Louisiana Coastal Area (LCA), Louisiana

Ecosystem Restoration Study

November 2004

Final

Appendix C – Hydrodynamic and Ecological Modeling

LOUISIANA COASTAL AREA (LCA), LOUISIANA
ECOSYSTEM RESTORATION STUDY

APPENDIX C
HYDRODYNAMIC AND ECOLOGICAL MODELING

TABLE OF CONTENTS

List of Figures

List of Tables

Foreword

This Louisiana Ecosystem Study (LCA) Report Appendix entitled, “Hydrodynamic and Ecological Modeling” is designed to provide an understanding of the basis on which initial subprovince wide model efforts were conducted. These efforts provided the LCA Project Delivery Team (PDT) with tools to evaluate various proposed restoration measures. The modeling effort summarized here was conducted during a period between August 2002 and September 2003. This modeling effort developed tools used to select the seven original coastwide frameworks developed through phase five of the LCA plan formulation (see Main Report).

The models represent a landmark achievement in collating the extensive scientific and technical knowledge currently available. They were created for the purposes of formulating and evaluating subprovince-level alternative plans (which were comprised of multiple project features) for ecosystem restoration. Although the lack of extensive data sets constrains the models' ability to accurately predict individual project benefits over 50 years, the conceptual frameworks developed for the models are sound and represent the best available scientific understanding of ecosystem function. Even though precise project benefits over 50 years could not be predicted, resource managers were able to compare the relative effectiveness of alternative subprovince plans. They could also distinguish between these plans with reasonable certainty that the most cost-effective and ecologically beneficial alternatives were being considered. Further, these models represent the most objective and powerful predictive tool at the subprovince scale available to resource managers at this time.

Output provided by these models assisted the PDT in the determination of 7 cost-efficient alternative plans from which cost-efficient and ecologically meaningful projects could be chosen. The projects that comprised each of the 7 plans were considered in the development of the near-term plan for the Louisiana Coastal Area (LCA) Study. Upon completion, only 13 of the 79 project features considered passed through the selection process for inclusion in the near-term plan. Of those 15 projects, only 5 are being recommended for programmatic authority for construction. These 5 have been selected because they have significant value in addressing critical ecological needs, they have some level of planning and design already completed, and because they will utilize technology which has already been proven to be cost-efficient and ecologically beneficial by similar projects implemented under other Federal and State programs. This is also consistency with the Adaptive Environmental and Assessment and Management (AEAM) process, described elsewhere in this report, wherein the design of future actions is built upon lessons learned regarding the efficacy of past restoration actions.

Uncertainty is inherent in ecosystems, and is therefore unavoidable when managing large-scale ecological systems. Thus, assumptions must be made when creating predictive ecological tools. As acknowledged above, the lack of extensive data sets for all parameters being considered creates further uncertainty in the models' ability to accurately predict benefits over the 50-year project life. Acknowledging and identifying these and other uncertainties is critical for the most appropriate utilization of output. It is the consensus of the scientists who created these models that the outputs are a sound basis for decision making at the subprovince scale.

As the LCA Program proceeds, these subprovince-level models will continue to be developed and – where possible – uncertainty will be reduced through the Science and Technology Program. This is an integral step in the LCA AEAM program, and it allows for large-scale ecosystem restoration to proceed even as researchers work to reduce those uncertainties.

Executive Summary

The Hydrodynamic and Ecological Modeling appendix describes the development of the LCA ecosystem model. The purpose of this model was to establish a framework to evaluate alternatives of the LCA Ecosystem Restoration Plan that would eventually support the planning, implementation and evaluation of the preferred plan and coastal restoration features. This model serves as a tool for linking alternatives of engineering design to the desired ecological response.

An Applied Science Strategy tailored to coastal Louisiana was used in the development of a model that supported engineering and environmental aspects of plan formulation and assessment. The intent of the LCA ecosystem model was to define causal linkages, rationale of desired site conditions, and engineering requirements in order to reach desired landscape and ecosystem endpoints. This appendix describes: (1) the conceptual ecological models needed to plan the LCA study; (2) the formulation of the LCA mathematical ecosystem model as an effective tool for coastal restoration science; (3) desired ecological endpoints or restoration response based on sustainable ecosystem processes in deltaic environmental settings; (4) objectives of ecosystem rehabilitation including desired endpoints; and, (5) model limitations, uncertainties, and possible future actions to reduce uncertainties.

The goal of the LCA Plan is to reverse the current trend of degradation of the coastal ecosystem. The plan maximizes the use of restoration strategies that reintroduce historical flows of river water, nutrients, and sediments to coastal wetlands and that maintain the structural integrity of the coastal ecosystem. To achieve this goal, coastal framework features were developed and evaluated by a variety of modeling approaches that linked changes in environmental drivers (processes such as riverine input) to specific restoration endpoints (hydrodynamic, ecological and water quality). By combining existing conceptual models of delta evolution and ecological succession, the model attempted to evaluate the effects of various combinations of conceptual restoration features on the sources of ecosystem stress, to identify areas of influence and to project possible ecological benefits along the Deltaic and Chenier plains. Assumptions of causal linkage mechanisms and desired final conditions (endpoints) were used to estimate feature requirements that will move ecosystems toward their target endpoints. The endpoints were constructed into algorithms and then used to calculate benefits of specific alternatives at the subprovince scale.

The construction of the LCA Ecosystem Model provided the linkage between restoration alternatives and restoration endpoints. The modeling system consists of five major steps in the evaluation process. First is the development of alternatives that approximate the degree of change in environmental settings to achieve specific restoration goals. In step two, the alternatives were provided to the ecosystem modeling team for estimates of change in five different modules. These five modules included: (1) hydrodynamics, (2) land building, (3) habitat switching, (4) habitat suitability, and (5) water quality. This approach is similar to coastal ecosystem landscape models that have been developed over the last two decades to simulate processes in specific regions of coastal Louisiana (Costanza *et al.* 1988; Martin *et al*. 2000; Reyes *et al*. 2000; Martin *et al.* 2002). Each module requires knowledge of existing conditions and will then predict changes in the landscape based on assumptions of how the ecosystems respond to coastal processes. Third, each module produced a set of endpoints specific to the environmental conditions of the particular subprovince. Many of these endpoints became the input to other specific modules. The details of how these modules were linked and specifics on the modeling tools for each module are described in chapter C.2. The fourth step was to use the endpoints of these five modules in a series of benefit calculations to determine specific types of ecosystem response. Finally, the original restoration alternatives were evaluated using a collection of the benefits and compared to the original restoration objectives.

Hydrodynamic endpoints were used to drive the other four modules: land building, habitat switching, habitat suitability, and water quality. This process required that the assumptions used in each module be consistent and that the endpoints determined by each module be compatible with the input needs of the other modules. The LCA ecosystem model used a spatial framework consisting of 43,138 cells (1 km^2 each) to provide key information to build the landscape base for model development. This framework would serve to define the model domain and provide a mechanism to facilitate spatial data exchange into and out of the various modules.

Information of hydrodynamic attributes for each month for each LCA cell was passed to the desktop modules for further analysis. Results of these simulations were used to interpolate salinities and hydrodynamic attributes for the subprovince alternatives. These hydrodynamic data were transferred to the other four modules (land building, habitat switching, habitat use, water quality) to evaluate ecosystem response. Module results were calibrated using field data and professional observations, and their limitations and uncertainties were identified. In addition, a preliminary sensitivity analysis was performed on the modules.

Chapters C.3 through C.6 describe the hydrodynamic models that were developed for each subprovince. The objectives of each model were to investigate how potential restoration opportunities could change hydrologic and salinity regimes, to provide indicators of the relative impact of the various restoration opportunities and to assist in the preparation of habitat impacts for the subprovinces. The hydrodynamic model for subprovince 1, described in chapter C.3, uses the Princeton Ocean Model (POM) developed by Blumberg and Mellor (1987). The model for subprovince 2, described in chapter C.4, uses the TABS-MD (RMA 2, RMA 4) model developed by Mr. David Elmore, P.E., of the U. S. Army Corps of Engineers, New Orleans District (USACE). Subprovince 3, described in chapter C.5, developed and validated the Acadian Basin Model, a version of the Coastal Ecological Landscape Spatial Simulation (CELSS) model. The Calcasieu-Sabine Basin and the Rockefeller Refuge south of Highway 82 in the Chenier Plain, subprovince 4, were modeled with 2 separate packages as described in chapter C.6. The Calcasieu-Sabine Basin was modeled using the hydrodynamic and salinity three-dimensional modeling system H3D; while the Rockefeller Refuge was modeled using a one-dimensional model, MIKE11, developed by the Danish Hydraulic Institute (DHI). Endpoints from each of the hydrodynamic models were used as drivers in the four other modules: land building, habitat switching, habitat use, and water quality.

Chapter C.7 describes the salinity and residence time calculation module, or box module. The purpose of the box module is to provide a rational method of scaling the results of the hydrodynamic numerical simulations during preliminary assessment of basin level restoration plans. The desktop tools serve two functions: (1) to provide order of magnitude characterization of altered basin hydrology and (2) to provide a method for approximating the response of aggregated salinity patterns and residence times for a range of alternatives, i.e. various combinations of diversion size and location. The mass-balance models provide predictions of aggregated salinity for each water body at the end of each calculation time step. These models will directly provide a time-series of aggregated salinity values (spatial averages within cells).

Additionally, residence time can be extracted as an output which can later be utilized to simulate the decay of a conservative tracer introduced in a cell of the model.

Chapter C.8 describes the Wetland Nourishment Module. The objective of this module is to predict the effects of different restoration scenarios on the acreage of wetland in the coastal ecosystem for 50 years into the future. This module uses a combination of empirical relationships and landscape analogs to reflect the complex processes controlling land change in the Louisiana coastal zone. The original purpose of this module was to predict elevation changes that would be used by the habitat switching module to predict habitat changes, including conversion from water to different wetland habitats. Although limits of available data prevented assessment of elevation changes per se, elevation is indirectly reflected by changes in the land-water configuration. The wetland nourishment module predicts land formation in the direct impact area of the different diversion areas. All cells followed historic land loss rates for the area unless affected by land building or nourishment effects. The land change module was used to predict the amount of land at year 50 under all different restoration alternatives within each subprovince. As expected, increased sediment loads result in increased land area in year 50.

Chapter C. 9, the Habitat Switching Module, describes the predicted distribution of habitats at year 50 under all restoration alternatives resulting from the habitat switching algorithm. Assumptions for the habitat switching module are: (1) emergent herbaceous communities appear to switch in progression from one community to another along a salinity gradient (i.e., fresh< >intermediate< >brackish< >saline); (2) swamp forests can switch to intermediate marsh based on salinity; (3) seed sources for these habitats are available; and (4) upland habitats will remain upland habitats. The responses of vegetation to physical factors are often indirect, but habitat switching is mediated by biological factors including competition, grazing, fertility and even mutualism. The results from the habitat switching algorithm are dependent on the salinity distribution resulting from the hydrodynamic outputs and the land change outputs. As expected, increases in land resulting from the different restoration scenarios are primarily reflected by the increase in fresh attached marshes, while brackish marshes and saline wetlands decrease as amount of sediment diverted increases.

The Habitat Suitability Module, Chapter C.10, provides a methodology for estimating the effect of various restoration scenarios on the habitat capacity for key life stages of representative species of fish, shellfish, and wildlife. The habitat suitability algorithms were employed to predict the habitat suitability for all species at 10 year intervals under all restoration alternatives within each subprovince. Factors to be used in calculating habitat suitability include habitat type (bottomland hardwood forest, swamp, fresh marsh, intermediate marsh, brackish marsh, saline marsh, open water, barrier island, and maritime forest ridge), average monthly water salinity, average monthly water temperature, average water depth, and the percent of cell that is land. One limitation is the lack of information on interspersion (i.e., spatial arrangement of the land within the spatial cells). Interspersion, and the related quantity of edge between emergent vegetation and open water, is critical to some species, especially muskrats, dabbling ducks, juvenile red drum, juvenile brown shrimp, juvenile white shrimp, and other fish and decapod crustaceans. The final product of the habitat suitability algorithms is a single table that shows the habitat suitability for each of the twelve species for each basin across the alternative restoration scenarios. In general, habitat suitability for wildlife species increases with increasing sediment load and the resulting increase in fresh marsh area. This increasing trend is significantly large for alligator and dabbling ducks, species with a high suitability index value for fresh and intermediate marshes.

Chapter C.11 describes the approach for the Water Quality Module. Several published papers that discuss empirical relationships relating nitrogen removal, chlorophyll-*a* concentrations and primary productivity to nitrogen loading rate and water residence time aided in the development of this module. The purpose of the Water Quality Module was to estimate nitrogen (N) removal rates, chlorophyll-*a* concentrations, and primary production rates as a result of the different freshwater diversion alternatives. Each estimate integrates N-loading rates, fresh water residence time, and wetland-water ratios for the entire estuarine system. In addition, hydrodynamic output such as salinity, water level, and water depth was incorporated into the estimates. Diversion scenarios were demonstrated to remove nitrogen from diverted water, with quantity removed mainly dependent on residence times and wetland to water ratios.

The Benefits Assessment Protocols, described in Chapter C.12, provide a method for comparing the effects of plan alternatives. Investments in ecological restoration are based upon evaluation of the effectiveness of restoration measures on ecosystem value and productivity. The Benefits Assessment Protocols were developed to synthesize the wealth of ecosystem dynamics information, covering an array of ecosystem attributes and functions, being generated in the assessment of alternatives. The Benefits Assessment Protocols provide a means of comparing complex patterns of ecosystem change both in space and time. Each protocol was designed to contribute to the LCA decision-making process in different ways. Input of Benefit Protocol #2 was incorporated into the incremental cost-effectiveness analysis. The other Benefits Assessment Protocols provide additional information on how alternative actions influence specific aspects of the ecosystem. This information was used by the LCA Project Delivery Team to determine which alternative restoration plans best met LCA goals and objectives. In all cases the Benefits Assessment Protocols are used to compare the effects of alternatives on the coastal ecosystem rather than to specifically predict future conditions.

Chapter C.13 describes Model Uncertainties and Limitations. A predictive model contains two types of knowledge uncertainty. The scientific rigor of the information and assumptions used in determining how driving forces influence model simulation output is known as model uncertainty. The quality of available data that is used to develop parameters of environmental drivers and inputs is known as parameter uncertainty. This chapter describes the current strengths and weaknesses of each module and recommendations for their future improvement.

Chapter C.14 reports on Model Evaluations based on Simulations of a Virtual Basin. This virtual estuarine basin and simulations of varying parameter values evaluated the logic of the models' results and tested system behavior. To quantify the influence of each major model input (i.e., salinity, inundation and wetland area) on model indices, one variable at time was incrementally modified. Assessment of uncertainty, model sensitivity, verification, and empirical comparisons are on-going and will continue. The work described in this chapter provides assurance that the models have been used consistently in the assessment of alternatives.

Chapter C.15 discusses linking monitoring programs with modeling efforts. Sensitivity analyses during model development provide insight into the most significant parameters to system behavior and the most cost-effective monitoring variables for evaluation of ecosystem response. This linking process is required to adequately test causal hypotheses of system degradation upon which restoration measures are designed. In addition, the link can provide a strategic process in performing adaptive management and assessment. Effective monitoring programs can benefit conceptual and mathematical modeling by describing system response. Uncertainty in model simulations not only depends on the natural variability of the ecosystem but also quantity and quality of knowledge and parameters used in model development. Monitoring programs may reduce knowledge gaps by providing data for parameters that can improve simulation capabilities. This relationship improves simulation models and reduces the scientific uncertainty associated with understanding causal mechanisms of system degradation. Quantitative rigor in simulation models in the initial stages of restoration planning will improve the ability to predict ecosystem response to prescribed changes in environmental settings. Linking monitoring programs with modeling efforts contributes to the development of ecological theory and is critical in developing restoration strategies and directly linking science and management.

The final chapter, C.16, is a literature review of available data and previous studies in Region 4. The goal of this chapter is to establish a basis for developing comprehensive water and sediment budget analyses and to setup region-wide comprehensive hydrodynamic, salinity, and sediment modeling tools. Region 4, also known as the Chenier Plain, extends from Fresh Water Bayou west of Vermilion Bay to Sabine Lake. It is the western most region of Louisiana's coast that extends across the border to the State of Texas. Since this unique region is lacking in scientific understanding, a better comprehension of the hydrology (water and sediment) and ecology of the region is essential to successfully implement an ecosystem-scale wetland restoration plan. Currently, no accurate accounting of water and sediment volumes exist in the region, but this information is vital in order for future modeling efforts to assess restoration plans and strategies. As a first step toward developing comprehensive water and sediment budget analyses and comprehensive numerical modeling tools, all available data, field measurements, published reports and technical papers in this region were identified and compiled.

The alternative plans described in the restoration plan and simulated (evaluated) in this appendix are based on the geophysical, geomorphic, and ecologic processes that historically formed and sustained this river-dominated coastal landscape. In subprovinces 1-3, these processes include the formation of several deltaic lobes of the Mississippi River. In the subprovince 4 to the west, major processes include the formation of a series of beach ridges or cheniers. These models are first estimates of how linkages in coastal processes will effectively achieve a sustainable coastal landscape. Further model development is required to evaluate changes to present and future project design and/or operation to ensure that subprovince scale objectives are obtained. It is important to note that projections based on model development in this stage of restoration planning are scaled to represent the basic "features" of a plan, or strategies, and not the operational nature of proposed measures.

CHAPTER C.1
CONCEPTUAL ECOLOGICAL MODELS FOR PLANNING AND EVALUATION

Robert R. Twilley [1]

[1] *Center for Ecology and Environmental Technology, University of Louisiana at Lafayette*

1.1 Introduction

The proposed LCA Ecosystem Restoration Plan establishes a framework or blueprint for solution of the Louisiana coastal problems and opportunities for wetland rehabilitation over the near term of 10 years. The near-term course of action restoration opportunities capitalize on the set of coastal framework features developed by the LCA Study team's ecological modeling efforts.

This appendix provides a summary of the conceptual ecological modeling process utilized to support the planning and evaluation processes of the LCA Ecosystem Restoration Plan. Further, this appendix focuses on the following modeling tasks to support the evaluation of proposed coastwide restoration frameworks: 1) Development of ‘Conceptual Ecological Models’ used to integrate ecological needs and opportunities with engineering designs that provide the most benefit to coastal Louisiana ecosystems; 2) Use rates of wetland loss to describe the most likely future without scenario for variety of ecosystem attributes; 3) Establishment of broad ecosystem responses to restoration alternatives based on processes associated with succession of geomorphic and ecological systems; 4) Assessed water and sediment needs from the Mississippi and Atchafalaya rivers, and other sources, to establish site criteria necessary to obtain restoration goals within the Mississippi River Delta; 5) Development of ecological benefits assessment protocols that associate large-scale geomorphic and hydrologic processes that would lead to rehabilitation of the Mississippi River deltaic and Chenier Plains.

The Applied Science Strategy approach outlined in the Comprehensive Everglades Restoration Plan (Appendix D Attachment A, pages 1-90 of the Central and Southern Florida Project Comprehensive Review Study) was modified for the specific site conditions of coastal Louisiana to provide a level of detail required for engineering and environmental aspects of plan formulation and justification of a LCA coastwide study. To ensure there are clear statements of problems, needs and opportunity in the planning phases, the Applied Science Strategy described focuses on Conceptual Ecological Models of both the degrading natural system and the steps needed for ecosystem rehabilitation. The initial step of this Conceptual Model was to define disturbances, sources of ecosystem stress, and development of desired ecosystem response. These assumptions are based on clear causal linkages between disturbances and ecological effects. Second, the model describes desired ecological endpoints or restoration response based on the principles of sustainable ecosystem processes in deltaic environmental settings (self-design). These responses require an understanding of present ecosystem state, desired endpoints, and necessary site conditions to obtain specific endpoints.

The focus of the efforts in the LCA Ecosystem Model was to add a level of detail in the causal linkages, rationale on desired site conditions, and engineering requirements to reach landscape and ecosystem endpoints that are the goal of this ecosystem restoration plan. Chapter C.2 of this appendix describes the formulation of a LCA Ecosystem Model that uses conceptual frameworks and ecosystem objectives to design an effective tool in coastal restoration science. Chapters C.3 through D6 discuss the use of hydrodynamic models utilized for each subprovince to provide input for the LCA conceptual ecological model. Chapter C.7 discusses the LCA box model with specific parameter models discussed in Chapters C.8-C.11. The protocols for assessment of benefits is presented in Chapter C.12. Chapters C.13-C.15 discuss model evaluation, limitations, uncertainties and future requirements for refinement.

1.2 LCA Study Area

The study area, which includes Louisiana's coastal area from Mississippi to Texas, is made-up of two wetland-dominated ecosystems, the Deltaic Plain of the Mississippi River and the closely linked Chenier Plain, both of which are influenced by the Mississippi River. For planning purposes, the study area was divided into four subprovinces, with the Deltaic Plain comprising Subprovinces 1, 2, and most of 3, and the Chenier Plain comprising the western part of Subprovince 3 and Subprovince 4 **(Figure C.1-1)**. The Mississippi River Deltaic and Chenier Plains consists of diverse geomorphological basins with distinct vegetation zones and patterns of development.

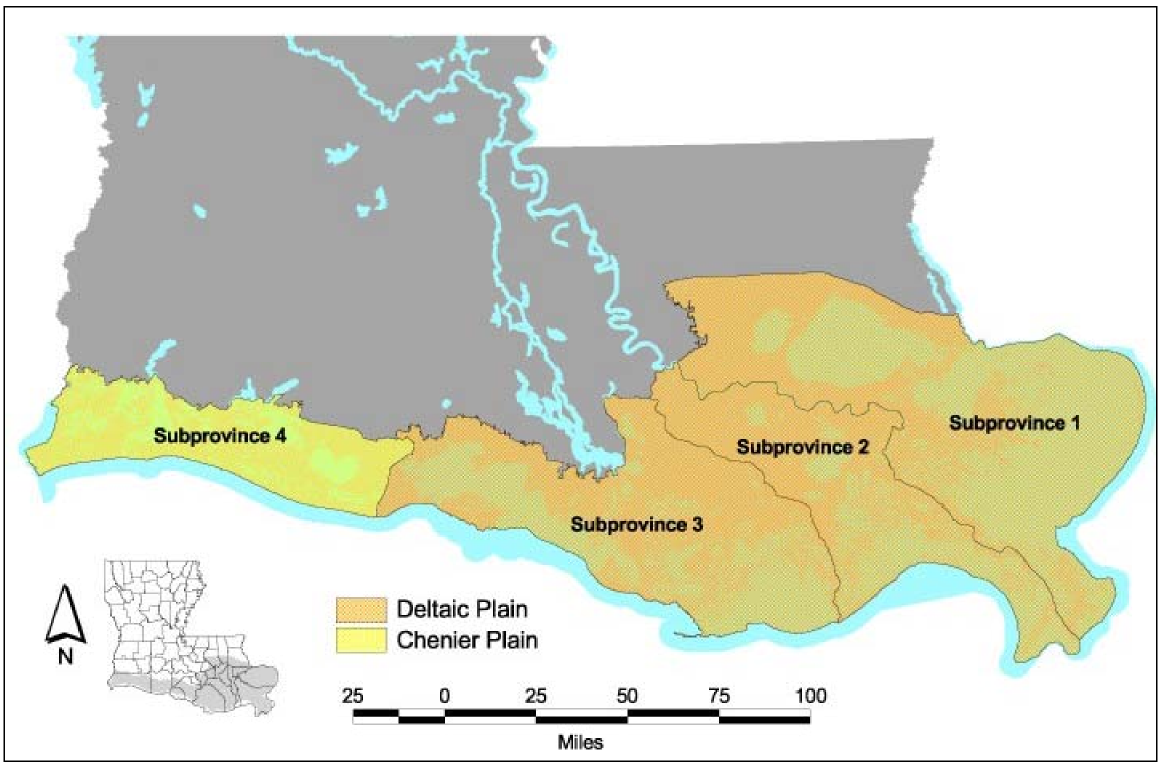
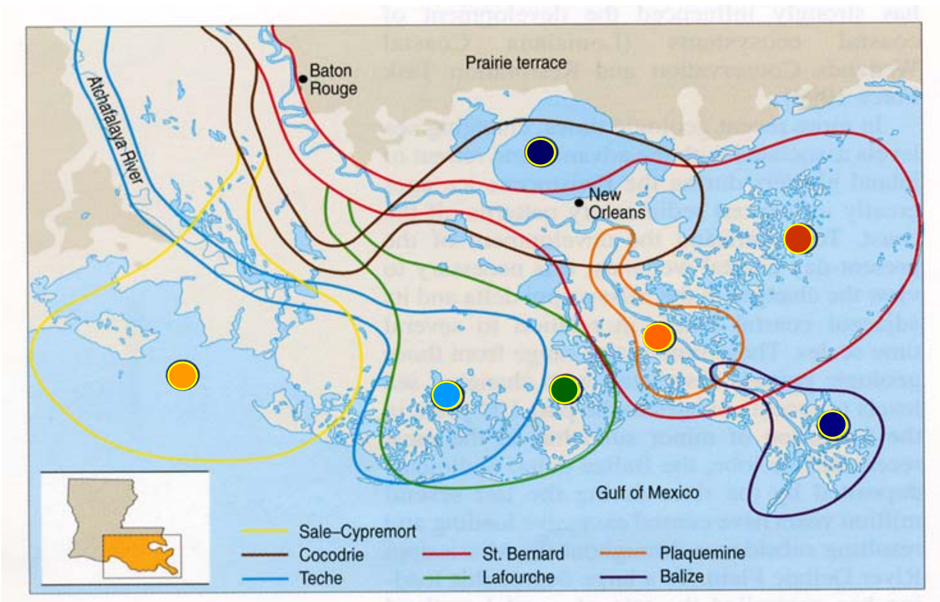


Figure C.1-1 LCA Study Area and Subprovinces

1.3 Causal Mechanisms of Wetland Loss in Coastal Louisiana

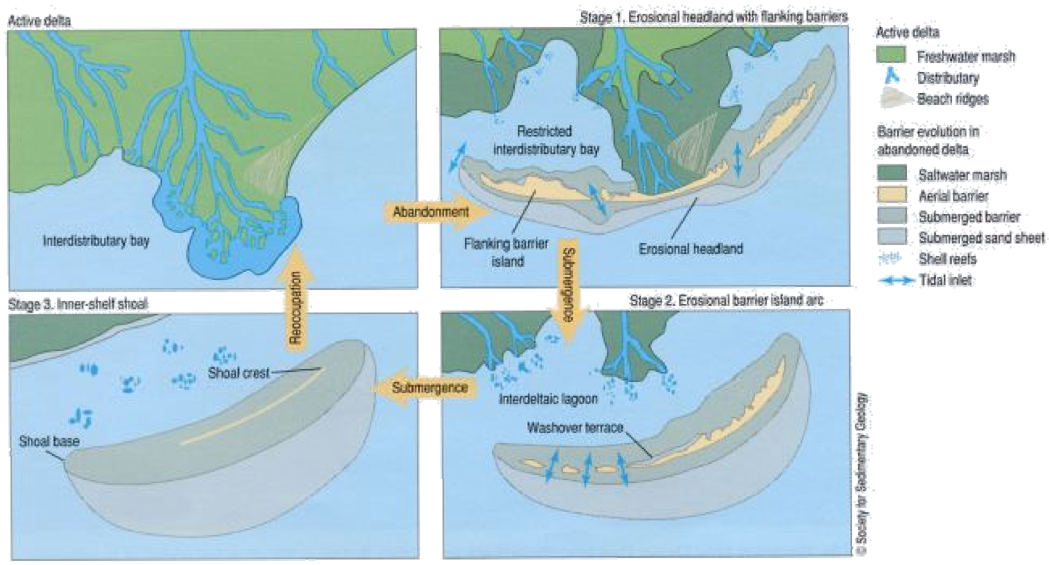
Deposition of sediments by the Mississippi River led to the formation of the present Mississippi Delta and associated Chenier Plain, which is composed of more than 9.9 million acres (4.0 million ha) of wetlands, lakes and bays (Roberts 1977). Discharge of fresh water and sediment from the Mississippi River has changed course over the last 7000 years (Figure C.1-2), resulting in the formation of two distinct provinces along the coast: a deltaic plain to the east and Chenier Plain to the west (Boesch *et al*. 1994). The delta is ecologically diverse and productive and economic activities depend on the productivity of this natural resource. The Mississippi Deltaic Plain is characterized by high riverine input, shallow bays, vast wetlands, in a warm temperate, low energy coastline. The Mississippi River deltaic plain has the eighth highest annual mean freshwater discharge in the world, 640,000 ft^3/s (18,000 m^3/s), which causes extreme spatial and temporal variation in distribution of particulate and dissolved materials within the coastal waters. The broad continental shelf and prevailing winds tend to isolate the land margin from open ocean processes such as upwelling of slope waters. Daily tidal amplitudes are small, averaging only 0.98 ft (30 cm), but water level fluctuations over 3.3 feet (1 m) can occur during frontal passage. On a longer time scale the relative rise in sea level in this region is in excess of 0.033 ft/yr (1 cm/yr) due primarily to a high rate of regional subsidence. In addition, the hydrodynamics of the region are directly influenced aperiodically by hurricane surges that occur about once every 5 yrs. Thus significant water level changes in the coastal margin of the Mississippi Deltaic Plain range from daily to geologic time scales.



Source: Gosselink 1998; original modified from Kolb and Van Lopik 1958

Figure C.1-2 Seven Delta Lobes of the Mississippi River Delta formed over the last 7,000 years

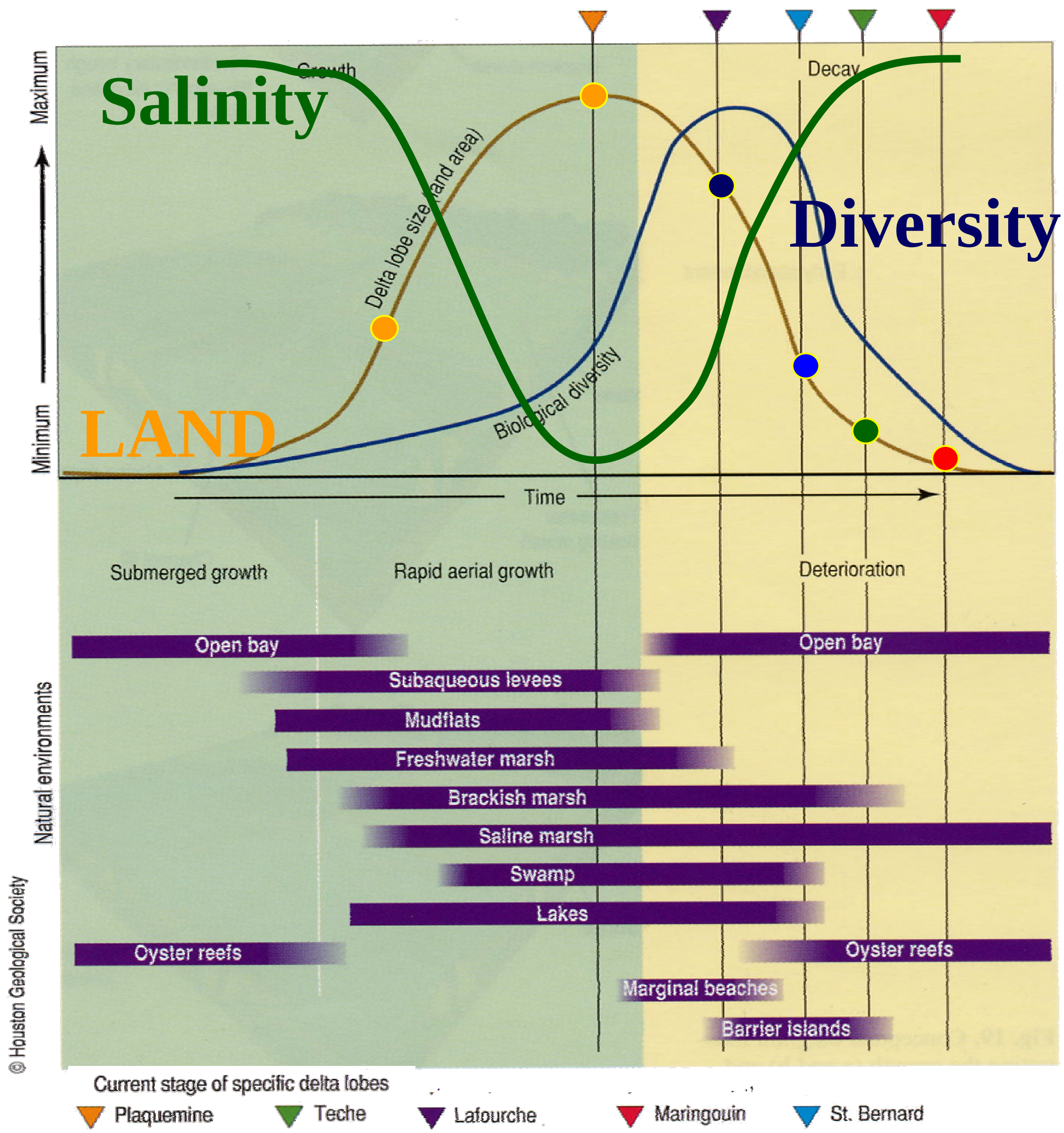
The delta cycle is fundamental to understanding the succession of geomorphic and ecologic features of this coastal landscape (Figure C.1-3). Transgressional sequences at the subprovince and basin scales of coastal Louisiana govern smaller scale successional changes at the habitat scale of the marsh. The proximity of fluvial processes to marshes shift as distributaries of the Mississippi River migrate along the coast, changing the distribution of sediment, nutrients, and salt that control the type of habitat that colonizes the emergent zones of the basin. Thus there are continued changes not only from emergent to open water as part of the transgressional sequences, but the community composition of the emergent lands changes among fresh water, intermediate, brackish, and salt marsh vegetation (Figure C.1-4). As fluvial processes decrease, there is a lack of fresh water discharge to control sea water encroachment, causing salt and brackish marshes to migrate landward, either replacing fresh water marshes or converting marshes to open water (Figure C.1-4). During active delta formation, such as observed in the Atchafalaya River basin, there is a migration of fresh water and intermediate vegetation toward the coast as salinity regimes decrease in the coastal zone (Madden *et al.* 1988). Processes at all three spatial scales including subprovince, basin and habitat levels are coupled to produce a spatial mosaic of changes in wetland cover and composition that form very complex and dynamic patterns of coastal wetland succession. The result of these processes across the Mississippi River deltaic plain is 6,200,000 acres (2,500,000 ha) of marshes that account for 60% of the coastal wetlands in the lower 48 states (Turner and Gosselink 1975). These patterns of coastal processes have to be incorporated in any perspective of coastal restoration and rehabilitation.



Source; Gosselink 1998; Original from Penland et al. 1988

Figure C.1-3 Model of the Evolution of a Barrier Island System in the Mississippi River deltaic plain

The Mississippi River actually formed two distinct geomorphic regions of coastal Louisiana over the last 7000 years – the Deltaic Plain and the Chenier Plain. The Deltaic Plain formed in the central and southeastern portions of the coast (Fisk and McFarlan 1954), and the Chenier Plain in the southwestern part of the state (Gould and McFarlan 1959; Penland and Suter 1989). The hydrology and landscape formation of marshes in these two coastal regions are distinctly different. Subsidence in the deltaic region of coastal Louisiana averages 0.036 ft/yr (1 cm/yr) compared to 0.019ft/yr (0.57 cm/yr) in the Chenier Plain region (Penland and Ramsey 1990). These differences in regional subsidence rates are associated with the erosion of Pleistocene surfaces by the Mississippi River in the Deltaic Plain followed by deposits of fine silts to depths of over 656 ft (200 m) there (Penland and Suter 1989). In the Chenier Plain, much less erosion occurred because the river never flowed directly through the region; therefore depths to Pleistocene surfaces are only 49 ft (15 m) (Nichols 1959). In the Mississippi River deltaic plain, wetlands initially form as freshwater marshes at the mouths of active distributaries and convert to saline marshes as the delta lobe cycle progresses toward the degradation phase (Coleman 1988). In the Chenier Plain, wetlands initially form as saline marshes in the Gulf of Mexico and convert to freshwater marshes as new marshes and chenier isolate them from the Gulf of Mexico.



Source: Gosselink 1998, modified from Gagliano and Van Beek 1975; Neill and Deegan 1986

Figure C.1-4 Conceptual Model of the Delta Cycle Depicting the Growth and Decay of a Delta Lobe

The Mississippi River Deltaic and Chenier Plains consists of diverse geomorphological basins with distinct vegetation zones and patterns of development. Within each of these geomorphological basins are ecological habitats that can be distinguished by the adaptation of plants to soil fertility, relative water levels, and salinity (Buresh *et al.* 1980, DeLaune *et al.* 1989). Marshes in coastal regions that differ in geomorphology and nutrient (fresh water and sediments) loading have different plant strategies to resource availability and abiotic stressors (Hopkinson and Schubauer 1984; White and Howes 1994), and thus different patterns of marsh stability. Natural shifts in proximity to fluvial inputs will change the relative loadings of N and P (and Fe), as well as salinity, and this should cause shifts in relative production and decomposition of organic matter in marsh wetlands (Day *et al.* 1995). The conceptual model of the delta lobe cycle predicts that diversity and possibly productivity actually peaks following the peak in land mass formation, with slight increase in salinity during the early phases and delta degradation.

The biological productivity of this coastal landscape is linked to the extensive diversity of coastal habitats in this geographically distinct central Gulf Coast region. The biological diversity and productivity of the Mississippi River Delta includes the largest wetland landscape and most productive near shore fishery and migratory bird habitat in the contiguous United States. Much of this biological diversity and productivity of these higher trophic levels is associated with the delta cycle and corresponding distribution of land mass and salinity regimes. Thus the succession of wetland vegetation and habitat development influences the relative dominance of marine and terrestrial fauna. One of the unique features of this broad landscape from the delta to the Chenier Plain is the seasonal use of these habitats by fauna during critical stages of their life cycle.

Coastal Louisiana has the highest rate of coastal wetland loss in the nation, reaching a peak of 0.86% per year 41.7 mile^2/yr (108 km^2/yr) in the 1970's (Gagliano *et al*. 1981; Turner and Cahoon 1987; Barras *et al.*, 2003. Appendix G). Although the rate has declined since the 1980's (Britsch and Dunbar 1993), over one-third of the wetlands present in 1930s have been lost, equivalent to an area equal the size of Rhode Island (Boesch *et al.* 1994). This has resulted in the conversion of vegetated areas to open water decreasing the wetland:water area ratio. A large proportion of this loss occurs as conversion of interior marshes of all types (salt, brackish, and fresh) to open water (Gagliano *et al.* 1981; Turner and Cahoon 1987; Penland *et al*. 1996). Hence, wetland loss is related not only to erosion of the marsh edge but also factors contributing to submergence of interior wetlands. Much of this wetland loss is associated with a high rate of regional subsidence and erosion characteristic of degrading deltas (Figure C.1-4). At the mouth of the Atchafalaya River, however, a wetland system representing the early progradational stages of delta formation is evolving (van Heerden 1983). Here the levels of sediment discharge compensate for the relative increase in water levels due to subsidence and sea level rise (Day *et al*. 1995). This huge landscape of wetlands and coastal bays fluctuates in total area depending on a balance between the progradational processes of active delta formation, and degradational processes during abandonment that lead to natural and unnatural wetland loss (Figure C.1-4).

There are several factors in the environmental setting of coastal Louisiana which contribute to an inability of wetlands to maintain surface elevation leading to marsh instability (Figure C.1-5): (1) a high rate of regional subsidence (Penland and Ramsey 1990); (2) a reduced sediment load in the Mississippi River (Kesel 1988); (3) elimination of spring overbank flooding of the Mississippi River and direct delivery of river sediment to the marshes (Templet and Meyer-Arendt 1988; Day *et al*. 1997); and (4) extensive landscape and hydrologic alterations from human activities, including energy related activities and navigation channels (Turner and Cahoon 1987). Determining which process is most important at controlling elevation (*e.g.*, mineral vs. organic matter accumulation; waterlogging vs. salinity stress) is important in developing a rehabilitation program. In a comprehensive evaluation of the wetland loss problem in Louisiana, a panel of expert coastal scientists recommended that fundamental emphasis should focus "...on processes of soil formation, including the importance of mineral sediments in different types of wetlands, geochemical conditions affecting organic matter incorporation into sediments, and historical changes in soil characteristics." (Boesch *et al.* 1994).

Levees along the Mississippi River were initially constructed in the late 1700s to prevent waters during high river stage from flooding homes and agricultural fields, causing death and economic ruin to families all along the river. Several catastrophic breaches occurred as a result of record flood events along the river as recently as the early 1900s, each resulting in repairs to the levee system improving its capacity to prevent flooding. Thus, with the exception of short periods of time up to the early 1900s, the levees have been in place for over 100 years. However, extremely high rates of land loss along the coastal landscape of Louisiana during the late 1900s brought attention to the potential impacts of limited river flooding in hydrologic basins. Land loss was attributed to sea level rise, land subsidence, and the lack of river sediments being delivered to the marshes. Coastal marshes in deltaic environments are highly dependent on land building by soil formation that is enhanced by periodic delivery of rich new sediments from river floodwaters, as described above. The Mississippi River levee prevented sediment deposition from occurring in deltaic marshes, prompting managers to find ways of restoring river flow to impacted coastal areas. Navigation and other factors keep the river from switching and form a larger delta lobe within the Atchafalaya Bay.

Land loss in the Chenier Plain was been attributed largely to erosion of shoreline resulting in the loss of habitat; and salt water intrusion that has converted many marshes to open water. In addition, there is evidence that increased water logging in some regions may contribute to wetland instability. It is important that casual mechanisms of wetland loss be specific to the deltaic and Chenier Plain in any recommendation of coastal rehabilitation.

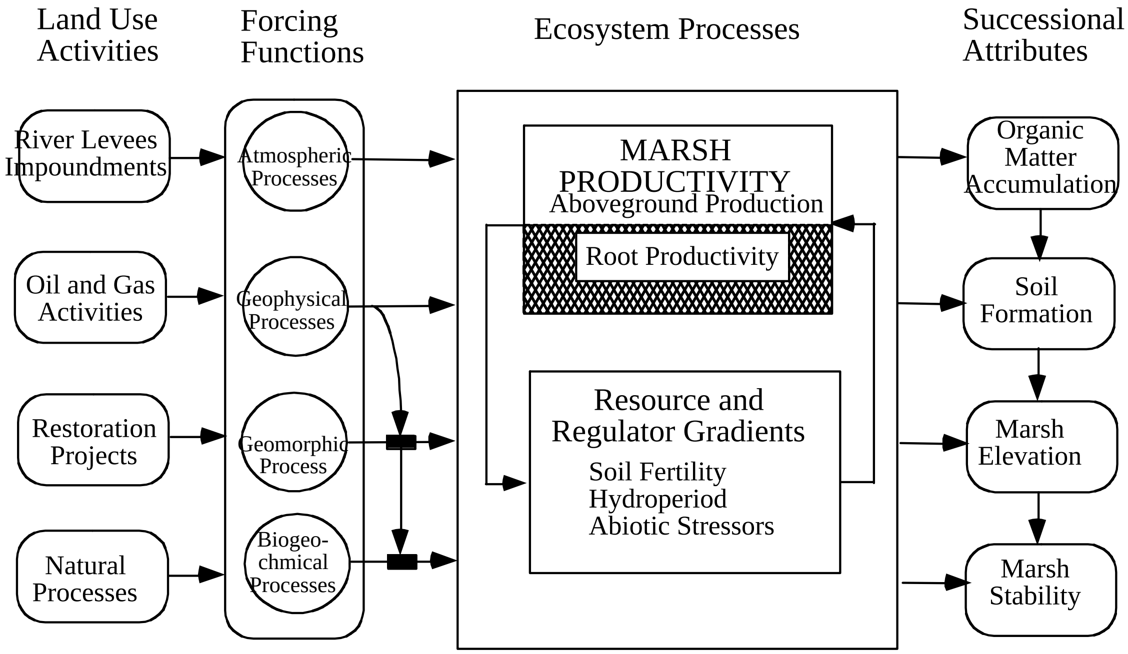


Figure C.1-5 Linkages in Land-Use Activities (including coastal restoration), biogeochemical processes that are the focus of this project, and ecosystem attributes that contribute to the ecological succession of coastal wetlands

Marsh stability is critically linked to the relationship between marsh elevation and soil formation. Processes influencing elevation include mineral sedimentation, organic matter production, organic matter decomposition, and subsidence (Figure C.1-5). When sea level rises faster than marsh elevation, an aggradation deficit develops resulting in the eventual submergence of the marsh. The productivity and health of the vegetation are central to maintaining this balance because wetland soils in coastal Louisiana depend on marsh vegetation to create enough soil organic matter not only to create new soil, but to also offset soil organic matter decomposition (Callaway *et al*. 1997). Therefore, the net accretion rate is determined principally by the balance between productivity of the vegetation and the rate of decomposition of soil organic matter. Organic matter production and decomposition rates are determined by a myriad of factors, but those that are relevant to wetland losses in Louisiana include nutrient and sediment supply, salinity concentrations, hydroperiod, and waterlogging.

Under natural conditions, sediment deposition in wetlands is an important factor in maintaining vertical accretion by stimulating the primary production process (Hatton *et al.* 1983; Nyman *et al.* 1990; Nyman *et al*. 1993). The mineral contribution of sediment has been described as critical to increasing the elevation of the marsh, by helping maintain a surplus of production over decomposition. Thus the importance of the mineral supply is actually secondary through its contribution to soil formation by adding organic matter via stimulating net primary productivity. Activities in the Mississippi Delta such as those described above have greatly reduced the level of sediment deposition in wetlands (Reed 1995). Levee construction along the Mississippi River prevents sediment deposition in coastal wetlands and this has resulted in a reduction of vertical accretion (Craig *et al*. 1979). Another contributing factor to reduced sedimentation is the extensive network of canals and impoundments in southern Louisiana. Canal spoil banks inhibit the deposition of suspended sediments and limit water exchange with surrounding areas (Conner and Day 1987; Swenson and Turner 1987; Baumann *et al.* 1984, Boumans and Day 1993). Studies have shown that high land loss rates are directly proportional to high canal densities (Turner 1987; Turner and Cahoon 1987). Additionally, canals have contributed to the reduction of water quality by allowing nutrient-rich upland runoff to flow past wetlands directly to water bodies (Gael and Hopkinson 1979). Wetland impoundments consisting of a system of dikes and water control structures have been widely constructed in the Mississippi Delta (Day *et al.* 1990). Studies have shown that these impoundments can reduce the influx of suspended sediments, lower accretion rates, lower wetland productivity, and reduce the movement of migratory marine fishes (Cahoon and Groat 1990; Cahoon 1994; Boumans and Day 1993; Flynn *et al* 1990; and Rogers *et al.* 1993). However they have been able to maintain the emergent marsh or with active systems restore degraded emergent marsh (Minority Report 1991).

1.4 Concepts of Restoration Science

The development of ecosystem management plans to restore and rehabilitate natural resources requires an understanding of how specific ecological mechanisms regulate the structure and function of ecosystems. The idea that the specific responses of ecological systems can be projected in time under specific initial conditions is known as ‘succession’. The increasing impact of humans on natural resources has outpaced the accumulation of scientific understanding of ecosystem processes, resulting in their rapid destruction and degradation. The science of restoration ecology applies the fundamental ecological processes of succession to rehabilitate degraded landscapes, sustain technological development, and improve environmental quality (Twilley *et al.* 1998; 1999).

Restoring disturbed ecosystems to hasten their rehabilitation is simply the manipulation of ecological succession to obtain a specific goal or purpose. Knowledge of the ecological theory that pertains to ecosystem development fosters more effective restoration planning that is less expensive, can be effectively implemented, and gives a more desirable final result (Christensen et al. 1996). This requires diagnostic capabilities that are based on ecological theory of succession and ecosystem development. These diagnostic capabilities are presently limited by the ability of scientists to: 1) anticipate ecological responses of ecosystems to specific manipulations or site conditions; 2) monitor responses of ecosystems at sufficient space and time scales to validate these responses; and 3) modify operations of rehabilitation projects according to the response of the ecosystem to obtain specific goals. One of the most difficult tasks in restoring ecological systems is to select the proper set of criteria for site manipulations that will rehabilitate habitats to obtain a specifically defined structure and function. Thus, a fundamental need of restoration programs is to develop practical tools and approaches that can be used to predict, monitor, and validate the response of ecosystems to rehabilitation criteria.

Changes in ecosystem attributes with time, such as specific characteristics in structure or function, are known as trajectories (Figure C.1-6). Restoration ecology requires the investigation of ecological trajectories of ecosystems in response to a variety of rehabilitation conditions. In the case of coastal Louisiana, the challenge is to determine the causal linkages to the degradation of this ecosystem over the last 100 yrs (1.2 million acres), and to develop features that will move the system to some rehabilitated condition. Developing features to move a system to some desired condition of both community structure and ecosystem function requires testing hypothesis of causal mechanisms described above.

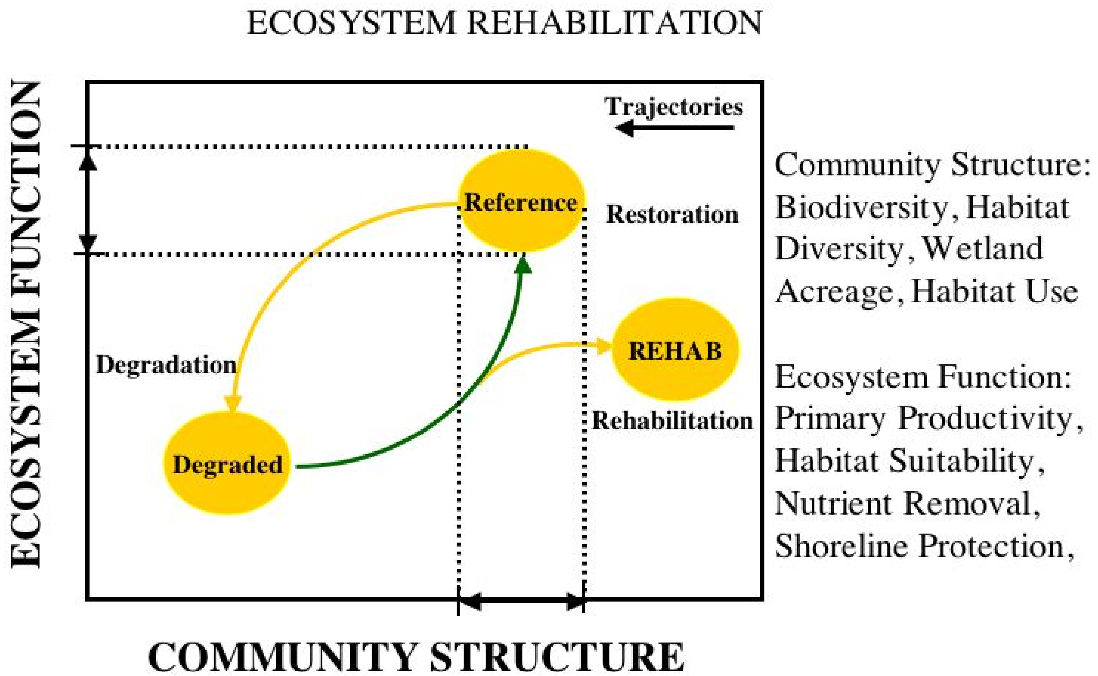


Figure C.1-6 Changes in Ecosystem Trajectories relative to a reference condition associated with restoration objectives

The future of the Mississippi River deltaic plain will depend on either a strategy that will allow present rates of degradation to continue, versus mounting an effort to restore natural processes of the delta cycle (Figure C.1-7). Environmental drivers are the major processes external to the coast that form coastal landscapes and ecosystems (Figures C.1-4 and C.1-5). A major assumption of the LCA Restoration Plan is that interruptions of environmental drivers are responsible for the degradation of the coastal landscape by destabilizing wetland ecosystems.

The benchmark for all restoration goals is a prediction of further landscape degradation under a 'no action' or 'future without' scenario. Again, this prediction includes the assumptions that historical causal mechanisms of ecosystem degradation, and associated rates of loss, will continue over a specific time frame. Land loss rates under 'no action' scenario have been estimated to 2050 in the LCA plan for both the deltaic and Chenier Plain provinces (USGS). Restoration scenarios considered by the LCA study effort are defined by three classes: (1) reduce; (2) maintain; (3) or increase. These LCA restoration scales assume that a certain change in degree of environmental drivers (forcing functions in Figure C.1-5) can achieve the three restoration goals described above (Figure C.1-7). Coastal Frameworks or features that are designed to help restore environmental drivers, such as reintroduction of the river, require estimates (projections or predictions) as to how much landscape will be built and what will be the function of resulting coastal ecosystems.

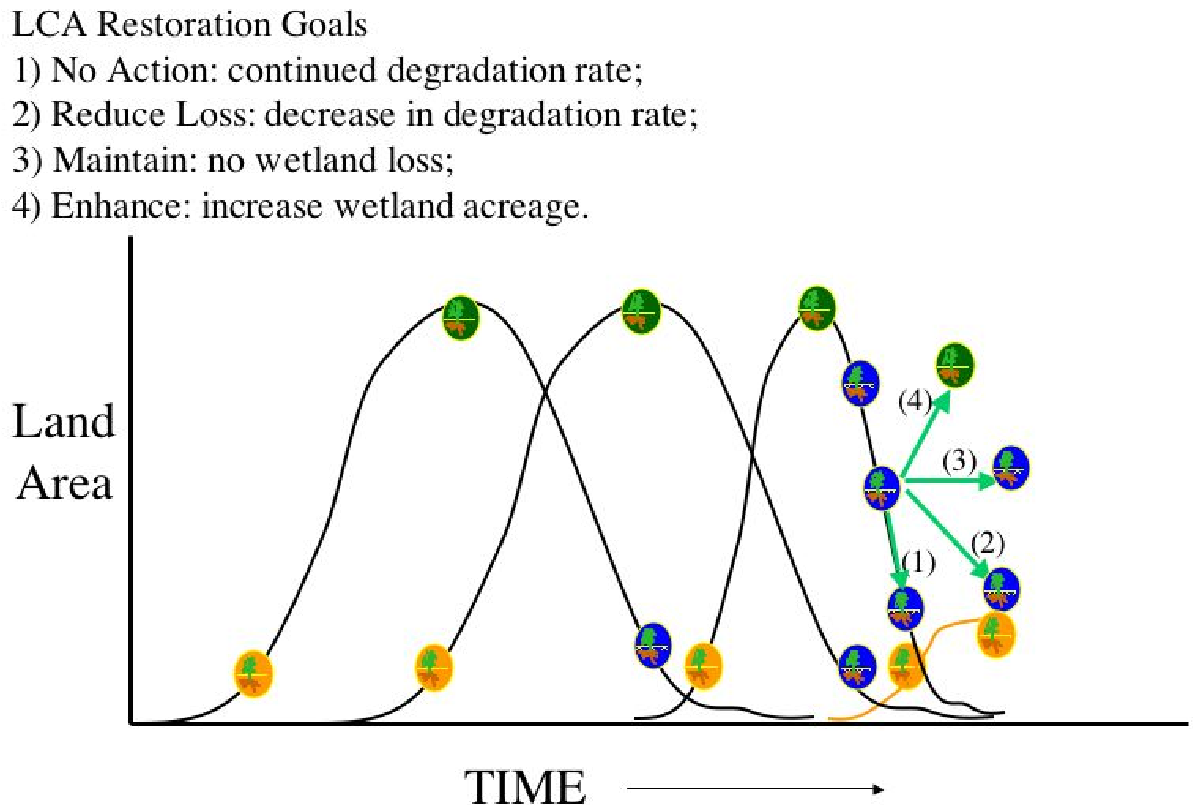
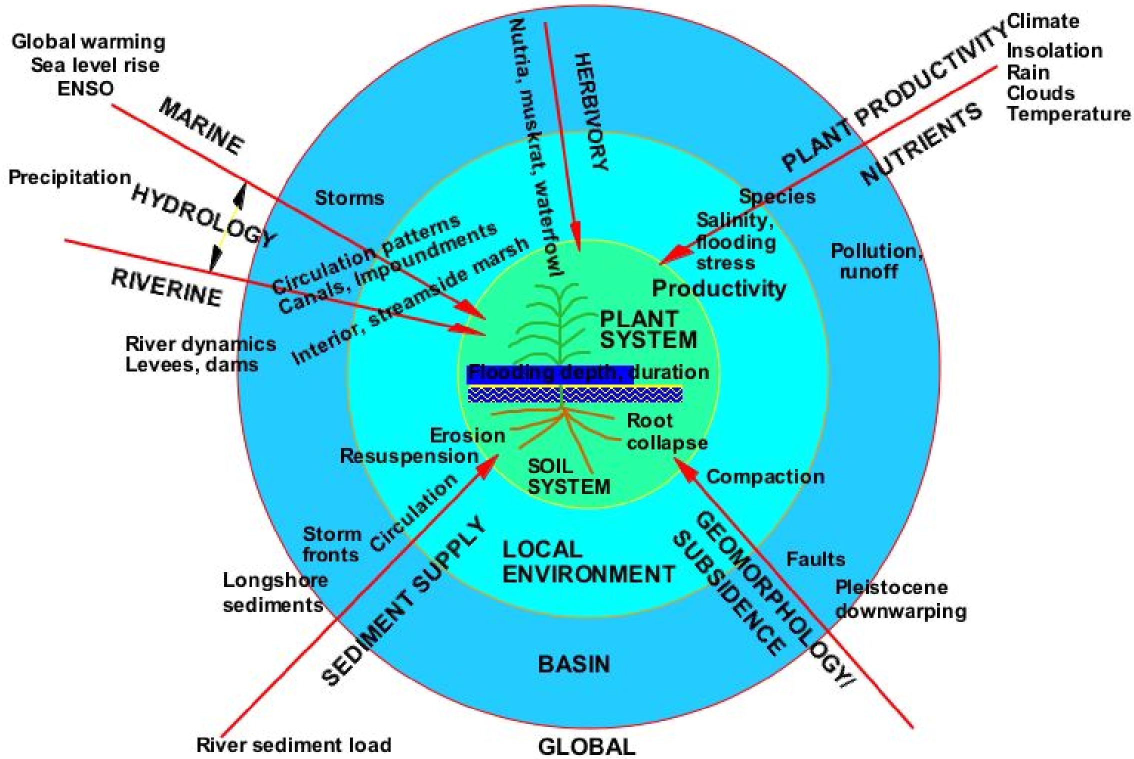


Figure C.1-7 Goals of the LCA Ecosystem Restoration Plan Relative to Present Assumptions of Land Loss

The environmental drivers of a coastal landscape reflect the complex behavior of regional climate, river discharge, tides, wind, and oceanographic currents (Figure C.1-9). Coastal settings can be catalogued as river deltas, river-dominated estuaries, lagoons, and oceanic islands (Thom 1982; Woodroffe 1992). These geomorphologically distinct landforms have local variations in topography and hydrology that result in the development of particular ecological types of wetland ecosystems. Coastal wetlands ecosystems have specific community structure and function, dependent upon local effects of topography that modify the regional impacts of environmental drivers across the coastal landscape. The combination of global (climate and biogeography) and regional (geomorphology) processes modified by the local (topographic) factors determines how regulators, resources, and hydroperiod will control the patterns of wetland development (Figure C.1-8). This hierarchy in geophysical, geomorphological, and ecological processes determines the level of stress at the plant system level (core of Figure C.1-8). At any location and specific time, local factors constrain the specific attributes of the plant system in the form of gradients in resources, regulators and hydroperiod (described below). And such constraints result from basin level processes that produce a variety of subsidies and stressors to ecological processes. To achieve restoration goals, plans must effectively change environmental drivers at the hydrologic basin level that reduce stress conditions at the local environment that are responsible for ecosystem degradation (Figure C.1-8).



Source: Gosselink as part of Coast 2050 planning document

Figure C.1-8 Conceptual Diagram Describing the Coastal Processes Wetland Ecosystem development

Conceptual models must be able to link processes at the subprovince, basin, local spatial and temporal scales to recommend adjustments in environmental drivers that will allow natural processes to restore the delta and Chenier Plain ecosystems (Boesch *et al.* 1994). At the core of such predictions, which are based upon high scientific uncertainty, is the understanding that these assumptions represent hypotheses that must be tested during the implementation stage of the restoration program (Figure C.1-1). Determining which processes contribute significantly to the destabilization of coastal wetlands has historically been the approach of wetland ecology related to understanding impacts of land use change. Restoration objectives and goals, with the purpose of promoting marsh stabilization, represent tests of the mechanisms that were proposed above as responsible for marsh destabilization. Destabilization of marsh sediments has been described as resulting from changes in regional hydrology such as hydroperiod (Gosselink and Turner 1978; Reed and Cahoo 1992), salinity (Chabreck and Hoffpauir 1962), and chronic waterlogging stress (DeLaune *et al* 1994; Day *et al.* 1994) that are linked to reductions in plant growth (as described above). Waterlogging stress, even without added salinity stress, can be a primary cause of marsh dieback (Webb *et al.* 1995).

Succession in coastal wetlands has to account for biomass production, along with rates of soil decomposition, to understand marsh stability. Optimization theory predicts plants adapt to environmental stressors via variations in biomass allocation (Bloom *et al.* 1985; Gleeson and Tilman 1992; Bazzaz 1997). Variations in morphology and productivity allow a plant to maximize effort in either obtaining a limited resource or responding to lethal concentrations of a plant regulator. Resources, such as nutrients and light, are defined as those elements in nature that are required for growth, and when consumed are no longer available for another individual. Regulators are defined as those physical and chemical properties that regulate physiological processes, but are not consumed by an individual, such as salinity, pH, and temperature. Stress, or reduced growth, can be manifested by the limited concentrations of resources, or by extreme concentrations of regulators. In Figure C.1-9, stress is defined as the deflection from maximum biomass levels at different concentrations of either resources (upper panel) or regulators (lower panel). The life strategy of wetland species differs from that of most terrestrial species in that tolerance to growth regulators, such as soil salinity, are as critical in plant succession as the influence of resource gradients (Grime 1977). Thus concentration gradients of both resources and regulators at the local environment (Figure C.1-8) can drive biomass allocation and succession in wetland ecosystems (Huston 1994). In addition, wetland succession is controlled directly by hydroperiod, which includes both the frequency and duration of flooding, and constitutes a third factor to consider in wetland restoration projects.

Plant productivity can be defined along these three axes that define the gradients of resources, regulators or hydroperiod as presented in the triangles in Fig. 1.9. A constraint envelope defines the productivity of coastal wetlands based on combined gradients of resources, regulators, and hydroperiod (Figure C.1-9). For most wetlands in coastal Louisiana, the most important resource gradients are bulk sediments and nutrients. Regulator gradients include salinity and sulfide, and hydroperiod gradients depend on the duration of flooding. A condition exists across each gradient with maximum productivity, and this is the farthest point from the origin representing benign environment. Points close to the origin represent maximal conditions of stress. The surface area of the envelope that results from connecting the three points along the axis of each condition is proportional to net primary productivity of the wetland. The productivity of a particular wetland site can be characterized by some combination of these three conditions of the local environment, and that combination can be defined relative to the stability of a wetland. Thus, wetlands with conditions that are plotted farthest from the origin along each axis should have maximum rates of total net primary productivity compared to those plotted nearer the origin which have severely reduced productivity.

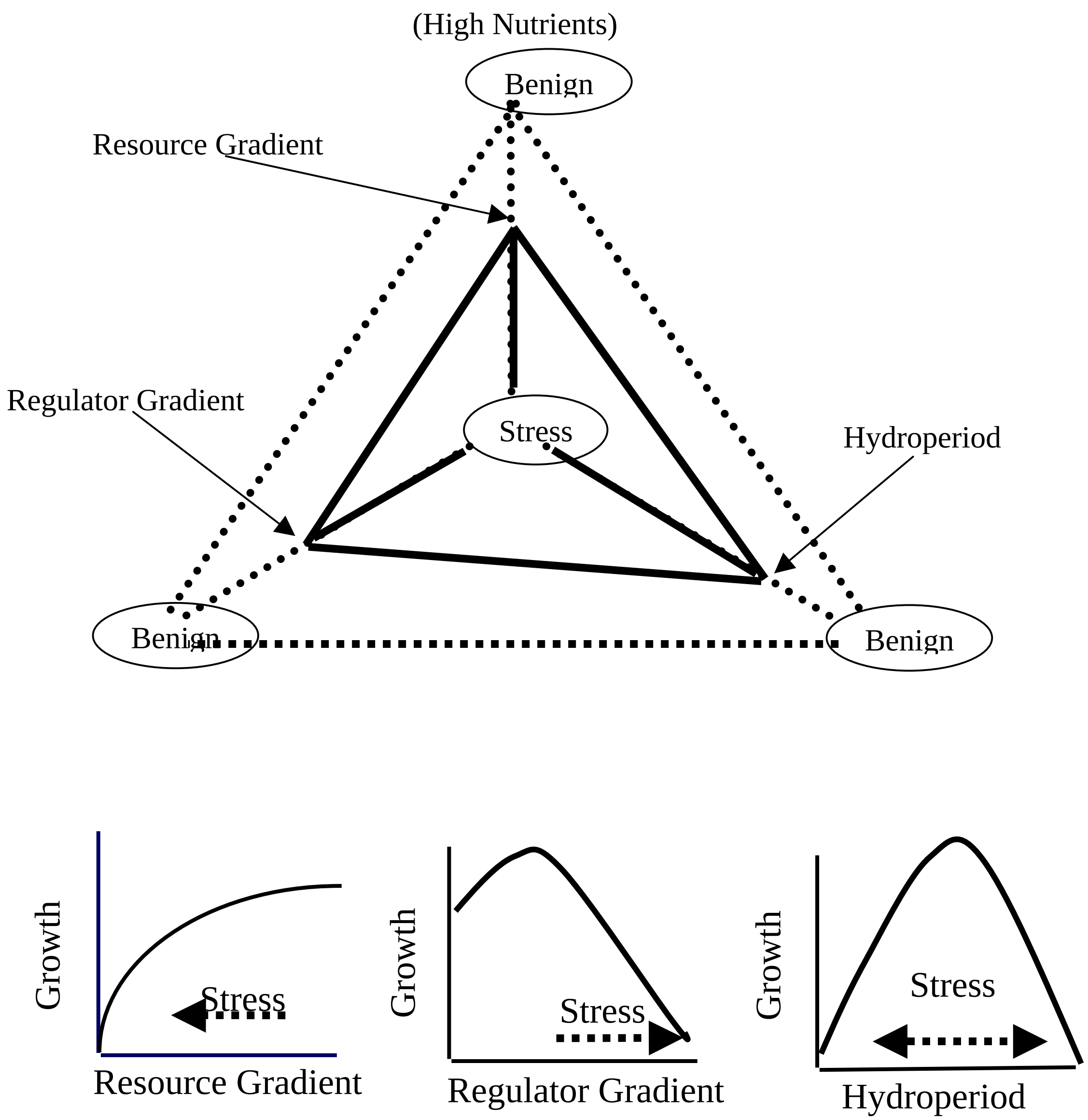


Figure C.1-9 Production Envelopes of Net Primary Productivity in response to the relative values of resource gradient, regulator gradient, and hydroperiod.

The LCA Ecosystem Model uses this approach to search for an optimum set of environmental drivers that will produce conditions of reduced stress and thus restore the productivity and stability of wetland ecosystems. Restoration measures should provide environmental drivers at the basin level that alter combined levels of resources, regulators, and hydroperiod at the local level that reduce the continued degradation of coastal landscape. At the same time, strategies may be necessary at the more local level that can also modify these measures at the basin level that may interfere with restoring local conditions. For example, spoil banks and canals may interfere with basin level strategies to restore resources, regulators and hydroperiod at the local environment. So that while basin strategies may be the focal point of the

LCA plan, the impact must be able to cascade from the larger to the more local level of the landscape to insure benefit to the wetland system. As the combination of resource, regulator and hydroperiod gradients changes over time, responses in primary productivity will give rise to successional patterns in wetland ecosystems. Restoration measures have to provide a combination of these three factors from the subprovince to the local that allow optimum marsh productivity and thus sustainable coastal ecosystems.

Habitat use by fauna also follows the sequence of vegetation patterns of the delta cycle. Thus the three gradients in resources, regulators and hydroperiod can also be used to define approaches to modeling habitat suitability in the coastal landscape. The difference with higher trophic levels, compared to the focus on wetland vegetation above, is that resources are not abiotic requirements of growth (as for plants), but are spatial and organic characteristics of the landscape. Vegetation structure can be considered the structural species of an ecosystem, while most fauna represent interstitial species that colonize the physical structure provided by macrophyte vegetation (Huston 1994). Examples of interstitial species in coastal Louisiana are the marine nekton and benthic fauna that colonize wetland habitats; as well as birds that utilize vegetated areas of the landscape. This explains the general pattern that structural species have a major influence on the presence of interstitial species. Yet the use of a particular habitat depends on the spatial patchiness of emergent habitat and coastal waters – referred to as landscape ecology. This is true for both fisheries and waterfowl. In addition, models of habitat suitability must account for important regulators such as salinity, water temperature, and water flow. And as for plants, hydroperiod is an important factor in habitat use.

The hierarchical approach to restoring coastal ecosystems of the Mississippi River Delta and Chenier Plain must account for the impacts of environmental drivers at the subprovince level to ecological processes of both wetlands and waters at the local level. There are strong linkages in the landscape arrangement of geomorphic features that control not only the types of ecosystems that will develop (community structure), but also the utilization of those ecosystems by higher trophic levels (ecosystems function). The delta cycle is a complex interaction of geomorphic landscapes, geophysical processes, and ecological succession. The LCA Ecosystem Model was developed to capture the various scales by which these physical, biogeochemical, and ecological processes will change the attributes of coastal ecosystem with incremental change in environmental drivers.

1.5 LCA Ecosystem Model

The goal of the Louisiana Coastal Area Plan is to reverse the current trend of degradation of the coastal ecosystem. Developing and evaluating restoration Coastal framework features of the LCA to achieve this goal required linking the changes in environmental drivers (processes such as riverine input) to specific restoration endpoints (hydrodynamic, ecological and water quality) using a variety of modeling approaches (Figure C.1-10). This modeling effort was designed to evaluate the effects of various frameworks on the sources of ecosystem stress, identify areas of influence and project possible ecological benefits along the deltaic and Chenier Plains. This was accomplished by combining existing conceptual models of delta evolution and ecological succession. The endpoints were constructed into algorithms and used to calculate benefits of specific frameworks at the subprovince scale.

The linkage between restoration frameworks and restoration endpoints was provided by the construction of the LCA Ecosystem Model (Figure C.1-10). The modeling system consists of five major steps in the evaluation process. First is the development of frameworks that approximate the degree of change in environmental settings to achieve planning scales (reduce, maintain, increase, see Figure C.1-7). In step two, the frameworks were provided to the ecosystem modeling team for estimates of change in five different modules. These five modules included: (1) hydrodynamics, (2) land building, (3) habitat switching, (4) habitat use, and (5) water quality (Figure C.1-10). This approach is similar to the coastal ecosystem landscape models that have been developed over the last two decades to simulate processes in specific regions of coastal Louisiana (Costanza *et al.* 1988; Martin *et al*. 2000; Reyes *et al*. 2000; Martin *et al.* 2002). Each module requires knowledge of existing conditions, and will then predict changes in the landscape based on assumptions of how the ecosystems respond to coastal processes. Third, each module produced a set of endpoints specific to the environmental conditions of the particular Coastal Framework. Many of these endpoints became the input to other specific modules. The details of how these modules were linked and specifics on the modeling tools for each module are described in chapter C.2. The fourth step was to use the endpoints of these five modules in a series of benefit calculations to determine specific types of ecosystem response. Finally, the original restoration frameworks were evaluated using a collection of the benefits and compared to the original restoration objectives.

Developing and evaluating Restoration frameworks of Louisiana Coastal Area Plan will link the changes in forcing functions (processes such as river input) to specific restoration endpoints (hydrodynamic, ecological and water quality) using both Simulation and Desktop Modeling Approaches. Values of these endpoints and other metrics were used to calculate benefits of specific frameworks.

This chapter has described the conceptual framework of ecosystem needs in the Mississippi River Deltaic and Chenier Plain, and approach to develop a restoration plan. The trajectories described in the restoration plan and simulated (evaluated) in this appendix are based on the geophysical, geomorphic, and ecologic processes that historically formed and sustained this river-dominated coastal landscape. In the delta subprovince, these include the formation of several deltaic lobes of the Mississippi River. In the Chenier subprovince to the west, major processes include the formation of a series of beach ridges or cheniers. These models are crude estimates as to how these linkages in coastal processes will effectively achieve a sustainable coastal landscape. Future model development will be required to evaluate the feasibility of reducing scientific uncertainty by specific changes in the design and/or operation for both existing and future projects to reach targets at the subprovince scale. It should be understood that projections based on model development in this stage of a restoration plan are scaled to represent the basic “features” of a plan, or strategies, and not the operational nature of proposed measures.

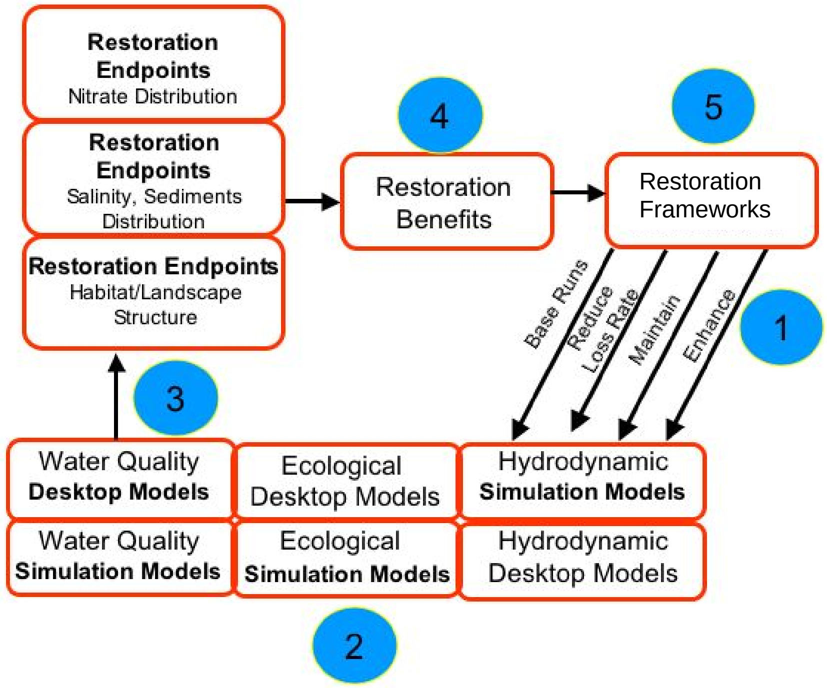


Figure C.1-10 Developing and evaluating restoration frameworks of Louisiana Coastal Area Plan linked the changes in forcing functions (processes such as river input) to specific restoration endpoints (hydrodynamic, ecological and water quality) using both Simulation and Desktop Modeling Approaches. Values of these endpoints and other metrics were used to calculate benefits of specific alternatives.