct comparison of risk reduction benefits from structural and nonstructural risk reduction projects using the CPRA Planning Tool.

- *Structural projects:* Benefits are calculated by comparing damage estimates in the FWOA and future-with-project (FWP) conditions in year 50 of the analysis. For structural projects in the 2012 Coastal Master Plan analysis, this was operationalized by running eight separate grids containing geographic information system (GIS) representations of different groupings of protection projects through CLARA. Damage estimates were then calculated by census block or CPRA-defined community and passed to the Planning Tool to calculate differences and determine benefits for each project.
- *Nonstructural projects:* The CLARA economic module includes logic that can apply nonstructural projects in a variety of different configurations and estimate the reduced damage with nonstructural risk reduction in place. In the 2012 Coastal Master Plan analysis, we used CLARA to compare damage from the FWOA condition with damage when nonstructural projects were included. Nonstructural projects were applied directly to the surge and wave inputs from the FWOA condition because no changes to surge and wave effects are expected when applying risk mitigation projects to individual structures. Once again, with- and without-project damage levels were passed to the Planning Tool, and the corresponding benefits (change in damage by project) were calculated by the Planning Tool team.

**d. Ability to Export Results into Project Reports**

CLARA outputs can be used to create maps suitable for reports that indicate surge elevations or flood depths at the block level along the entire coast or specific to particular regions, such as New Orleans. Maps can also show the differences between the FWOA scenario and with the modeled groupings of projects in place. Depths and damage at the target-community level can also be exported in a tabular format for reporting purposes. Other useful intermediate outputs include results of nonstructural projects, such as the number of homes elevated and other properties flood-proofed by each project.

**e. Training Availability**

Transferring the CLARA model to others for use external to RAND and training for other users are not included in the current scope of work. Transferring the model to other users might involve adapting the model to other computer systems and improving ease of use.

**f. User Documentation Availability**

This technical manual provides the most-detailed information available about CLARA's methodologies and inner workings. Various other materials expounding on parts of the model have been produced for interim briefings or through email exchanges, but there is currently no detailed user guide or help manual. Effort has been made in the source code to comment and document the model to aid use of the model by a technically proficient user.

**g. Technical Support Availability**

Currently, the model does not require technical support for external users. If a public version is produced and released in the future, support could be maintained through telephone or email communication.

**h. Software and Hardware Platform Availability**

To the extent possible, the CLARA model has been developed using open-source software packages. The major components required for use are R 64-bit (open source), PostgreSQL with PostGIS extension (open source), ArcMap with ArcSDE package and Spatial Analyst license (commercially available), Analytica 64-bit (commercially available but with a free reader available), and any text editor or spreadsheet package capable of manipulating .txt and .csv files. ArcMap and Analytica are available only for the Windows operating system.

The biggest hurdle to running CLARA is hardware availability. The economic module requires a substantial amount of memory to process multidimensional calculations on 35,000+ census blocks. We recommend use of the model on a Windows-based server with at least 30 GB of RAM and significant processing power.

**i. Accessibility of the Model**

Currently, CLARA is housed and accessible only on a single server at RAND. Adapting the model to run on other computing facilities would require minor changes to source code (e.g., adjusting absolute and relative directory and file references). Interfacing ArcMap with the PostGIS geodatabase using the ArcSDE package requires significant technical knowledge. Other than these two issues, transference of the model would be relatively straightforward and would consist of file transfers to the new system, installation of the relevant software packages, and restoration of a backup of the geodatabase.

### j. Transparency of the Model

The model is constructed with sensible variable names and, where possible, using modular functions and straightforward calculations that should be easily readable and traceable by a technically proficient programmer. The complexity and scale of model calculations dictated that some sacrifices in usability were made in the name of computational efficiency; some code may be difficult to follow as a result.

Comments are also provided liberally throughout the model source code to help with understanding the purpose of each source file and any complex calculation steps. These can be used along with this technical document to verify proper operation of the model.

## Section 5: Sources of Uncertainty in the Coastal Louisiana Risk Assessment

### a. 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, though 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, and 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).

The CLARA model 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 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 and 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 the 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 model was designed to be consistent with the overall 2012 Coastal Master Plan analysis, which is described in detail in the main body of the master plan.

## b. Scenario Inputs

The number and choice of scenario variables implemented in the CLARA analysis reflects 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 also were 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 the CLARA model are summarized in this section. Those denoted with an asterisk were defined as part of the overall 2012 Coastal Master Plan analysis and are discussed in detail in Appendix C of the master plan.

### ***Storm Surge and Wave Inputs***

#### *Sea-Level Rise**

Sea-level rise scenarios are defined by CPRA for all modeling teams, and range from 0.3 to 0.5 meters from 2011 to 2060. 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.

*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 smaller or greater number of storms making landfall on the Louisiana coast, on average, by 2060. 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). The 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 2060, 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 frame. 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 2060 coastal populations using these growth rates are 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, flood-proofing, 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 a separate document.

**Table 12: 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. | | | | |

## Section 6: Suggested Model Improvements

The CLARA model was developed over a six-month period in order to provide analytic results for the master plan on a rapid timeline. Many decisions made regarding model structure and data sources were guided by these time constraints, and the current version of the model includes some simplifications and assumptions that could be improved on in subsequent development cycles. Furthermore, by dividing the model into a series of independently developed modules and a separate supportive database, the Risk Assessment and Damage modeling team deliberately structured CLARA so that iterative improvements could be made while retaining the basic functionality of the model.

In this section, we describe a series of improvements and extensions that could be made to CLARA to better support future coastal planning.

### a. 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 on coastal Mississippi.

***New Extensions***

- Develop parametric uncertainty methodology to estimate flood depth and damage confidence intervals for each scenario.

### b. Flood Depth Module

***Improvements to Existing Functionality***

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

***New Extensions***

- Improve treatment of levee run-around and wave overtopping for semiprotected areas.
- Consider the additional risk introduced by operational failures (e.g., not all gates closed during a storm).
- Improve fragility methodology to incorporate estimates of local effects of failure in semiprotected areas.

- 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.

### c. 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 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.

## Section 7: Quality Review

Specific quality review (QR) procedures for the Risk Assessment and Damage model to support the 2012 Coastal Master Plan included the following:

### a. Model Quality Review Procedures

- The development team reviewed the code three times prior to implementation and testing. The first time was by the developer of individual methods, who checked to ensure that the code conformed to the documentation prepared in support of the model. The second review was by a different developer responsible for integrating the methods into modules. In general, these developers were different people. The final check was by the lead developer as the modules were integrated into CLARA.
- RAND staff conducted an independent peer review of the CLARA model and code. A researcher at RAND with a background in modeling, Lance Menthe, reviewed the architecture, code, and algorithms to ensure that they were correct and provided a formal review report, for which the model team prepared a formal response. Menthe was also a reviewer of this documentation.

### b. Output Quality Review Procedures

A four-step process was instituted to review the results of the CLARA model prior to delivering to CPRA.

#### *Step 1: Scenarios, Projects, and Cases to Be Run in the Coastal Louisiana Risk Assessment Model*

The modeling ran CLARA for each scenario of the future and grid of protection projects. The scenarios represented alternative “futures” for the Louisiana coast, representing changes in hurricane activity, rainfall, and subsidence, among others. There were eight different grids of protection projects, organized as follows:

- Set 0. This is the case in which no changes to the protection system are made.
- Sets 1–7. These are seven sets of projects, selected so that interactions among individual projects are minimized.

For each scenario and project, the CLARA model is able to consider several cases. For the purpose of performing initial quality assurance, there are two cases:

- Case V30. This is the case in which (1) all pumping systems in areas protected from hurricanes are working and (2) potential failures of the HPS are not considered.
- Case V32. This is the case in which (1) all pumping systems in areas protected from hurricanes are working and (2) potential failures of the HPS are considered and the degree of fragility is nominal.

For each (1) scenario, (2) set of protection projects, and (3) case, the modeling team produces outputs of either the storm surge or the flooding that results representing 50-year, 100-year, 400-year, 500-year, and 1,000-year exceedances.

### *Step 2: Create Review Maps*

Once the modeling runs were complete, the modeling team created a series of maps for the purposes of reviewing output. Table 13 lists the maps that were created to facilitate the QA review process. Also, the data contained in the maps and damage estimates were posted as comma-delimited text files, facilitating quantitative review if necessary.

**Table 13: 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 with no changes to the protection system as compared with those that result when the protection measures under consideration are in place | 50, 100, 500 |
| 3 | 6 | Absolute floods | The flooding that results for cases V30 and V32 under each future scenario | 50, 100, 500 |
| 4 | 3 | Difference between floods | Difference in the flood height that results in protected areas with no changes to the protection system as compared with those with the protection system measures under consideration in place | 50, 100, 500 |
| 5 | 3 | Difference between floods | Differences in the flood height in cases V30 and V32 | 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. | | | | |

The modeling team posted the maps to an internal file server and notified the QA manager for flooding (David Ortiz) and damage (David Groves) that the results were ready to review.

***Step 3: Review Modeling Results***

The QA managers reviewed the maps posted to the file server. The purpose of the review was to ensure consistency and to make note of any anomalies in the results. The following are key considerations that 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.

The end of this document includes a reporting form that was to be filled out during review of the maps.

***Step 4: Post Results to Coastal Protection and Restoration Authority of Louisiana***

Once the QA managers reviewed the results and felt that they were ready for public release, they sent the completed review to the director of the RAND Environment, Energy, and Economic Development program (Keith Crane) for concurrence that the results were complete and correct. After approval of the results, the modeling team posted the results to the CPRA server for use by CPRA and others.

## Section 8: Uncertainty Analysis

### a. Flood Depth and Economic Module Scenario Analysis

The CLARA team conducted a complete scenario analysis by varying the key uncertain inputs identified in Section 5 for the flood depth and economic modules (see Table 12). This analysis was conducted when evaluating the draft alternative and entailed running a full factorial experimental design across all key inputs at the values specified in Table 12 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 draft master plan, then, we produced 216 (6 × 9 × 4) scenario results.

### b. 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 Assessment and Damage modeling 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 the model.

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 points, and 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 Section 2b of this document).

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 13. The values shown on the map are calculated as the 154-storm exceedance minus the 40-storm exceedance, with positive values (in blue) indicating that the CPRA storm set underestimates surge values compared with the 154 storm sample, and negative values (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- and 154-storm sets.

There are several notable exceptions, however. At the 50-year exceedance, surge 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 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 exceedance estimates in several BHUs (not shown) but did not notably shift the flood depth probability distributions as a whole for these areas.

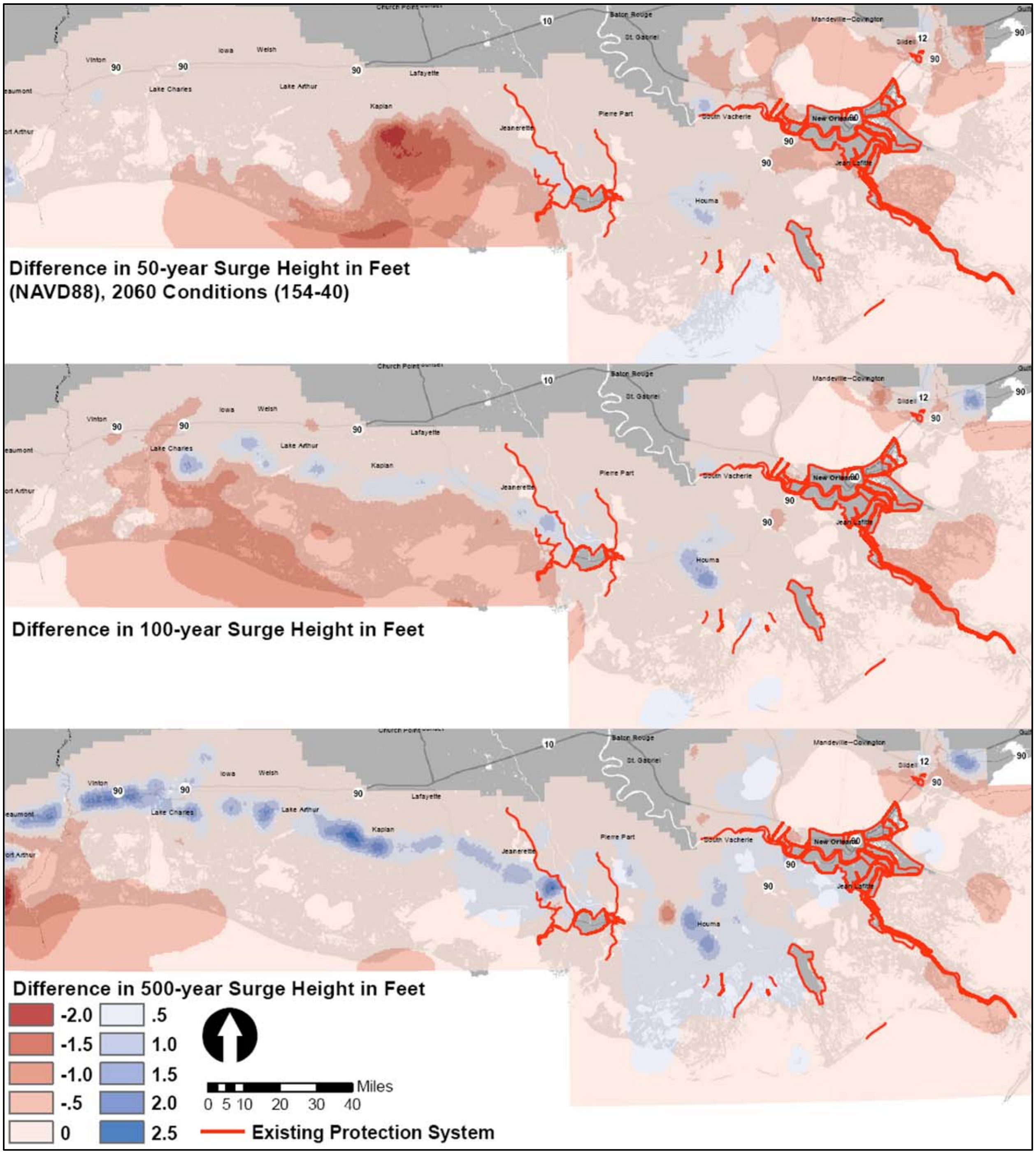



**Figure 13: Comparison of Storm Surge Exceedances from the 154-Storm and 40-Storm Subsets at the 50 (Top), 100 (Middle), and 500-Year (Bottom) Exceedances**

## Section 9: References

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