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Implications of global climatic change and energy cost and availability for the restoration of the Mississippi delta

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Abstract

Over the past several thousand years, inputs from the Mississippi River formed the Mississippi delta, an area of about 25,000 km². Over the past century, however, there has been a high loss of coastal wetlands of about 4800 km². The main causes of this loss are the near complete isolation of the river from the delta, mostly due to the construction of flood control levees, and pervasive hydrological disruption of the deltaic plain. There is presently a large-scale State-Federal program to restore the delta that includes construction of water control structures in the flood control levees to divert river water into deteriorating wetlands and pumping of dredged sediment, often for long distances, for marsh creation. Global climate change and decreasing availability and increasing cost of energy are likely to have important implications for delta restoration. Coastal restoration efforts will have to be more intensive to offset the impacts of climate change including accelerated sea level rise and changes in precipitation patterns. Future coastal restoration efforts should also focus on less energy-intensive, ecologically engineered management techniques that use the energies of nature as much as possible. Diversions may be as important for controlling salinity as for providing sediments and nutrients for restoring coastal wetlands. Energy-intensive pumping-dredged sediments for coastal restoration will likely become much more expensive in the future. © 2005 Elsevier B.V. All rights reserved.

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1. Introduction

The Mississippi River has the largest discharge and drainage basin in North America and is one of the largest rivers in the world. The watershed encompasses about 3 million km², about 40% of the area of the lower 48 United States, and accounts for about 90% of the freshwater inflow to the Gulf of Mexico. The Mississippi delta is the largest contiguous coastal ecosystem in the U.S.; approximately 60% of the estuaries and marshes in the Gulf of Mexico are located in coastal Louisiana. The delta is ecologically and economically important. Ecologically, the coastal wetlands and shallow waters of the delta provide habitat for fish and wildlife, produce food, regulate chemical transformations, maintain water quality, store and release water, and buffer storm energy (Day et al., 1997, 2000). These processes support a variety of economically important, natural resource-based activities valued at several billion dollars annually including recreational and commercial fisheries, fur mammals, and alligators, ecotourism, and hunting (LCWCRTF, 1993; Day et al., 1997). The lower Mississippi River in Louisiana is home to the largest port activity by tonnage in the world (LCWCRTF, 1993). Petroleum products produced by refineries located in the Louisiana coastal zone are valued at US\$ 30 billion annually and approximately 20% of crude oil and 33% of natural gas of the United States flow through the Louisiana coastal zone (Davis and Guidry, 1996).

The Mississippi delta (Fig. 1) was formed over the past 6000–7000 years as a series of overlapping delta lobes (Roberts, 1997). There was an increase in wetland area in active deltaic lobes and wetland loss in abandoned lobes, but there was an overall net increase in the area of wetlands over the past several thousand years. Currently, only two of the distributaries of the river are functioning, the lower river and the Atchafalaya River which carries about one-third of the total flow of the Mississippi River. At the time European occupation began, however, numerous distributaries were functioning, either year round or during the seasonal spring flood. The delta was sustained by a series of energetic forcings or pulsing events that occurred over different spatial and temporal scales. These pulses include shifting deltaic lobes, crevasses, great river floods, hurricanes, annual river floods, frontal passages, and tides (Day et al., 1997, 2000). The area of the delta is about



Fig. 1. Louisiana coastal zone showing estuarine basins and vegetation zones (modified from Lindscombe et al., 2001).



Fig. 2. Historical and projected land change trend in coastal Louisiana, 1932–2050 (from U.S. Geological Survey, National Wetlands Research Center).

25,000 km² including wetlands, shallow inshore water bodies, and low elevation uplands (mostly associated with river distributary ridges and beach ridges).

There was, however, a dramatic reversal of this condition of net growth in the 20th century. There has been an enormous loss of coastal lands in the delta with a total loss of about 4800 km² since the 1930s (Fig. 2; Boesch et al., 1994; Britsch and Dunbar, 1993; Barras et al., 1994, 2003). Over 95% of this loss was wetland, primarily as marshes converted to open water. In the 1970s, the loss rate was as high as $100 \text{ km}^2/\text{year}$ and the loss rate from 1990 to 2000 was about $60 \text{ km}^2/\text{year}$ (Barras et al., 2003). Between 1956 and 2000, the average loss rate was $88 \text{ km}^2/\text{year}$ (Barras et al., 1994, 2003). These high rates of wetland loss are projected to continue for the next half century; and by 2050, it is estimated there will be an additional net wetland loss of 1329 km^2 (Barras et al., 2003).

An understanding of the causes of this land loss is important not only for a scientific comprehension of the mechanisms involved, but also so that effective management plans can be developed to restore the delta (see Boesch et al., 1994; Day et al., 2000 for a review of these issues). A number of factors led to the massive loss of wetlands. Foremost among these are floodcontrol levees along the Mississippi River that resulted in the elimination of riverine input to most of the delta (Boesch et al., 1994; Day et al., 2000). In addition to the flood-control levees, most active distributaries were closed, and the river mouth was made more efficient for navigation by dredging. This resulted in the loss of most river sediments, which once sustained the wetlands, directly to deep waters of the Gulf of Mexico. There has also been a reduction of the suspended sediment load in the Mississippi River caused by dam construction in the Upper Mississippi River (Kesel, 1988, 1989).

Pervasive altered wetland hydrology, mostly caused by canals, is another important factor contributing to wetland loss. Canals, originally dredged for drainage and navigation, are now overwhelmingly linked to the petroleum industry. Drilling access canals, pipeline canals, and deep-draft navigation channels have left a dense network of about 15,000 km of canals in the coastal wetlands. Although canals are estimated to comprise about 2.5% of the total coastal surface area, their destructive impact has been much greater (Turner et al., 1982). Spoil banks, composed of the material dredged from the canals, interrupt sheet flow, impound water, and cause deterioration of marshes. Long, deep navigation canals that connect saline and freshwater areas tend to lessen freshwater retention time, and allow greater inland penetration of saltwater.

In sum, there is a broad consensus that wetland loss is a complex interaction of a number of factors acting at different spatial and temporal scales (e.g., Turner and Cahoon, 1987; Day and Templet, 1989; Boesch et al., 1994; Day et al., 1995, 1997). Day et al. (2000) concluded that isolation of the delta from the river by levees was perhaps the most important factor.

2. Approaches to restoration of the Mississippi delta

The State of Louisiana and the Federal government have embarked on an ambitious program, called the Louisiana Coastal Area (LCA) Ecosystem Restoration Plan, to restore the Mississippi delta (http://www.lca.gov). In the remainder of this paper, we describe elements of the restoration program and discuss the implications for restoration of two global trends, climate change and the cost and availability of energy.

The primary approaches to restoration of the delta involve reversal of the impacts that have occurred due to human activity. These include the near complete separation of the river from the delta and the pervasive hydrological alteration of the delta plain. There are several primary approaches to addressing these impact including river diversions, hydrological restoration, marsh creation and restoration using dredged sediments, and barrier island restoration.

2.1. Diversions of river water into deteriorating wetlands

Freshwater diversions are the major management approach for restoration of the Mississippi delta (Fig. 3a). There are at present, two diversions operating (with a maximum discharge between 200 and $250 \text{ m}^3 \text{ s}^{-1}$) with several more planned. The aim is to reconnect the river with its delta. The idea of diversions is not new and was proposed nearly a century ago by Viosca in 1927. When freshwater diversions were first planned in Louisiana over three decades ago, the primary goal was to reduce salinity to enhance ovster production in surrounding regions (Chatry et al., 1983; Chatry and Chew, 1985). More recently, diversions have increasingly been used as a way of delivering sediments and nutrients to wetlands in an attempt to counter relative-sea-level-rise (RSLR) and restore deteriorating wetlands (Day and Templet, 1989; Day et al., 1997, 2000; LCA Plan, http://www.lca.gov). Recently completed and ongoing research indicates that diversions lead to enhanced accretion, substantial reductions in nutrients, higher marsh productivity, and higher fishery yield (Day et al., 1997; Lane et al., 1999, 2001, 2004; Perez et al., 2003; DeLaune and Pezeshki, 2003: DeLaune et al., 2003). There is concern that nutrients in diverted water will lead to eutrophication and there is continuing research on the issue and ways to manage diversions to minimize the potential for water quality problems.

There is concern that introductions of river water will lead to water quality problems in estuaries and coastal bays similar to the hypoxia zone in the Gulf of Mexico. This zone forms when excess nitrogen in the river, mainly from agricultural runoff, lead to algal blooms that sink and consume oxygen (Rabalais et al., 1996). It is thus imperative that restoration of the Mississippi basin be carried out at the same time as delta restoration. Mitsch et al. (2001) suggested an ecological engineering approach for the basin where constructed and restored wetlands are used to reduce nutrients in agricultural runoff.

2.2. Reopening distributaries and hydrologic restoration

In addition to diversions, the LCA planning process is studying the potential for reopening one or more of the Mississippi River distributaries that have been closed (i.e., Bayou Lafourche) and putting more water down the Atchafalaya River. All of these efforts are designed to introduce river water into shallow inshore areas to restore coastal wetlands.



Fig. 3. (a) A river diversion at Caernarvon, LA. The gated structure allows Mississippi River water to flow into the adjacent coastal system (Courtesy of U.S. Army Corps of Engineers, New Orleans District). (b) A typical sediment dredging operation in a coastal bay in Louisiana (Courtesy of U.S. Army Corps of Engineers, New Orleans District).

Another important aspect of coastal restoration is hydrologic restoration. As stated earlier, the pervasive hydrologic disruption of the delta has led to reductions in overland flow, decreased sedimentation, changes in wetland productivity, increased flooding, higher subsidence, and salt water intrusion (Swenson and Turner, 1987; Reed, 1992; Cahoon, 1994; Boumans and Day, 1994; Conner and Day, 1988, 1991, 1992; Morton et al., 2002). Hydrological restoration seeks to reduce these impacts by such management activities as spoil bank removal, closure of some deep navigation channels (such as the Mississippi River Gulf Outlet, southeast of New Orleans) and putting locks in others (Day and Templet, 1989; Turner and Streever, 2002; Day et al., 2004). Such restoration can be particularly effective if done in conjunction with diversions so that river water is used most effectively.

2.3. Use of dredged sediments for wetlands creation and restoration

Dredged sediments have long been used for wetland creation (Fig. 3b). This has been done rather extensively in the "bird's foot" delta at the mouth of the river and in the Atchafalaya delta. Dredged sediments have also been used in many parts of the coast where dredging projects have been carried out. However such use of dredged sediments as part of navigation projects has been done opportunistically and can address only a small part of coastal land loss. Recent work has shown that nourishment of low elevation, unhealthy marshes with dredged sediments results in an increase in marsh elevation and thus productivity (Mendelssohn and Kuhn, 2003). There are now plans to dredge sediments specifically for marsh creation and nourishment and to pump the sediments over long distances (10s of km). Such pumping is expensive, economically and energetically, and costs increase as boosters and pipe are added to pump longer distances. Currently the average cost of sediment dredging for wetlands restoration in the northern Gulf of Mexico is about US\$ 40,000/ha, excluding additional activities such as construction of protective structures, planting, re-contouring, and monitoring (Turner and Streever, 2002, p. 95).

2.4. Barrier island restoration

Barrier islands in coastal Louisiana are important for protecting coastal wetlands by mitigating wave energy, to provide wildlife habitat for migrant birds and to maintain estuarine conditions. However, the islands have eroded significantly, due to RSLR, reduced sediment availability, and erosion during storms (Dingler et al., 1992). Hurricanes are particularly damaging to barrier islands (Stone et al., 1997). Barrier islands are restored by pumping sands from offshore to rebuild the islands. At times, engineered structures are also used. Sand-trapping fences and vegetative plantings are used to stabilize sand dunes on barrier islands along with beach nourishment (LA DNR, 1997, p. 15). After vegetative planting, re-vegetation takes place and is affected by both biotic and abiotic factors (e.g., soil salinity, Courtemanche et al., 1999). Control of grazers, such as nutria, is also important to maintaining vegetative cover (Hester et al., 1994).

Barrier island restoration is expensive. For example, the cost for 1700 liner feet of beach front restoration at East Island, Louisiana, was US\$ 1.3 million (LA DNR, news release, April 18, 1996), and around US\$ 500 million are needed to restore about 85 miles of barrier islands in coastal Louisiana (St. Pé, 1999). Barrier islands must be renourished periodically to ensure sustainability.

3. Global trends and their implications for delta restoration

3.1. Global climate change

There is a broad consensus in the scientific community that human activity is affecting global climate (IPCC, 2001). Climate change will significantly alter many of the world's coastal and wetland ecosystems (Poff et al., 2002). Global climate change will affect temperature, the amount and seasonality of rainfall, and the rate of sea level rise. The Intergovernmental Panel on Climate Change (IPCC) predicts that global temperatures will rise from 1 to 5 °C during the 21st century. This increase in temperature will affect coastal biota directly and lead to changes in precipitation and an acceleration of sea level rise. It is predicted that as the tropics gain more heat, there will be a greater transport of water vapor toward higher latitudes. Thus, it is likely that, in general, lower latitudes will experience a decrease in precipitation and higher latitudes will experience an increase in rainfall.

General circulation models (GCMs) are not consistent in their predictions of the effects of climate change on precipitation and temperature, which are two important drivers of freshwater inflow to estuaries. For example, runoff estimates for the Mississippi River basin differ greatly between the Canadian CGCM1 model and the Hadley HADCM2 model (Wolock and McCabe, 1999). Both models predict an increase in future extreme rainfall and runoff events, but they disagree in terms of both the magnitude and direction of changes in average annual runoff. The average annual runoff of the Mississippi River basin, for example, was projected to decrease by 30% for the Canadian model, but increase by 40% for the Hadley model by the year 2099. Estimated changes of freshwater inflow into major U.S. estuaries projected by the Hadley model by



Fig. 4. Projected global average sea level rise, 1990–2100 (*Source:* IPCC, 2001).

the year 2099 range from -40% to +100%. Similar calculations based on the Canadian model indicate significantly reduced inflows for all coastal regions except the U.S. Pacific coast (Wolock and McCabe, 1999). It is likely many coastal and estuarine ecosystems will experience changes in freshwater inflow. However, at present it is unclear in what manner these changes will occur. There has already been a small, but significant, increase in the flow of the river during the past half-century (Justic et al., 2003). While there is much uncertainty in predictions of local changes in precipitation and runoff, the precautionary principle suggests that management plans for delta should take such changes into consideration.

There is strong consensus that global warming will lead to accelerated eustatic sea level rise in the 21st century. IPCC (2001) predicted that sea level will rise by 20–65 cm in the 21st century, with a best estimate of 30–50 cm (Fig. 4). This is much higher than measured eustatic sea level rise for the 20th century of 1-2 mm/year (Gornitz et al., 1982). This increase in sea level must be added to subsidence to obtain the RSLR that coastal wetlands in the Mississippi delta will be subject to over the 21st century. Thus, RSLR in the delta will increase from about 1 cm/year to 1.3-1.7 cm/year within this century (a 30-70% increase).

Two important physiological reasons that lead to the loss of wetlands are flooding stress due to increased flooding duration and salinity stress (Mendelssohn and Morris, 2000). Global climate change will likely exacerbate both of these stresses. Accelerated sea level rise will lead to significant increase in flooding duration. Unless wetlands can accrete vertically at the same rate as water level rise, coastal vegetation will become progressively more stressed and ultimately die. Even at current rates of RSLR of about 1 cm/year, most wetlands of the Mississippi delta do not have sufficient rates of vertical accretion to survive (Delaune et al., 1983; Hatton et al., 1983; Conner and Day, 1991). Rising sea level combined with lower freshwater input will lead to increased saltwater intrusion and salinity stress. This especially threatens the extensive tidal freshwater wetlands of the delta. This combination of high RSLR, increased temperature, and lower freshwater input results in the north central Gulf having the highest vulnerability to climate change in the United States (Thieler and Hammar-Klose, 2001).

Increased temperature may interact with other stressors to damage coastal marshes. For example, during the spring to fall period of 2000 in the Mississippi delta, there were large areas of salt marsh that were stressed and dying. This appears to be the result of a combination of effects related to a strong la Niña event which resulted in sustained low water levels caused by a global circulation pattern, prolonged and extreme drought and high air temperatures. This combination of factors apparently raised soil salinities to stressful and even toxic levels. McKee et al. (2004) suggested that increases in temperature and decreases in rainfall associated with climate change may dramatically affect tidal marshes.

Another major climate driver in warm temperate zones is reduction in the frequency of extreme freezes, which is presently occurring along the coastal fringes of the Mississippi River Deltaic Plain. An important result of increasing temperature along the northern Gulf of Mexico will likely be a northward migration of mangroves replacing salt marshes. Mangroves are tropical coastal forests that are freeze-intolerant. Chen and Twilley (1998) developed a model of mangrove response to freeze frequency. They found that when freezes occurred more often than once every 8 years, mangrove forests could not survive. At a freeze frequency of 12 years, mangroves replaced salt marsh. Along the Louisiana coast, freezes historically occurred about every four years. By the spring of 2004, however, a killing freeze had not occurred for 15 years and small mangroves occur over a large area near the coast. If this trend continues, mangroves will probably spread over much of the northern Gulf and part of the south Atlantic coast. In fact, mangroves are already becoming established and more widespread due to warming. According to Dr. J. Visser (personal communication, Coastal Ecology Institute, LSU, June 25, 2004), there are approximately 150 km² of mangrove habitat in the Barataria and Terrrebonne basins. It was observed during the drought in 2000, that mangroves were able to withstand higher temperatures and salinity and water stress (McKee et al., 2004). Thus, succession from tidal marshes to mangroves may lessen the impact of drier, higher salinity conditions.

Because mangroves have many of the same ecological functions as salt marshes (high productivity, habitat for wildlife and fishes, sites of nutrient uptake, etc.), a switch in the U.S. coastal wetlands from salt marshes to mangroves might not change ecosystem function much. However, if the climate becomes more variable with freeze-free periods interspersed with occasional hard freezes, it could be more difficult for either marshes or mangroves to survive, resulting in a loss of wetland habitat.

3.2. The availability and cost of energy

The availability and cost of energy will likely become an important factor affecting the way that natural resource management is carried out in the future. Over the past decade, increasing information has appeared in the scientific literature suggesting that world oil production will peak within a decade or two (Fig. 5a) implying that demand will consistently be greater than supply and that the cost of energy will increase significantly in the coming decades. This information has come primarily from petroleum geologists with long experience in petroleum production (Masters et al., 1991; Campbell and Laherrère, 1998; Kerr, 1998; Bentley, 2002; Deffeyes, 2001, 2002; Hall et al., 2003; Heinberg, 2003).

The various projections of when world oil production will peak are based on the approach developed by M. King Hubbert who became well known because of his famous prediction made in 1956 that U.S. oil production would peak in the early 1970s (it peaked in 1971). Hubbert also predicted that world oil production would peak around the year 2000 (see Deffeyes, 2001 and Heinberg, 2003 for a discussion of Hubbert's work). In essence, projections of future oil production and peak oil production use statistical and physical



Fig. 5. (a) Historical global oil production and past and projected oil discovery, 1930–2050 (*Source:* Campbell, 2004; http://www. oilcrisis.com/campbell/). (b) Published estimates of total ultimate oil recovery (modified from Hall et al., 2003, p. 321).

methods based on reserve estimates and the lifetime production profile of typical oil reservoirs. Oil production from reservoirs tends to follow a bell-shaped curve with a rapid increase in production followed by a relatively rapid decrease in production. Thus, by knowing the early production history of a reservoir (or many reservoirs together) and an estimate of reserves, the time of peak production and total oil production can be estimated. Based on this information, various authors have predicted that world oil production will peak sometime during the first two decades of the 21st century (see Masters et al., 1991; Campbell and Laherrère, 1998; Deffeyes, 2001; Bentley, 2002; Heinberg, 2003). Some have augured that additional discoveries will provide abundant oil well into the future (see Deffeyes, 2001; Hall et al., 2003; Heinberg, 2003 for a review). But most estimates of ultimately recoverable oil (URO) have remained relatively constant since about 1965 at about 2 trillion barrels (Fig. 5b). This is the value of URO that most authors have used to predict the timing of peak oil production. Oil discoveries peaked in the 1950s and 1960s and have declined substantially since (Fig. 5a). We now consume about two barrels of oil for each one discovered.

An important factor that affects consideration of energy use is energy return on investment (EROI). EROI is the ratio of the energy in oil that is produced to all the energy used to discover and produce oil. During the period of exponential increases in conventional oil production, the EROI was between 100:1 and 50:1. Over the last two decades, EROI for world conventional oil production fell to between 20:1 and 10:1 (Cleveland et al., 1984; Cleveland, 2005). Thus, it is costing more and more to find and produce oil. The EROI for nonconventional sources of oil (oil shale and oil sands) and most renewables are all less than 15:1 and most are substantially less than 10:1 (Heinberg, 2003). We believe that the implication of all of this is that oil production will not be able to meet demand and that the cost of energy will increase substantially.

4. Implications for delta restoration and management

Global climate change and energy availability have important implications for management of the Mississippi delta. Global climate change is predicted to lead to accelerated sea level rise, increased temperatures, perhaps higher Mississippi River discharge, but lower precipitation and local freshwater discharge to Louisiana estuaries. Droughts, such as occurred in 2000, may become more frequent and salt-water intrusion will likely be more severe. Thus, two of the most detrimental stressors leading to vegetation mortality, prolonged flooding and salinity, probably will be exacerbated with climate change. Vertical accretion rates will have to be 30-70% higher in a century than at present if coastal marshes are to survive. Both river diversions and utilization of dredged sediment will become even more important in the future in enabling coastal marshes to survive accelerated sea level rise. River water introduces sediments that contribute directly to vertical accretion, nutrients that stimulate vegetation productivity and organic soil formation, and iron that detoxifies sulfide by precipitation (DeLaune and Pezeshki, 2003; DeLaune et al., 2003). An important consideration is that marshes created with dredged sediments will have a shorter lifetime in the future than at present because of the acceleration of the rate of sea level rise. It is a paradox that river discharge is predicted to increase significantly by one GCM while local freshwater discharge is predicted to decrease. Therefore, one of the most important benefits of river diversions will probably be the use of the excess water in the Mississippi River to counter higher salinities due to sea level rise and lower local fresh water surpluses. Thus, river diversions will probably become more critical in delta restoration to offset the impacts of climate change (Table 1).

Energy price and availability will also likely have important implications for delta restoration. The remarkable economic growth of the last century has been fuelled by cheap energy, most importantly oil (Hall et al., 2003). Much of the infrastructure of our industrial society was put in place using 50:1 to 100:1 oil (and equivalently cheap coal and natural gas). The massive flood control and navigation works on the Mississippi River were part of this infrastructure. This includes the giant Bonnet Carré Spillway built on the Mississippi River in the early 1930s to protect New Orleans. The spillway is still functioning today.

If the end of era of cheap energy comes to pass, energy intensive management methods will become increasingly expensive and untenable. Louisiana has relatively little political power at the national level, so it is possible that we will not be able to obtain large amounts of resources for delta restoration. We will be forced to consider less energy-intensive, less expensive options for restoring deteriorating coastal marshes in the postoil peak era.

Increased cost and reduced availability of energy suggests that those methods of restoration that use relatively low amounts of energy are the ones most sustainable in the long term. The combination of diversions with use of dredged sediments is very important because marshes created with dredged sediments will have a shorter lifetime in the future because of increased sea level rise. Restoration of the Mississippi basin should also be carried out in conjunction with delta restoration in order to minimize water quality problems as well as solve environmental problems throughout the basin (Mitsch et al., 2001; Day et al., 2003). Pumping sediments, which is very expensive energetically, has a role early in the restoration program in conjunction with construction of diversions.

Approach	Description	Effects	Cost
Freshwater diversion	Diverting Mississippi River water into coastal wetlands for the purpose of restoration using siphons or gates. This is ecological engineering. A major restoration tool	Dissolved nutrients, freshwater, and suspended sediments contribute the nourishment of degraded marshes, along with enhanced fishery habitat. Impacts are ecosystem wide, rather than specific or individual. Land building is a long-term goal. Large scale	Relatively high capital cost, and low annual operation and maintenance cost
Hydrologic restoration	Restoring natural drainage patterns to remedy altered hydrology. Includes backfilling of canals, closure of canals, restoration of natural drainage features, reducing salt water intrusion. A secondary restoration tool	The integrity of altered wetlands is restored by a return towards natural hydrology. Small scale	Moderate to high financial and energy costs per unit area
Use of dredged sediments for wetlands creation/restoration	Beneficial use of sediment materials that can come from dredging projects or that are dredged specifically for the purpose of restoration. A major restoration tool	Newly created intertidal flats can be rapidly colonized by vegetation or planted. Most effective when used in conjunction with diversions	High financial and energy costs. Periodic additional sediment may be required
Barrier island restoration	Deposition of coarse dredged materials to increase barrier island height and width. Engineering structures, sand trapping, and vegetative plantings are used to stabilize sand dunes on barrier islands. A major restoration tool	Rapid restoration. Requires perpetual nourishment to maintain barrier islands. Barrier island restoration restores island habitat, protects wetlands, and maintains estuarine conditions	Labor intensive, capital intensive, very costly (e.g., US\$ 1.3 million for 500 m of beach front restoration at East Island, Louisiana)

Table 1 Approaches to restoration of the Mississippi delta

Restoration project type descriptions for CWPPRA-funded restoration projects in coastal Louisiana (LA DNR, 1997).

In this way, wetlands created can be nourished and sustained with diversions that are likely to have a life of a century or more.

Wherever possible, gravity, winds, and tides should be used to move water and sediments. Diversions. such as the Bonnet Carré Spillway and the diversion at Caernarvon, Louisiana, are examples of this. The Bonnet Carré was constructed over 70 years ago; it is still functioning and is likely to do so for decades. This argues for the construction of needed diversion structures in the near future when energy is still relatively cheap. After construction, they can be operated using relatively little energy, probably for the next century and longer. Energy intensive approaches, such as pumping sediments over long distances to build wetlands, should be used now but they may not be affordable 40-50 years from now. New land created by pumping sediments will last for a shorter period than would have been the case in the past because of the acceleration of sea level rise and higher salinities. Thus, diversions of river water should be planned in conjunction with pumping to maintain the marshes. Modelling has shown that that riverine input can create and maintain wetlands (Martin et al., 2002).

This approach of using the energies of nature to the greatest extent possible is called ecological engineering. This is the ecological principle where small amounts of fossil fuel energies are used to channel much larger flows of natural energies (Odum, 1971; Mitsch and Jørgensen, 2003). Ecological engineering offers both a conceptual and practicable approach for long-term management of the delta in an era when the cost of fossil energies will become much more expensive.

In conclusion, we have presented evidence that climate and the availability and cost of energy will change significantly in the 21st century. Such changes have major implications for the restoration of the Mississippi delta. However, since the future is uncertain, this is a cautionary tale. But we believe that it is unwise to not

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take these factors into consideration because choices made will strongly affect future restoration activities in the delta.

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