Restoration of the Mississippi Delta: Lessons from Hurricanes Katrina and Rita

John W. Day Jr.,[1]* Donald F. Boesch,[2] Ellis J. Clairain,[3] G. Paul Kemp,[4] Shirley B. Laska,[5] William J. Mitsch,[6] Kenneth Orth,[7] Hassan Mashriqui,[8] Denise J. Reed,[9] Leonard Shabman,[10] Charles A. Simenstad,[11] Bill J. Streever,[12] Robert R. Twilley,[1] Chester C. Watson,[13] John T. Wells,[14] Dennis F. Whigham[15]

Hurricanes Katrina and Rita showed the vulnerability of coastal communities and how human activities that caused deterioration of the Mississippi Deltaic Plain (MDP) exacerbated this vulnerability. The MDP formed by dynamic interactions between river and coast at various temporal and spatial scales, and human activity has reduced these interactions at all scales. Restoration efforts aim to re-establish this dynamic interaction, with emphasis on reconnecting the river to the deltaic plain. Science must guide MDP restoration, which will provide insights into delta restoration elsewhere and generally into coasts facing climate change in times of resource scarcity.

The Mississippi Deltaic Plain (MDP) is a 25,000-km^2 dynamic landscape of water, wetlands, and low upland ridges, formed as a series of overlapping delta lobes. An understanding of how humans and Hurricanes Katrina and Rita affected the MDP in 2005 requires knowledge about the complex processes that formed and sustained the delta for millennia before human impact. The delta emerged about 6000 to 7000 years ago after eustatic sea level stabilized (Fig. 1) (*1*–*3*). A variety of processes formed and sustained the delta and increased its overall size (Table 1) (*4*). Riverine sediments were deposited at river mouths and via overbank flooding, crevasse formation, and older distributaries (*2*, *3*). Crevasses were usually short-lived (<100 years) and formed depositional splays about 10 km wide, as compared to hundreds of kilometers for delta lobes (*5*). Many former distributaries functioned, either permanently or seasonally, at the beginning of European colonization, around 1700. A skeletal framework of distributary ridges and barrier islands (*6*) protected interior fresher wetlands from marine forces and saltwater intrusion (Fig. 1).

To survive, the soil surface of coastal wetlands must grow vertically to keep pace with local sea level. This is critical in the MDP, where geologic subsidence causes a relative sea-level rise (RSLR) of about 1 cm/year as compared to ~1.5 mm/year of eustatic SLR. Plant growth contributes organic soils; the rest of the vertical growth comes from mineral sediments (*7*). Riverine inputs benefit coastal wetlands in several ways: Mineral sediments increase accretion and bulk density, nutrients enhance plant growth, fresh water buffers saltwater intrusion, and iron precipitates toxic sulfides (*8*, *9*). The deposition of older river sediments resuspended from bays and the nearshore Gulf of Mexico or eroded from other wetlands is especially important during winter storms and hurricanes (*7*, *10*, *11*). However, most sediment is introduced directly from the river (*12*).

In the MDP, barrier islands grow and diminish in conjunction with deltaic lobe cycles (Fig. 2) (*13*). Coarser sediments are deposited at active river mouths, and as the delta advances, sand is transported laterally to form beach ridges. After channel abandonment, delta-front sands are reworked to form erosional headlands attached to marshes behind the barrier. Waves and currents rework and redistribute headland sands laterally to form flanking barrier islands, and the islands move landward as sand is transported in wash-

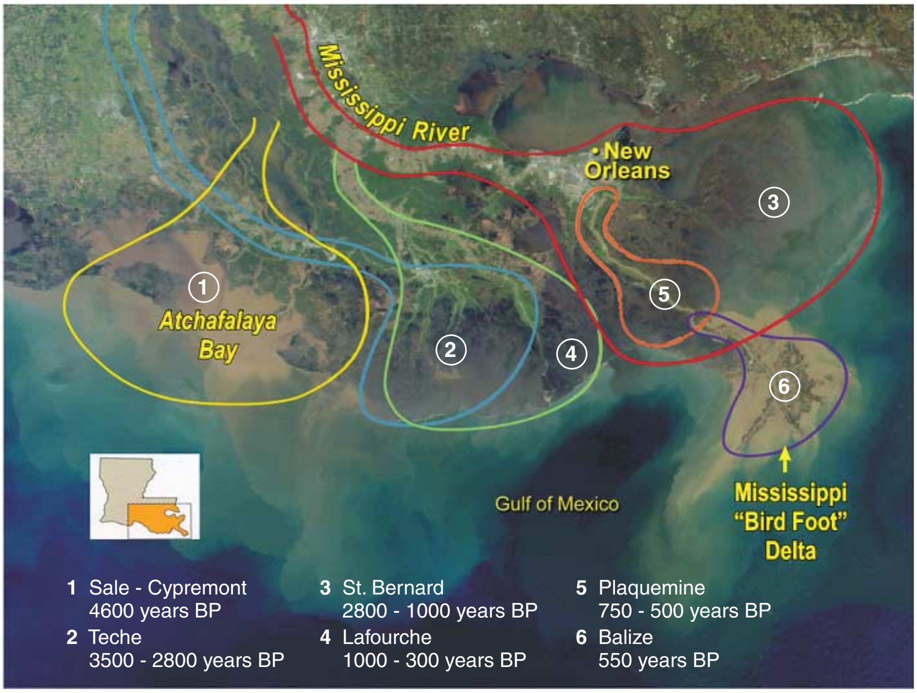

Fig. 1. The MDP was formed by a series of overlapping delta lobes as the river occupied different channels. The delta is characterized by current and abandoned river channels, barrier islands, and extensive coastal wetlands. Currently, about two-thirds of flow is discharged via the lower Mississippi directly to the Gulf and one-third is discharged via the Atchafalaya River to a shallow bay where a new delta is forming. The location of levees is shown on the lower river as well as the location of the MRGO. The turbid plume shown on the right results from a river diversion. BP, before the present. [Modified from (*66*)]

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[1] Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, LA 70803, USA. [2] University of Maryland Center for Environmental Science, Post Office Box 775, Cambridge, MD 21613, USA. [3] Engineer Research and Development Center, U.S. Army Corps of Engineers, Vicksburg, MS 39180, USA. [4] The Hurricane Center, Louisiana State University, Baton Rouge, LA 70803, USA. [5] Department of Sociology, University of New Orleans, New Orleans, LA 70148, USA. [6] Olentangy River Wetland Research Park, The Ohio State University, 352 West Dodridge Street, Columbus, OH 43202, USA. [7] Institute for Water Resources, U.S. Army Corps of Engineers, 7701 Telegraph Road, Alexandria, VA 22315, USA. [8] Department of Civil and Environmental Engineering, Louisiana State University, Baton Rouge, LA 70803, USA. [9] Department of Geology and Geophysics, University of New Orleans, New Orleans, LA 70148, USA. [10] Resources for the Future, 1616 P Street, NW, Washington, DC 20036, USA. [11] School of Aquatic and Fishery Sciences, Box 355020, University of Washington, Seattle, WA 98015, USA. [12] BP Exploration (Alaska), Post Office Box 196612, Anchorage, AK 99519-6612, USA. [13] Engineering Research Center, Colorado State University, Fort Collins, CO 80523, USA. [14] Virginia Institute of Marine Science, Box 1346, Gloucester Point, VA 23062, USA. [15] Smithsonian Environmental Research Center, Box 28, Edgewater, MD 21037, USA.

*To whom correspondence should be addressed. E-mail: johnday@lsu.edu

over fans. As wetlands deteriorate, a barrier island arc is formed. Over time, the barriers fragment into smaller islands, and extensive washover terraces or sandy shoals are formed inshore of the islands, eventually producing a submerged complex of shoals and sand sheets. This process continues until another distributary channel forms and the cycle begins again.

Deterioration of the MDP

Since 1900, about 4900 km^2 of wetlands in coastal Louisiana have been lost at rates as high as 100 km^2/year (*14*, *15*). Wetland loss is much lower on the central coast, where the Atchafalaya River, a distributary that carries one-third of the flow of the Mississippi River, discharges into a shallow inshore bay (*16*). Loss occurs at the wetland edge because of wave erosion and in interior wetlands by submergence as soil accretion fails to keep up with RSLR (*17*). Most loss was initially internal, but as wetlands opened up, wave erosion has become more important (*18*). Although a delta grows and decays as a natural outcome of the delta lobe cycle, the MDP experienced an overall net growth for several thousand years after the sea level stabilized. Human activities during the 20th century reversed this trend (*15*, *17*, *19*).

The main cause of loss was the isolation of the river from the MDP (*17*, *19*). The river is now almost completely leveed, preventing overbank flooding and crevasse formation, so most of its discharge is into the deep Gulf of Mexico (Fig. 1). With the exception of the Atchafalaya River, all distributaries of the river have been closed. The lower Mississippi is prevented from seeking a shorter course to the Gulf via the Atchafalaya by the Old River Control Structure.

Over 15,000 km of canals have been dredged for navigation, drainage, and logging, but mostly for oil and gas development (*17*). This and the construction of impoundments have altered the hydrology that sustains the system (*20*). Spoil banks associated with canals reduce sheet flow of water through wetlands (*21*). Deep, straight navigation canals cause saltwater intrusion and the death of freshwater plant communities (*17*). One of the most notable is the Mississippi River Gulf Outlet (MRGO), a 12-by-300–m canal dredged through the Breton Sound Basin in 1963. Saltwater intrusion via the MRGO killed thousands of hectares of freshwater wetland forests. As Katrina's path crossed Breton Sound, levees along the MRGO were breached and storm surge funneled through the MRGO and into the Gulf Intracoastal Waterway to contribute to the flooding of New Orleans. The withdrawal of oil, natural gas, and formation waters lowered pressures in underlying geologic features, probably causing downfaulting and increasing the rate of subsidence by two to three times during active oil and gas production (*22*).

The construction of reservoirs in the Mississippi basin dramatically reduced the supply of both suspended and bedload sediments to the delta (*6*). Inputs of sand are particularly important for maintaining barrier islands; thus, all barrier islands in the deltaic plain are deteriorating (*13*) because the deterioration phase of the barrier island cycle has accelerated while the development phase has been greatly reduced.

Hurricanes and Mississippi Delta Wetlands

Hurricanes are a regular, if episodic, force in the MDP. Thousands of tropical storms affected the delta as it grew over the past 6000 to 7000 years. Under some conditions, runoff generated by hurricane precipitation introduces fresh water and nutrients that reduce salinity and enhance coastal productivity (*23*). Hurricanes also deposit large amounts of resuspended sediments on wetland surfaces, helping to offset RSLR, and thus are important for the sustainability of marshes (*7*, *10*). Hurricanes Katrina and Rita were the fourth and fifth most powerful storms to strike the MDP since 1893 with respect to maximum wind speed at landfall, but were more remarkable in both cases for the hundreds of kilometers of the coast affected by a storm surge of more than 3 m. As Katrina progressed across Breton Sound and Lake Borgne as a category 3 storm (sustained winds of 194 km $hour^{-1}$), it generated a storm surge that exceeded 10 m on the Mississippi coast and measured up to 6 m southeast of New Orleans, with up to 2 m of additional wave run-up in the most exposed locations (Fig. 3) (*24*). In southeast Louisiana, communities unprotected by levees were inundated, and the storm destroyed levees protecting eastern New Orleans and St. Bernard and Plaquemines parishes to the south and east. Floodwalls failed along drainage and navigation canals connected to Lakes Pontchartrain and Borgne, inundating most of the rest of New Orleans. Because much of this area is below sea level, the floodwaters remained for 3 or more weeks while emergency repairs were made and the water was pumped out. More than 1500 people died as a direct or indirect result of Hurricane Katrina, almost 1100 of them in Louisiana.

Katrina and Rita deposited 5 to 10 cm of sediment over large areas of coastal wetlands (*11*). But about 100 km^2 of wetlands in the Breton Sound Basin lying in the storm path were converted to open water (*25*). Although some of this area is now 1 m or more deep, most of the damaged area is shallow mud flats interspersed with myriad marsh clumps uprooted by the storm. The disturbance of buoyant low-salinity marshes with low-density organic soils often occurs during hurricanes. The Caernarvon river diversion structure is presently being operated to the maximum extent possible to enhance marsh recovery in the most heavily affected area. Initial observations indicate substantial marsh recovery.

Hurricane Rita made landfall near Sabine Pass at the Louisiana-Texas border on 24 September 2005, generating a storm surge of up to 5 m (Fig. 3) and reflooding parts of New Orleans more than 200 km east of landfall. Coastal communities in Cameron Parish were destroyed, and parts of the city of Lake Charles experienced 2-to-3-m–deep flooding associated with surge propagating up a ship channel. To the east, the 30-to-50-km–wide Chenier Plain wetlands reduced surge inland. Because of the lesser storm surge and lower population densities, fewer than 10 people lost their lives directly as a result of Rita's winds and surge. Rita's surge displaced residents from all Louisiana coastal parishes, however, and drove salt water tens of kilometers inland, killing freshwater wetlands in artificially impounded areas (*25*).

Hurricane Rita's highest storm surge was nearly as great as the surge confronting the

Table 1. A hierarchy of forcings or pulsing events affecting the formation and sustainability of deltas. [Modified from (*4*)]

Event	Time scale	Impact
Major changes in river channels	500–1000 years	New delta lobe formation (avulsions), major sediment deposition
Major river floods	50–100 years	Avulsion enhancement, major sediment deposition, enhancement of crevasse formation and growth
Major storms	20–25 years	Major sediment deposition, enhanced production
Average river floods	Annual	Enhanced sediment deposition, freshening (lower salinity), nutrient input, enhanced primary and secondary production
Normal storm events (frontal passage)	Weekly	Enhanced sediment deposition, enhanced organism transport, higher net materials transport
Tides	Daily	Marsh drainage, stimulated marsh production, low net transport of water and materials

eastern side of New Orleans during Katrina, but had to cross 30 to 50 km of Chenier Plain wetlands before reaching main population centers, whereas Katrina's surge was less impeded as it traveled through large lagoons, degraded wetlands, and artificial channels. Barrier islands, shoals, and wetlands can reduce storm surge and waves, but the full range of these effects is not well captured at present by most numerical models. Although it has been shown that damage from the 2004 Indian Ocean tsunami was less in communities sheltered by intact mangroves (*26*), the existence of an extensive barrier island system off of the Mississippi coast did not protect it from a 10-m surge during Katrina. Observations of water levels indicate that Rita's surge was attenuated at an average rate of 4.7 cm per kilometer of wetland landscape where channels were not present. This is similar to previous hurricanes, including Hurricane Andrew in 1992, indicating storm surge attenuation of 7.9 cm per kilometer for intact wetlands along the central Louisiana coast (*27–29*).

Emergent canopies of forested wetlands can greatly diminish wind penetration, thereby reducing the wind stress available to generate surface waves as well as storm surge (*30*, *31*). The sheltering effect of these canopied areas also affects the fetch over which wave development takes place. Shallow water depths attenuate waves via bottom friction and breaking, whereas vegetation provides additional frictional drag and wave attenuation (*32*) and also limits static wave setup (*33*). Extracting energy from waves either by breaking or increased drag reduces destructive wave action on levees. During Katrina, wave-induced run-up and overtopping washed away many miles of turf-covered earthen levees along the MRGO (*24*). Few wetlands or fast lands protected these levees from high-energy surge currents and waves that broke on the levee face. Conversely, other earthen levees nearby that were overtopped by the low-velocity surge, but fronted by extensive wetlands, escaped substantial damage (*34*).

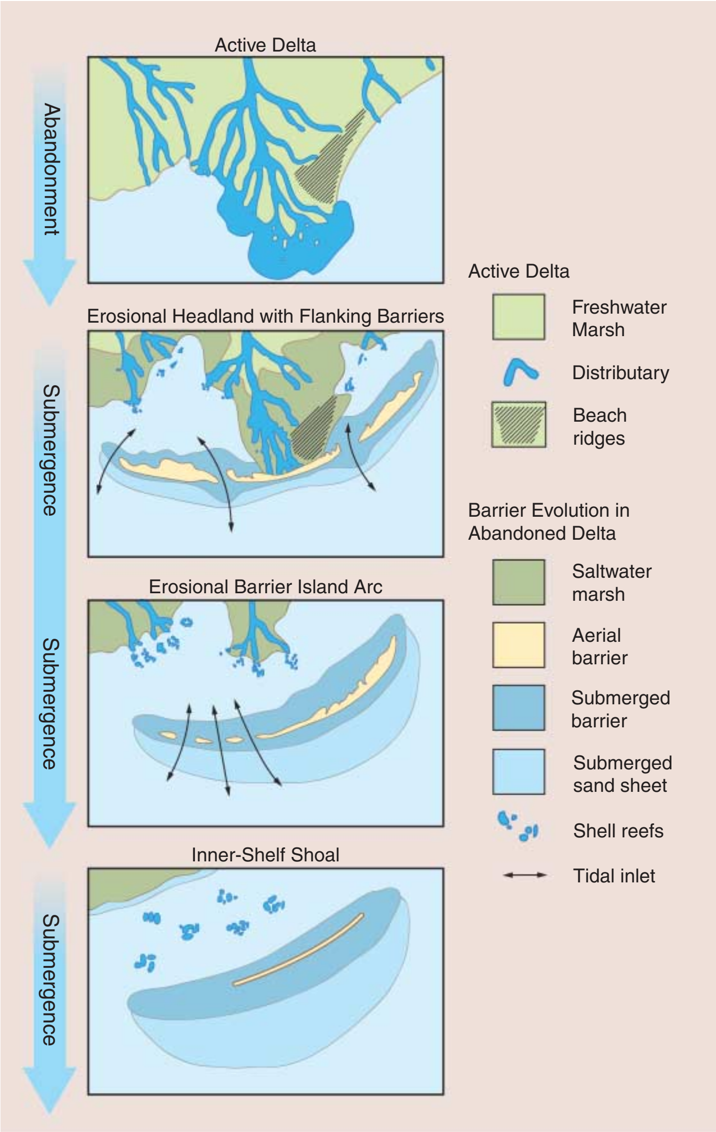

Fig. 2. The barrier island cycle in the MDP. [Modified from (*13*)]

Depending on the rate of RSLR, coastal wetlands maintain a near–sea-level elevation by trapping sediments and forming organic-rich soils. Thus, wetlands play an important role in maintaining elevations near sea level, in contrast to the –3 to –4-m elevations that characterize the equilibrium depth of large bays along the Louisiana coast. Although the relative effects of shallow open waters versus intertidal wetlands on both waves and storm surges from strong hurricanes remain to be fully resolved, it is clear that the intact barrier islands, wetlands, and ridges that once characterized the coastal landscape of Louisiana afforded substantial protection to New Orleans and other coastal communities that cannot be depended on today and must be replaced by more massive levees.

Consequently, maintaining and, where possible, using deltaic processes to increase the area of marshes, mangroves, and swamps in strategic locations would provide a self-sustaining complement to the structural protection of levees. Unfortunately, the physical and hydrologic integrity of the wetlands southeast of New Orleans has been greatly compromised by large navigation channels, which may now also require elaborate gates and other closure structures.

The Evolving MDP Restoration Effort

Planning the restoration of the coastal landscape requires the design of sustainable ecosystems that integrate human society with the natural environment (*35–37*) and work with rather than against natural processes. Such ecological engineering approaches rely primarily on the energies of nature, with human energy being used in the design and control of key processes. Because of the dimensions of the delta's problems, traditional engineering approaches such as levee construction and the placing of dredged sediments are also required. An important goal of MDP restoration is the application of the optimum mix of ecological and standard engineering approaches. With this in mind, four general approaches to restoration are being evaluated, planned, or implemented in the MDP:

(1) Reconnecting the river to the deltaic plain via river reintroductions, the reopening of old distributaries, and crevasse-splay development (*35*, *37*, *38*). Over the past two decades, it has become increasingly clear that this will have to be done on a large scale.

(2) Using dredged sediments to create and restore wetlands by pumping them over distances of tens of kilometers. This is expensive, but because dredged sediments can be used to create wetlands quickly, this technique may be useful for restoring wetlands that would soon be lost or quickly creating large areas of wetlands that would then be sustained through river reintroductions (*39*).

(3) Restoring barrier islands by pumping sands from offshore, constructing groins and breakwaters, placing riprap, and using fences and plantings to stabilize sand dunes (*40*, *41*). Because MDP barrier islands do not just migrate but deteriorate over time, restoration will require ongoing maintenance. Restoration and maintenance can be justified, however, because islands reduce waves and storm surge and provide important habitats in the coastal landscape. In the future, the remobilization of sand trapped in up-basin reservoirs may become a source of coarse sediments that will aid in maintaining barrier islands.

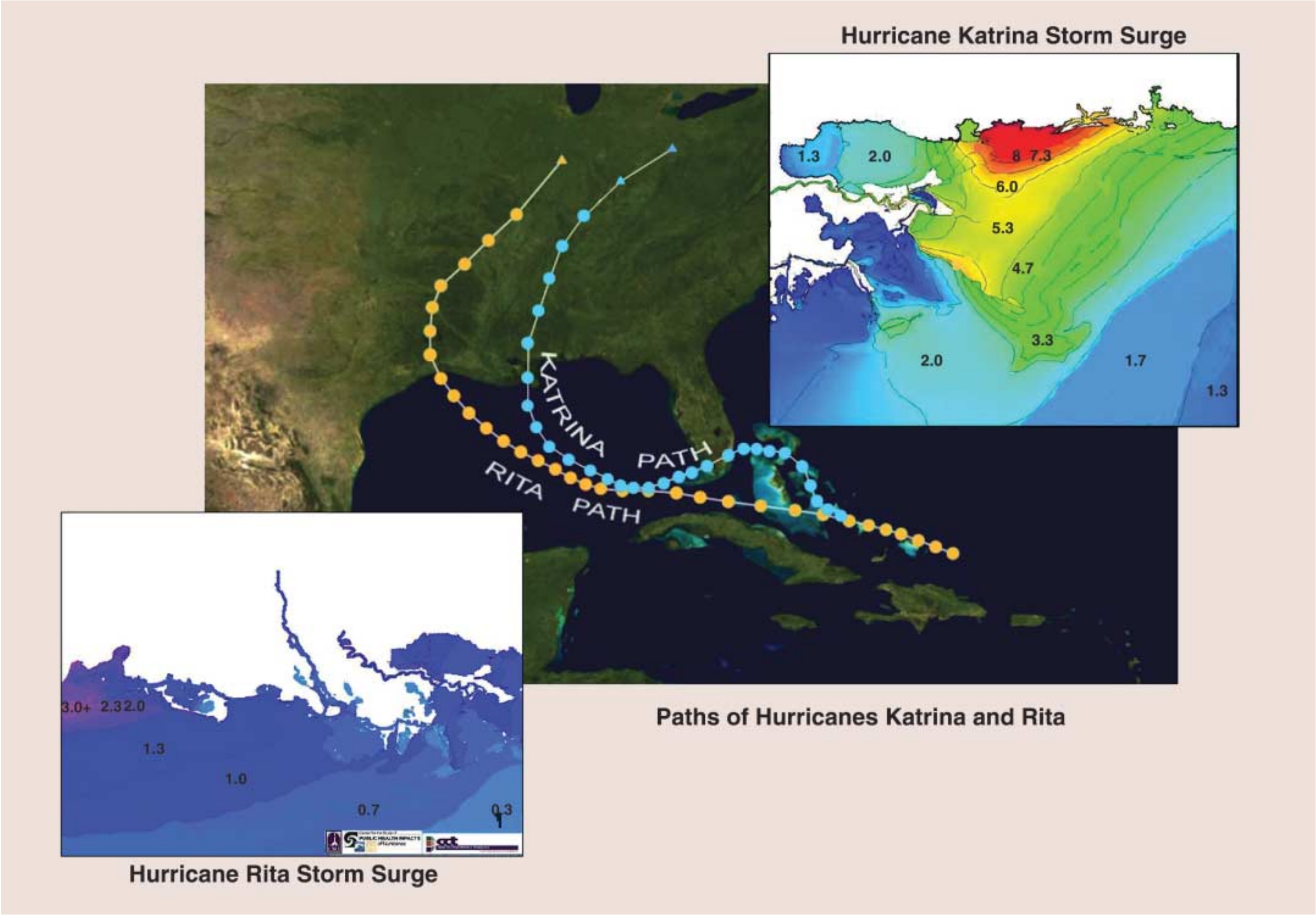

Fig. 3. A composite figure showing paths of Hurricanes Katrina and Rita, surge levels [in meters, as estimated by the ADCIRC model (*67*)], areas flooded, sites of levee failures, and wetland loss due to the hurricane.

(4) Restoring hydrological processes by removing spoil banks, backfilling canals, closing deep navigation channels (such as the MRGO), installing locks (*42*), trapping sediments (*43*), and protecting interior shorelines against erosion. Such restoration generally affects a relatively small area, but can be particularly effective if done in conjunction with diversions so that river water is used most effectively.

Even with its bountiful natural resources, it must be remembered that the MDP is a "working coast" (*38*, *44*), and restoration must be integrated with navigation and flood-protection infrastructure, agriculture, urban development, commercial and recreational fishing, and oil and gas production. In turn, these activities will have to adapt to projects, such as diversions, that seek to return the delta to a more natural state. This is a lesson to be learned regarding most deltas.

Coastal restoration will be more effective if it takes into account changes in fresh water supply, suspended sediment, and nutrient fluxes in the Mississippi River Basin (*45*, *46*). It should work cooperatively with efforts to better manage and restore the resources and environments of the basin, including the restoration of the Missouri and Upper Mississippi Rivers, reservoir management, the reconnection of wetlands and flood plains, and reducing loadings of nutrients from agricultural lands that result in hypoxia in the Gulf of Mexico (*47*–*49*).

Global climate change and the availability and cost of energy have important implications for delta restoration (*50*). Accelerated sea-level rise, changes in precipitation patterns, and changes in the frequency and intensity of hurricanes (*51*–*54*) must be taken into account in designing effective restoration strategies. Less energy-intensive restoration techniques that use the energies of nature, rather than dwindling and costly fossil fuels (*55*, *47*), should be emphasized (*50*).

A New Institutional Framework

For most of the 20th century, public decisions and investments in coastal Louisiana focused on flood protection, navigation, oil and gas extraction, or wildlife management. Growing awareness of the dimensions and consequences of wetland loss has resulted in considerable regional advocacy and planning for substantial public investments for restoration of the MDP. The federal Coastal Wetlands, Planning, Protection and Restoration Act (CWPPRA) of 1990 has provided up to $50 million per year in the United States, but it became apparent that larger-scale restoration efforts were needed (*56*). A more inclusive ecosystem restoration plan, "Coast 2050—Toward a Sustainable Coastal Louisiana," was developed in 1998, which included a diverse amalgamation of projects of various sizes and purposes located throughout the coastal zone (*57*).

To further refine the Coast 2050 Plan, the U.S. Army Corps of Engineers undertook the Louisiana Coastal Area (LCA) Ecosystem Restoration Study (*58*). The LCA Study produced detailed quantitative analyses of various restoration features and of the cost and effectiveness of suites of various features in achieving ecosystem benefits, ranging in total cost from $5 billion to 17 billion. The Office of Management and Budget directed the Corps to prepare a scaled-back LCA Plan that was submitted to Congress in January 2005 (*38*). It recommended authorization of five "near-term critical ecosystem restoration features," a science and technology program, a demonstration program, beneficial use of dredged materials, and further investigations of other near-term restoration features, at a cost of nearly $2 billion. The Assistant Secretary of the Army requested programmatic authorization for elements totaling $1.12 billion, which currently awaits passage of a Water Resources Development Act or some other statute.

A National Research Council review of the LCA Plan concluded: “although the individual projects in the study are scientifically sound, there should be more and larger scale projects that provide a comprehensive approach to addressing land loss over such a large area. More importantly, the study should be guided by a detailed map of the expected future landscape of coastal Louisiana that is developed from agreed upon goals for the region and the nation.” (*59*, *60*). Congress directed the Corps to develop a plan for closure of the MRGO to deep-draft navigation, and in December 2006 the Corps recommended that the channel be permanently blocked and not maintained even for shallow-draft navigation.

Before the hurricanes of 2005, planning and decision-making for delta restoration remained largely separate from that for storm protection and navigation (*33*). In LCA planning, restoration features were evaluated on the basis of ecosystem benefits and financial costs, so that the most cost-effective array of features could be identified. Benefits did not specifically include the value of storm damage reduction, and costs were only financial outlays by governments, even though the features might impose costs or yield benefits to current ecosystem users (such as fishers and oil and gas and navigation interests). These analytical limitations effectively isolated restoration plan formulation from other potential synergies or conflicts with flood protection, storm damage reduction, and navigation.

It has become clear not only to scientists and engineers (*38*) but also to a growing segment of the public and political leadership that sustaining a coastal landscape is necessary to ensure the habitability and economic enterprises of the MDP (*61*, *37*). The implications of this new awareness are twofold: First, activities that could further diminish the coastal landscape have to be adjusted so that they are consistent with that sustainability; and second, ecosystem restoration efforts must now include storm damage reduction benefits as a major consideration in the overall restoration plan (*38*). In the aftermath of the 2005 hurricanes, the Louisiana Legislature created the Louisiana Coastal Protection and Restoration Authority and Congress directed the Corps to undertake the 2-year Louisiana Coastal Protection and Restoration Project (LACPR) in order to identify, describe, and propose a full range of flood control, coastal restoration, and hurricane protection measures for south Louisiana. At this point, the preliminary LACPR report and the preliminary draft State Master Plan (*61*) deal predominantly with hurricane protection barriers, including coastwise levees with floodgates that could diminish the sustainability of the coastal landscape. Much remains to be done to integrate hurricane protection and coastal ecosystem restoration in a compatible manner.

Nonetheless, the 2005 hurricanes have also given new impetus to more comprehensive and aggressive coastal ecosystem restoration approaches than those included in the 2005 LCA Plan proposed to Congress. These include larger-scale diversions, the long-distance conveyance of sediment slurries, and reengineering of the navigational access at the mouth of the Mississippi River so that more of the sediment load of the river is retained in the nearshore zone to contribute to constructive and sustaining deltaic processes. Furthermore, the damage wrought by the hurricanes has lessened some previous social obstacles to these more aggressive approaches by forcing relocation away from the coast, causing losses of resources and/or infrastructure, and lowering public tolerance for obstructions by narrow interests. All of this is evidence that there is a growing recognition that delta restoration and hurricane protection will demand a suite of activities that are much greater in scale and more profound than those considered barely a decade ago.

The Gulf of Mexico Energy Security Act, signed into law in December 2006, gives Louisiana and other Gulf Coast states 37% of the revenues from newly opened oil and gas tracts. Louisiana has constitutionally dedicated these revenues to coastal restoration and protection. Along with other anticipated revenue streams, this could provide approximately $1 billion per year over 30 years for these purposes. Consequently, the state may have the resources to pursue coastal ecosystem restoration on a scale larger than any other U.S. region. This poses a major challenge to science and science-based planning to develop the most strategic and effective strategies, while minimizing the conflicts and maximizing the synergies in achieving multiple social objectives within a sustainable coastal landscape required for the future of the region. At the same time, the substantial uncertainties must be recognized, accepted, and incrementally reduced through adaptive management approaches that promote learning while executing and enhancing the effectiveness of future decisions—for this must truly be a long-term commitment. That will require substantial improvements in science, engineering, planning, and management capacity, operating with a sense of urgency and purpose.

The restoration of the MDP is important not only in its own right, but because it provides understanding needed to contend with the many other deteriorating delta systems around the world. Moreover, it serves as a model for adaptation to future climate change in coastal ecosystems more generally. Because of high rates of subsidence, the MDP presently has a rate of relative sea-level rise equivalent to that predicted for many coasts toward the end of this century. Human impacts have caused both substantial increases and decreases in freshwater inflow to parts of the coast. And the area has one of the highest frequencies of tropical cyclone impacts in the world. The management approaches developed to restore and sustain the MDP in the face of present-day forces will undoubtedly influence future adaptation to climate change impacts elsewhere, especially during a period of resource scarcity. In addition, the experience in the MDP indicates that restoration on such large scales requires long time periods and complex stakeholder engagement.

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