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Louisiana's 2012 Coastal Master Plan: Overview of a Science-Based and Publicly Informed Decision-Making Process

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ABSTRACT

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Louisiana is in the midst of a land loss crisis that has claimed more than 4800 km^2 since the 1930s. Unless aggressive, large-scale action is taken, Louisiana could lose an additional 4500 km^2 in the next 50 years, resulting in a projected increase in annual damages from hurricane storm surge flooding of more than $23 billion. Louisiana's 2012 Coastal Master Plan is a long-term plan with clear economic, social, and environmental benefits, such as decreasing potential damages from storm surge by $5.3 billion to $18 billion. Implementation of projects in the master plan should result in no net loss of land after 20 years and an annual net gain of land after 30 years. To develop the plan, the Coastal Protection and Restoration Authority (CPRA) utilized a state-of-the-art systems approach to coastal planning and a science-based decision-making process that resulted in a funding- and resource-constrained plan that makes the greatest progress toward achieving a sustainable coast. A series of integrated, coastwide predictive models were developed to provide data for a new planning tool used to identify the suite of projects that would make the greatest progress toward meeting the master plan objectives while considering uncertainties in future environmental conditions. Recognizing that the success of the plan hinges on stakeholder support, as well as science, the CPRA also implemented a comprehensive outreach plan to obtain input and feedback from key stakeholders and the public. The resulting plan recommends a specific list of restoration and protection projects and has achieved widespread support.

ADDITIONAL INDEX WORDS: *Restoration, risk reduction, protection, coastal planning, ecosystem services.*

INTRODUCTION

The wetlands, swamps, barrier islands, and ridges of coastal Louisiana are part of a unique and complex system that developed in response to delta switching of the Mississippi River system over the past 7000 years (Day *et al.,* 2007). Unfortunately, this dynamic region has experienced drastic land loss since at least the 1930s (Couvillion *et al.,* 2011). The deltaic system of SE Louisiana has been deprived of sediment and freshwater inputs due to the current management regime of the Mississippi River. The entire system, including the Chenier Plain of SW Louisiana, has been affected by manmade canals and channels, which have caused direct and indirect impacts to the landscape (Turner, 1997). Ongoing geological and physical processes, such as subsidence, sea level rise, and tropical cyclonic activity, also continue to exacerbate the loss of land (Barras, 2009; Chmura, Costanza, and Kosters, 1992; Deegan, Kennedy, and Costanza, 1983; Georgiou, Fitzgerald, and Stone, 2005). Combined, all of these factors have contributed to the loss of approximately 4877 km^2 since the 1930s and to a recent land loss rate of 42.9 km^2/y (Couvillion *et al.,* 2011).

Not only has this land loss resulted in increased environmental, economic, and social vulnerability, but these vulnerabilities have been compounded by multiple disasters,

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including hurricanes, river floods, and the 2010 Deepwater Horizon oil spill, all of which have had a significant impact on the coastal communities in Louisiana and other Gulf coast states. For example, nine of the 10 costliest U.S. hurricanes have impacted a portion of the Gulf coast, and six of these have occurred in the last decade (Blake, Landsea, and Gibney, 2011). Hurricane Katrina resulted in at least $105 billion in direct property damages (Blake, Landsea, and Gibney, 2011); however, reactionary spending is estimated to be more than $250 billion (CPRA, 2012). A 2005 study found that $1 spent on flood and wind disaster mitigation saves $4 in response, with a range of benefit–cost ratios from 2.8 to 24.9 for specific communities (MMC, 2005).

Decades of planning have focused on addressing either risk reduction or coastal restoration or focused only on specific regions of coastal Louisiana. The Coastal Wetlands Planning, Protection and Restoration Act was passed in 1990 to provide funding to plan, design, and construct coastal restoration projects across coastal Louisiana. Although more than 150 projects have been authorized to date, the scale of these projects and the funding available for the program (more than $1 billion since 1990) have not resulted in a net gain of wetlands. The Louisiana Coastal Area (LCA) study was initiated in 2002 following the realization that a systems-level approach was needed to support the development of a comprehensive large-scale restoration program for coastal Louisiana. Conceptual models were developed by the Coastal Louisiana Ecosystem Assessment and Restoration (CLEAR) program to identify drivers, interactions, and outcomes of ecosystem restoration alternatives for Louisiana and to establish project performance measures (Nuttle *et al.,* 2008). The CLEAR framework of desktop numerical models was used to forecast the effects of alternative restoration projects for the LCA study (USACE, 2004), as well as for the 2007 Master Plan (CPRA, 2007). The Louisiana Coastal Protection and Restoration (LACPR) Technical Report, provided to Congress in 2009 by the U.S. Army Corps of Engineers (USACE), presented an array of risk reduction and restoration options using a multiple lines of defense approach (USACE, 2009). This report also informed stakeholders of the tradeoffs among options that should be considered in future decisions to maintain existing risk levels, reduce risk, or both along the Louisiana coast. The plan did not include specific recommendations for projects to be funded by state or federal governments.

It was not until the hurricanes of 2005 that planning efforts began to integrate coastal restoration with coastal protection. The 2007 Master Plan, developed under the direction of the Louisiana Legislature, was the first effort to emphasize coordinated storm risk reduction and coastal restoration planning. The Coastal Protection and Restoration Authority (CPRA), the state entity responsible for planning, designing, and implementing coastal protection and restoration projects, was tasked by the Louisiana Legislature to update the master plan every 5 years. For the first update in 2012, the CPRA focused on expanding the technical analysis and outreach and engagement (O&E) efforts to best identify specific projects that represent sound, efficient investments for Louisiana, considering resource and funding constraints, as well as future uncertainties. *Louisiana's Comprehensive Master Plan for a Sustainable Coast* (commonly referred to as *Louisiana's 2012 Coastal Master Plan*) built on previous efforts by including a detailed prediction of the future without action and an objective evaluation of the performance of hundreds of previously proposed projects, including nonstructural measures, over the next 50 years. The 2012 Coastal Master Plan includes a specific list of 109 recommended restoration and protection projects, as shown in Figure 1.

METHODS

The CPRA developed a decision-making process aimed to ensure that formulation of the 2012 Coastal Master Plan relied on the best science and technical information while still incorporating extensive public outreach (Figure 2). The decision-making process was guided by the articulation of a clear mission, the review and refinement of the 2007 Master Plan objectives to reflect lessons learned, and the development of guiding planning principles to aid in meeting the mission and objectives of the 2012 Coastal Master Plan. The CPRA clearly defined these objectives to reflect key issues affecting communities in and around Louisiana's coast: (1) reduce economic losses from storm surge flooding, (2) promote a sustainable coastal ecosystem by harnessing the natural processes of the system, (3) provide habitats suitable to support an array of commercial and recreational activities coastwide, (4) sustain the unique cultural heritage of coastal Louisiana, and (5) promote a viable working coast to support regionally and nationally important businesses and industries.

Although guided by the overall objectives, the CPRA developed O&E principles, planning principles, and a technical analysis to best understand the potential for the master plan to successfully meet the defined objectives (Figure 2). As depicted in Figure 2, each of these overarching areas was intertwined with active inputs and feedback from the other areas.

The CPRA developed O&E principles (Table 1) to ensure structured and transparent conversations with key businesses and industries, federal agencies, nonprofits, academia, fisheries interests, and the public as a critical element of a well-rounded plan. Several groups were organized to provide input to the decision-making process. The Framework Development Team, consisting of an array of key stakeholders, worked to confront, discuss, and reach consensus on the issues that arose during plan formulation. Focus groups were developed to provide details about issues and solutions particular to specific user groups, such as navigation, oil and gas, or fisheries. A Science and Engineering Board and three technical advisory committees were formed and populated with national and international experts who offered high-level input and assessment of the technical components of the planning process. Community meetings, public meetings, and more than 120 civic presentations were held, and a community survey and a telephone poll survey were conducted to gather information on citizens' ideas and concerns to incorporate into the decision-making process. Local elected officials, legislators, and community groups were also targeted to provide input throughout the planning process.

With input from the advisory groups, the CPRA developed 15 planning principles to guide the decision-making process

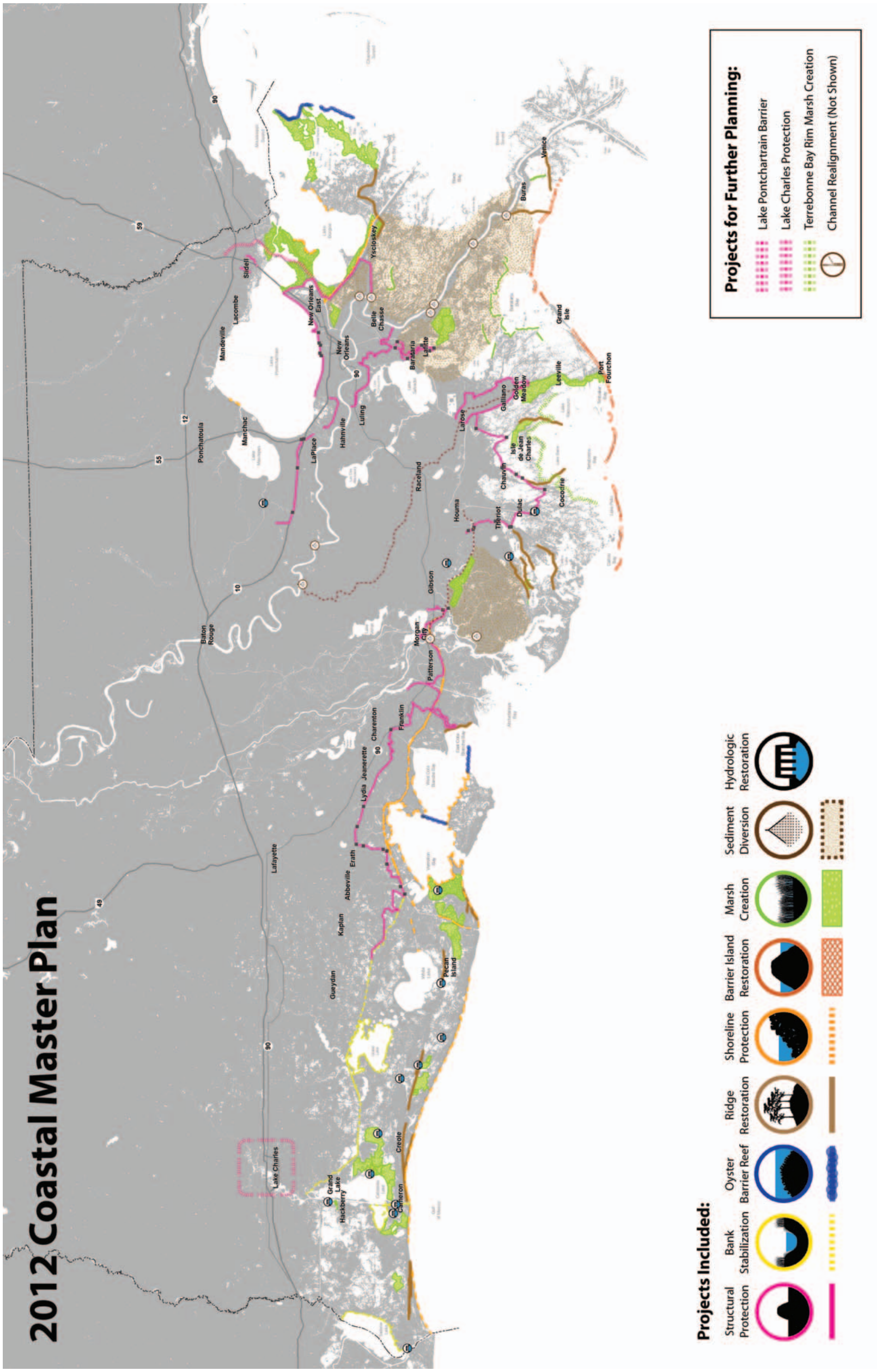

Figure 1. Map of restoration and protection projects included in the 2012 Coastal Master Plan. Project footprints or sediment diversion influence areas are indicated. The coastwide nonstructural program is not indicated on the map.

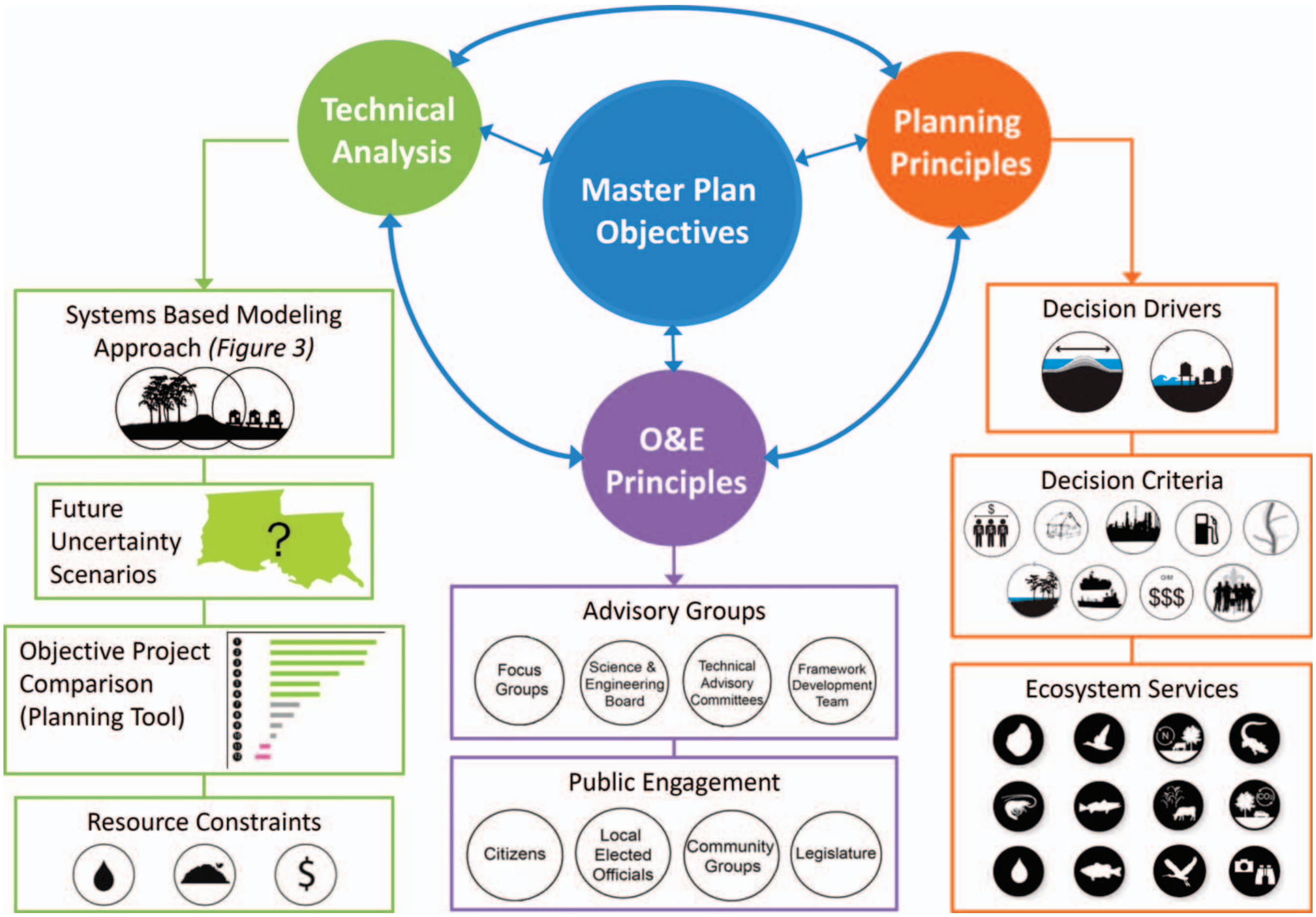

Figure 2. The decision-making process is a complex interaction of input and feedback among a technical analysis, O&E principles, and planning principles. The overall goal of the master plan is defined by the objectives (see "Methods"). The systems-based modeling approach, future uncertainty scenarios, planning tool, and resource constraints all contribute to the technical data needed for the decision-making process. The planning principles and formulation involve decision drivers, decision criteria, and ecosystem service metrics (as described in "Methods"), which help determine the plan's ability to meet the objectives. The O&E strategy was designed to ensure public input and acceptance throughout the decision-making process, and multiple groups were involved in defining and reviewing the technical analysis and plan formulation.

(CPRA, 2012). In summary, these planning principles were (1) providing long-term solutions, (2) seeking sustainability, (3) using a systems approach, (4) articulating clear expectations, (5) acknowledging residual risk, (6) defining the public's role, (7) providing for transition, (8) encouraging a participatory process, (9) accounting for uncertainties, (10) adapting to changing circumstances, (11) using resources efficiently, (12) focusing on renewable sediment sources, (13) ensuring consistency, (14) understanding regulatory effects, and (15) partnering with the private sector. These principles helped guide the decision-making process, greatly contributing to the depth and breadth of the master plan.

In addition to extensive outreach and planning principles, the decision-making process was supported with a systems-

Table 1. *O&E principles*.

Scope	Citizens should be given opportunities to learn about and comment on the tools and processes that create the plan, not just the finished plan.
Timing	Citizens' comments and ideas should be received, reviewed, and incorporated while the plan is being developed, not after the fact.
Fair Hearing	Not every citizen preference can be included in the plan. However, the state can promise that each idea will receive a fair hearing and that questions will be answered promptly and honestly.
Access	The state must provide a variety of ways for citizens to learn about and participate in the master planning process, including small group gatherings, web offerings, direct communication with local and state governments, and public meetings.

based scientific analysis that focused on forecasting ways in which restoration and risk reduction projects could contribute to the achievement of the objectives of the 2012 Coastal Master Plan. The 2012 Coastal Master Plan utilized technical tools and analysis to demonstrate the consequences of continued loss of coastal land, as well as the benefits from investment and implementation of coastal protection and restoration projects. Building and maintaining land and reducing risk were the key decision drivers for selecting projects. Decision criteria and ecosystem service models were also used to reflect the objectives of the master plan. In addition, project implementation constraints were defined to reflect planning conditions not necessarily under the control of the state, such as funding and sediment availability. The CPRA used data generated by seven integrated predictive models (or model suites), nine decision criteria, and various project implementation constraints. The integrated models were imperative to the decision-making process, because they provided an objective evaluation of hundreds of projects to ensure that informed decisions were made. The models also provided the technical support needed to defend project decisions to the public, key stakeholders, and elected officials.

The 2012 Coastal Master Plan also demonstrated the need for decision support tools that allow massive amounts of data to be evaluated objectively and efficiently. The Planning Tool was used to filter data, prioritize projects, and formulate groups of projects based on select specifications. The Planning Tool was instrumental in providing a scientific and objective basis for evaluating the terabytes of data produced by the predictive models for each risk reduction and restoration project proposed for Louisiana. It developed and analyzed hundreds of different groups of projects that would best meet Louisiana's goals of reducing hurricane flood risk and achieving a sustainable landscape. It also provided decision makers with the ability to specify planning parameters, such as total available funding, funding splits between risk reduction and restoration projects, near- and long-term goals, and minimum levels of projected achievement of goals for ecosystem service and decision criteria. Lastly, the Planning Tool identified groups of projects that could be implemented over the 50-year planning horizon to maximize achievement of Louisiana's risk reduction and land building goals, while considering other preferences or decision criteria.

Systems-Based Modeling Approach

A comprehensive list of 1500 candidate projects was developed by mining studies, reports, presentations, and plans going back to 1998. The list needed to be comprehensive enough to represent the breadth of thinking in coastal restoration and protection but manageable enough that each project could be evaluated individually. Screening criteria included elimination of duplicate projects or concepts, availability of adequate information for analysis, standardization of similar project types, and project scale, with a general focus on projects greater than 2 km^2 (or approximately 500 acres). The result was a candidate list of 397 projects.

The 397 projects were evaluated individually within a systems context through a new and improved suite of predictive models, as depicted in Figure 3. The linked models predict change in the conditions of the Louisiana coastal system under two types of future management strategies: a future without the implementation of additional restoration and risk reduction projects (future without action) and a future with implementation of individual projects (future with project). The concept of linked models in Louisiana coastal planning is not new, because linked models were applied to aid restoration planning for the 2004 LCA study (USACE, 2004) and several linked models were used to inform the 2007 Master Plan (CPRA, 2007, Appendix G). Substantially improved or entirely new feedback and links among models were developed and utilized to support the 2012 Coastal Master Plan process (Figure 3, yellow arrows). In addition to new links, several entirely new models were created to support this effort. Each of the models provides inputs to other models, produces outputs, or both that are used to estimate how the landscape might change, as well as how projects might perform on the landscape over time (Figure 3).

Ecohydrology

The ecohydrology model consists of three individual models (Chenier Plain region, Atchafalaya–Terrebonne region, and Pontchartrain–Barataria region) that are integrated to provide coastwide outputs (Meselhe *et al.,* 2013). Each model predicts the salinity, stage, and other selected water quality constituents of the open water bodies (including channels) within estuaries. For each region, a mass-balance approach was used to estimate the exchanges of solids and chemicals due to advection and dispersion. These models use conveyance links and storage cells or boxes (ranging from 0.05 to 5844 km^2) to allow multiyear simulations to be run in a few hours using a desktop computer. This approach was used previously to support restoration planning in the Pontchartrain Basin (McCorquodale *et al.,* 2009) and has been extended to the entire coast.

Wetland Morphology

The wetland morphology model tracks the changes in wetland-dominated landscapes over time, including the loss of existing wetlands, the creation of wetlands by both natural and artificial process, and the fate of those newly created wetlands (Couvillion *et al.,* 2013). Whereas previous modeling efforts simply projected past trends into the future, this model considers more characteristics of the landscape as predictors of change. The model operates on a spatially explicit platform and utilizes spatially explicit input data sets, another improvement from past modeling efforts.

Barrier Shoreline Morphology

A barrier shoreline morphology model was created for the 2012 Coastal Master Plan. Changes in barrier shorelines and headlands are derived from a simple shoreline change model driven by analysis of historical shorelines that are a part of the Barrier Island Comprehensive Monitoring project (Hughes *et al.,* 2012). The model tracks changes in both Gulf and bay sides of islands along shoreline segments to estimate changes in island shape and migration. The character of tidal inlets is determined by both barrier configuration and tidal prism, which depends on wetland loss or gain (as determined by the wetland morphology model) within the estuarine basin.

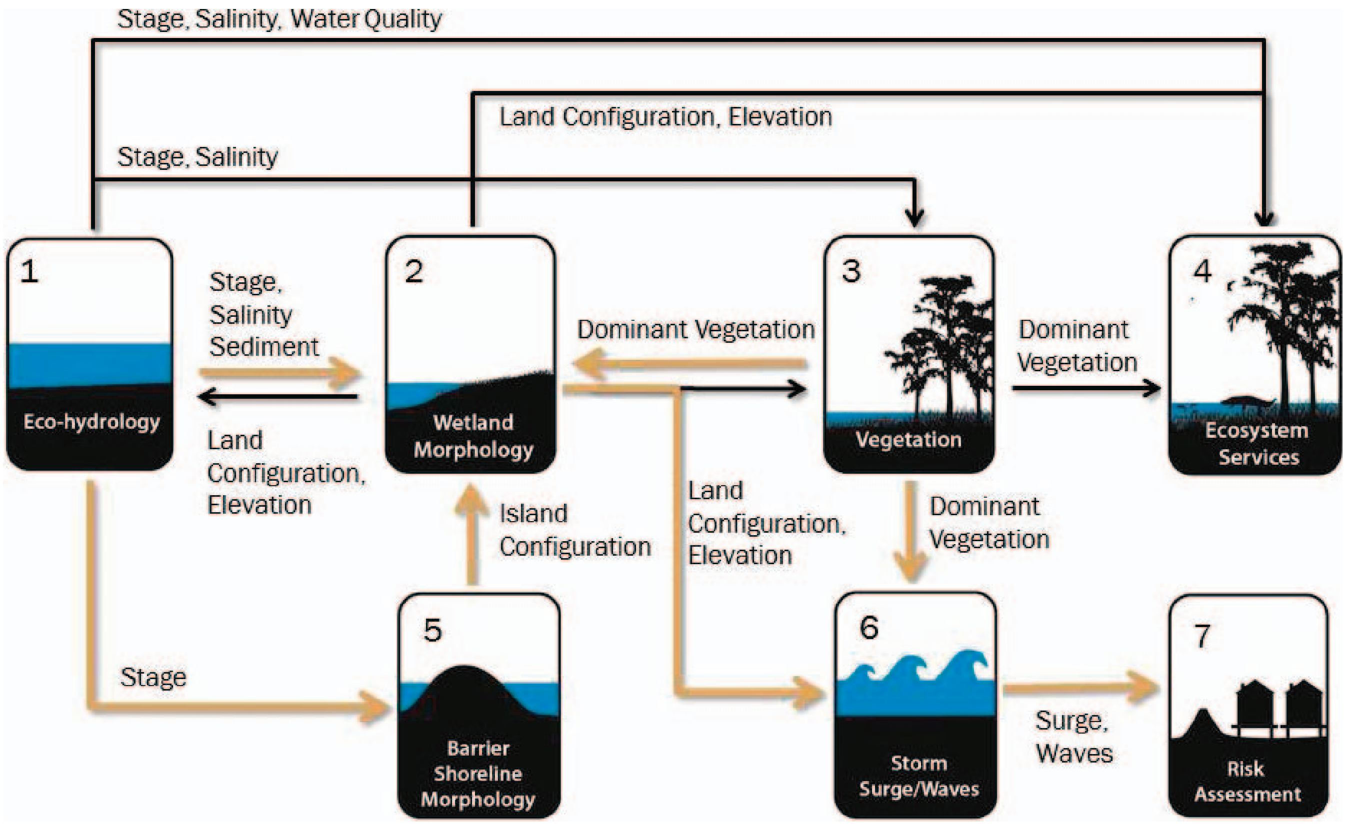

Figure 3. The modeling framework for the 2012 Coastal Master Plan used a series of integrated, coastwide predictive models within a systems context (CPRA, 2012, Appendix D). The main input and outputs of each model that are linked to other models are indicated. The yellow arrows indicate substantially improved or entirely new feedback and links developed and utilized to support the 2012 Coastal Master Plan process.

Vegetation

A vegetation model was also created for the 2012 Coastal Master Plan. It predicts the extent of 19 types or communities of emergent vegetation and submerged aquatic vegetation (Visser *et al.,* 2013). It estimates spatial and temporal changes in vegetation types or communities based on environmental drivers, such as salinity and water level change. Coastwide Reference Monitoring System data were used to establish relationships between physical conditions and plant distributions, and these relationships were used to predict change in dominant species.

Ecosystem Services

Ecosystem service models are used to predict how well Louisiana's future coast will provide habitat for commercially and recreationally important coastal species, habitats for other key species, and key services for coastal communities (Nyman *et al.,* 2013). In total, 19 ecosystem service models were utilized and included habitat suitability indices for the following species: American alligator (*Alligator mississippiensis*), muskrat (*Ondatra zibethicus*), river otter (*Lontra canadensis*), spotted sea trout (*Cynoscion nebulosus*), brown shrimp (*Farfantepenaeus aztecus*), white shrimp (*Litopenaeus setiferus*), largemouth bass (*Micropterus salmoides*), gadwall (*Anas strepera*), green-winged teal (*Anas crecca*), mottled duck (*Anas fulvigula*), neotropical migrants (varied species), roseate spoonbill (*Platalea ajaja*), wild-caught crawfish (*Procambarus clarkii*), and eastern oyster (*Crassostrea virginica*). These species were selected because they are thriving in coastal Louisiana, they are of commercial or recreational importance, or their habitat would likely be altered by protection and restoration projects. In addition to these habitat models, many of which are based on existing habitat suitability indices, new ecosystem service models were developed to reflect surge or wave attenuation potential (restoration projects only), nature-based tourism, freshwater availability, potential for agriculture or aquaculture, nitrogen uptake potential (Rivera-Monroy *et al.,* 2013), and carbon sequestration potential (CPRA, 2012).

Storm Surge and Waves

For risk reduction projects or groups of projects, the storm surge and wave model uses the widely adopted Advanced Circulation (ADCIRC) large-domain storm surge model, coupled with the unstructured Simulation Waves Nearshore (UnSWAN) wave model (Cobell *et al.,* 2013). ADCIRC uses an unstructured mesh that allows variation of resolution from coarse in the open ocean to very fine near islands, channels, levees, and areas where flow gradients are large (such as in channels and wave breaking zones). The unstructured mesh, titled *CPRA2012*, provides a precise representation of the topographic and bathymetric features and accurate representation of the flow conditions. The storm surge and wave model requires output from the wetland and barrier shoreline morphology models to determine landscape configuration, as well as output from the vegetation model to set roughness parameters. This model provides flood stage and wave time series at select locations for use by the risk assessment model.

Risk Assessment

The risk assessment model, Coastal Louisiana Risk Assessment model (CLARA), was created specifically for the 2012 Coastal Master Plan and uses an asset inventory based on 2010 census estimates (Johnson, Fischbach, and Ortiz, 2013). To estimate residual economic damages from storm surge flooding, the CLARA model predicts the overtopping of flood risk reduction structures due to surge and waves, assesses probabilistically flooding due to breaching of hurricane risk reduction systems, calculates flood elevations, and identifies economic consequences. For unprotected areas, flood height is the sum of the maximum surge height and significant wave height. For protected areas, the model calculates a distribution of flood elevations that results from overtopping and breaching of the risk reduction system. A simplified interior drainage model, including pump system performance, is used to normalize flood elevations among adjacent basins.

Environmental Uncertainty Scenarios

In developing a 50-year plan, it is important to recognize the potential for future changes and uncertainties. Therefore, each model considers environmental uncertainty factors that influence Louisiana's coastal system (Figure 4). To capture the full range of plausible future conditions and key scientific uncertainties, a high–low boundary was set for each uncertainty factor investigated. In some cases, ranges in values were selected by modeling team members based on supporting literature and their collective best professional judgment. For the subsidence rates and values and the marsh collapse threshold, plausible ranges were determined by panels of experts convened to address those uncertainties.

Three future environmental scenarios were developed that reflect specific environmental uncertainties that affect coastal planning. These uncertainties were sea level rise, subsidence, storm frequency, storm intensity, Mississippi River discharge, rainfall, evapotranspiration, Mississippi River nutrient concentration, and marsh collapse threshold. The three environmental scenarios designed to evaluate the robustness of project and plan outcomes over 50 years were designated moderate, moderate with high sea level rise, and less optimistic. The value for each uncertainty (Table 2) was selected not to represent "best" and "worst" cases but rather to represent reasonably likely values within the designated range.

A number of risk reduction uncertainties (Figure 4) were also considered by the risk assessment model. These uncertainties, which apply specifically to risk reduction projects and analysis of flood damages, include effectiveness of risk reduction project features, economic trends, and demographics (Johnson, Fischbach, and Ortiz, 2013). The environmental scenarios were paired with other scenarios reflecting uncertainty about future flood risk and potential funding available during the project evaluation.

The uncertainties in future environmental conditions are fundamentally different from the uncertainties described in the model uncertainty analysis. Herein, uncertainties refer to driving factors that may change and should be considered when planning 50 years into the future, as a means of capturing a variety of potential conditions and assumptions about how the system works. In the model uncertainty analysis, uncertainties about parameters within the models were tested and are described in Habib and Reed (2013).

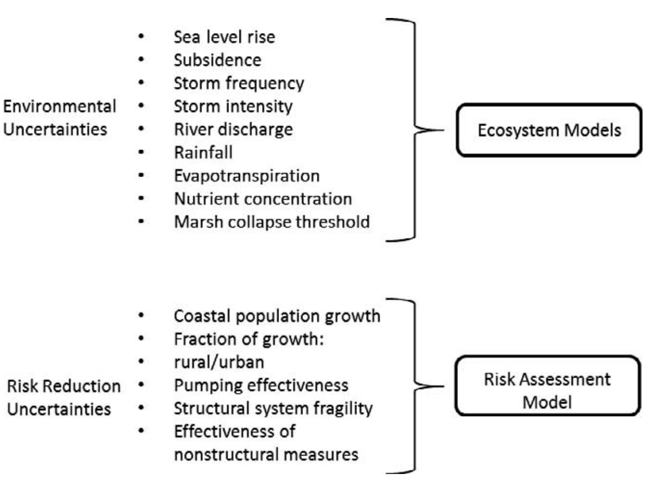

Figure 4. Key environmental and risk reduction uncertainties were used as inputs to the predictive models. The risk reduction uncertainties were considered specifically by the risk assessment model (CPRA, 2012, Appendix C).

Planning Tool

The Planning Tool is a decision support tool designed to provide an analytical and objective basis for comparing different risk reduction and restoration projects and for developing groups of projects, or alternatives, for consideration in the master plan (Groves and Sharon, 2013). The Planning Tool integrates estimates of project costs, planning and construction duration, and other project attributes with modeled output of both future without action conditions and project effects on risk reduction, land building, ecosystem services, and decision criteria. The Planning Tool ensures that each group of projects formulated satisfies a set of constraints. For example, estimated costs cannot exceed available funding, sediment requirements cannot exceed available sediment resources, and river discharge from diversions cannot reduce downstream flows below a given threshold.

River Use Constraint

The master plan analysis evaluated large sediment diversion and channel realignment projects that acknowledged the need to take large-scale action with respect to utilizing the resources of the Mississippi River. At the same time, it is understood that diverting water and sediment can affect the use of the river for

Table 2. *Environmental uncertainties used in the modeling effort.*

Environmental Uncertainty	Plausible Range	Moderate Value	Moderate with High Sea Level Rise Value	Less Optimistic Value
Sea level rise (m over 50 y)	0.16–0.78	0.27	0.78	0.45
Subsidence* (mm/y)	0–35	0–19	0–19	0–25
Storm intensity (% current intensities)	Current to +30	+10	+10	+20
Storm frequency (% current storm frequency)	−20 to +10	Current storm frequency	Current storm frequency	+2.5
Mississippi River discharge				
% Annual mean	−7 to +14†			−5
Mean annual discharge (m^3/s)		15,120	15,120	14,400
Rainfall	Historical monthly range; varies spatially	Variable percentage of historical monthly mean	Variable percentage of historical monthly mean	Variable percentage of historical monthly mean
Evapotranspiration*	Historical monthly range (±1 SD)	Historical monthly mean	Historical monthly mean	+0.4 SD from historical monthly mean
Mississippi River nutrient concentration	−45% to +20% of current nitrogen and phosphorus concentrations	−12% of current concentrations (mg/L)	−12% of current concentrations (mg/L)	Current concentrations (mg/L)
Marsh collapse threshold				
Salinity (ppt)	Swamp, 4–7 Fresh marsh, 6–8	Midrange values of salinity and inundation result in collapse	Midrange values of salinity and inundation result in collapse	Lower 25th percentile values of salinity, inundation ranges, or both result in collapse
Inundation (depth, cm)	Intermediate marsh, 31–38 Brackish marsh, 20–26 Saline marsh, 16–23			

* Values vary spatially.
† Adjusted for seasonality.
SD = standard deviation.

nationally important commerce and reduce available drinking water for coastal communities such as New Orleans. A river use constraint requires that a minimum of 5660 cubic meters *per* second (cms) (200,000 cubic feet *per* second, or cfs) be maintained in the lower Mississippi River to limit effects on navigation or drinking water supplies.

Sediment Constraint

Sediment is an essential building block for the Louisiana coast, but it is also a key constraint on the success of coastal restoration and risk reduction projects. Sediment can be delivered to the coastal ecosystem through mechanical means (dredging and pipelines) or through gravitational flow (sediment diversions). For the Planning Tool to assess adequately those projects that require sediment inputs, the predicted sediment volumes available were estimated for each borrow area identified for mechanical excavation. Where possible, existing monitoring information was used to estimate the amount of available borrow. In cases where no data exist, assumptions were made based on professional knowledge and experience. Project development aimed to identify sediment sources outside the coastal system. This is especially important considering the size of large-scale marsh creation projects (*e.g*. more than 10,000 acres), where dredging large quantities of material needed for construction would be detrimental to estuarine bays and lakes. Exceptions to this principle were made with input from key stakeholders for specific areas with adequate sediment (*e.g*. Lake Pontchartrain) and for projects with small footprints.

Funding Constraint

The master plan accounts for projections of future state and federal funding over 50 years. Because future funding levels are uncertain and have not been secured, various funding projections were developed. Future funding was projected based on estimates of existing funding and possible sources of new funding. An initial candidate list of existing funding sources was developed by reviewing relevant documents, including the 2007 Master Plan and past fiscal year annual plans. Interviews with federal and state experts were used to verify existing sources of funding, to gather data on projected future funding, and to examine assumptions on the restrictions for a particular source and the timing and levels of funding expected.

Estimates were developed for total levels of funding that could reasonably be expected by the state over a 50-year period, from 2012–61. The 50-year planning period is divided into three time intervals: 2012–31, 2032–51, and 2052–61. A low funding level was estimated at \$20 billion over 50 years, with \$8 billion in the first 20 years, \$6 billion in the next 20 years, and \$6 billion in the last 10 years. A high-level funding estimate of \$50 billion is split into \$26 billion in the first 20 years, \$13 billion in the next 20 years, and \$11 billion in the last 10 years.

Plan Formulation

The Planning Tool was designed to translate the output from the models into a visual representation of the practical implications of different combinations of projects. The formulation of the master plan focused on the selection of high-performing projects based on their individual outcomes. By focusing on individual outcomes, the master plan was able to objectively compare projects. The Planning Tool used project data over the 50-year planning horizon under different future uncertainty scenarios to rank projects that would best achieve the master plan objectives under the constraints on funding and other resources and given CPRA preferences and stakeholder values.

Decision Drivers

Two primary factors drove decisions about the projects that were selected in the 2012 Coastal Master Plan: progress toward reducing risk and progress toward building or maintaining land. These two decision drivers utilize the data created in the technical analysis to compare projects and groups of projects.

Progress toward Reducing Risk. Progress toward risk reduction across the coast is estimated by how well a risk reduction project would reduce expected annual damages at year 20 (near term) and year 50 (long term). To measure how much progress a project makes toward eliminating expected annual damages, this criterion utilizes estimates of expected annual damages at year 50 to estimate damages for communities under future without action conditions and under future with project conditions.

Expected annual damages estimates consider the risks and potential flood damages from a range of potential hurricane flood events and weight the calculated damages proportionally to the frequency that each event would be predicted to occur. The expected annual damages metric was used to allow consistent evaluation of risk reduction across the coast. The analysis focused on the likelihood of flooding over a 50-year time frame and predicted an average amount of annual flood damages for each community. Damages were expressed as dollars of damage for the year in consideration (current, year 20, or year 50).

The risk reduction score of each project (or group of projects) was based on the percentage of total expected annual damages under future without action conditions that is eliminated for each community when a project or group of projects is implemented. A coastwide score is calculated using a weighted average across communities of the percentage of total expected annual damages under future without action that are eliminated. The weighted average is designed to ensure that $1 of reduction in expected annual damages, regardless of the community, is equally valuable. The percentage of progress made toward eliminating expected annual damages is assumed to be additive across projects when calculating an alternative's score. The percentage of progress toward eliminating expected annual damages in each community is capped at 100 using linear constraints when calculating an alternative's score. The capping is applied to prevent reduction of expected annual damages below zero (because of the additive assumption) in one community from compensating for underprotection in another community.

Progress toward Building or Maintaining Land. Land creation or maintenance across the coast is evaluated for both near-term (20 years) and long-term (50 years) progress. This criterion utilizes estimates of land area under current conditions, future without action conditions, and future with project conditions to measure how much progress a project or alternative makes toward building the amount of land lost between current conditions and future without action conditions. The algorithm used to calculate the restoration score of each project (or group of projects) is based on the percentage of total land lost between current conditions and future without action conditions that is prevented by implementing a project or group of projects. This decision driver is calculated at the coastwide level, and it is assumed that land is equally valuable across the coast. This score is assumed to be additive across projects when calculating a score for a group of projects. The percentage of progress toward land maintained or created is not capped for individual regions, allowing the creation of land in one region to compensate for loss of land in another region of the coast.

Decision Criteria

The CPRA developed decision criteria to capture project effects on other landscape uses and social variables that reflect the master plan objectives. Each decision criterion relates to a specific master plan objective and was estimated for a specified project or group of projects using some combination of project attribute data, outputs from the predictive models, and expert judgment.

The following nine decision criteria were defined and included in the analysis:

(1) *Distribution of Flood Risk across Socioeconomic Groups:* Calculates a project's impact on the amount of expected annual damages in census tracts classified as impoverished by the U.S. Census Bureau in the 2005–09 American Community Survey poverty data.
(2) *Use of Natural Processes:* Represents a project's tendency to support the use of natural hydrological patterns, referred to as natural processes.
(3) *Sustainability of Land:* Reflects the sustainability of land created by restoration projects. Sustainability is approximated by a simple measure of persistence of land: the degree to which land present 40 years after construction of a project is present, shrinking, or growing 10 years later (50 years after construction).
(4) *Operation and Maintenance Costs at Year 50:* Calculates costs as the negative ratio of a project's annual operations and maintenance cost to its total cost for a 50-year planning horizon.
(5) *Support of Cultural Heritage:* Reflects the level of risk reduction to communities and the provision of natural resources within a reasonable distance of the community.
(6) *Flood Protection of Historic Properties:* Data from the Louisiana State Historic Preservation Office, Department of Culture, Recreation and Tourism, identified 5472 properties and 32 districts as historic. This decision criterion represents the ratio of the number of properties protected from flooding to the total number of historic properties under consideration.
(7) *Support of Navigation:* Represents a project's tendency to maintain the navigability of federally authorized waterways or to support or affect the navigation industry.
(8) *Flood Protection of Strategic Assets:* Represents the ratio of the number of assets protected from flooding to the total of 179 strategic assets under consideration (*e.g.* critical chemical plants, natural gas facilities, strategic petroleum reserves, power plants, petroleum refineries, ports and terminal districts, airports, military installations, and other federal facilities).

(9) *Support of Oil and Gas:* Reflects the ability of a group of projects to support the persistence of land and the ability to reduce flood risks to communities with strong ties to the oil and gas industry.

Other Metrics

Additional ecosystem service metrics, risk reduction metrics, and a critical landform criterion were also incorporated into the analysis:

(1) *Ecosystem Service Metrics:* The ecosystem service models predict changes in characteristics of the coast that can be more readily predicted (*e.g*. habitat), recognizing that service provision is ultimately limited by those characteristics (*e.g*. oyster harvest cannot flourish unless there is a sufficient quantity of high-quality habitat for oysters). Scores for ecosystem service metrics were calculated as the change in a given suitability index attributable to a project or alternative.

(2) *Risk Reduction Metrics:* The 2012 Coastal Master Plan includes varying levels of protection from storm surge–based flooding for population centers in coastal Louisiana. Scores for progress toward eliminating residual damages at 50-, 100-, and 500-year levels were calculated as the percentage of total residual damages eliminated in communities targeted at the respective level when a project or alternative is implemented.

(3) *Critical Landform Criterion:* A critical landform is one of 16 landscape features defined by the LACPR Technical Report (USACE, 2009) as important to the reduction in storm surge. This criterion represents the proportion of total possible land relative to critical landforms that is sustained or built by a specific project.

Key Assumptions

The Planning Tool calculations included a few underlying assumptions that could lead to biases when comparing groups of projects and were therefore important to consider when formulating the plan:

(1) *Risk reduction projects do not affect landscape or ecosystem measures, and restoration projects and landscape changes do not affect storm surge risk*. These assumptions are necessary because of the current computational limitations of running a complex suite of predictive models, but they may bias the effects attributed to groups of multiple projects. Without accounting for the effects of land building by restoration projects, the estimates of risk reduction attributed to an alternative are likely to be underestimated. As a result, alternatives may be formulated that overprotect some areas of the coast. Similarly, ecosystem service estimates may be biased upward or downward without accounting for the effects of structural risk reduction projects on the ecosystem.

(2) *Physical and biological effects of individual projects are additive*. This assumption applies to flood risk metrics, land area creation, ecosystem metrics, and most decision criteria and assumes that the combined effect of two or more projects is additive. In some instances, this assumption may lead to an overestimation or underestimation of the benefits attributed to an alternative.

(3) *Projects begin planning and design in the first year of an implementation period*. The Planning Tool divides the 50-year planning horizon into three time intervals referred to as implementation periods: years 1 through 20, years 21 through 40, and years 41 through 50. The Planning Tool then evaluates during which, if any, of these implementation periods a project should begin to allow the alternative to best achieve the objectives reflected in the Planning Tool. The Planning Tool includes an assumption that a project begins its planning and design during the first year of the implementation period for which it was selected. This assumption reflects the CPRA's desire to consider broad differences in implementation times while not overly constraining future sequencing of projects. Note that the implementation periods were simplified in the final plan to years 1 through 20 and years 21 through 50.

(4) *Project effects are offset by planning, design, and construction time*. Predictive models are structured such that the effects of a project begin immediately at the start of an implementation period. However, to account for differences in project planning, design, and construction times, the Planning Tool assumes that effects estimated by the predictive models can be offset by the number of years required to plan, design, and construct a project (CPRA, 2012, Appendix A).

(5) *Projects must continually operate*. The Planning Tool assumes that once the planning and design phases are begun, a project must continue through construction and be operated through the end of the 50-year planning horizon.

(6) *Funding scenarios are known, funding is available for the entire implementation period, and funding cannot be saved for use in later implementation periods*. These assumptions allowed the CPRA and stakeholders to understand the impact of funding on planning decisions. To simplify the description of the funding, funding results presented in the 2012 Coastal Master Plan are presented only in two periods: the first 20 years and last 30 years (CPRA, 2012, Appendix B).

RESULTS AND DISCUSSION

Comparison of Individual Projects

The Planning Tool was equipped with a desktop viewer to enable visual comparison of the outcomes of risk reduction projects and restoration projects. These comparisons allowed CPRA to gain insight into the range of possible effects that were estimated for each project. The Planning Tool organized data from the systems models so that it was easy to evaluate tradeoffs. For example, Figure 5 displays how an individual project (*i.e*. the Upper Breton Sediment Diversion at 7080 cms, or 250,000 cfs) can have a positive, a negative, and no effect on various ecosystem services in various basins of the coast.

In addition, the CPRA was able to compare the cost-effectiveness of each project for a given decision driver, metric,

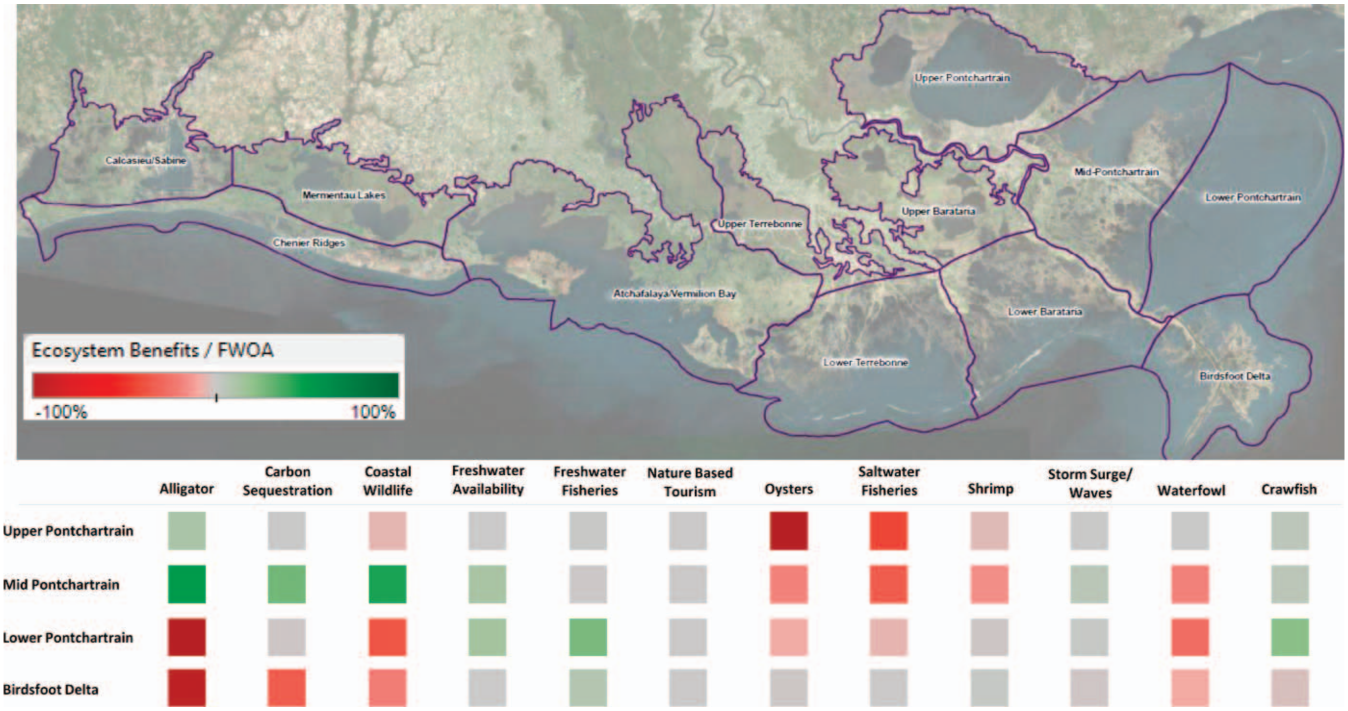

Figure 5. Each project has varying effects on ecosystem services and across different regions of the coast. As an example, the Upper Breton Sediment Diversion project demonstrates the complexities of the modeling results, which are scaled based on their difference between the future with project and the future without action. This figure indicates the complexity of the model outputs. For instance, freshwater input can increase the suitability for a specific service, but large increases in land mass could decrease suitability for the same service (*e.g.* freshwater fisheries).

or decision criterion. Because the master plan was funding limited, cost-effectiveness is an important factor in project selection.

Comparison of Alternatives

The CPRA used the Planning Tool to formulate a range of preliminary alternatives or groups of projects that could comprise the master plan. The starting point was to evaluate the benefits that can be achieved when the only focus is maximizing risk reduction and land building. Each additional step focused on understanding the sensitivity of project selection within a preliminary alternative to policy decisions and constraints. With each step, the results were compared to assess how incorporating variations in the analysis affected the maximum benefits that could be achieved.

Maximize Benefits

As the foundation of the analysis, the maximum benefits achievable were evaluated for both the moderate and the less optimistic scenarios as a benchmark for the greatest possible benefits with the projects and funding available. Max Risk Reduction and Max Land groups of projects were formulated without considering preferences other than the two decision drivers.

Funding

The plan was fiscally constrained by two estimates of potential future funding: \$20 billion and \$50 billion. The CPRA evaluated these two levels of funding in the analysis and determined that the lower end of the funding range did not provide the resources needed to significantly reduce coastal land loss or risk. Thus, the CPRA focused the remainder of the analysis on the \$50 billion funding scenario.

In addition, the CPRA evaluated the variation in benefits achieved under different allocations of funding between restoration projects and risk reduction projects. The analysis found that the CPRA could not achieve substantially more flood protection benefits by spending more than half of its available funding on risk reduction. Considering that many restoration projects provide risk reduction, the CPRA decided to take a balanced approach to funding protection and restoration projects.

Near- and Long-Term Benefits

Benefits analysis explored how restoration projects differed as the relative emphasis on the near term (year 20) and the long term (year 50) varied. The CPRA reviewed various percentages of near- vs. long-term benefits, from a primarily near-term focus (90/10) to a primary long-term focus (10/90). Using an approach that invested equally in near- and long-term projects (50/50), land building potential at the end of 50 years was less than 52 km^2 (20 mi^2) different from the Max Land project group. The CPRA decided a balanced approach provided the urgent land building needed today while also providing benefits for future generations.

Risk reduction projects, once constructed, are assumed to sustain their benefits through maintenance activities for the 50-year planning time frame. Therefore, near- vs. long-term performance did not affect the selection of risk reduction projects.

Future Uncertainties

Uncertainties analysis evaluated how alternatives performed when considering shifts in future coastal conditions. The CPRA evaluated project effects by developing Max Land and Max Risk Reduction alternatives under both the moderate and the less optimistic scenarios. The selection of risk reduction projects under the moderate scenario and the less optimistic scenario did not vary greatly. The projects selected under the Max Land less optimistic scenario tended to be located at the upper end of the estuaries, closer to existing land, and were more robust than projects selected for the Max Land moderate alternative. Heeding the adage, "Hope for the best but plan for the worst," the CPRA decided to focus on the less optimistic scenario results to increase the robustness of projects.

Decision Criteria and Other Metrics

Using the "constrained maximization" functions of the Planning Tool, the analysis explored how alternatives would change in terms of projects included and of expected outcomes as decision criteria, ecosystem service, or other metric constraints were added. The CPRA observed three categories of results: (1) the criteria or metric could not be increased because the Max Risk Reduction and Max Land project groups had already achieved the maximum possible level of that preference, (2) the increase in preference for a criteria or metric would cause a significant decline in risk reduction or land building potential, and (3) the preference for a criteria or metric is able to be increased without unduly affecting the outcomes achieved by the Max Risk Reduction and Max Land project groups.

Expert-Adjusted Alternatives and Public Input

Although the master plan was formulated on the best available science and technical information to help minimize subjective decision making, public acceptance is as important to the success of a planning effort as the science and technical foundation. Public preference or another limitation of the analysis would require that a specific project be included or excluded from an analysis. These explorations were done under guidance of the Framework Development Team.

A draft version of the master plan was released for a 45-day public comment period, during which time three public meetings and multiple briefings were held. The CPRA received thousands of comments on the draft master plan during the public comment period. Project-specific comments were used to make adjustments to the master plan, which were further evaluated in the Planning Tool. The Planning Tool allowed the CPRA to determine how project modifications requested by the public would affect the outcomes of risk reduction and land building. The CPRA considered project modifications that resulted in minor or insignificant reductions in the plan outcomes but satisfied public preference. Unacceptable project modifications consisted of proposed changes that would result in large reductions in the desired master plan outcomes, such as the removal of sediment diversions from the plan. The CPRA made minor adjustments to the plan based on this analysis. The final master plan included more than 85% of the projects selected in the Max Risk Reduction and Max Land project groups. The final 2012 Coastal Master Plan was submitted to the Louisiana Legislature, where it was unanimously approved without modification on May 23, 2012.

Modeled Individually vs. Modeled Simultaneously

The analysis conducted to support the formulation of the 2012 Coastal Master Plan focused on capturing each project's effects through a systems modeling approach. Projects modeled individually allowed the objective comparison of hundreds of projects that have been proposed for the protection and restoration of the Louisiana coast. Given time and resource constraints, it would have been impossible to model all possible combinations of projects to capture all possible project interactions. Therefore, the formulation of the master plan focused on the selection of high-performing projects.

Once the list of projects was finalized through the legislative process, the CPRA began conducting additional modeling to capture the effects of all projects modeled simultaneously. The systems modeling approach provided the opportunity to test the effects of restoration projects on protection projects and the effects of protection projects on the ecosystem. The modeling teams inserted 109 protection and restoration projects onto the modeling landscape. Projects identified for the first implementation period were added to the modeling landscape at year 0, and projects identified for the second implementation period were added to the modeling landscape at year 25. The reduction of risk from the coastwide nonstructural program was also simulated by assuming that half of the program would be completed by year 25 and the other half by year 50.

In some instances, project synergies were observed, whereby two projects have a more positive effect when constructed near each other than if either was constructed alone. Marsh creation projects are more sustainable when placed near a sediment diversion or hydrological restoration project that delivers sediment and freshwater, limits saltwater intrusion, or both. For the SE coast, the positive effects of constructing the Large-Scale Barataria Marsh Creation project in the outfall area of the Mid-Barataria Diversion project results in the maintenance of an additional 10 km^2 of land in the lower Barataria Basin over the 50-year planning period under the moderate scenario. Similarly, in the Atchafalaya–Vermilion Bay area, the construction of the Terrebonne Gulf Intracoastal Waterway Marsh Creation project within the receiving basin of the Atchafalaya River Diversion project results in the maintenance of 27 km^2 of additional land under the moderate scenario. In other instances, projects are competing for the same resource, such as sediment diversions on the Mississippi River. When modeled individually, each sediment diversion is able to take the maximum quantity of sediment and freshwater from the river. When modeled simultaneously, the sediment diversions have to share resources, which was modeled on a first come–first serve basis. Therefore, sediment diversions lower on the river do not build as much land when modeled simultaneously as when modeled individually. This is important to note when developing operation strategies for multiple projects.

When modeled simultaneously, the systems were able to capture some effects that risk reduction projects may have on the landscape. For instance, some levee systems are seen to reduce salinities in wetland areas and water bodies enclosed by the systems. This reduction in salinity can then lead to a reduction in marsh collapse and land loss. Another example is how restoration projects can significantly reduce storm surge by increasing ground elevations and providing thicker vegetation that reduces wave energy. The analysis demonstrated that some small projects reduced surge over much larger areas than the projects' footprint. These project synergies indicate that restoration, when used in tandem with risk reduction projects, can improve the level of protection provided to our coastal communities. Although the degree of protection varied with the size and track of the storm and the type of restoration project, restoration projects are shown to be an effective part of a large-scale flood protection system.

CONCLUSIONS

The 2012 Coastal Master Plan utilized technical tools and analysis to demonstrate the consequences of continued loss of coastal land, as well as the benefits from investment and implementation of coastal protection and restoration projects. Through an objective analysis of nearly 400 projects by a systems predictive modeling approach, decision makers were able to use the Planning Tool to support the selection of 109 specific restoration and protection projects that serve as the foundation of Louisiana's 50-year, $50 billion, 2012 Coastal Master Plan.

The 2012 Coastal Master Plan was unanimously passed without modification by the Louisiana Legislature on May 23, 2012. The master plan is a long-term plan for the coast with clear economic, social, and environmental benefits. The protection projects in the master plan can substantially reduce expected annual flood damages predicted at year 50 under future without action strategies ($7.7 billion and $23.4 billion under the moderate and the less optimistic scenarios, respectively) compared to future with the master plan strategies ($2.4 billion and $5.5 billion under the moderate and the less optimistic scenarios, respectively). The plan's investment in increased levels of protection could prevent $100 billion to $220 billion in direct asset damages to individuals, communities, and industry over the entire 50-year planning horizon. This savings figure does not account for reaction and recovery costs or for the incalculable human costs. These estimates do not account for improvements to the landscape by ongoing restoration measures. Future risk will be reduced even more if the land building projects in the master plan are implemented.

The restoration projects in the master plan have the potential to build or maintain between 1500 and 2100 km^2 of land over the next 50 years, depending on future coastal conditions. These projects are not predicted to prevent all land loss over the entire 50-year planning period, however, the master plan could change the trajectory of land loss, providing a positive net land change into the future (depending on when projects are funded and constructed). After 2032, the projects in the master plan could achieve no net loss of land under the moderate scenario. After 2042, the trajectory of net land change could become positive under the moderate scenario. Under the less optimistic scenario, the net land change remains negative at year 50. At that time, the models predict a land loss rate of approximately 100 km^2/y in a future without action, which could be offset by 80 km^2 of land gained annually by implementing the master plan.

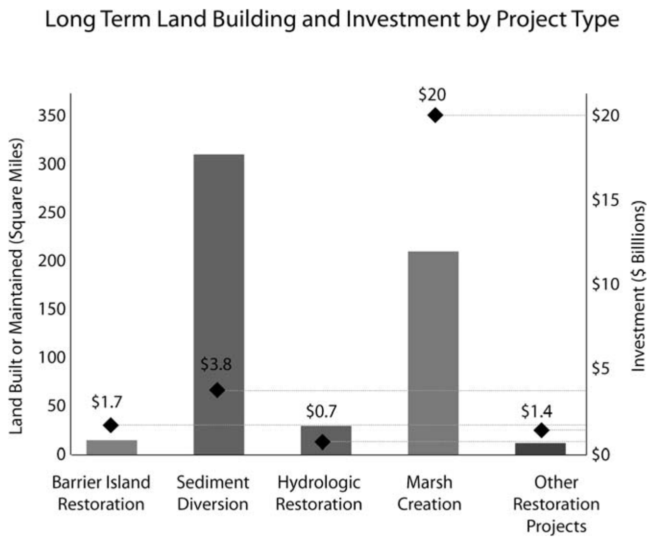

Figure 6. The cost-effectiveness of projects at year 50 under the moderate scenario, indicating that sediment diversions are the most cost-effective restoration project type.

The analysis only extends for the 50-year planning horizon; however, some land building projects could be building significant land well beyond that date. The master plan found that sediment diversions and channel realignments have the greatest land building potential of all the individual restoration projects the CPRA considered. The analysis indicates that multiple large-scale sediment diversions are the key to long-term land building, especially in the face of higher sea level and subsidence. Sediment diversions are also shown to be the most cost-effective restoration project type, as depicted in Figure 6. All sediment diversions recommended in the master plan, when operated at their maximum capacities during times of high river flow, would use up to 50% of the Mississippi River's water. Implementation of sediment diversions in the near term will have long-lasting benefits.

To be prepared for the complexity and magnitude of implementation, resources must be organized and coordinated to expedite delivery of the risk reduction and land building projects described in the plan. An adaptive management framework that captures this coordination is critical to successful implementation. It does so by systematically considering new information and changing characteristics of both environmental and social systems in response to project implementation, and when necessary, it makes appropriate adjustments at any stage of the implementation process to ensure continued progress toward achieving master plan objectives.

Successful implementation of restoration and structural protection projects will build on past experiences of the CPRA and other coordinating agencies. Implementation of projects will vary due to individual timelines and budgets. Some proposed projects, such as coastwide nonstructural measures, will depend on the development of new programs that provide mechanisms for funding, designing, and constructing projects. In addition, compliance with environmental policies and regulations will be required to implement projects within the plan.

The 2012 Coastal Master Plan demonstrated the importance of integrated modeling, decision-support tools, and extensive public outreach to inform and educate a decision-making process. The Planning Tool and supporting models that are described in greater detail in this journal will be used to guide implementation of the master plan in the years ahead. The tool can also be used in the future if there are changes in funding scenarios, new project concepts, or changes in the coastal system to determine whether additional projects should be included. The Louisiana Legislature requires the CPRA to update the master plan every 5 years; thus, the models and tools will continue to be improved to support future decision-making processes.

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