2023 COASTAL MASTER PLAN

# USE OF PREDICTIVE MODELS IN THE 2023 COASTAL MASTER PLAN

APPENDIX C

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COASTAL PROTECTION AND
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# COASTAL PROTECTION AND RESTORATION AUTHORITY

This document was developed in support of the 2023 Coastal Master Plan being prepared by the Coastal Protection and Restoration Authority (CPRA). CPRA was established by the Louisiana Legislature in response to Hurricanes Katrina and Rita through Act 8 of the First Extraordinary Session of 2005. Act 8 of the First Extraordinary Session of 2005 expanded the membership, duties, and responsibilities of CPRA and charged the new authority to develop and implement a comprehensive coastal protection plan, consisting of a master plan (revised every six years) and annual plans. CPRA's mandate is to develop, implement, and enforce a comprehensive coastal protection and restoration master plan.

# CITATION

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# ACKNOWLEDGEMENTS

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# EXECUTIVE SUMMARY

The master plan uses an array of predictive models that consider landscape change, storm surge and waves, and flood-related damages to coastal Louisiana structures and assets to understand what the future holds under a range of environmental conditions and risk scenarios. This appendix outlines the processes that the models simulate and describes the data used to drive those simulations. Summary results for the future with and without the 2023 Coastal Master Plan are also presented.

## THE LANDSCAPE MODEL (ICM)

The landscape of coastal Louisiana is represented using the Integrated Compartment Model (ICM), which predicts coastal hydrology, wetland morphology, vegetation dynamics, and the suitability of habitats to support an array of fish and wildlife. The ICM builds on the version used for the 2017 Coastal Master Plan, but recent improvements include refined resolution in key areas and the incorporation of additional processes. The State of Louisiana's Coastwide Reference Monitoring System (CRMS) is a large network of more than 300 wetland-based observation locations that, since 2006, have collected data about wetland elevation, water levels, salinity, vegetation, and land change. In the 2023 Coastal Master Plan, data from CRMS stations was used to refine how wetland vegetation in the ICM responds to changes in salinity and inundation stress. CRMS data, along with data and information from other CPRA-funded studies, were also used to improve the evaluation of subsidence across the coast. Future environmental change is an important driver of the predictive models used to inform master plan development and decision-making. During plan development, the most recent available global climate model outputs were leveraged to develop environmental scenarios that link climate-related variables, such as sea level rise (SLR) rates and temperature changes, to represent plausible future conditions.

## STORM SURGE AND WAVE MODELS

Storm surge and wave models (Advanced Circulation model (ADCIRC) + Simulating Waves Nearshore model (SWAN)) provide water level inputs to the risk assessment model. Synthetic storms with varying characteristics, such as wind speed and central pressure, are modeled to test the impacts of a range of plausible events. Working with the U.S. Army Corps of Engineers (USACE) Engineer Research and Development Center (ERDC), an updated set of storms, incorporating both more extreme and less intense storms than were previously available, was used to model hurricanes and tropical storms and evaluate associated storm surge and wave levels across the coast.

The Coastal Louisiana Risk Assessment (CLARA) model is designed to estimate flood depths and direct economic damage from hurricanes and other tropical events. CLARA is used to estimate risk under a range of assumptions about future environmental and economic conditions and with different combinations of structural and nonstructural risk reduction projects on the landscape. The CLARA framework considers uncertainty related to future storms and their associated storm surge and wave

levels, as well as the physical landscape. Multiple detailed asset inventories were combined to characterize residential, commercial, industrial, and public structures across the coast to improve economic damage estimates. Additionally, artificial intelligence was utilized to produce more accurate first floor elevation data (which informs damage estimates) than in any previous plan.

Expected annual damage in dollars (EADD), is an annualized estimate of storm surge damage. EADD includes damage to structures, their contents, and other direct losses incurred during the recovery period after a storm event, such as lost wages, costs associated with evacuation and temporary displacement, and other considerations. Expected annual structural damage (EASD) is an annualized estimate of structural damage. EASD is reported in 'structure equivalents' and represents an aggregate risk to structures, with damage to each structure expressed as a proportion of its replacement cost.

## MODEL RESULTS

The future without action (FWOA) landscape realizes significant land loss and increases to storm surge-based flood depths over the 50-year model prediction. Under the lower scenario, 1,100 sq mi of land are lost in 50 years; an equivalent amount of loss occurs by Year 34 under the higher scenario, with up to 3,000 sq mi of land loss in 50 years under those more severe environmental conditions. This land loss impacts not only the landscape configuration and ecology but also results in changes to storm surge and waves and, thus, flood-related damages. Without additional project implementation, flood damages could increase by up to $24 billion annually, with 22,000 additional structures damaged due to significant increases in flood depths under the higher environmental scenario.

With the master plan under the lower environmental scenario, the projects create or maintain approximately 310 sq mi of land over 50 years. In the higher scenario, they build or maintain 230 sq mi of land over the 50-year period.

Structural risk reduction measures are expected to reduce flood damage by $7.7 billion in EADD under the lower environmental scenario by Year 50 and by $11 billion in EADD under the higher scenario. In addition, $11.2 billion of the master plan budget is recommended to support nonstructural risk reduction measures, such as elevation, floodproofing, and voluntary acquisition.

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# LIST OF ABBREVIATIONS

1D ..... ONE DIMENSIONAL
ADCIRC ..... ADVANCED CIRCULATION MODEL
AEP ..... ANNUAL EXCEEDANCE PROBABILITY
CLARA ..... COASTAL LOUISIANA RISK ASSESSMENT MODEL
CMIP5 ..... COUPLED MODEL INTERCOMPARISON PROJECT
CPRA ..... COASTAL PROTECTION AND RESTORATION AUTHORITY
CRMS ..... COASTWIDE REFERENCE MONITORING SYSTEM
EADD ..... EXPECTED ANNUAL DAMAGE IN DOLLARS
EASD ..... EXPECTED ANNUAL STRUCTURAL DAMAGE
ERDC ..... ENGINEER RESEARCH AND DEVELOPMENT CENTER
FEMA ..... FEDERAL EMERGENCY MANAGEMENT AGENCY
FFIBS ..... FORESTED, FRESH, INTERMEDIATE, BRACKISH, OR SALINE
FWA ..... FUTURE WITH ACTION
FWOA ..... FUTURE WITHOUT ACTION
FWOCFP ..... FUTURE WITHOUT CURRENTLY FUNDED PROJECTS
H&H ..... HYDRAULICS AND HYDROLOGY
HAZUS ..... HAZARDS UNITED STATES
HSI ..... HABITAT SUITABILITY INDEX
ICM ..... INTEGRATED COMPARTMENT MODEL
ICM-BI ..... BARRIER ISLAND DIGITAL ELEVATION MODEL
ICM-BITI ..... BARRIER ISLAND TIDAL INLET MODULE
ICM-HYDRO ..... HYDROLOGY SUBROUTINE
ICM-LAVEGMOD ..... WETLAND VEGETATION SUBROUTINE
ICM-MORPH ..... WETLAND MORPHOLOGY SUBROUTINE
IPCC ..... INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE
JPM-OS ..... JOINT PROBABILITY METHOD WITH OPTIMAL SAMPLING
LDWF ..... LOUISIANA DEPARTMENT OF WILDLIFE AND FISHERIES
LSU ..... LOUISIANA STATE UNIVERSITY
MDT ..... MODELING DECISION TEAM

MEE ..... MARSH EDGE EROSION
NOAA ..... NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION
NSF ..... NATIONAL SCIENCE FOUNDATION
NSI ..... NATIONAL STRUCTURE INVENTORY
PM-TAC ..... PREDICTIVE MODELS TECHNICAL ADVISORY COMMITTEE
RAPID ..... ROUTING APPLICATION FOR PARALLEL COMPUTATION OF DISCHARGE
RCP ..... REPRESENTATIVE CONCENTRATION PATHWAY
SD ..... STANDARD DEVIATION
SLR ..... SEA LEVEL RISE
SWAN ..... SIMULATING WAVES NEARSHORE MODEL
TSS ..... TOTAL SUSPENDED SOLIDS
UNC ..... UNIVERSITY OF NORTH CAROLINA
USACE ..... U.S. ARMY CORPS OF ENGINEERS
USGS ..... U.S. GEOLOGICAL SURVEY
WSE ..... WATER SURFACE ELEVATION

# 1.0 INTRODUCTION

The 2023 Coastal Master Plan looks 50 years into the future to assess the effectiveness of an array of coastal protection and restoration projects. The decision drivers used to develop the plan are land area and reduction in expected annual damages, both outcomes of complex process interactions across the coast. In addition to the decision drivers, the effects of the plan on a number of other aspects of the coast are considered, including fish and wildlife habitat.

This appendix summarizes the components of the modeling process and how they interact with one another. The Integrated Compartment Model (ICM) simulates change in landscape and ecosystem characteristics, including land area. The ICM also provides future landscape and ecosystem information to the surge and risk models to support the prediction of future storm surge and waves and resulting damages. The improvements to the models made for the 2023 Coastal Master Plan, and their application, were guided by the Predictive Models Technical Advisory Committee (PM-TAC), and summaries of their meetings as well as their final report can be found in Attachment C1: Predictive Models Technical Advisory Committee (PM-TAC) Report.

Also included in this appendix are brief summaries of modeling results for the future without action (FWOA) and the future with action (FWA) simulations. Further details, as well as more detailed modeling results for selected projects, can be found in the following attachments:

- Attachment C2: 50-Year FWOA Model Output, Regional Summaries – ICM
- Attachment C3: 50-Year FWOA Model Output, Regional Summaries – Risk
- Attachment C4: Extended Project Narratives – ICM
- Attachment C5: Future with Master Plan Model Output, Regional Summaries – ICM
- Attachment C6: Future with Master Plan Model Output, Regional Summaries – Risk

Many aspects of the modeling were improved for the 2023 Coastal Master Plan. These are described in Appendix D: Overview of Improvements to Landscape Modeling (ICM) for 2023, and Appendix E: Overview of Improvements to Risk Modeling (ADCIRC+SWAN, CLARA) for 2023. Both of these appendices include more detailed attachments providing details on specific model updates and testing. Additional details about the component subroutines of the ICM and the risk model as used for project selection can be found in the following attachments:

- Attachment C7: 2023 ICM-Hydro Model
- Attachment C8: 2023 Modeling Wetland Vegetation and Morphology: ICM-LAVegMod and ICM-Morph
- Attachment C9: 2023 Barrier Island Model: ICM-BITI and ICM-BI
- Attachment C10: 2023 Habitat Suitability Index (HSI) Model
- Attachment C11: 2023 Risk Model

A description of the conditions used in the simulations are found in Appendix B: Scenario Development & Future Conditions and its associated attachments.

# 2.0 INTEGRATED COMPARTMENT MODEL (ICM)

## 2.1 ICM OVERVIEW

The ICM is a planning-level model that was developed by integrating into a single modeling platform several models (now referred to as ICM subroutines) that were previously used for coastal zone planning and research in Louisiana (White et al., 2017). Subroutines within the ICM framework include a hydrologic and hydraulic model, a vegetation dynamics model, a wetland morphology/elevation change model, as well as a barrier island model and several receptor models that summarize the hydrologic and landscape conditions into numerous habitat indices and metrics used in decision-making. The following sections provide an overview of these subroutine and outline updates made to many aspects of the ICM for use in the 2023 Coastal Master Plan.

### HYDROLOGY

Hydrologic conditions are simulated within the ICM-Hydro subroutine. This subroutine is a link-node mass balance model capable of simulating: water level (stage), flow rate, salinity, water temperature, suspended sediment concentration, sediment deposition and resuspension within open water areas, and sediment deposition on the marsh surface (Meselhe et al., 2013; White et al., 2019; Reed et al., 2020). The model is driven by boundary condition data representing tidal water levels and salinities as well as tributary inflows (and corresponding salinity and suspended sediment concentrations). Environmental forcing data representing rainfall, temperature, evapotranspiration, and wind are also required model inputs (see Appendix B: Scenario Development & Future Conditions for more details).

The link-node structure of ICM-Hydro utilizes an idealized geometry of the estuary where each model node, or compartment, represents a unit of open water surrounded by marsh area (and in some cases non-tidal upland drainage areas). Some of the compartment attributes included in the model are updated annually by other ICM subroutines, primarily ICM-Morph (e.g., open water bed elevation, marsh surface elevation, portion of compartment that is open water). Other attributes remain constant throughout the simulation periods (e.g., surface roughness of the bed, surface roughness of the marsh). For the 2023 Coastal Master Plan, compartment resolution was refined to better reflect landscape topography and water management features, the latter especially in the Chenier Plain (Figure 1). The domain was also extended into tributary basins to include the lowest gaging points.

A one dimensional (1D) open channel flow routing algorithm for channelized flows such as rivers and navigational channels has been added for the Mississippi River, the Atchafalaya River, and the Calcasieu River/Ship Channel (Figure 1). The addition of this 1D model resulted in two distinct improvements to ICM-Hydro. First, in the Mississippi and Atchafalaya River deltas, the use of the 1D

channel routing algorithms improves the ability of the model to simulate changing flow distributions in the river delta distributary passes as a result of upstream management (e.g., large scale river diversions) and downstream changes due to SLR. The second improvement relates to modeling flood tide propagation up-channel. This is of particular importance to the Calcasieu River/Ship Channel where salinity intrusion and tidal dynamics are an important driver of the hydrology of the Calcasieu-Sabine Basin.

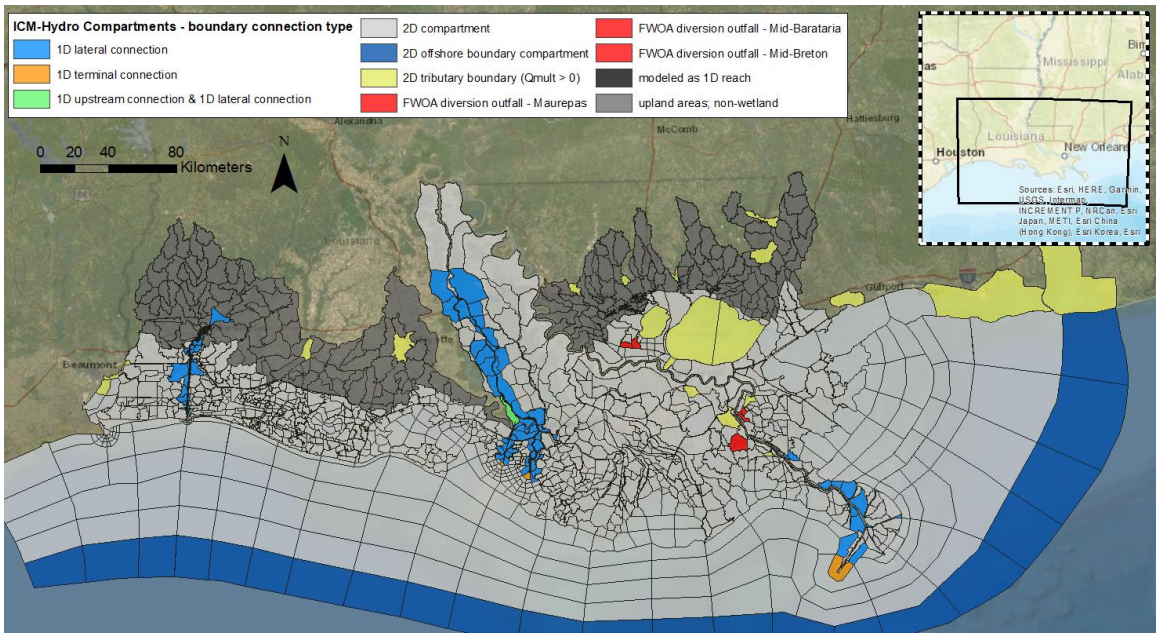


Figure 1. Final ICM-Hydro domain.

More details on ICM-Hydro are provided in Attachment C7: 2023 ICM-Hydro Model.

## VEGETATION

Annual land cover, represented by the relative abundance of vegetation species and the amount of bareground, is modeled within the ICM-LAVegMod vegetation modeling subroutine (Visser & Duke-Sylvester, 2017). This model utilizes mean salinity during the growing season (May through August), the maximum 2-week salinity (used for swamp forest and fresh marsh species), mean water level (used for bottom land hardwood species), and variability of the water surface, defined as the standard deviation (SD) of the water level during the year from ICM-Hydro. The vegetation model operates on an annual timestep. For most species, mean salinity during the growing season (May through August) and variability of the water surface are used to determine changes in vegetation, reflecting the damaging effect of 'stagnant' flooding conditions in some wetlands, especially forested wetlands (Conner et al., 2014; Shaffer et al., 2016).

These data determine the relative likelihood that a wetland plant species currently on the modeled landscape would experience any mortality. The further from its preferred hydrologic condition, the greater probability of mortality for the species. If coverage of a species is reduced, that area becomes bareground is eligible for new vegetation to establish. If the right environmental conditions exist, species will establish on the bareground, and the vegetation community will change. Dispersal rules govern this process and have been updated for the 2023 Coastal Master Plan to include three categories for species based on their proximity to the bareground, with one category that can establish anywhere that the right conditions exist (Attachment D2: ICM-Wetlands, Vegetation & Soils Model Improvements; Attachment C8: 2023 Modeling Wetland Vegetation and Morphology: ICM-LAVegMod and ICM-Morph). The result is that establishment will always occur if salinity is lower than ~3 ppt or greater than ~20 ppt (Figure 2). The species list has also been updated, and changes have been made to the flotant algorithm to allow thick mat flotant an opportunity to re-establish following mortality and transition to 'bare flotant' if environmental conditions are appropriate.

Once simulated, the 33 species modeled are assigned a score based on the habitat type they are most often associated with (Forested, Fresh, Intermediate, Brackish, or Saline [FFIBS]). Habitat type is then assigned based on the cover weighted average score assigned to each species (Visser, 2002). The habitat type and FFIBS score are used in the subsequent ICM subroutine, ICM-Morph.

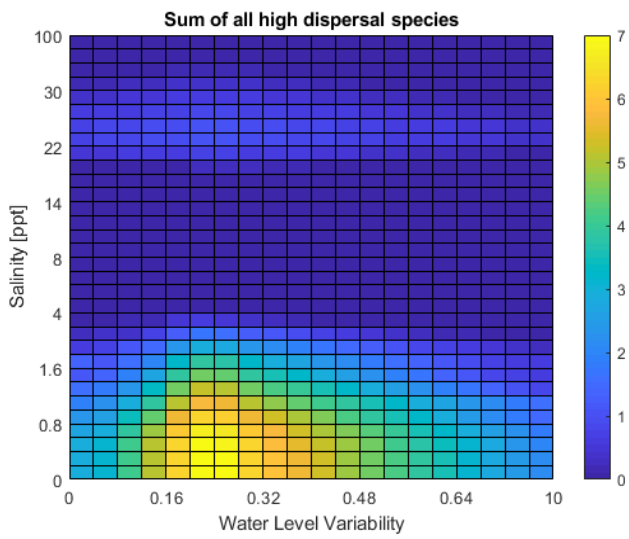


Figure 2. Sum of establishment conditions for all high dispersal species used in ICM-LAVegMod.

More details on ICM-LAVegMod are provided in Attachment C8: 2023 Modeling Wetland Vegetation and Morphology: ICM-LAVegMod and ICM-Morph.

## WETLAND MORPHOLOGY

The wetland morphology subroutine, ICM-Morph, simulates annual elevation change and wetland transition to and from open water over time as a function of dynamic variables modeled by the ICM-Hydro and ICM-LAVegMod subroutines: average and maximum annual water levels, mean annual salinity, inorganic sediment deposition on the marsh edge and interior surfaces, and FFIBS score.

Elevation change of the marsh surface is a function of downward and upward shifts. Surface elevation is lowered due to subsidence (Attachment B3: Determining Subsidence Rates for use in Predictive Modeling) and the gradual lowering of bareground where vegetation species have been subject to mortality the previous year and no species were established. Vertical accretion, based on mineral sediment deposition and organic matter accumulation, increases elevation. Mineral sediment deposition is dynamically linked to the ICM-Hydro simulations and is assessed on a monthly basis based on which areas have been subject to inundation (Figure 3). Organic matter accumulation rates by habitat, derived from Coastwide Reference Monitoring System (CRMS) data, are interpolated based on FFIBS score (Attachment C8: 2023 Modeling Wetland Vegetation and Morphology: ICM-LAVegMod and ICM-Morph). Mineral and organic accretion are derived using the ideal mixing model (Morris et al., 2016) and self-packing densities also developed from CRMS data (Attachment D2: ICM-Wetlands, Vegetation & Soils Model Improvements) (Figure 3). Total accretion on the wetland surface is the sum of mineral and organic components.

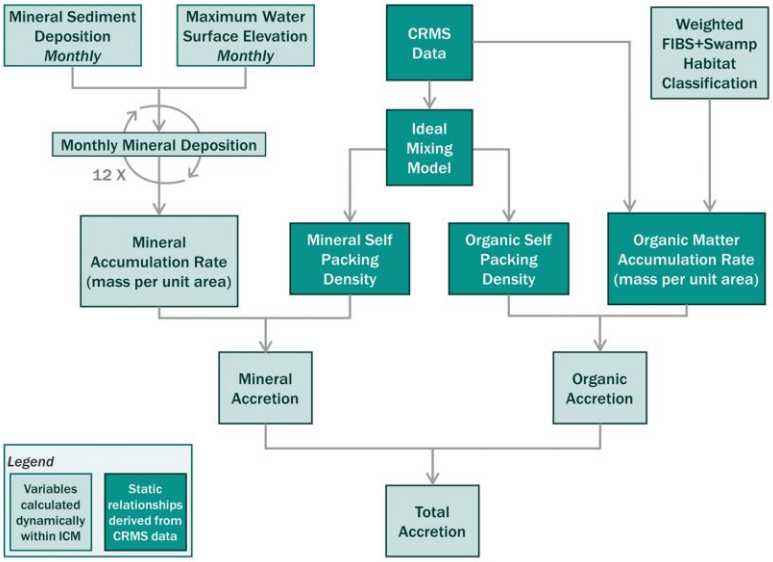


Figure 3. Process and conceptual diagram for vertical accretion functions in ICM.

Transitions from water to land occur when bed elevation of open water areas increases, through mineral sediment deposition, to within 10 cm of the annual mean water level. Areas meeting these

conditions are classified as bareground and eligible for vegetation establishment in ICM-LAVegMod.

Two mechanisms in the model drive transitions from land to water: marsh edge erosion and excessive inundation of vegetation. Marsh edge erosion (MEE) rates are based on historical rates estimated by U.S. Geological Survey (USGS) and imposed as a temporally constant, yet spatially varied, linear erosive rate (Attachment B1: Landscape Input Data; Allison et al., 2017). ICM-Morph pixels that are classified as edge, except in locations with revetment or shoreline protection features, are subject to the MEE rates, and 30 m pixels are converted from land to water over time as erosion proceeds, e.g., MEE rate of 2 m/yr results in loss of 30 m every 15 years.

The approach for converting vegetated wetlands to open water was changed for the 2023 Coastal Master Plan. CRMS data was used to identify environmental conditions, based on annual mean salinity and inundation (a function of surface elevation and water level), that can be tolerated by wetland vegetation, and those where emergent vegetation does not survive. The inundation tolerance of the vegetation varies by salinity (Figure 4), and if environmental conditions exceed the 99.5th percentile line shown in Figure 4 for two consecutive years, land is converted to open water and is not eligible for vegetative establishment.

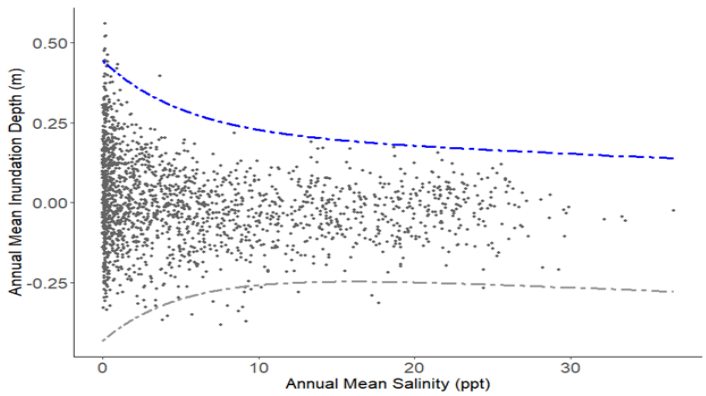


Figure 4. Salinity-inundation depth relationship used to define water depth limitation on vegetation (from CRMS data analysis). Lines are the 0.5th (gray) and 99.5th percentiles.

These processes are applied on an annual timestep in ICM-Morph and result in changes in the configuration of land and water across the landscape.

More details on ICM-Morph are provided in Attachment C8: 2023 Modeling Wetland Vegetation and Morphology: ICM-LAVegMod and ICM-Morph.

## BARRIER ISLANDS

Barrier islands are considered using two separate modules: the Barrier Island Tidal Inlet Module (ICM-BITI), which models the evolution of tidal inlets along barrier islands as informed by basin hydraulics,

and the Barrier Island Digital Elevation Model (ICM-BI), which models island configuration through time to support storm surge modeling (Attachment D4: ICM-BI Model Improvements). The ICM-BITI module is fully incorporated in the ICM, while ICM-BI informs the model at annual timesteps (Figure 5).

The ICM-BITI module captures the positive relationship between tidal inlet cross sectional area and backbarrier tidal prism. Due to the size of each coastal basin and the presence of multiple barrier island tidal inlets per basin, ICM-BITI assigns a fraction of the total tidal prism to each tidal inlet. The module evolves inlets as the size of the backbarrier basin and tidal prism increases over time as land converts to open water.

ICM-BI uses historic barrier island cross-shore retreat rates under varying SLR scenarios to migrate barrier island transects. The transects migrate based on cross-shore retreat rates of index profiles selected to represent key geomorphic features along the coast. The subroutine also includes an auto-restoration feature that increases the profile of the islands on restoration units that drop below a critical width threshold.

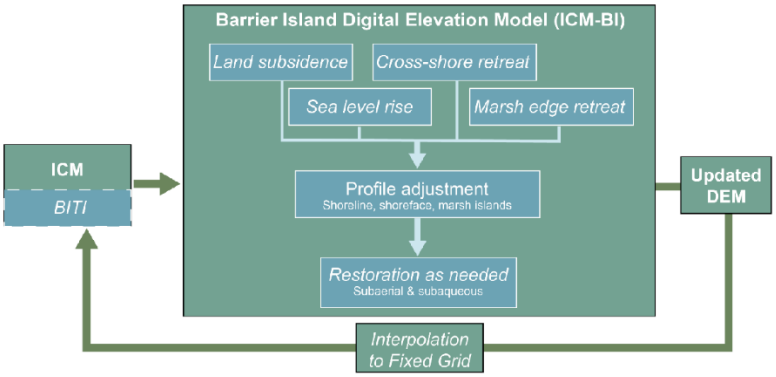


Figure 5. Flow diagram of ICM-BI and ICM-BITI.

ICM-BI simulates change for six island regions: Isles Dernieres, Timbalier, Caminada Headland and Grand Isle, Barataria, Breton Island, and Chandeleur Island, with a number of smaller restoration units within each region. A new digital elevation model for the barrier islands is available annually for use in other ICM subroutines and ADCIRC.

More details on the barrier island models are provided in Attachment C9: 2023 Barrier Island Model: ICM-BI and ICM-BITI.

## ECOSYSTEM OUTCOMES

Once the hydrologic and landscape modeling subroutines simulate a full year, model outputs are used to quantify effects on the ecosystem using a suite of habitat suitability indices. These use output data from other subroutines including salinity, temperature, sediment deposition, and changes in land cover, wetland coverage, and habitat features.

Habitat suitability index (HSI) models are used to generate a relative score for the condition (i.e., suitability) of an area to support a particular organism. HSI models consist of simplified relationships that relate key environmental variables to the quality of the habitat for that organism. The relationships, termed suitability indices, are standardized on a 0 to 1 scale, with 1 being the most favorable conditions and 0 being completely unsuitable. Statistical relationships were developed using field data (from the Louisiana Department of Wildlife and Fisheries [LDWF] long-term fisheries-independent monitoring program) to predict fish and shellfish catch-per-unit effort from key environmental variables collected concurrently with the fish sampling, namely salinity and temperature (Attachment D5: ICM-HSI Model Improvements). For key environmental variables in which statistical relationships could not be developed, such as availability of marsh habitat area, literature values and expert professional judgment were used to generate suitability indices. The final HSI equation for each species was then generated by aggregating both the statistically and expertly derived relationships into a single suitability index value. The bald eagle HSI model was developed using LDWF bald eagle aerial nest surveys and land cover data. Expert derived relationships are used for all variables in the oyster and wildlife HSIs, except for bald eagle. The species for which HSIs were calculated include mottled duck, green-winged teal, gadwall, wild-caught crawfish, alligator, brown pelican, seaside sparrow (new model), bald eagle (new model), blue crab (juvenile), brown shrimp (large and small juveniles), white shrimp (large and small juveniles), Gulf menhaden (adult and juvenile), bay anchovy (adult and juvenile), spotted sea trout (adult and juvenile), largemouth bass, and oysters.

More details on the habitat suitability models are provided in Attachment C10: 2023 Habitat Suitability Index (HSI) Model.

## 2.2 ICM BOUNDARY CONDITIONS

Many boundary forcings vary by environmental scenario (see Section 2.3). However, a single future scenario hydrograph is used for Mississippi and Atchafalaya River flows. The USACE continental-scale Routing Application for Parallel Computation of Discharge (RAPID) Hydraulics and Hydrology (H&H) model generated daily river flows for a 16-member ensemble using Intergovernmental Panel on Climate Change (IPCC) Representative Concentration Pathway (RCP)-4.5 daily precipitation forcing (Lewis et al., 2019). The ensemble runs were examined in terms of the total volume of freshwater, springtime flood peak discharge, and the number of Bonnet Carre openings. The ensemble mean +0.6 SD was used as it matches the historical spring flood peak and has a low bias in relation to Bonnet Carre openings, while increasing freshwater flux 15% over the historic mean. Suspended mineral sediment concentrations were derived for the Mississippi River based upon a separate sediment rating curve for sand and fines developed from field sampling conducted in the Mississippi River at Belle Chasse (Allison et al., 2012).

Separate sand and fines sediment rating curves were developed for the Atchafalaya River from observed USGS data. Rating curves were developed for total suspended sediments from paired

discharge-total suspended solids (TSS) observed data timeseries for tributaries in the Florida Parishes east of the Mississippi River. The derived TSS concentration timeseries were then partitioned into sand and fines portions by using the sand/fine partitioning relationships found in the Mississippi River observations. For Florida Parishes tributaries without any paired discharge-TSS observational data, tributary drainage area relationships developed by Roblin (2008) were used. Due to a lack of observational data for tributaries west of the Atchafalaya River, a single sediment rating curve was developed for Chenier Plain tributaries, with an adjusted-lower sand/fine partitioning relationship than the other coastal tributaries. For a full discussion of the sediment rating curves and sand/fine partitioning methodologies, refer to Attachment B2: Climate-Driven Environmental Scenario Variables.

Gridded wind velocity and direction timeseries were compiled from the North American Regional Reanalysis climate dataset. Salinity concentrations in the offshore Gulf waters were developed from observed data samples (Brown, 2017). Gridded rainfall timeseries were prepared for the ICM-Hydro domain, with one bias-adjusted radar rainfall timeseries provided for each ICM-Hydro compartment (Sharif et al., 2020). Observed daily air temperature, Mississippi River water temperature, and estuarine water temperature timeseries were also used. Observed tidal water levels in the Gulf of Mexico were used from five observation stations ranging from Dauphin Island, Alabama to Sabine Pass, Louisiana.

While the observed datasets described above were used for the model calibration (2010-2018) and validation (2006-2009) periods, the boundary conditions were adjusted for future environmental scenarios, as described in Appendix B: Scenario Development & Future Conditions. Temperature, precipitation, and coastal tributary river flow boundary forcings were adjusted independently for each future environmental scenario; the exact adjustments made were dependent upon temperature and rainfall anomalies that were calculated from climate change model ensembles made available through the World Climate Research Program's Coupled Model Intercomparison Project (CMIP5).

To project tidal water levels for each future environmental scenario, observed tidal data was first decomposed into six constituent components: 1) astronomic tidal fluctuations; 2) local gage-specific subsidence; 3) Gulf wide SLR; 4) acute surge from tropical cyclones; 5) seasonal temperature fluctuation; and 6) the residual water level fluctuation that was the result of wind, frontal passages, and other localized weather events. Each of these constituent tidal components could then be treated independently under future environmental scenario assumptions.

For all future environmental scenarios, the wind timeseries was not adjusted; the observed wind record from 2010 was used for every single year; this year was chosen for the lack of any hurricanes making landfall in coastal Louisiana. Corresponding to this single wind-year, water level deviations in coastal waters that corresponded to wind and frontal passages from 2010 were also used for every year in all future environmental scenarios. Additionally, the seasonal temperature and astronomic tidal fluctuations from 2010 were also repeated each year in all future scenarios.

Subsidence was treated as a scenario-specific variable applied to all model subroutines; and

therefore, was not directly applied to the tidal boundary conditions in ICM-Hydro; rather the entire modeled landscape was subjected to a subsidence forcing (see Section 2.3).

Eustatic SLR was a prime component of each assumed future environmental scenario and was subsequently applied to the tidal boundary condition in all ICM-Hydro simulations, with the exact rate of SLR being assigned as a unique value to each scenario, as discussed in section 2.3 (Table 1).

Storm forcing in the ICM is represented by a sequence of synthetic storms that maintains the same frequency of landfall as the historic record, while reducing the variability in the number and severity of events each ICM compartment experiences. The storms were identified by extracting water surface elevation (WSE) for both interior water bodies and more exposed coastal waters from ADCIRC simulations of the 645 synthetic storms (Attachment B4: Storm Selection for the ICM). The resulting ICM synthetic storm sequence balances the number of 20%, 10%, 2%, and 1% annual exceedance probability (AEP) – 5-, 10-, 50-, and 100-year return intervals, respectively – water surface elevation events at 33 locations across the coast. A storm was considered to "match" a given AEP if its peak WSE is within 0.5 ft of the estimated WSE exceedance corresponding to that AEP. This resulted in a "balanced" storm suite where each of the 33 locations across the coast was exposed to the same cumulative likelihood of storm-induced inundation across the 50-year FWOA period.

## 2.3 FUTURE ENVIRONMENTAL SCENARIOS

While a number of future environmental scenarios were used to generate information about the response of the coastal landscape and ecosystem to climate change and subsidence (see Appendix H: Exploratory Analysis), two scenarios were used for project selection. Model runs for future scenario simulations use boundary forcings (temperature, precipitation, evapotranspiration, coastal zone tributary hydrographs) coupled to the SLR curves included in the scenario (Table 1). The process used to develop the scenarios is described in Appendix B: Scenario Development & Future Conditions.

Table 1. Values used in lower and higher environmental scenarios

| | **Lower** | **Higher** |
|---|---|---|
| Sea level rise (regionally adjusted) | NOAA* Intermediate:<br>~0.50 m by 2070;<br>~1.07 m by 2100 | NOAA Intermediate High:<br>~0.77 m by 2070;<br>1.75 m by 2100 |
| Temperature and Evapotranspiration | following RCP 4.5 50th percentile | following RCP 8.5 50th percentile |
| Precipitation and Tributary flows | following RCP 4.5 50th percentile | following RCP 8.5 50th percentile |

| | **Lower** | **Higher** |
|---|---|---|
| Subsidence | deep subsidence + 1st quartile shallow subsidence by ecoregion | deep subsidence + median shallow subsidence by ecoregion |
| Storm Intensity (*Risk analysis only*) | +5% over 50 years | +10% over 50 years |

* National Oceanic and Atmospheric Administration (NOAA)

Subsidence values varied spatially across the model domain. The approach uses a deep subsidence map derived from data from geodetic survey benchmarks, both primary (Continuously Operating Reference Stations) and secondary (CPRA/National Geodetic Survey benchmarks), and two shallow subsidence maps created using data from rod surface elevation table-marker horizon measurements taken at CRMS sites (Attachment B3: Determining Subsidence Rates for use in Predictive Modeling). Two maps were created due to variability in the shallow subsidence data, and these were applied separately for the two environmental scenarios used in the master plan analysis. As the shallow subsidence maps are derived from CRMS data, no rates are calculated for the Atchafalaya Basin and the Verret Basin.

# 3.0 RISK ASSESSMENT MODELING

## 3.1 OVERVIEW OF SURGE AND RISK MODELING

The approach to surge and risk modeling used in the 2023 Coastal Master Plan builds on that developed for the 2012 and 2017 Coastal Master Plans (Peyronnin et al., 2013; Cobell et al., 2013; Johnson et al., 2013; Roberts & Cobell, 2017; Fischbach et al. 2017). Landscape and ecosystem characteristics including topography, bathymetry, and vegetation cover, as well as the specific alignments of structural protection measures, are used in ADCIRC and SWAN to produce water levels associated with storm surges and waves. The water level information is passed to the CLARA model which calculates flood depths and economic damage. The following sections provide an overview of these models and outline updates made for the 2023 Coastal Master Plan.

## 3.2 ADCIRC+SWAN MODEL

### STORM SURGE AND WAVES

The ADCIRC ocean circulation model has an unstructured mesh which makes it highly flexible for resolving complex coastal areas in southern Louisiana. ADCIRC is certified by the Federal Emergency Management Agency (FEMA) for use in performing storm surge analyses and has been used for many levee design and risk assessment projects in Louisiana (e.g., the Greater New Orleans Hurricane and Storm Damage Risk Reduction System). ADCIRC is tightly coupled with UnSWAN, a spectral-wave model, which accounts for propagation of nonstationary waves. Coupling of ADCIRC with UnSWAN allows for storm surge and wave modeling applications such as those used for the master plan.

The ADCIRC+SWAN model used in the 2023 Coastal Master Plan has a variable mesh resolution, from 80 km in the Atlantic Ocean to 30 m in inland channels and contains ~1.5 million nodes (Attachment E1: Storm Surge and Waves Model Improvements). The model uses land cover data from the ICM, as well as topography on which raised features and levees are superimposed. Model validation of storm surge impacts was conducted using hurricanes Gustav, Ike, Katrina, Rita, and Isaac (Figure 6). These are recent storms for which field measurements are available for validation. Validation runs removed various newly constructed protection features to reflect the conditions under which these storms occurred.

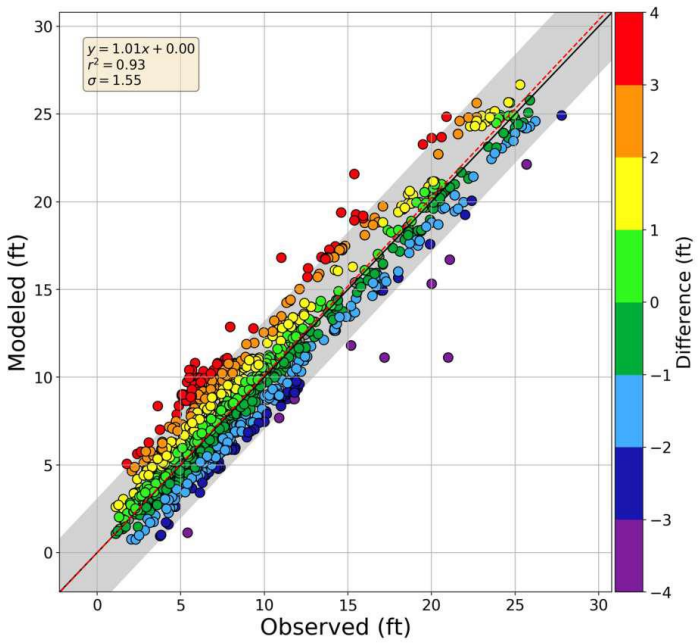


Figure 6. Model validation for Katrina, Rita, Gustav, Ike, and Isaac high water marks.

## MODEL SETUP

The initial water level for production simulations was set using local mean sea level generated from CRMS data. For future conditions, these values are incrementally raised due to SLR as dictated by the environmental scenarios used for the 2023 Coastal Master Plan. Only one flow per river was used to represent river conditions for 2023 Coastal Master Plan risk modeling, selected to be characteristic of flow conditions when tropical events occur. Median river flows were used for the Mississippi River (9,175 $m^3/s$) and the Atchafalaya River (3,936 $m^3/s$).

Land use data are critical for determining frictional parameters for use within the ADCIRC model. Manning's *n* bottom roughness and a direction-specific reduction factor (derived from the FEMA Hazards United States [HAZUS] methodology) applied to the wind vectors are both derived from land use data. Two datasets were distributed for the initial landscape condition: a 15-m resolution land use dataset containing 67 land use classes generated by USGS and a 480-m resolution dataset containing seven vegetation habitat type classes generated by ICM-LaVegMod. The ADCIRC model cannot solely rely on the ICM land classification data, as the domain includes areas that are not updated by the ICM model. In addition, the 480-m resolution provided by ICM-LaVegMod is significantly greater than the ADCIRC model, which resolves features as small as 30 m. First, the 15-m land use data is interpolated to the ADCIRC mesh and validated with specific adjustments for water bodies. Then, the 480-m land use data is applied to the same ADCIRC mesh. ADCIRC Manning's *n* bottom roughness and direction-

specific reduction factors are calculated based on the initial condition 480-m data and the difference calculated for future land use data layers. The difference is then applied to the initial conditions ADCIRC model frictional parameters derived from the 15-m dataset to reflect future conditions so that the fine granularity of the 15-m dataset is not lost.

Storm simulations used synthetic hurricanes from a synthetic storm suite developed by USACE which contains 645 storms in total. A subset of these storms was selected to most closely represent storm surge levels state wide, balancing accuracy in the statistics with the computational cost of running the storm surge model. Ultimately, a suite of 95 storms was used for the analysis (Figure 7).

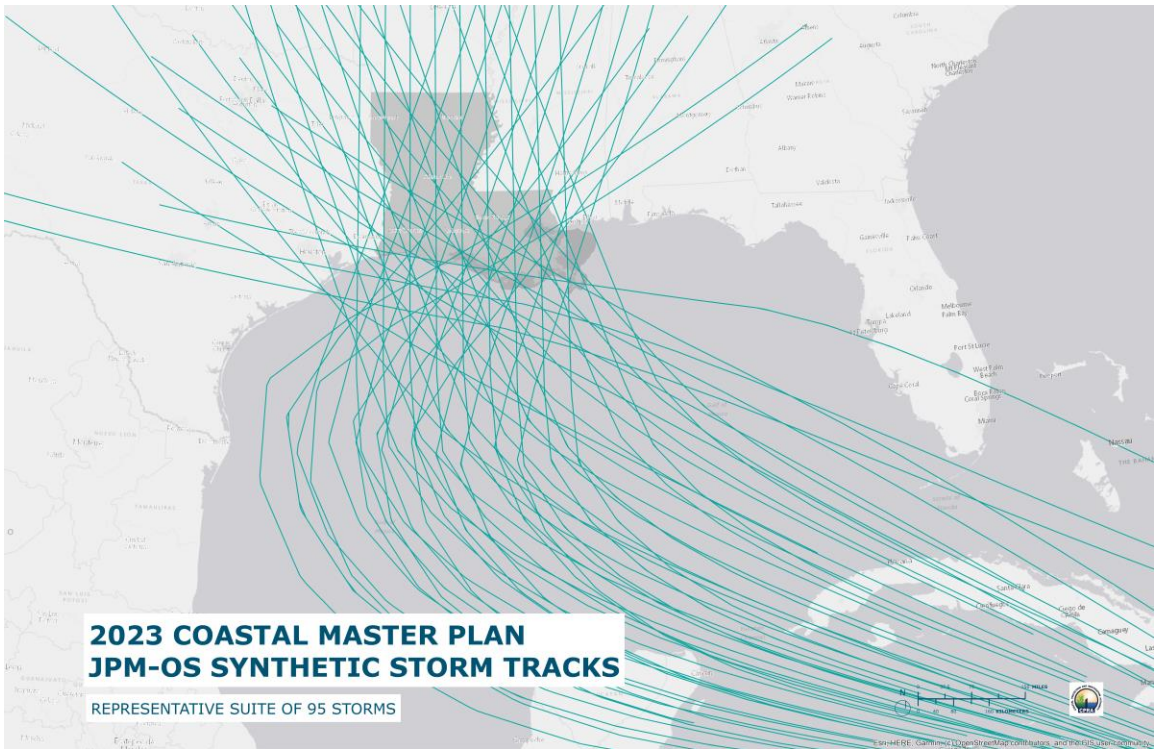


Figure 7. Storm tracks for the 95 synthetic storms used in the 2023 CLARA analysis. * Joint Probability Method with Optimal Sampling (JPM-OS)

Tests were conducted to assess wind drag and bottom friction formulations, and these were coordinated with USACE, Louisiana State University (LSU), and University of North Carolina (UNC) to ensure all ADCIRC modeling applied by state and federal agencies to coastal Louisiana is based on a consistent set of assumptions. The selected method uses the Garratt wind drag approach with a limit on bottom friction.

ADCIRC+SWAN generates peak water level, peak wave heights, and peak wave periods as well as time series. Water surface and wave height data are saved at each CLARA grid point for use in damage

calculations, and additional timeseries data are saved adjacent to levees to compute overtopping.

More details about the ADCIRC+SWAN model used for the 2023 Coastal Master Plan can be found in Attachment E1: Storm Surge and Waves Model Improvements.

## 3.3 COASTAL LOUISIANA RISK ASSESSMENT (CLARA)

### FLOOD DEPTH STATISTICS AND DAMAGES

The CLARA model was originally created to support development of Louisiana's 2012 Coastal Master Plan. It is designed to estimate flood depth exceedances, direct damage exceedances, and expected annual damage from tropical cyclones. Monte Carlo simulation is used to estimate risk under a range of assumptions about future conditions and with different combinations of structural and nonstructural risk reduction projects on the landscape. The focus of CLARA is flood risk to structures, physical infrastructure, and other local assets (Attachment C11: 2023 Risk Model).

CLARA accounts for uncertainty in storm surge and wave levels, noise in Lidar measurements of topographic elevations, physical variability of overtopping rates, the possibility of levee/floodwall breaches, and randomness in the historical record of observed storms. Losses are calculated as a deterministic function of inundation depths and structural attributes, but the model does consider uncertainty in those attributes for both existing and future structural assets. Losses are limited to direct economic damage. This includes damage to structures, their contents and inventory, but also losses incurred during a restoration period such as lost wages and rents, costs associated with evacuation and temporary displacement, etc. Results are expressed in terms of flood damage at different AEP and an overall average across the distribution of plausible storm events (expected annual damage).

The CLARA model uses estimated storm surge and wave characteristics, along with data that characterize the landscape, hurricane protection systems, and assets at risk on the coast. CLARA distinguishes between areas with no full perimeter of levees, floodwalls, or other barriers or protection structures (unenclosed) and those with hurricane protection that surrounds the area in a ring that creates a "polder" (enclosed).

In unenclosed areas, CLARA estimates flood depths as the sum of peak surge and wave heights above ground elevation. CLARA estimates still-water flood depths for enclosed areas, based on storm surge and wave overtopping and system fragility. The model uses Monte Carlo simulation to develop a frequency distribution of enclosed flood depths resulting from randomness in overtopping rates and system breaches. Enclosed depths also account for rainfall within polders and water pumped out of the system, where pumping stations exist. Probabilistic rainfall estimates for each synthetic storm are developed using a bias-correction approach that takes into account storm characteristics such as the storm central pressure deficit, the radius of maximum winds, and the storm track (Villarini et al., 2022).

The depth of the flood directly determines the amount of damage that occurs. Model outputs include summaries of flood depth and damage exceedance values, at a selected set of AEP, expected annual damage in dollars (EADD) and expected annual structural damage (EASD) from storm surge-based flooding events. These statistical outputs are calculated by aggregating the flood depths generated by a suite of individual storms run through the model. CLARA also evaluates how many critical infrastructure facilities or historically significant structures might be flooded to a certain depth with a certain probability.

The CLARA model's spatial domain as used in the 2023 Coastal Master Plan is shown in Figure 8. It covers the Louisiana coastal zone, extends inland to encompass the 2,000-year floodplain as projected 50 years into the future, and includes Mississippi's three coastal counties. This domain is subdivided into a mixed-resolution grid of ~129,000 polygons, 105,000 of which are in Louisiana. Each grid polygon is paired with a single grid point which, in areas unenclosed by protection systems, is the location from which storm surge and wave data are extracted from the coupled ADCIRC+SWAN model. Within enclosed protection systems, the grid point is where still-water elevation and flood depth exceedances are calculated. Grid points are spaced at a resolution no coarser than a regular 1 km grid.

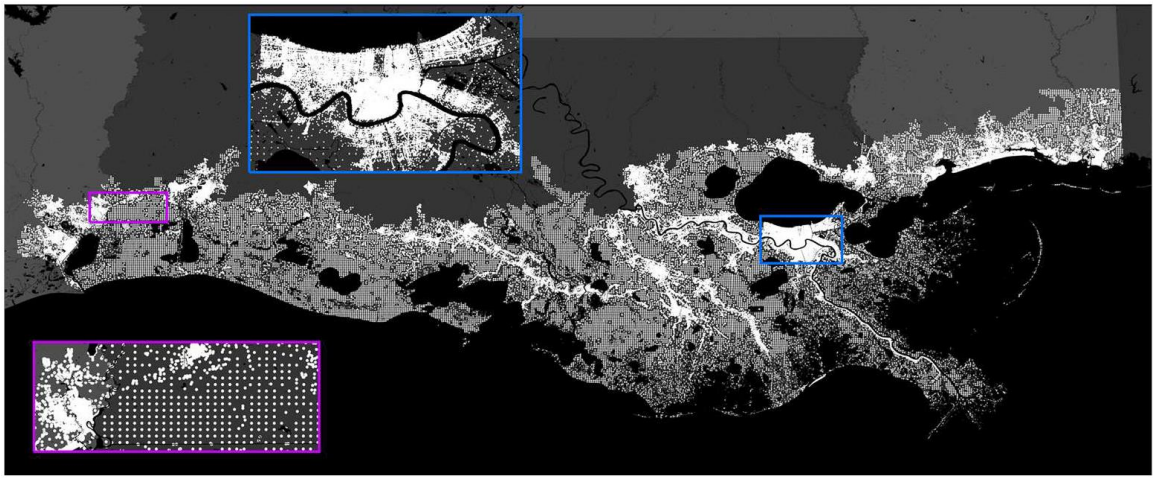

Figure 8. The CLARA model spatial domain.

The model's baseline structure inventory was assembled from multiple sources of structure- and parcel-level data: building footprint polygons developed by Microsoft Corporation (2018); building attributes (e.g., foundation type, foundation height) extracted from Google Street View imagery as described in Chen et al. (under review); the National Structure Inventory v2 (NSI), developed by USACE (Georgist, 2019); ATTOM Data Solutions; and Open Street Maps. The baseline structure inventory consists of 811,871 buildings in the Louisiana portion of the model domain. Other assets included in CLARA are vehicles, roads, and agricultural crops.

The 2023 Coastal Master Plan analysis uses a single population change scenario based on the methods described in Attachment H7: Population Projections for the 2023 Coastal Master Plan. The population is stratified into various demographic groups, and a growth rate is estimated for each at the block group level based on historical census data. Growth is then projected for each group and aggregated to estimate total population changes over time in each block group. CLARA assumes that most economic assets (all but roads, crops, and agricultural structures) scale in direct proportion with population change and the future number of assets of each type within a grid polygon are changed by the same percentage as the population change within the polygon's parent block group.

EADD for structures is calculated based on the annual probability of flood elevations, damage as a percentage of structure replacement cost, and the asset value. This implicitly prioritizes protection of higher value assets when projects are selected based on EADD. To avoid this, EASD is calculated based on only the annual probability of flood elevations and damage as a percentage of structure replacement cost. EASD for a polygon can be expressed as 'structure equivalents' summing the results for all structures in the polygon.

More details about the CLARA model used for the 2023 Coastal Master Plan can be found in Attachment C11: 2023 Risk Model.

## 3.4 FUTURE SURGE AND RISK SCENARIOS

The environmental scenarios described above are used in the ICM to produce different future landscape and vegetation conditions. These are passed to ADCIRC+SWAN for use in the surge and wave analysis and to CLARA for the determination of flood depths. Changes in the frequency and magnitude of future storms are also considered by CLARA as part of the environmental scenarios.

Two fragility scenarios are used by CLARA in the 2023 Coastal Master Plan analysis: 1) the fragility curve used in the Interagency Performance Evaluation Task Force (USACE, 2007), and 2) fragility does not occur. The fragility curves and assumptions were not applied to the levees along the Mississippi River as these river levees are assumed not to fail or breach even when overtopped.

Three pumping scenarios are used in the estimation of flood depths within poldered areas: 1) pumps operate at 100% capacity, 2) pumps operate at 50% capacity, and 3) no pumping is assumed to occur.

# 4.0 MODEL RESULTS

The models are used to predict future conditions with and without individual projects in place. The results of model runs with individual projects are compared to those without the project in place to calculate the net effect of the project on the decisions drivers – either land area or reduction in expected annual damages.

## 4.1 FUTURE WITHOUT ACTION

### LANDSCAPE CHANGE

The FWOA condition in the 2023 Coastal Master Plan serves as the baseline for predicting changes to the landscape and storm surge-based risk into the future. The initial landscape represented in the ICM and passed to the ADCIRC+SWAN and CLARA models does not necessarily reflect ongoing work. Completed projects and existing landscape features are included on the landscape with additional projects and features added based upon expectations around progress in implementing those projects. The FWOA for the 2023 Coastal Master Plan includes the Mid-Barataria and Mid-Breton sediment diversion projects, the River Reintroduction to Maurepas Swamp project, and the West Shore Lake Pontchartrain risk reduction project. To estimate the benefits of these 'currently funded' projects in terms of land area, the ICM was also used for an additional simulation without them. These future without currently funded projects (FWOCFP) runs were not used for project selection.

Figure 9 shows that for the lower scenario, by Year 50 the projects included in FWOA build or maintain an additional 74 $mi^2$ compared to the FWOCFP. Over the 50-year simulation for the lower scenario, 1,100 $mi^2$ of land are lost under FWOA (Figure 10). Much of the projected loss is concentrated in the lower basins and on marsh edges. Under the higher scenario, the effect of the FWOA projects compared to FWOCFP is a net gain of 122 $mi^2$ by Year 50 (Figure 9), although 3,000 $mi^2$ are lost compared to Year 0 (Figure 11), with every region of the coast being affected.

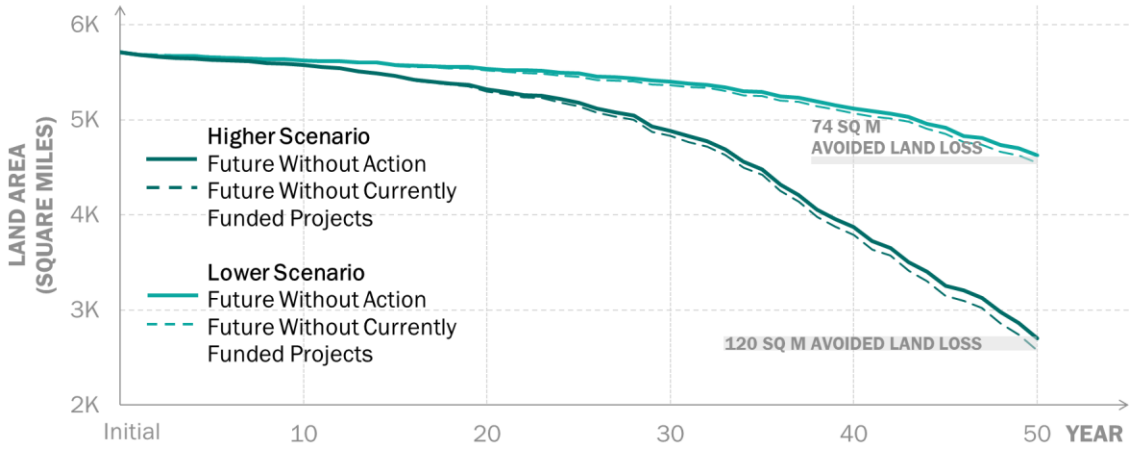


Figure 9. Land change over time for FWOA and FWOCFP for the lower (S07) and higher (S08) environmental scenarios.

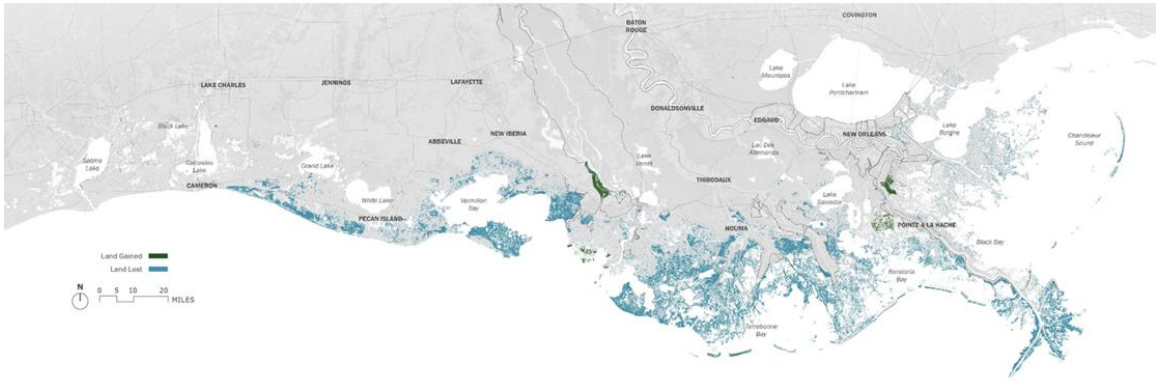


Figure 10. Land loss and gain by Year 50 for the lower scenario for FWOA.

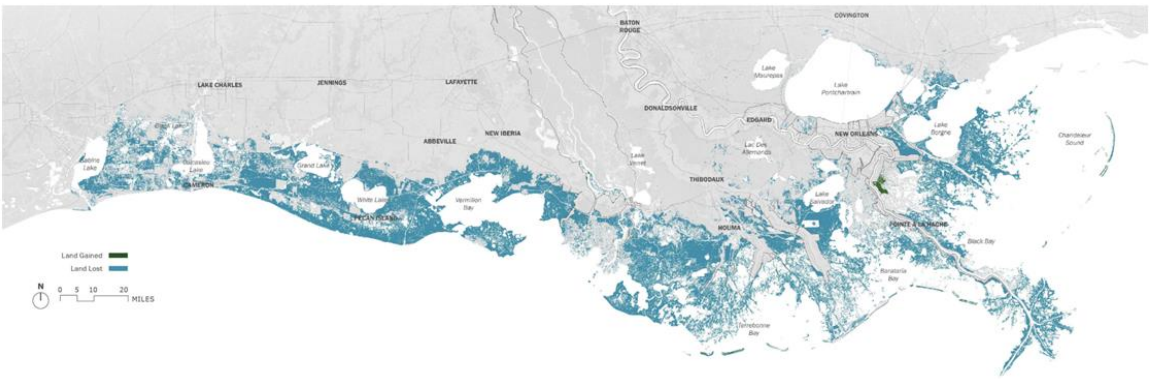


Figure 11. Land loss and gain by Year 50 for the higher scenario for FWOA.

## FLOOD RISK

The ICM simulations are continuous over the 50-year time period. However, the selected storm suite for ADCIRC+SWAN is run every decade using the topography and bathymetry and landcover change from the ICM. These outputs are used by CLARA to develop maps of flood depths based on different AEPs. Under the lower scenario at Year 50 (Figure 12) flood depths are highest east of the Mississippi River, around Vermilion Bay and West and East Cote Blanche bays, and along the coast in the Chenier Plain. For the higher scenario (Figure 13), these areas show even greater flood depths and higher flooding in the Chenier Plain, in the Terrebonne Basin, and around Lake Pontchartrain.

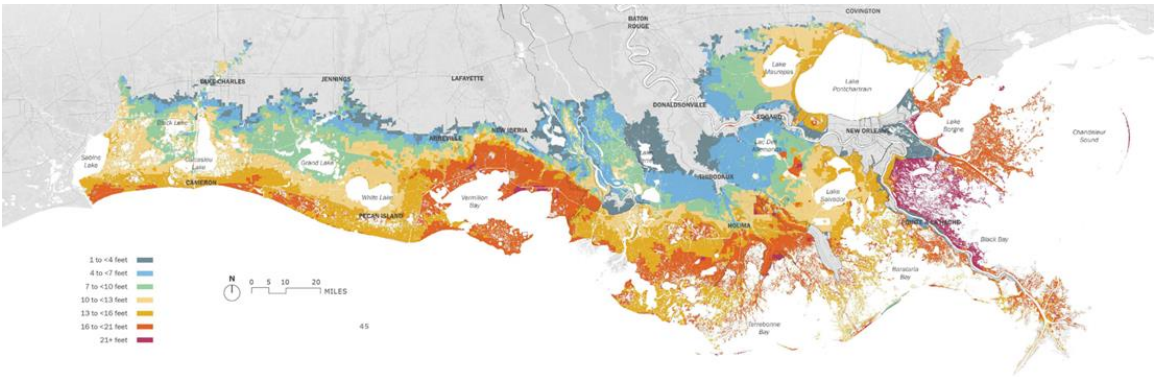


Figure 12. Flood depths at Year 50 for 1% AEP for FWOA under the lower scenario.

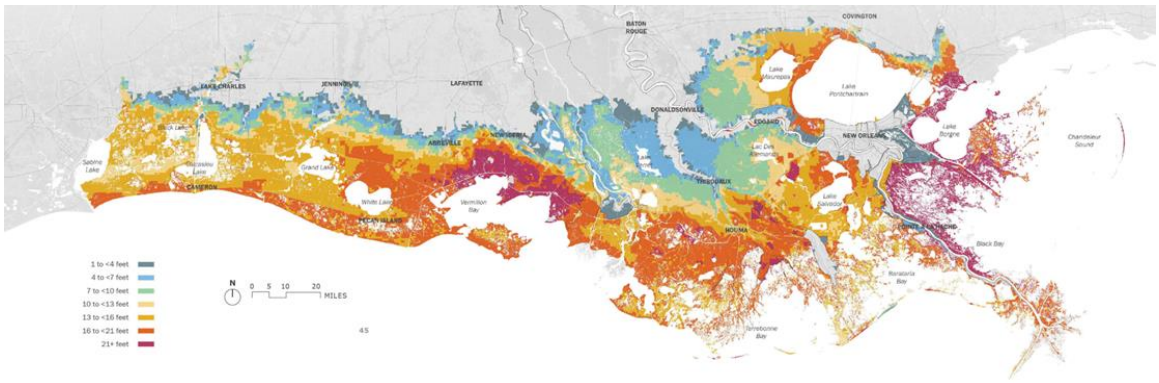


Figure 13. Flood depths at Year 50 for 1% AEP for FWOA under the higher scenario.

Figure 14 shows the consequences of these flood depths for damages in dollars. EADD increases over time for both scenarios with greater increase in later decades. EADD at Year 50 is $15 billion for the lower scenario and $24 billion for the higher scenario. Similar trends over time are shown for EASD (Figure 15) with 14,000 and 22,000 structure equivalents damaged at Year 50 in the lower and higher scenarios, respectively.

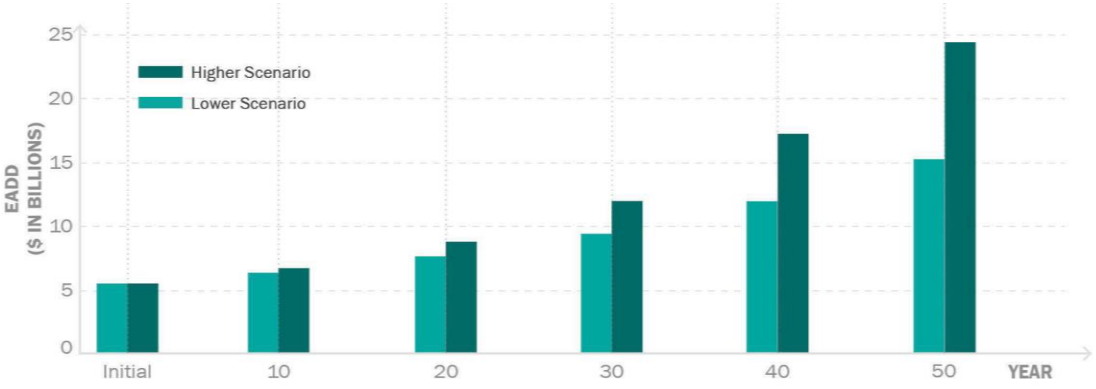


Figure 14. EADD for the higher and lower scenarios by decade for FWOA.

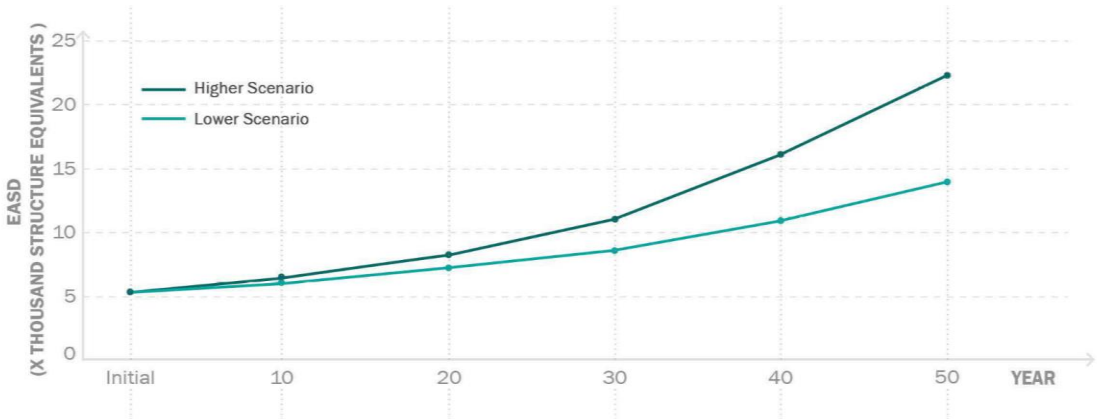


Figure 15. EASD for the higher and lower scenario for FWOA.

## 4.2 FUTURE WITH ACTION

### LANDSCAPE CHANGE

The 2023 Coastal Master Plan includes 61 restoration projects, 12 structural risk reduction projects and $11 billion allocated to nonstructural risk reduction. The ICM simulations of the FWA include both restoration and risk reduction projects on the land scape. Figure 16 shows their combined effect on land area for the lower and higher scenarios. Avoided land loss, or the net effect of the plan, is 314 $mi^2$ at Year 50 for the lower scenario and 233 $mi^2$ at Year 50 for the higher scenario.

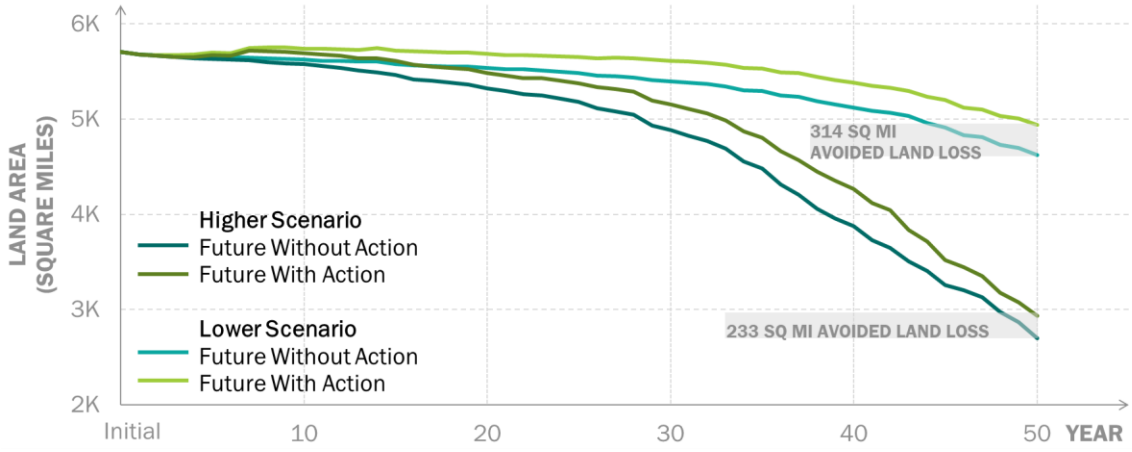


Figure 16. Land area change over time for FWOA and FWA for the lower and higher scenarios.

The net benefit varies over time and by scenario (Figure 17). Under the lower scenario there is a gradual increase in the benefits over time. Under the higher scenario the maximum benefit of 395 $mi^2$ of additional land is at Year 40. The benefits of many of the early projects diminish in the final decade as they can no longer keep pace with subsidence and accelerated rates of SLR.

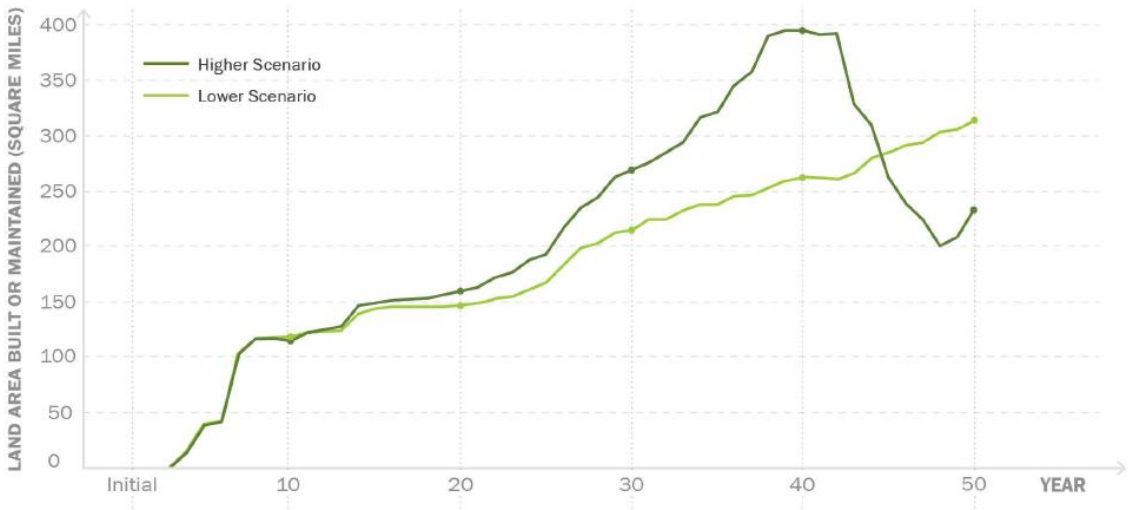


Figure 17. Net land area benefits of the master plan projects over time for the lower and higher scenario.

Across the coast, the effects of the restoration projects are apparent at Year 50 in the lower scenario (Figure 18) where marsh creation and other projects that directly build land show as land gain. There are also extensive areas of land sustained, i.e., land that would have been lost without the projects in place. Loss still occurs across much of the Terrebonne Basin and in the Bird's Foot Delta.


Figure 18. Land change at Year 50 compared to FWOA, lower scenario.

As discussed above, due to accelerated SLR in later decades and the higher rates of subsidence, land loss is much more extensive at Year 50 in the higher scenario (Figure 19). Several projects are sustaining or maintaining land, and loss is lower near areas of riverine input including the Atchafalaya Delta and near the mid-basin and Maurepas swamp diversion projects.


Figure 19. Land change at Year 50 compared to FWOA, higher scenario.

## FLOOD DAMAGES

The impact of the master plan projects (structural risk reduction and restoration projects) on flood depths compared to FWOA is best shown in a difference map (Figure 20 and Figure 21). The effects of the structural risk reduction projects can be seen in the central and eastern parts of the coast where flood depths are reduced landward of structures and there is some increase in flood depths on the seaward side. The effects of restoration projects on flood depths can be seen in the Chenier Plain, especially west of Lake Calcasieu where flood depths are reduced over large areas even though there are no structural risk reduction projects.

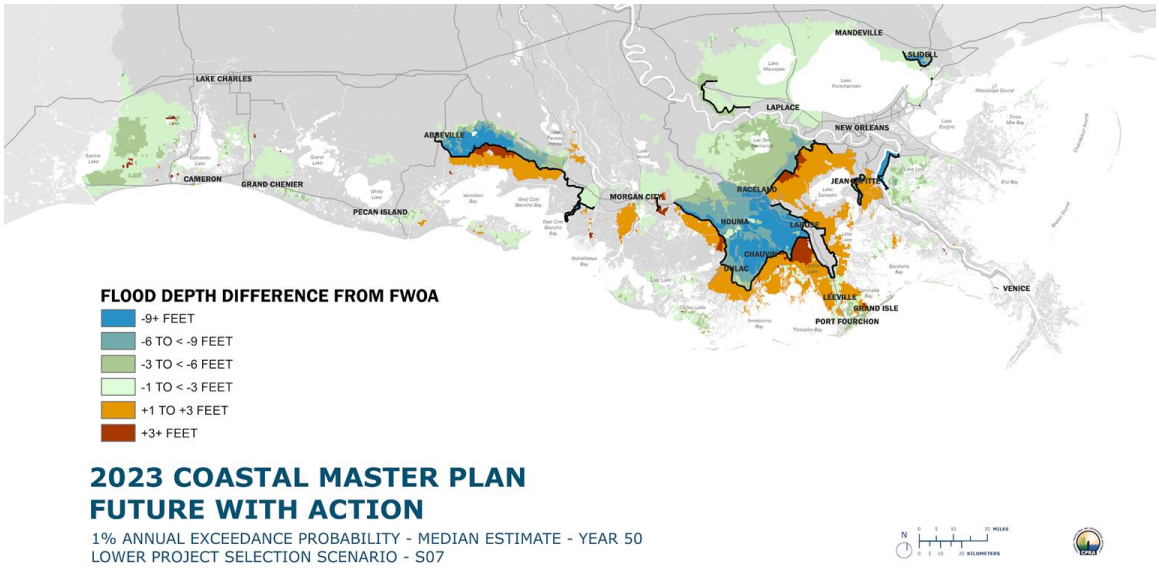


Figure 20. Flood depth differences for the master plan compared to FWOA for 1% AEP at Year 50, lower scenario.

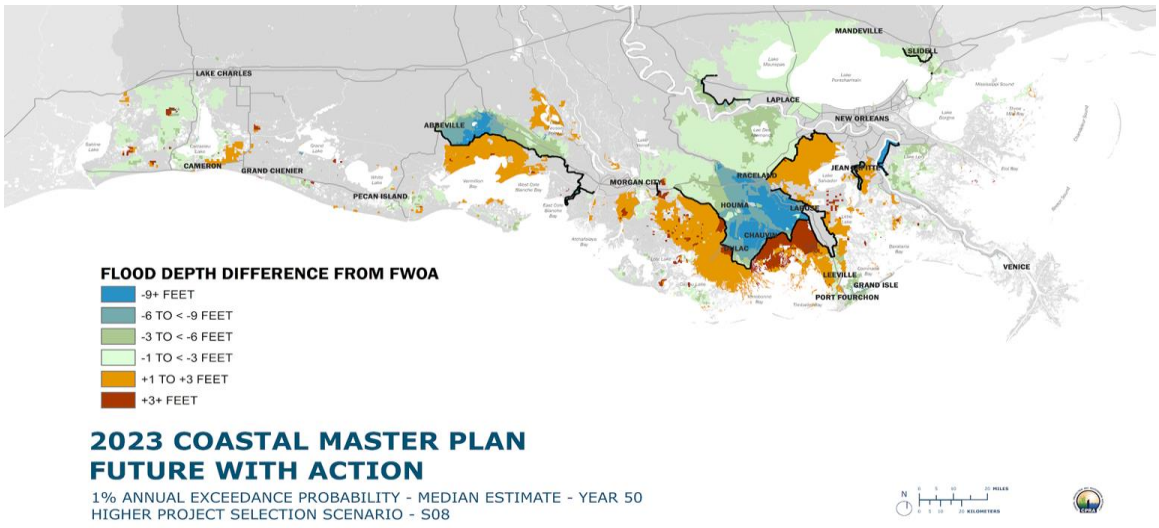


Figure 21. Flood depth differences for the master plan compared to FWOA for 1% AEP at Year 50, higher scenario.

An example of how these changes in flood depths influence flood damages is shown in Figure 22. Some areas do show a slight increase in damage (purple shading), but the magnitude is much smaller than the benefit shown in other areas either due to structural protection (e.g., Slidell area) or due to the effects of restoration (e.g., Lake Charles area). Fully implementing the plan could reduce future damage by up to 70% under the lower scenario and 60% under the higher scenario (measured in EADD) compared to a future without action. The risk reduction, as measured in EASD, shows similar effects reducing coastwide risk by up to 78% under the lower scenario and 65% under the higher scenario.

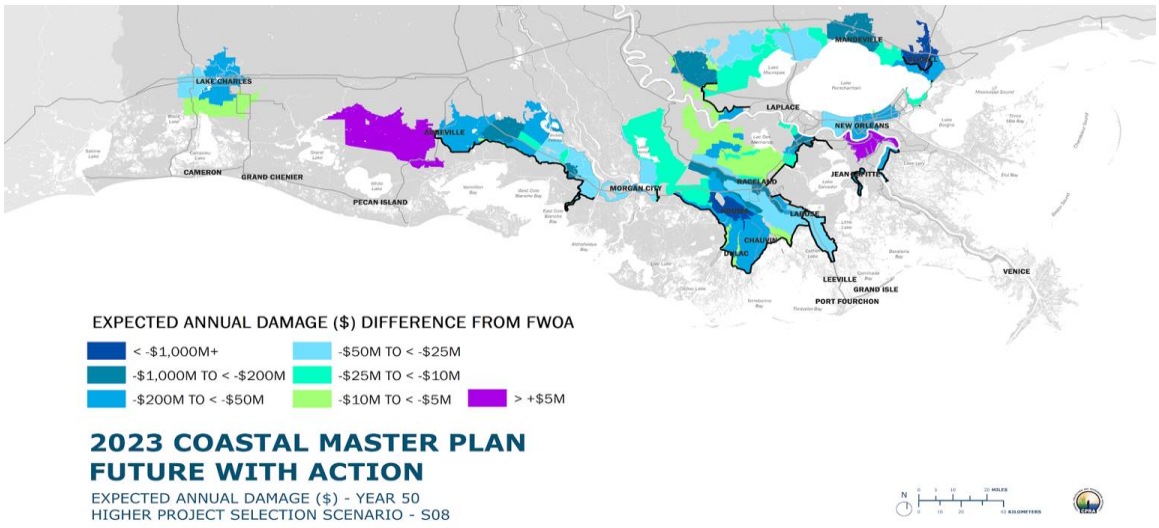


Figure 22. Difference in EADD, compared to FWOA, for the master plan at Year 50, higher scenario.

As nonstructural projects are expected to be implemented at a local scale, their effects on communities cannot be mapped. However, estimates can be made at the coastwide scale of the effects of these investments on risk reduction. Figure 23 show this for the lower scenario with the effects of nonstructural projects calculated based on the flood depths with the full master plan in place. Residual risk in the future, i.e., that which is not mitigated by the plan, remains relatively stable over time, while the effects of both structural and nonstructural projects increases over time. Figure 23 also shows that a greater proportion of the risk is reduced by the projects when measured in EASD.

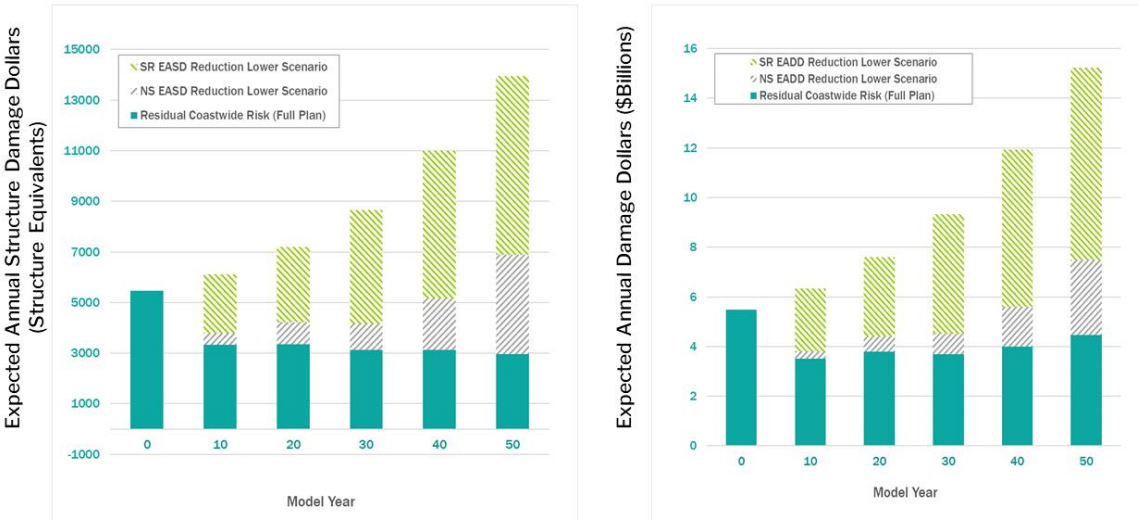


Figure 23. Coastwide residual risk and risk reduced by master plan structural and nonstructural efforts for the lower scenario. Left: EASD. Right: EADD.

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