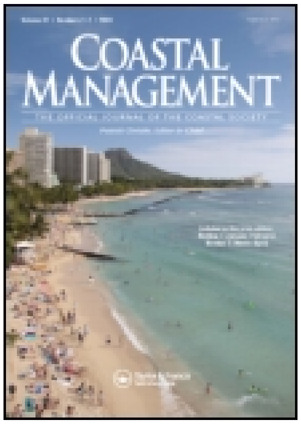

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System functioning as a basis for sustainable management of deltaic ecosystems

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25TH ANNIVERSARY INVITED PAPER

System Functioning as a Basis for Sustainable Management of Deltaic Ecosystems

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Deltas are very important ecologically and economically, and much of the world's coastal wetlands are located in deltas. These areas are in crisis because various human impacts have led to deterioration of deltas. In this article, we address the functioning of deltas, human impacts in deltas, and the concept of sustainable management of deltas. It is implicit in this discussion that only management that is based on the functioning of deltas is sustainable.

In spite of sea-level rise and subsidence, deltas have greatly increased in area because of riverine sediment delivery over the past several thousand years. Recently, human impacts have altered natural pulsing energies and sediment distribution. It is clear that deltas are not being managed in a sustainable manner and there is a need to move toward more sustainable management. Such management must be based on a carefully controlled return to the natural functioning of deltas by utilizing, rather than diminishing, beneficial natural pulsing energies. We propose ways to

Many of the ideas for this article were stimulated by work in the Mississippi, Grijalva-Usumacinta, Rhone, Po, Ebro, and Rhine deltas. This work benefited from discussions with a number of colleagues, including Carles Ibañez, Didier Pont, Donald Cahoon, Denise Reed, Alejandro Yáñez-Arancibia, Paul Kemp, Joseph Suhayda, Robert Costanza, Philippe Hensel, and David Tilley. Research findings on which this article is based were supported by a number of agencies, including Louisiana Sea Grant Program, Environmental Protection Agency, Corps of Engineers, U.S. Geological Survey, the French National Program of Coastal Oceanography, the Fulbright Program, and the EC Environmental Research Programme "Climatology and Natural Hazards": MEDDELT, Impact of Climate Change on Northwestern Mediterranean Deltas (Contract EV5V-CT94-0465).

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determine if deltas are geomorphically, ecologically, and economically sustainable. The article is concluded with an EMergy analysis to holistically test for deltaic sustainability.

Keywords delta, management, pulsing, sea-level rise, sustainability

Deltas are important ecologically and economically; most of the world's coastal wetlands are located in deltas. These areas, however, are in crisis because various human impacts have led to their deterioration. Activities such as the construction of dams, impoundments, dikes, and canals; water and mineral extraction; and habitat destruction have led to such problems as enhanced subsidence and reduced accretion, salinity intrusion, water quality deterioration, and decreased biological production. In this paper, the authors will address the functioning of deltas, human impacts in deltas, and the concept of sustainable management of deltas. It is implicit in this discussion that only management which is based on the functioning of deltas is sustainable.

From a geomorphological point of view, deltas can be considered as one endpoint in the continuum of coastal systems, which includes deltas, estuaries, and coastal lagoons (Kjerfve, 1989). Deltas are riverine dominated systems, while lagoons are marine dominated, with estuaries intermediate between the two. The primary forces shaping deltas are riverine input and the forces governing the deposition of riverine sediments. Deltas are generally characterized by broad expanses of near-sea-level wetlands and shallow water bodies.

It is important to understand that present day deltas, and other coastal systems, are relatively young geologically. At the height of the last glaciation about 15,000 years ago, sea level was more than 100 m lower than it is today. With the melting of the glaciers, sea level rose, reaching nearly its present level about 5,000 years ago. Since that time sea level has fluctuated within a few meters of its present level. All coastal systems as we know them today were formed during the past 5,000 years, and deltas were formed over this period as their rivers successively occupied different channels and filled shallow coastal waters. Thus, deltas are the result of strong interactions with rivers and the sea, with riverine influence generally dominant over marine forces. The effects of human activities have been to upset the balance and to isolate, often to a considerable extent, the delta from the river and the sea. Most rivers have also been dammed, resulting in a reduction in the amount of freshwater and sediments reaching the delta.

The Concept of Sustainability and Sustainable Management of Deltas

What is *sustainability*? The Brundtland Report, *Our Common Future*, marked the first time the international community embraced sustainable development as a goal for the future. Defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (World Commission on Environment and Development [WCED], 1987), this politically acclaimed definition spawned many other international efforts, bodies, and commissions such as the 1992 Rio Summit that produced the Convention of Biodiversity (United Nations Conference on Environment and Development [UNEP], 1992). As best expressed by Goodland and Daly (1996), the concept of "[s]ustainability arose from the recognition that the profligate and inequitable nature of current patterns of development, when projected into the not too distant future, leads to biophysical impossibilities. The transition to sustainability is urgent because the deterioration of global life support systems—the environment—imposes a time limit."

There is evidence that global environmental health is declining, with global warming due to burning of fossil fuels, the decline of the ozone shield, and land degradation due to soil erosion, salination, and desertification. It is estimated that at least 35% of the earth's land is degraded and has exceeded its regenerative capacity. Biodiversity is also threatened; at least 55% of rain forests have been destroyed (Goodland, 1991). In terms of primary productivity, human activities consume approximately 40% of the net primary photosynthesis of terrestrial producers (Vitousek et al., 1986).

While international bodies and commissions are the appropriate vehicles to espouse global objectives, sustainability remains an elusive term that provides little firm guidance to local and regional decision makers who must decide which policies are to be implemented and thus will ultimately affect sustainability. The immediate challenge is to determine what sustainability means in the context of local environments; in this case, deltas. Without this guidance, deltaic environments will suffer from piecemeal decision making and will fall victim to the "tyranny of small decisions" (W. E. Odum, 1982).

While the concept of environmental sustainability is grounded in the biological concepts of carrying capacity and sustainable yield, there is a fundamental difference in scope and scale. *Carrying capacity* refers to the maximal population size of a given species that an area can support without reducing its ability to support the same species in the future (Daily & Ehrlich, 1992, 1996). *Sustainable yield* usually refers to a particular population or resource being harvested and is utilized to determine the optimal level of harvesting. *Environmental sustainability*, however, expands the reference populations and resources to include all the natural resource services in an ecosystem. The goal of environmental sustainability is to maintain the crucial environmental sink and source functions that ensure long-term survival (Goodland & Daly, 1996). This implies that in the case of deltas where the natural resource services are dependent on dynamic pulsing cycles, environmental sustainability necessitates accommodation of these events in management strategies. Past efforts to harness deltaic environments with levees, canals, and impoundments have led to the deterioration of deltaic resources.

Economic incentives are necessary to change the current patterns of production (O'Neill, 1996). In order to achieve environmental sustainability, current methods of evaluating contributions of natural resources to the human economy need to be reevaluated. The current accounting system looks at inputs and outputs of goods and services as if they are separate from the environment from which they are derived. The alternative is to view natural resources as what ecological economists (see Costanza, 1991; Daily & Ehrlich, 1996; Daly, 1991) term "natural capital." This category includes the basic parameters necessary for any ecosystem, such as soil, water, and flora and fauna. Economic activity based on depleting these resources should not count as income. Rather, rates of harvest and waste generation should be based on regenerative and assimilative capacities, respectively, and be included in economic assessments, thereby maintaining source and sink functions (Costanza, 1996). Later in this paper, the authors analyze several approaches to quantifying sustainability.

Goodland and Daly (1996) further expanded this concept by creating the category of cultivated natural capital that encompasses enhancement of natural production by means of agriculture or intensified livestock production. This enhancement is done with operating costs traditionally not factored into economic analyses. In the case of agriculture, costs include traditional capital expenses such as tractors, diesel irrigation pumps, and chemical fertilizers, and most importantly, natural capital such as topsoil, sunlight, and water. This suggests that for delta management, the natural capital of river water, sediments, and nutrients should be part of an economic analysis.

Deltas are dynamic systems that are constantly in flux. While some of the pulses are minor and others are major, all are critical to the health of the ecosystem. Alterations that undermine sediment supply and transport will inevitably lead to a loss of sustainability and to the decline of the delta. Critical functions of a delta will be lost when the ecosystem shifts to an unsustainable level of production if economic activities reduce important pulsing functions. Environmental sustainability of deltas requires management of a wide range of fluxes. As stated by Jansson and Jansson (1994), "[t]he dynamic behavior of the ecosystems has to be respected as a basic rule in human affairs." The wide range of fluxes in deltas calls for the ability to respond adaptively; hence, preservation of these functions is most crucial to sustainability. Thus, utilizing natural pulsing energies reduces the economic costs associated with trying to maintain both human and natural habitats in deltas.

Objectives and Hypotheses

In this article, we define, in a quantitative manner, sustainability in deltaic systems which is based on the fundamental functioning of deltas. We hypothesize that deltaic sustainability can be defined and quantified using geomorphic, ecological, and economic bases, and that deltas can be managed in a sustainable manner only if natural energetic events are used in their proper spatial-temporal scales.

1. From a geomorphological point of view, we hypothesize that a deltaic landscape is sustainable if the rate of vertical accretion and surface elevation gain is greater than or equal to the rate of relative sea-level rise (RSLR). Deltas can be managed to withstand a moderate acceleration of sea-level rise by increasing accretion. By enhancing the delta's ability to withstand sea-level rise, ecosystem functioning will be enhanced (in terms of primary productivity, fisheries, and material processing).
2. From an ecological point of view, we hypothesize that a delta is sustainable if change in total net primary productivity (NPP) over the long term is greater than or equal to zero. Under natural conditions, deltaic NPP is maintained within an equilibrium range based on the total area of the delta and the relative proportions of different habitat types. Both reclamation of wetlands and conversion of wetlands to open water will generally result in lower NPP because of the high productivity of wetlands. It is likely that most deltas have experienced decreasing NPP over time and we will analyze various management scenarios that stop this decrease and possibly increase NPP toward the optimum equilibrium range.
3. From an economic point of view, we hypothesize that a delta is sustainable if the output of economic goods and services is greater than the economic inputs or subsidies required for production.

Natural Functioning of Deltas: Pulse Subsidized Sustainability

General Conceptual Model of Deltaic Functioning

A generalized model of the ecological functioning of typical deltas in a natural state is presented in Figure 1. One of the purposes of this model is to diagrammatically present

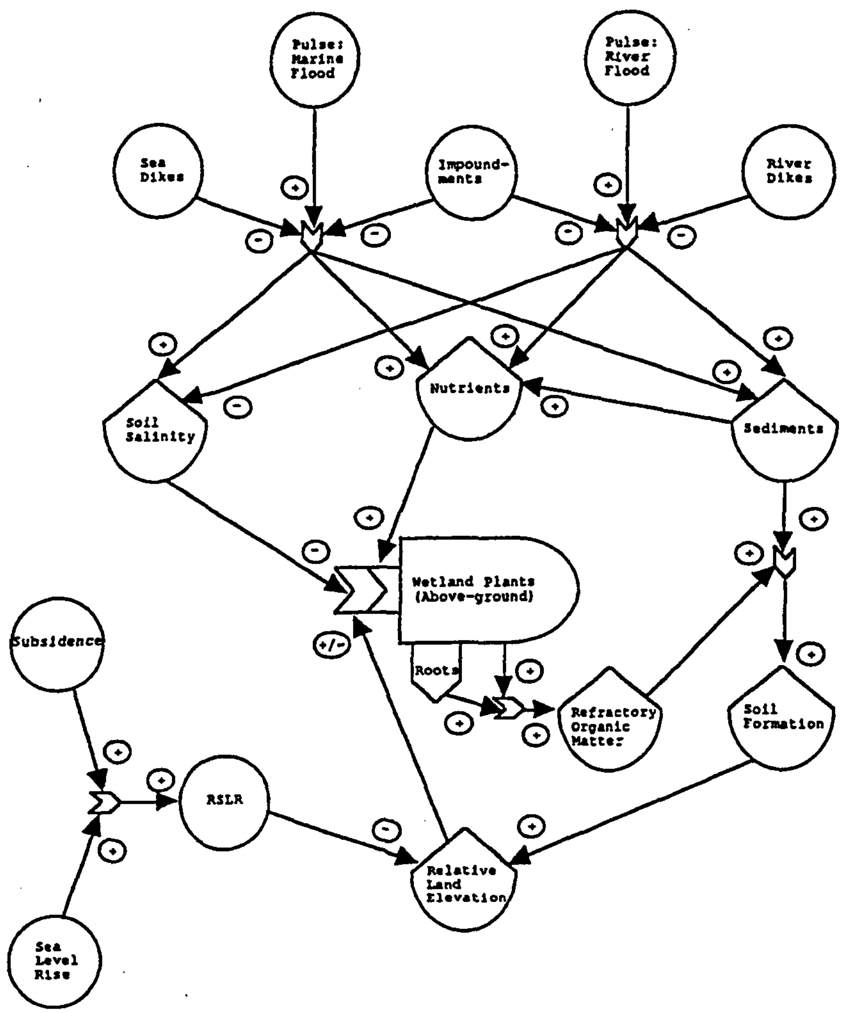

Figure 1. Conceptual model of deltaic functioning. The model shows how natural pulses of freshwater, nutrients, and sediments enhance productivity and soil formation, and buffer against relative sea-level rise (RSLR). Soil formation is broken down into inorganic and organic fractions, and organic matter production depends on relative land elevation, a balance between RSLR and soil formation. The symbols + and – indicate whether interactions are positive or negative. (From J. W. Day et al., 1995.)

the hypothesis of the relationship between overall deltaic functioning and energetic inputs. The focus is mainly on the annual cycle of riverine flooding. In the natural state, deltas are broad areas of near-sea-level wetlands interlaced with channels through which freshwater and seawater mix. Each year, the river flood supplies a pulse of freshwater, suspended sediments, inorganic nutrients, and organic materials. These stimulate primary and secondary production. Increased plant production leads to higher rates of food production for consumers and to increased organic soil formation. Sediments and nutrients fertilize wetland plants. Freshwater input also maintains a salinity gradient from fresh to saline that creates estuarine conditions and supports a high diversity of wetland and aquatic habitats which are optimal for estuarine species. The increased area and productivity of wetlands resulting from riverine input lead to higher secondary production of fisheries and wildlife. Wetlands also assimilate and process nutrients. This leads to higher wetland productivity and lessens water quality problems. The relationship between riverine input and the productivity of estuaries has been demonstrated by a number of authors (Boynton et al., 1982; Cadee, 1986; Moore et al., 1970; Nixon, 1982). Over the longer term, rising water levels due to a combination of subsidence and eustatic sea-level rise poses particular problems for deltas. This is addressed in the following section.

Subsidence, Relative Sea-Level Rise, and the Functioning of Deltas

Deltas are particularly sensitive to sea-level rise. As indicated above, subsidence in deltas leads to an RSLR rate which is often much greater than eustatic rise. For example, while the current rate of eustatic rise is between 1 and 2 mm/yr (Gornitz et al., 1982), the RSLR in the Mississippi delta is in excess of 10 mm/yr; thus, eustatic sea-level increase accounts for only 10–15% of total RSLR in these deltas. The RSLR in the Nile is as high as 5 mm/yr, and is between 2 and 6 mm/yr for the Rhone and Ebro deltas (Baumann et al., 1984; Conner & Day, 1991; Day & Templet, 1989; Ibañez et al., 1996; L'Homer, 1992; L'Homer et al., 1981; Sestini, 1992). Subsidence in deltas results naturally from compaction, consolidation, and dewatering of sediments. Because of the high rate of RSLR, deltas can serve as models for the impacts of accelerated eustatic sea-level rise in other coastal systems (Day & Templet, 1989).

Sinking of the land surface can be caused by factors other than geological subsidence. The sinking rate can be increased locally due to withdrawals of water, oil, and gas. Perhaps the most well-known example is that of Venice where groundwater withdrawal between 1930 and 1970 led to an RSLR of 24 cm, about half of which was due to groundwater withdrawals (Bondesan et al., 1995; Sestini, 1992). Natural gas withdrawal led to high subsidence rates in the Po delta and large areas of the delta are more than 2 m below sea level (Sestini, 1992; Figure 2). Drainage of wetlands also can lead to subsidence rates due to oxidation of soil organic matter which are much greater than geologic subsidence rates. There have been enhanced rates of subsidence in the Rhine and Sacramento deltas because of soil oxidation. In the Sacramento delta, for example, over 100,000 ha of reed swamp have been drained for agriculture and are now constantly pumped (Newmarch, 1981; Weir, 1950). Initial subsidence rates were greater than 20 cm/yr, and it is predicted that after 100 years the rate will be 3.2 cm/yr. In the Mississippi delta, initial rates of subsidence in drained wetlands were on the order of 10 cm/yr (Okey, 1918).

If wetlands in deltas do not accrete vertically at a rate equal to the rate of RSLR, they will become stressed due to waterlogging and salt stress, and ultimately will disappear (Mendelssohn & McKee, 1988). Current evidence indicates that water-level rise (due to both eustatic rise and subsidence) is leading to wetland loss, coastal erosion, and saltwater intrusion in a number of coastal areas (Clark, 1986; Conner & Day, 1989; Hackney & Cleary, 1987; Kana et al., 1986; Salinas et al., 1986; Sestini, 1992; Stanley, 1988; Stevenson et al., 1988; Templet & Meyer-Arendt, 1988). The relative elevation of the land with respect to sea level is a function of the balance between RSLR and accretion. The rate of accretion is a function of the combination of the inputs of both inorganic and organic material to the soil. Inorganic sediments can come either from the sea or from terrestrial (usually riverine) sources. Organic material is usually from in situ plant production. The higher the inputs of both organic and inorganic material to the

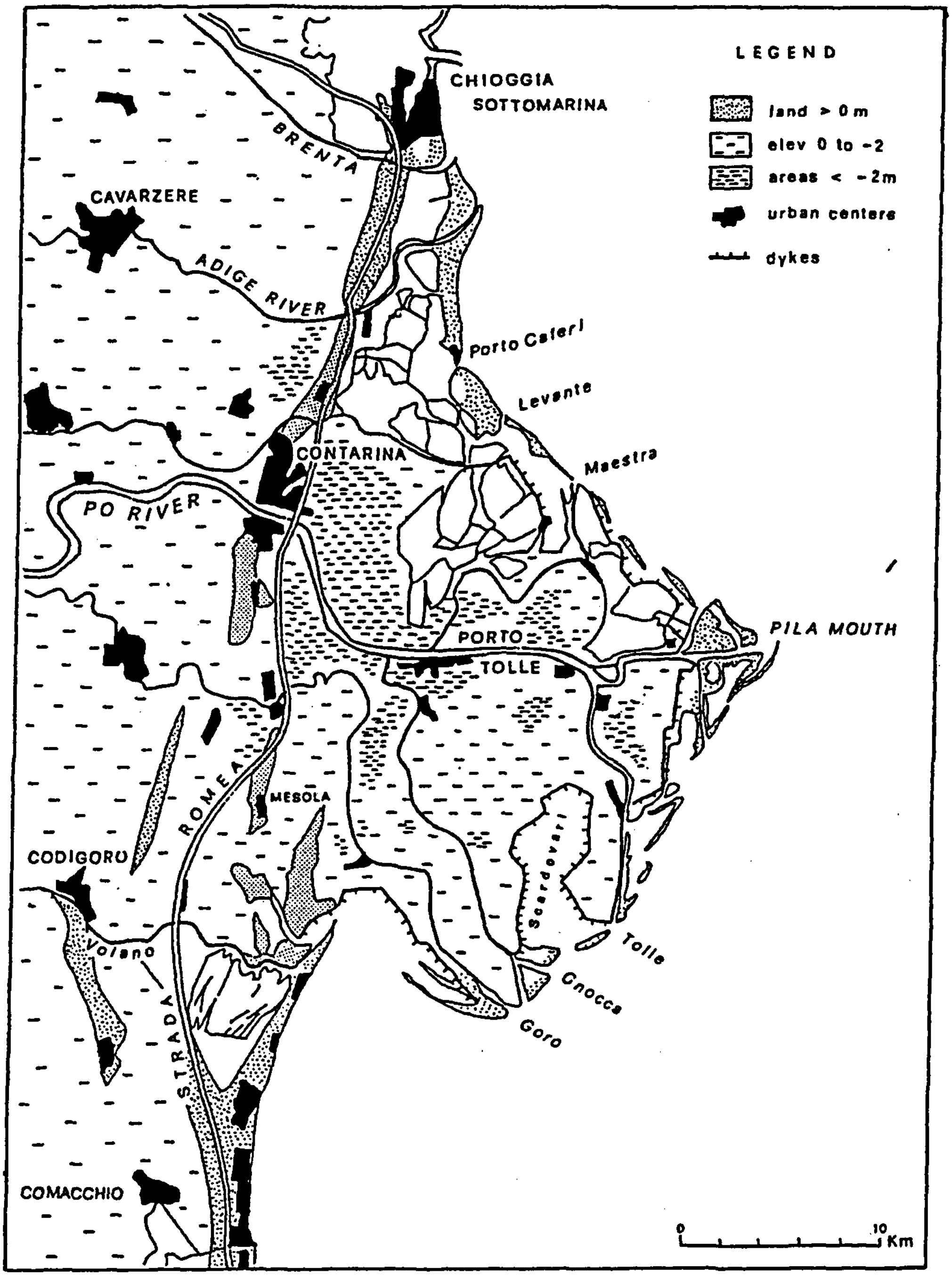

Figure 2. Map of the Po delta in Italy showing areas of the delta which are 2–4 m below sea level because of subsidence due primarily to extraction of shallow reserves of natural gas. This delta is not sustainable without large inputs of outside energy and resources. (From Sestini, 1992.)

soil, the higher is the rate of RSLR which can be tolerated without loss of wetland surface elevation. Therefore, management should attempt to increase both organic soil formation and the input of inorganic sediments. Using river water to bring in sediments also brings nutrients, which enhances organic soil formation. Thus, management to increase the ability of deltas to survive rising water levels also will enhance deltaic functioning in terms of higher productivity.

Coastal managers must now contend with global warming and an acceleration in the rate of rise in sea level which will exacerbate problems associated with rising water levels. The Intergovernmental Panel on Climate Change (IPCC) has recently reviewed the issues of global warming and acceleration of sea-level rise. The IPCC has projected that sea level will likely rise by 21–71 cm by the year 2070, with a best estimate of 44 cm (Wigley & Raper, 1992). There is no conclusive evidence that the rate of sea-level rise has accelerated during this century, but there is some indication that sea-level rise in the twentieth century has been faster than in the previous two centuries (Warrick & Oerlemans, 1990). Most of this rise has been due to an intensification of the factors causing present sea-level rise; thermal expansion of ocean water, and melting of mountain glaciers and the margins of the Greenland ice sheet. Melting of Antarctic ice is not expected to contribute to sea-level rise in the next century. The projected rate of sea-level rise in the twenty-first century is 3–6 times higher than that of the past 100 years.

A Spatial-Temporal Hierarchy of Natural Subsidies

As indicated above, the functioning of deltas is the result of external and internal inputs of energy and materials. These inputs are not constant over time, but occur as pulses, which happen over different spatial and temporal scales (J. W. Day et al., 1995). This type of pulsing is not exclusive to deltas, but applies to many natural systems, especially coastal ecosystems (e.g., *Estuaries*, Vol. 18, 1995). These pulsing events have a hierarchical distribution and produce benefits over different temporal and spatial scales. These energetic events range from daily tides to switching of river channels, which occurs on the order of every 1,000 years, and include storm fronts, normal river floods, strong storms, and great river floods (J. W. Day et al., 1995; Table 1). The primary importance of the infrequent events such as channel switching, great river floods, and very strong storms like hurricanes is in sediment delivery to the delta and major spatial changes in geomorphology. The more frequent events such as annual river floods, seasonal storms, and tidal exchange are also important in maintaining salinity gradients, delivering nutrients, and regulating biological processes.

The major growth cycles of deltas take place through the formation of new delta lobes. A series of overlapping deltaic lobes is an efficient way to distribute sediments and continually build land over the entire coastal plain. Evidence of major changes in a river's route to the sea, which occur approximately every 1,000 years (Roberts et al., 1980), and affect thousands of kilometers, has been documented for many deltaic systems (Figure 3) (Coleman & Wright, 1971; Freeman, 1928; Kazmi, 1984; Ibañez et al., 1997; Stanley & Warne, 1993; Todd & Eliassen, 1938; Tornqvist et al., 1996; Van Andel, 1967; Wells & Coleman, 1984). Channel switching occurs as the existing channel lengthens, the slope decreases, and the channel becomes less efficient. Eventually, the height of the river bed is raised (Freeman, 1928) and the upstream natural levee is breached permanently in favor of a more hydraulically efficient, shorter, and steeper route to the sea. This process is generally pulse dependent as the breaching of the levee takes place during large flood events. Natural river flow is never confined to one

Table 1
Temporal scale of pulsing events in deltaic systems

Event	Timescale	Impact
River switching	1,000 yrs	Deltaic lobe formation Net advance of deltaic landmass
Major river floods	50–100 yrs	Channel switching initiation Crevass splay formation Major deposition
Major storms	5–20 yrs	Major deposition Enhanced production
Average river floods	Annual	Enhanced deposition Freshening (lower salinity) Nutrient input Enhanced 1° and 2° production
Normal storm events (Frontal passage)	Weekly	Enhanced deposition Organism transport Net material transport
Tides	Daily	Drainage/marsh production Low net transport

Modified from J. W. Day et al. (1995).

channel, but generally the primary channel receives on the order of 80% of total discharge with the remainder divided among older distributaries (Gagliano & Becker, 1973), thus ensuring efficient dispersal of sediments over the entire deltaic plain.

Major river floods occur once or twice a century. When conditions are right for channel switching, the major shift in flow between channels normally occurs during great river floods. In addition, these floods are important in delivering major sediment pulses to the delta plain. Both of these processes are exemplified for the Atchafalaya delta in the great flood of 1973 on the Mississippi River (Belt, 1975). Peak discharge for the 1973 flood was 64,051 m^3s^{-1} (2,261,000 cfs), compared with a peak discharge of 66,345 m^3s^{-1} for the great 1927 flood (U.S. Army Corps of Engineers, 1987). For several decades prior to the 1973 flood, Atchafalaya Bay filled with fine-grained sediments. In 1973, large amounts of coarse sediments were mobilized and the Atchafalaya delta became subaerial for the first time (van Heerden & Roberts, 1980). It is mainly during major floods, such as 1973, that current velocities and bedload are large enough for course-grained material to reach a new delta lobe and provide a foundation on which to build land (Roberts et al., 1980). The 1973 flood almost undermined the control structure at Old River that prevents the Atchafalaya from capturing the Mississippi. If the control structure had not been in place, the major portion of the Mississippi probably would have been captured by the Atchafalaya. While every major river flood does not

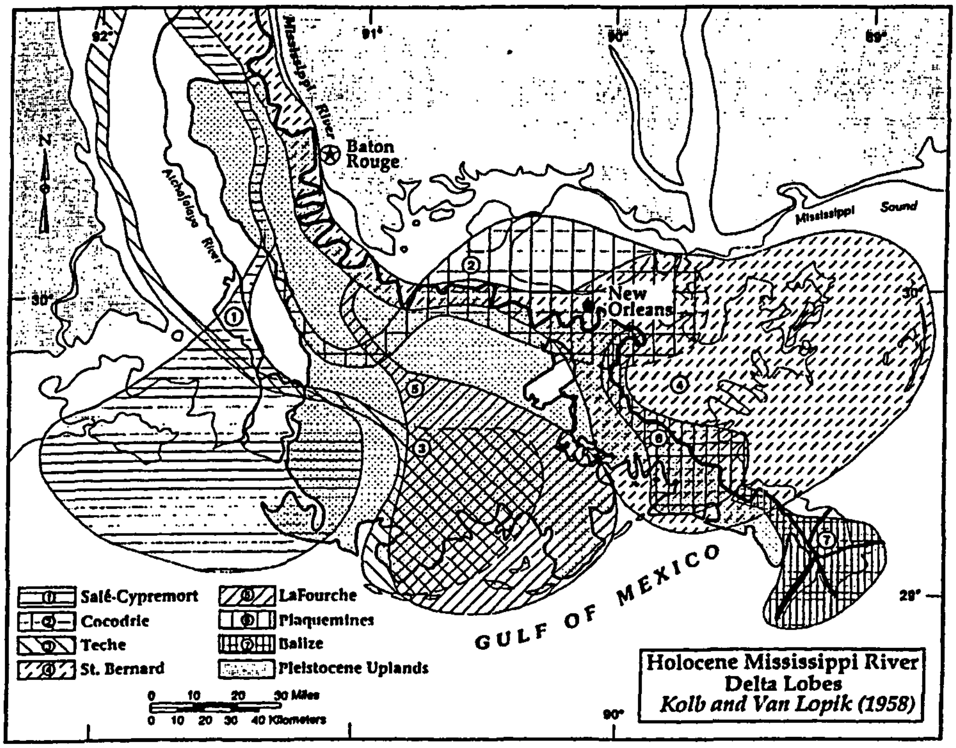

Figure 3. Major deltaic lobes that make up the active delta of the Mississippi River. (Modified from Kolb & Van Lopik, 1958.)

result in channel switching, natural levees normally are breached and large amounts of sediments contribute to the delta plain via overbank flooding at crevasses (Kesel, 1988). In the Ebro delta in Spain, the last major switch in the position of the river mouth occurred during the large flood in 1937 (Ibañez et al., 1996, 1997). The effects of such events are clearly evident in areas affected by floodwaters. In 1993–94, there were two "100-year" floods on the Rhône River. Massive flooding of the upper delta occurred as the levee along the Petit Rhône broke at separate locations during each flood. In sites affected by the escaped river, there was accretion up to 24 mm (Hensel, 1997). Accretion in impounded habitats not impacted by the river was very low, showing that these habitats were largely uncoupled from riverine processes.

Large storms such as hurricanes and typhoons, occurring every 10 to 20 years, are another pulsing mechanism which supplies deltaic wetlands with sediments. Baumann et al. (1984) reported that two tropical storms were responsible for 40% of total accretion over a 5-year period in salt marshes in the Mississippi delta. Cahoon et al. (1995b) reported that during the passage of Hurricane Andrew in 1992, short-term sedimentation rates in Mississippi delta marshes were between 3 and 8 g m^{-2} d^{-1} as compared with rates generally less than 0.5 g m^{-2} d^{-1} during nonstorm periods. Longer term accretion as measured by marker horizons was 2–12 times higher than nonhurricane periods. Storm events resuspend a large quantity of the bottom sediments of coastal bays and the nearshore coastal ocean, and deposit it on coastal wetlands. Strong storms breach barrier islands, but they also mobilize a large volume of sand from offshore and move it in front of beaches, where it is then transported to barrier islands by normal waves and winds.

Yearly river floods are another hierarchical level of the pulses responsible for distributing riverine sediments and freshwater throughout the delta. Similar to major river floods, but to a lesser extent, yearly floods overtop natural levees about 50% of the time and supply a pulse of sediments, nutrients, and freshwater to wetlands. The regularity of these pulses results in an annual, and predictable, reduction of salinity and an input of nutrients throughout the delta. The biota within deltaic systems have adapted to this seasonality, and therefore are dependent on their regular occurrence (J. Day et al., 1989).

Frontal passages associated with storms have been shown to be important in causing sedimentation in deltaic areas of low tidal range (Baumann et al., 1984; Cahoon et al., 1995b; J. W. Day et al., 1995; Hensel, 1997; Reed, 1989; Roberts et al., 1989). Currents generated by winds associated with storm fronts are also important in transporting organisms and organic matter into and out of estuaries. The mixing and transport of nutrients by the daily rise and fall of tides lead to higher biological production and enhanced interaction between wetlands and adjacent water bodies. The rise and fall of the tide allow drainage of wetland sediments and permit fish to use the surface of the marsh for feeding during periods of high tide. Because of this, E. P. Odum (1971) called estuaries "tidally subsidized, fluctuating water level ecosystems."

Ecological and Economic Value of Deltas

It is now well-known that coastal wetlands are ecologically and economically important. Ecologically, coastal wetlands provide a habitat for fish and wildlife, produce food, regulate chemical transformations, improve water quality, store and release water, and buffer storm energy (J. Day et al., 1989). These processes support economically important activities. For example, approximately 60% of the estuaries and marshes of the Gulf of Mexico are located in Louisiana (J. Day et al., 1989). Commercial fishing harvests in 1995 for the State of Louisiana accounted for approximately 81% of the total catch in the Gulf of Mexico and 40% of the market value. The majority of this harvest (76%) was caught within 3 miles of the coast. (National Marine Fisheries Service, Fisheries Statistics Division, 1995). The Gulf of Mexico is one of the most commercially important fishing areas in the United States. Total catch surpasses the entire Atlantic coast (e.g., 1994 landings: 976,000 kg for the Gulf of Mexico vs. 792,000 for Atlantic coast) (NMFS, FSD 1995).

Current wetland estimates for the entire Mississippi delta indicate that there are 963,000 ha of wetlands remaining (National Wetlands Research Center, 1994). These wetlands support a diversity of economic activities vital to local economies. Fishing alone contributes over $1 billion dollars annually. This includes monies collected from fishing licenses and associated goods and services. Other wetland-related activities, such as ecotourism, hunting, production of wild furs, and alligator harvest, generate well over $1 billion when associated good and services are incorporated (Table 2). Shrimp production associated with the Grijalva-Terminos delta system in Mexico has a dockside value of about $150 million per year (Yañez-Arancibia, 1985). Wetlands are therefore very valuable, and much of the world's coastal wetlands occur in deltas. Table 3 shows the area of a number of the major deltas of the world. A considerable portion of this area is, or was, wetlands. A few deltas still are relatively natural, such as the Lena, MacKenzie, and Orinoco, but most deltas have been seriously altered. However, deltaic wetlands still represent one of the most important ecological resources of the planet.

Table 2
Nonfishing wetland dependent sources of income[a]

Sources	Income
Waterfowl hunting	$430 million in 1991
Ecotourism	$220 million in 1991
Cattle production	$25 million/per year
Wild furs and hides	$20 million, 40% of U.S. production/per year
Alligator harvest	$13.5 million/per year

[a]Louisiana Coastal Wetlands Conservation and Restoration Task Force (1993).

Human Impact in Deltas: The Reduction of Pulses and Loss of Sustainability

Human activities have had a pervasive impact on deltaic ecosystems. These impacts most often are classified and discussed in terms of the types which occur. Thus, for example, there are discussions of water quality deterioration in terms of eutrophication and toxic materials; physical alterations such as dredging, channelization, and filling; habitat loss; heat pollution and entrainment by electricity generating stations; declines in fishery populations; and introduction of exotic species (e.g., J. Day et al., 1989). Many solutions have been proposed to deal with these individual impacts. But, from a comprehensive, holistic point of view, human activity has systematically isolated deltas from the river and the sea which sustained them and reduced the inputs of energy and materials at all spatial and temporal scales.

At the longest temporal scale and the broadest spatial scale, channel switching and new delta lobe development have been stopped for many deltas. This has been done using water control structures, closure of minor distributaries, and construction of dikes. In the Mississippi delta, for example, there currently are two functioning distributaries: the lower Mississippi River and the Atchafalaya River, which carries about one-third of the flow of the Mississippi. There were at least four other distributaries which carried significant flows at the beginning of European colonization, but these all have been closed. Crevasse splays from breached levees also have been largely eliminated.

Most important rivers have been dammed, which has reduced floods and resulted in a reduction in the pulses of freshwater and sediments reaching the deltas. The amount of sediment carried in the Nile, Indus, and Ebro has been reduced by over 95%; for the Po, the reduction is about 75%, and for the Rhône and Mississippi, the reduction is greater than 50% (Day & Templet, 1989; Kessel, 1988; L'Homer, 1992; Milliman et al., 1984; Sestini, 1992; Stanley & Warne, 1993; Varela et al., 1983). Reduction of freshwater flood surges and average flow can lead to salinity intrusion, and in arid and semiarid areas, to hypersalinity which in turn can lead to wetland vegetation death. In the Indus delta, for example, more than 99% of the original quarter million ha of mangroves has disappeared, primarily because of hypersalinity (Snedaker, 1984). Hypersalinity and increased waterlogging due to lack of sedimentation are leading to wetland deterioration in the Rhône delta (D. Pont, personal communication, 1997, Laboratoire d'Ecologie, Arles, France; Hensel et al., 1997).

Within many deltas, the canals, dikes, diversions, and impoundments have isolated large parts of the delta plain from riverine input. River dikes prevent changes in the

Table 3
Area of several major deltas throughout the world[a]

Delta	Country	Area of deltaic plain (km^2)
Amazon	Brazil	467,078
Ganges-Brahmaputra	Bangladesh	105,641
Mekong	South Vietnam	93,781
Yangtze-Kiang	China	66,669
Lena	Russia	43,563
Hwang Ho	China	36,272
Indus	Pakistan	29,524
Mississippi	United States	28,568
Volga	Russia	27,224
Orinoco	Venezula	20,642
Irrawaddy	Burma	20,571
Rhine	The Netherlands	20,000
Niger	Nigeria	19,135
Shatt al Arab	Iraq	18,497
Grijalva/Usumacinta	Mexico	17,028
Po	Italy	13,398
Nile	Egypt	12,512
Red	North Vietnam	11,903
Chao Phraya	Thailand	11,329
Mackenzie	Canada	8,506
Godavari	India	6,322
Paraná	Brazil	5,440
Senegal	Senegal	4,254
Ord	Australia	3,896
Tana	Kenya	3,659
Danube	Romania	2,740
Burdekin	Australia	2,112
Klang	Malaysia	1,817
Rhône	France	1,736
Magdalena	Columbia	1,689
Colville	United States	1,687
Sagavanirktok	United States	1,178
São Francisco	Brazil	734
Ebro	Spain	624

[a]Wright et al. (1974).

course of the lower river; the development of crevasse splays; and input of riverine *freshwater, sediments, and nutrients to the deltaic plain during river floods.* Sea dikes and canals, with their associated spoil banks, inhibit water movement into marshes and the deposition of sediments during pulsing events such as coastal storms and frontal passages (Reed, 1992; Swenson & Turner, 1987). Wetland loss rates in the Mississippi delta, for example, are proportional to canal densities (Scaife et al., 1983). Impoundments consisting of a system of dikes and water control structures have been shown to reduce tidal exchange and the influx of suspended sediments, lower accretion rates, lower productivity, and reduce the movement of migratory fishes (Boumans & Day, 1994; Cahoon, 1994; Hensel et al., 1997; Reed, 1992; Rogers et al., 1992).

Reclamation of deltaic wetlands and shallow water bodies for agricultural, urban, and industrial development is widespread in deltas and is, in essence, the complete elimination of the energy subsidies which maintain deltas. Practically all of the Nile, Ebro, Po, Rhine, Sacramento, and a number of other deltas has been reclaimed (Ibañez et al. 1997; Knights, 1979; Newmarch, 1981; Sestini, 1992; Stanley, 1988; Stanley & Warner, 1993; Weir, 1950); while in others, such as the Mississippi and Rhône (Corre, 1992; J. W. Day et al., 1995; R. Day et al., 1990; Day & Templet, 1989; Harrison & Kollmorgen, 1948; Tamisier, 1990), large portions have been reclaimed. Reclamation and drainage almost always lead to high rates of subsidence due to soil oxidation so that the reclaimed land sinks below sea level and must permanently be put under pump (Kazmann & Heath, 1968; Knights, 1979; Wagner & Durabb, 1976). Removal of subsurface fluids can greatly increase the rate of subsidence. In the Po delta, for example, extraction of high water content natural gas led to total subsidence of 2–4 m (Sestini, 1992).

Drainage from reclaimed agricultural and developed areas often leads to eutrophication in adjacent waters. This is due to both high nutrient concentrations and changes in hydrology (Ibañez et al., 1997). Under natural conditions, much water flow was through wetlands where nutrient assimilation and transformation took place. Agricultural runoff is normally channelized directly to water bodies. This not only leads to eutrophication of receiving bodies, but also deprives wetlands of nutrients which would increase productivity and organic soil formation, thus helping to decrease accretion.

Management for Sustainability: Reintegrating Natural Subsidies

In order to deal with the problems of deltas, especially within the context of rising water levels, comprehensive management is needed because these problems cannot be solved in a piecemeal way. It is the unorganized, fragmented way that deltas have been managed in the past which has reduced the energy pulses that sustain deltas and given rise to the problems which exist today. Management must take into consideration not only the delta itself, but also the drainage basin. Within the overall context of sustainability, the following specific management needs must be addressed: sediment management, nutrient management, fresh/saline water and hydrological management, and maintenance of habitat quality and quantity.

Sediment Management

Sediment management should include plans for both transport of sediments in the river and retention of suspended sediments within deltas, as well as utilization of dredged sediments whenever possible. Important sources of sediments are river water and resuspended sediments from coastal lakes and bays and those transported shoreward from the nearshore zone. For example, much of the sediments deposited on the surface of coastal marshes in the Mississippi delta are resuspended from bay bottoms or transported from the nearshore area (Baumann et al., 1984; Cahoon et al., 1995b; Reed, 1989). The work of resuspending and transporting these sediments is done by natural forces of wind, waves, and tidal currents. Brush fence baffles have been used in the Dutch Wadden Sea and in the Mississippi delta to encourage settling of suspended sediments and inhibit resuspension (Boumans, 1994; Schoot & de Jong, 1982). This raises the elevation of the sediment surface, allowing revegetation to occur. Along the north coast of the Netherlands, thousands of hectares of new wetlands have been created using sediment fences. Dredge spoil also should be used to create habitat whenever possible.

As discussed above, the quantity of freshwater reaching deltas and deltaic lagoons has been reduced, and in the case of some rivers (e.g., the Nile, Ebro, and Indus Rivers), the input of sediments and freshwater has been almost completely eliminated. For sustainable management to take place, there likely will have to be some degree of mobilization of the sediments which are now trapped in reservoirs (Wasp et al., 1977). There is a great need for engineering methods to accomplish this, and then to move these segments toward the coastal zone.

Nutrient Management

Enrichment with excess nutrients is leading to eutrophication in many deltaic systems (Nielson & Cronin, 1981; Turner & Rabalais, 1991). Well-designed management to control eutrophication should include plans to reduce the sources of nutrients and to enhance their uptake in coastal wetlands. Management activities such as better agricultural practices, use of vegetation buffer strips along waterways, and use of nonphosphate detergents can reduce nutrient input. Management also should include the use of wetlands and shallow waters to assimilate nutrients at a rate which would increase productivity but lessen the problems of enrichment. The use of wetlands for cleansing water is particularly appropriate in deltas, because there are several possible routes of permanent uptake and reduction of nutrients in runoff water (Breaux & Day, 1994). The high rate of subsidence in most deltas provides a mechanism for the burial of materials, and thus a permanent loss pathway. Denitrification is a permanent loss of nitrogen to the atmosphere. Finally, if plants are harvested, then plant uptake is also a permanent loss pathway. It is important that the application rate of nutrients (the loading rate) be managed so that it is equal to the uptake rate (Kadlec & Knight, 1996). If this is done, there will be a balanced and sustainable system. When wetlands are properly managed for nutrient uptake, there are a number of ecological and economic advantages: (1) water quality can be improved, (2) habitat quality and productivity can be increased, (3) accretion can be stimulated, and (4) wetland treatment generally is more economical than traditional methods of treatment. Wetland waste treatment is being used successfully in the Mississippi delta to clean water and increase the productivity of wetlands (Breaux & Day, 1994).

Fresh/Saline Water and Hydrological Management

In many deltas, there have been great changes in hydrology leading to alterations in the fresh/saline water balance and changes in the way water flows (J. W. Day et al., 1995; Day & Templet, 1989, Ibañez et al., 1997). In order to maintain and restore wetlands, as well as improve water quality, there needs to be better management of hydrology. This management should include controlling both the amount and timing of water flowing into coastal systems, as well as the pathways of flow within the systems.

As indicated above, many rivers are channeled and diked all the way to the sea. River water should be diverted into deltaic areas to enhance accretion and maintain high productivity, wetland habitat, and low salinity areas. Such freshwater diversions are now being carried out in the Mississippi delta (Day & Templet, 1989). Large-scale diversions already are carried out in many deltas of the world for irrigation purposes and these could be incorporated into an overall management plan for salinity, sediments, and nutrients. Salinity intrusion often is reduced by the use of barriers which lead to isolation of deltaic systems from marine water. Salinity management uses freshwater to form a buffer against saltwater intrusion and allows the coastal systems to remain open to some extent, thus allowing the movement of fishery species which use brackish water and wetlands as important habitat. This also maintains important energetic pulses originating from the sea, such as storms.

Channelization and construction of canals has led to hydrological changes resulting in more rapid flushing of some water bodies, isolation of wetlands behind spoil deposits, and saltwater intrusion (Boumans & Day, 1994; Swenson & Turner, 1987). Impoundments consisting of a system of dikes and water control structures have been widely used in deltaic and lagoon areas. 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. Careful planning of canal construction and development of impoundments are necessary if the negative impacts are to be avoided. Care should be taken not to isolate wetlands so that tidal action is maintained. The proper design of systems to deliver freshwater, sediments, and nutrients to deltaic areas will enhance the conservation and productivity of natural habitat. Proper planning also will ensure that there is a diversity of fresh, brackish, and saline habitats including wetlands, submerged vegetation, and open water, which leads to an enhancement of fisheries and wildlife.

Agriculture in Deltas

The sustainability of agriculture in deltas depends on its location and the degree to which it is integrated into the natural functioning of deltas. Agriculture generally exists in two locations in deltas; on the elevated natural levees bordering river channels or in reclaimed wetlands or shallow water bodies. We contend that agriculture on natural levees can be sustainable, while that in reclaimed areas generally cannot. Agriculture which is integrated into the natural functions of a delta utilizes the freshwater, nutrient, and sediment resources of the river to maintain high productivity and accretion rates, and wetlands to filter nutrients and maintain water quality.

There are a number of problems associated with agriculture in reclaimed wetlands and water bodies. Foremost among these is enhanced subsidence. Wetlands generally have a high organic content, and when these soils are exposed to air, the organic matter oxidizes and the remaining soils consolidate. High rates of subsidence have been reported for many areas, including the Sacramento, Rhine, and Mississippi deltas (Knights, 1979; Newmarch, 1981; Okey, 1918). Once reclaimed wetlands subside below sea level, there basically are two options: abandonment or putting the areas permanently under pump. In the Mississippi delta, most of the drained impoundments failed rather quickly due both to subsidence and heavy rainfall during hurricanes (Okey, 1918). These areas are visible today as large rectilinear ponds (Turner & Neill, 1983). Some areas which remain under pump, such as much of metropolitan New Orleans, flood regularly during heavy rains.

Using constant pumping to maintain water levels below natural equilibrium is costly. In the Netherlands, large areas of the Rhine delta have been reclaimed and are now up to 6 m below sea level. The Dutch have used a variety of drainage methods, including low tide drainage, windmills, and electric pumps. Over the centuries, the system has failed repeatedly, with great loss of life and property. To counter this, the Dutch have continually upgraded the system so that now there is a countrywide drainage system which consumes a considerable portion of the national budget. Much of the Sacramento delta also is maintained below sea level at a considerable expense (Newmarch, 1981). The fringes of the Ebro delta are sinking below sea level and an extensive pumping system is being put in place (Ibañez et al., 1997). Much of the Po delta is 2–4 m below sea level, due to pumping of shallow reserves of natural gas (Sestini, 1992). In the Nile delta, a considerable portion of the eastern part of the delta may become unsuitable for agriculture in the next century, due to subsidence and saltwater intrusion (Stanley & Warne, 1993). For delta management plans to function properly, there should be an appropriate balance of aquatic, wetland, and agricultural habitats. In many deltas, it is likely that some agricultural habitats will have to be converted back to wetland or shallow water habitat. Agricultural areas which are now below sea level and heavily subsidized are good candidates for this.

Holistic Management of Deltas

Management actions for deltas should be part of a holistic strategy which aims to reintegrate the natural subsidies into deltaic functioning. A number of elements of such an approach have been proposed, including construction of salt marshes and tidal flats with dredge material, vegetative plantings, reintroduction of river inflow to deltas for sediments and salinity management, and use of wetlands to reduce nutrient levels. Pethick (1993), Day and Templet (1989), and Templet and Meyer-Arendt (1988) have proposed such holistic management approaches for the southeastern coast of the United Kingdom and the Mississippi delta. Management should anticipate future change, especially accelerated sea level, since coastal wetlands are very sensitive to water-level changes. A reintegration of the natural energy pulses into delta management does not mean that humans cannot continue to utilize delta areas. However, it requires changes in present practices. Navigation, flood control, agriculture, and urban development can coexist in a sustainable delta. But, the approach of confining rivers with continuous levees so that they are isolated from the delta plain must be changed, using other approaches such as diversions and ring levees. What has to change is the large-scale alteration of deltaic hydrology. Features such as canals, spoil banks, and impoundments cannot be placed in a manner so that salinity balances, sediment flows, and wetland drainage are altered to the detriment of the system. In most cases, agriculture in reclaimed wetlands and impoundments probably is not sustainable, except at great cost.

Approaches to Measuring Sustainability

In this final section, we will discuss several tools or approaches which have been used to measure sustainability of deltas. In doing so, we present some results that exemplify both sustainable and nonsustainable management. This should not, however, be considered a comprehensive discussion of ways to quantify sustainability. These should serve as examples, and perhaps, to stimulate further thinking about ways that sustainability can be measured and put into practice.

Geomorphic Sustainability

It is hypothesized that deltaic wetlands are sustainable if the long-term net change in wetland surface elevation is greater than or equal to RSLR. Various techniques are now

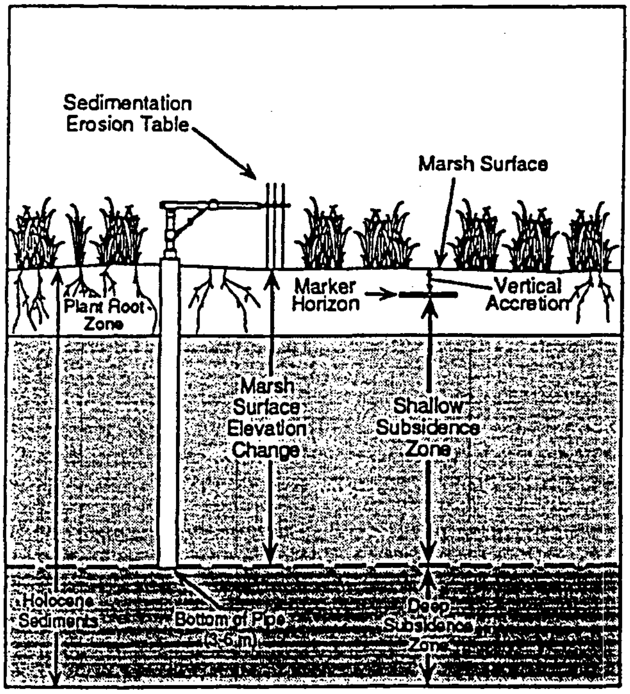

Figure 4. Conceptual diagram showing two important techniques which can be used to measure accretion (marker horizons) and surface elevation change (sedimentation-erosion table [SET]) in deltas to test geomorphic sustainability. The diagram differentiates between those portions of the soil profile being measured by the SET and the marker horizon techniques. The boundary separating the shallow and deep subsidence zones is defined operationally by the bottom of the SET pipe. (From Cahoon et al., 1995a.)

available to directly measure both rates of accretion and surface elevation change. Accretion can be measured as the accumulation of sediments over marker horizons or radioactive markers, and elevation change can be measured with a sedimentation-erosion table (SET) (Boumans & Day, 1993; Cahoon & Turner, 1989). These are shown diagrammatically in Figure 4 (Cahoon et al., 1995b). These rates are then compared to RSLR to determine if the area is sustainable. Cahoon (1994) showed that accretion in an impounded marsh in the Mississippi delta area had accretion rates 10 times lower than natural marshes (Figure 5), indicating that the natural marshes were sustainable while the impounded marshes, where energy pulses had been reduced, were not.

Accretion alone is not always sufficient to determine sustainability. Cahoon et al. (1995a) measured both accretion and surface elevation change in two Mississippi delta marshes, and found that one marsh in an advanced state of deterioration had high accretion rates but no increase in elevation (Figure 6). The soil strength was so weak in this marsh that newly deposited sediments could not be supported. This was in contrast to the other marsh near the river mouth, where accretion and elevation gain were highly correlated. These results show that the deteriorating marsh is not sustainable, but the riverine marsh is, because of regular inputs of riverine sediments. In a similar study, Hensel (1997) used both marker horizons and a SET to show that both accretion and surface elevation change were much higher in riverine marshes compared with impounded

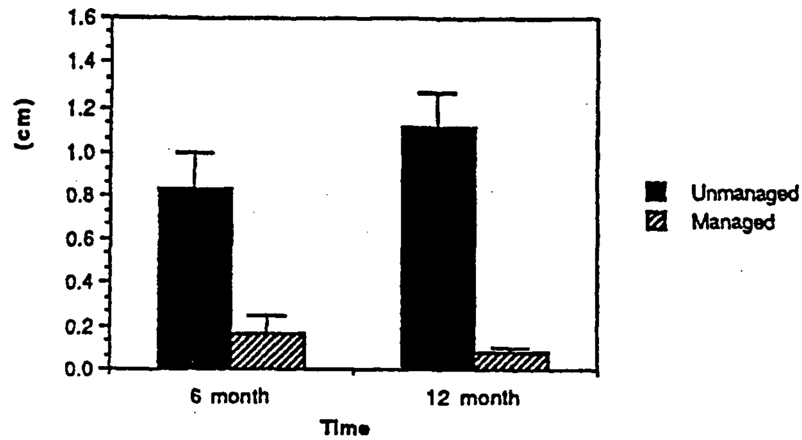

Figure 5. Vertical accretion as measured by marker horizons in two brackish marshes in coastal Louisiana. One of the sites was an impounded (managed) marsh and the other was a nearby nonimpounded area (unmanaged). The accretion rate in the nonimpounded site is approximately equal to local relative sea-level rise and thus is geomorphically sustainable. (Modified from Cahoon, 1994.)

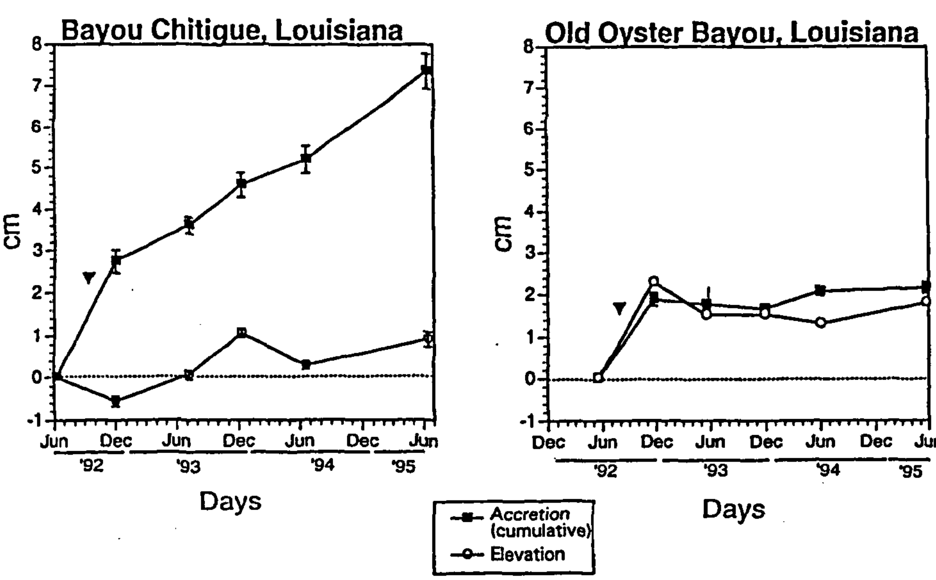

Figure 6. Marsh surface elevation change and vertical accretion at two sites in the Mississippi delta. Open circles, elevation change measured with the SET; shaded squares, vertical accretion measured with marker horizons. Bayou Chitigue is a deteriorating marsh and Old Oyster Bayou is a healthy marsh near the river mouth. Arrows indicate the passage of Hurricane Andrew. In the healthy site, accretion led to elevation gain, while in the deteriorating site, soil strength was weak and accretion did not lead to elevation gain. See text for further explanation. (Modified from Cahoon et al., 1995b.)

and marine marshes in the Rhône delta. The riverine marsh was sustainable, while the impounded marshes were dying because the lack of accretion led to low elevation and plant stress due to excessive waterlogging.

Measurements of accretion and elevation change, when compared with local RSLR, give a clear indication of the sustainability of deltaic wetlands. Rybczyk (1997) has developed a site specific model of soil processes to predict whether different deltaic marshes will survive, and if not, how long it will take for the marshes to deteriorate due to rising water levels. The techniques used for these measurements are relatively inexpensive, and we suggest that a network of monitoring stations be established in different deltas to determine the sustainability of representative wetland areas.

Ecological Sustainability

It is hypothesized that a delta is ecologically sustainable if the change in NPP is greater than or equal to 0. Estimates of total NPP can be determined for different deltas in a straightforward manner from changes in different habitat types over time. This information is available for many deltas from maps and aerial imagery. For example, in the Ebro, Po, and Nile deltas, almost all wetland habitats have been converted to agriculture (Ibañez et al., 1997; Sestini, 1992; Stanley & Warne, 1993), and over half of wetlands in the Rhône delta have been reclaimed (Tamisier, 1990). In the Mississippi delta, wetland deterioration during the twentieth century has been well-documented (Britsch & Dunbar, 1993; Gagliano et al., 1981). The rate of wetland loss has been very high; for example, decreases in the Barataria and Terrebonne basins of the Mississippi deltaic plain from about 820,000 ha in the 1950s to about 560,000 ha in the late 1980s (Figure 7). The NPP can be calculated using estimates of productivity rates for different habitats, which indicate that total NPP for these two basins decreased from 2.82×10^{10} to 2.08×10^{10} kg of dry plant material yr^{-1} or by 26% over a period of three decades (Table 4, Figure 7; Bahr et al., 1982). If present management continues, loss rates of this magnitude are expected to continue for the next several decades. These losses of wetland and reduction of NPP are directly due to the systematic reduction of the energetic pulses which formerly maintained the delta. Clearly, much of Mississippi delta is not ecologically sustainable at present. Similar calculations can be done in other deltas to determine if they are ecologically sustainable. Ecological productivity also is important because it is related to economic health. For example, Templet (1995a) has calculated NPP for 95 countries and used it to evaluate appropriate economic scale and gross national product (GNP). In developing countries, NPP relates significantly and positively to GNP in a multiple regression analysis.

It is clear that new management approaches are needed which will reintegrate the uses of deltaic areas with the energy pulses of the river and sea. One technique which can be used to evaluate the potential success of new management proposals is landscape modeling. In the past, suggested management solutions often have been evaluated independently of each other. Modeling offers an objective integrated approach of evaluation. In the Mississippi delta, spatial simulation landscape models have been used to investigate the effects of different management scenarios on coastal wetland loss (Costanza et al., 1988, 1990; Sklar et al., 1985; White et al., 1991). In this modeling technique, the landscape is divided into a grid of cells, each of which contains a unit model with exchanges of water and materials with each adjacent cell (Figures 8 and 9). Water crossing from one cell to another carries both organic and inorganic

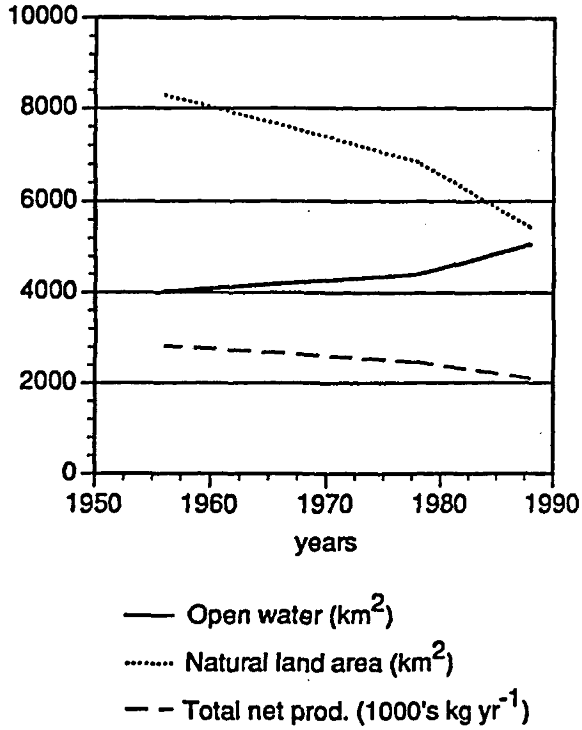

Figure 7. Landcover and net productivity (dry weight) changes within the Barataria and Terrebonne basins of the Mississippi delta. Natural land area includes swamp, fresh, brackish, and salt marshes, and excludes agriculture and developed areas. Net productivity within agricultural and developed areas was accounted for in total net production.

materials. The suspended particles can be deposited, resuspended, lost due to subsidence, or carried to the next cell depending on conditions in the model. The relative rates of each of these exchanges in each location is a function of habitat type. Plants and nutrients within each cell also influence these exchanges and flows. Changes in other abiotic material concentrations (i.e., salts) also are a function of water flow between cells and concentration of materials in the cells, along with internal deposition and resuspension.

Habitat succession occurs in the model when the physical conditions in a cell become indicative of a different habitat type. The state variables in each cell are monitored and compared with the physical environment (e.g., salinity, elevation, water level). If the values of the state variables change to the extent that the environment in the cell is outside the range for the currently designated habitat type, then the cell's habitat type and all the associated parameter settings are switched to a new, better adapted set (Figure 10). This modeling approach has been used to investigate the impacts of river diversions, hydrologic modification, and sea-level rise (Costanza et al., 1990; White et al., 1991). Such models can be used to investigate questions like the impacts of different rates of sea-level rise and subsidence on delta survival, impacts of salinity and waterlogging on wetland survival and growth, and the role of new sediment input in combating sea level rise.

Table 4
Landcover and net productivity changes within the Barataria and Terrebonne basins of the Mississippi delta. Natural land area includes swamp and all marsh types

Habitat type	Landcover km² 1956	Landcover km² 1978	Landcover km² 1988	Net P.P.[a] (kg km^{-2} yr^{-1})[b]	Total net productivity (kg yr^{-1}) 1956	Total net productivity (kg yr^{-1}) 1978	Total net productivity (kg yr^{-1}) 1988
Swamp	1,825	1,691	1,436	1.59E + 6	2.90E + 9	2.69E + 9	2.28E + 9
Fresh marsh	3,539	1,863	1,876	2.70E + 6	9.56E + 9	5.03E + 9	5.07E + 9
Brackish marsh	2,327	1,882	1,317	4.40E + 6	1.02E + 10	8.28E + 9	5.79E + 9
Salt marsh	592	1,401	802	3.00E + 6	1.78E + 9	4.20E + 9	2.41E + 9
Open water	4,013	4,386	5,053	8.90E + 5	3.57E + 9	3.90E + 9	4.50E + 9
Agriculture/developed	143	384	572	1.33E + 6	1.90E + 8	5.11E + 8	7.61E + 8
Natural land area	8,283	6,837	5,431				
Total annual net productivity (kg yr^{-1})					2.97E + 10	2.46E + 10	2.08E + 10

[a]Bahr et al. (1982).
[b]Dry weight plant material.
Abbreviations: P.P., Primary Productivity.

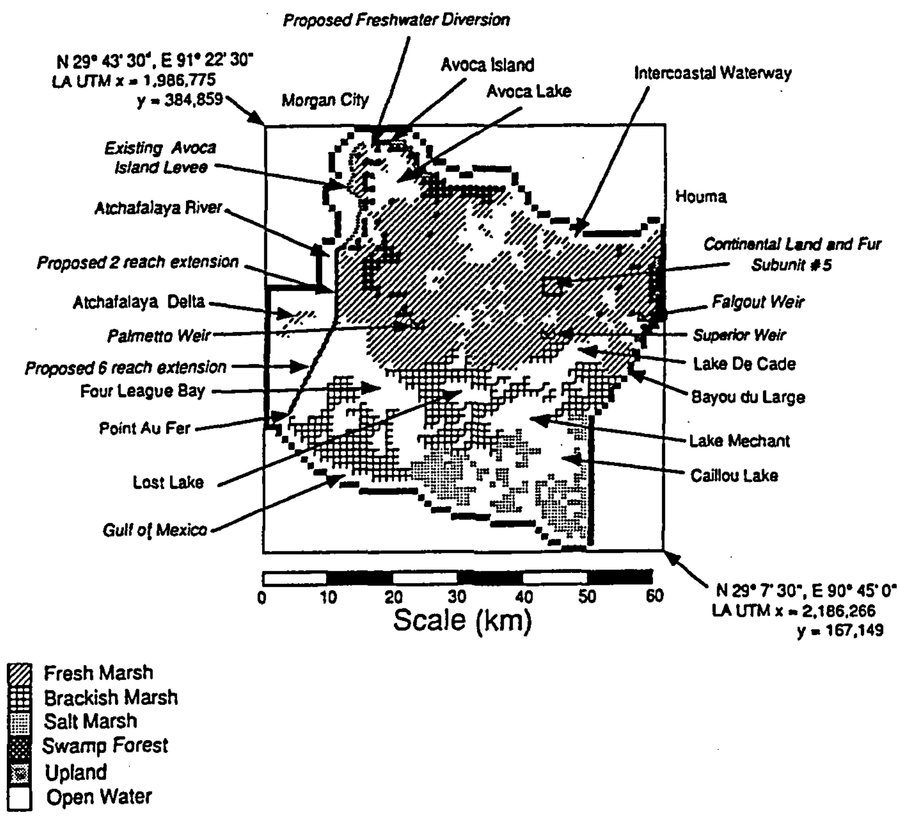

Figure 8. Diagram showing the spatial grid of 1 km² cells used to model landscape interactions in the Atchafalaya/Terrebonne portion of the Mississippi delta. The map shows major geographic features, aquatic and wetland habitat types, and the locations of management options analyzed with model simulations. (From Costanza et al., 1990.)

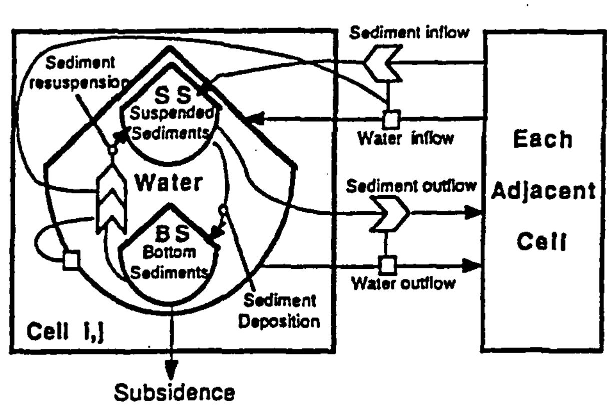

Figure 9. Diagram of the unit model for sediments and water showing storages (tank symbols) and flows (lines) of water and sediments. This unit model is in each cell of the landscape model shown in Figure 8. Fluxes of suspended sediments are a function of water flows and sediment concentrations. (From Costanza et al., 1988.)

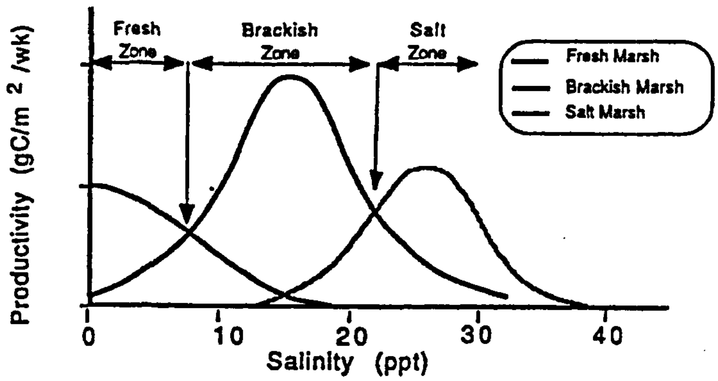

Figure 10. Conceptual diagram showing how the habitat switcher functions in terms of the effects of salinity on wetland habitat type. Plant primary production is a function of salinity, and the diagram shows the salinity levels where habitat succession takes place in the model for three of the habitat types. Habitat productivity peaks from left to right; fresh marsh, brackish marsh, and salt marsh. (From Costanza et al., 1988.)

Economic Sustainability

From a historical perspective, economic growth has resulted in the substitution of human capital for natural capital, because the benefits resulting from the use of human capital can be more easily directed to certain groups or individuals. For example, leveeing the Mississippi River improved navigation and flood control, thus subsidizing and benefiting those dependent on these activities. However, a severe opportunity cost was incurred in that natural capital (i.e., the sediments in the river were no longer used constructively and the resulting accretion deficit led to a loss of wetlands and the services they provide). The costs were externalized to those benefiting from the wetlands (i.e., the citizens of Louisiana and the public commons). Templet (1995b) showed that increasing manmade subsidies leads to poorer environmental and socioeconomic conditions, and less sustainability. The subsidies are the result of externalities created for the purpose of maximizing one economic sector's returns. He found that "[t]he effect of the externalization then is a net loss to public welfare with private interests benefiting while public interests lose considerably more, i.e. public costs exceed private benefits and distributional inequities arise." This analysis applies to the deltaic case because deltas are among the most productive of all ecosystems, and the loss of such systems incurs very large opportunity costs which would make the deltaic region economically and environmentally poorer and less sustainable. If instead of substituting nonrenewable fossil fuel energies for natural capital energy, natural capital, in conjunction with other energies, was to be used in reaching economic goals, then less would be expended to achieve more and attain a higher level of sustainability. Practically, this means using manmade energies to engineer the system to allow the river's water and sediment and other energy pulses to sustain and build wetlands, which then would produce goods and services at minimum cost.

The natural losses mentioned above occur because economic projections traditionally have calculated inputs and outputs irrespective of environmental costs. Increasingly, economists are including the costs of consumed natural capital goods and services into the cost of economic activities (Costanza, 1991; Costanza, 1996; Daily & Ehrlich, 1996; Daly, 1991; O'Neill, 1996). Central to this thesis is the idea that economic estimates which incorporate environmental degradation reveal true costs of operating in those environments. This ultimately could result in better environmental management, due to long-term economic incentives. In the case of deltas, determining economic stability is intimately tied to the existence of the delta itself which depends on geomorphical and ecological sustainability, which in turn, often are dependent on economic decisions. Recognizing this mutual codependence is a central feature involved in designing sustainable system management.

Sea-level rise places additional pressures on coastal wetlands. As atmospheric warming continues and sea level rises, wetlands may deteriorate, resulting in lost productivity that translates into economic losses. Projections for coastal wetlands losses (Table 5) in the United States estimate a 48% loss with a 1 m rise in sea level. Economically, the loss would be over $20 billion annually. A portion of these losses comes from declines in fishery productivity. Dow et al. (1987) modeled declines in marsh primary productivity and predicted that a reduction of 50% could result in a 15–20% drop in estuarine dependent fish harvests. Declines naturally would increase with prolonged periods of reduced productivity.

Such a scenario has grim implications for the state of Louisiana, the most deltaic state in the nation. Louisiana has lost a significant portion of its wetlands, due to natural and human impacts. The Birdfoot delta of the Mississippi River deltaic plain basin, for example, has lost 70% of historic wetlands (over 40,000 ha) since 1932 (see Table 6). Currently, there are 25,000 ha of coastal marshes left in this area. Predictions for the next 20 and 50 years indicate that another 35% (8,700 ha) and 87% (22,000 ha), respectively, of existing wetlands will be lost.

Projections for the entire Mississippi deltaic plain also indicate pronounced losses. In 50 years, over 240,000 ha could be lost (see Table 7). The cost to the local economy would be well over $3 billion dollars annually. This does not account for lost natural services provided, such as waste assimilation and flood protection. In 1993, Louisiana suffered over $10 million dollars in flood damage in spite of the billions already spent on levees and other flood protection devices (approximately $12 billion; Louisiana Coastal Wetlands Conservation and Restoration Task Force [LA C.W.C.R.T.F.], 1993).

Local efforts to harness pulsing events such as floods, with levees, canals, and impoundments, effectively accentuate sea-level rise and accelerate decline of the delta. Milliman et al. (1989) reported the risks associated with sea-level rise in the Nile and Ganges deltas, and illustrated the economic implications of rising sea levels in deltaic

Table 5
Projected wetlands and dollar losses for sea-level rise in the United States

Sea-level increase (m)	Wetlands lost (km^2)	Wetlands lost (acres)	U.S. wetlands lost (%)	Estimated dollars lost[a] (in billions)
0.5	6,229	1.54×10^6	17	7.70
1.0	17,169	4.24×10^6	48	21.20
2.0	22,618	5.59×10^6	63	27.95
3.0	27,387	6.77×10^6	76	33.85

Adapted from Bigford (1991).
[a]Based on a $5,000 value per acre as established by Costanza et al. (1989).

Table 6
Historic wetlands loss in the Bird Foot delta of the Mississippi River drainage basin

Time period	Total acres lost	Estimated dollars lost (in millions)
1932–58	49,928	249.6
1958–74	46,237	231.1
1974–83	8,021	40.1
1983–90	9,125	45.6
Total	113,311	566.4

Adapted from LA C.W.C.R.T.F. (1993).

environments. They projected that Egypt and Bangladesh could lose 19% and 22%, respectively, of their gross domestic product (GDP) in the affected areas due to a combination of subsidence and eustatic sea-level rise. The Mississippi delta has a higher rate of RSLR than either the Nile or the Bengal, thus similar impacts presumably can be expected for Louisiana.

Loss of the natural system has important economic consequences, because energy analysis (Templet, 1996) shows that those countries and states which rely most heavily on commercial energy (i.e., fossil fuels) to generate GNP generally have the poorest economic and environmental conditions. Their energy intensity (the amount of energy necessary to generate a unit of GNP) is high, which results in more pollution, poorer socioeconomic conditions, and restricted development. Relying more on natural energies, such as the power of rivers to build wetlands, would lower the energy intensity and improve conditions. High energy intensity is a sign of early economic development, analogous to early ecological succession, in which the benefits of stability, efficiency, and equitable distribution of goods characteristic of mature systems are forgone (E. P. Odum, 1969). Economic systems in early development can be held for long periods by particular economic sectors which may be benefiting. However, such states are highly consumptive of resources and are not sustainable indefinitely. In the case of the Mississippi delta, a loss of natural energies has promoted higher commercial energy intensities, with negative economic and environmental impacts.

Table 7
Projected wetlands losses in the Mississippi delta[a]

Years	Projected wetlands loss (acres)	Percent projected loss	Estimated economic loss (in billions of dollars)
20	263,650	11	1.3
50	631,290	27	3.1

[a]Includes the following drainage basins: Atchafalaya, Barataria, Breton Sound, Mississippi River delta, Ponchartrain, Teche/Vermillion, and Terrebonne. Excludes: Chenier plain.

These results indicate a net loss of economic activity in deltas when pulsing energies are reduced, especially with accelerated sea-level rise. This suggests there will have to be an increasing input of subsidies from outside the delta if the level of economic activity is to be maintained. Based on the hypothesis, this situation indicates a lack of sustainability. Deltas can, and should, be economically sustainable. In other words, deltas should be net yielding to the larger society. Originally, this was the case. The first civilizations arose in deltaic situations, reflecting the rich net production of these ecosystems (J. Day et al., 1989). The net yield has become a net sink for many deltas, because of the loss of natural subsidies. There has been a substantial investment in deltas, but much of this activity has led to a deterioration of deltas because of the loss of sustaining energy pulses. An important goal for the future is to use further investment to build a system for humans and nature where society is better integrated into natural deltaic functioning.

Determining Overall System Sustainability: EMergy Analysis

In this section, the authors use EMergy analysis to quantify the sustainability of different management scenarios for deltas. EMergy analysis offers a holistic approach for evaluating economic and environmental alternatives, which integrates all system components to arrive at quantitative conclusions about system sustainability. As opposed to evaluating deltas independently on economic, ecological, and geological bases, or assigning dollar values to system functions and outputs, EMergy is a unifying analysis which evaluates both natural and human-related systems using a common basis. Applying economic values to ecological and environmental processes may provide an incomplete or inaccurate understanding of these processes, because the value of the dollar fluctuates and is circularly based on the resources that it is valuing. EMergy analysis is a form of energy analysis that determines values of resources and other inputs on a similar basis, and is capable of deriving the value of nature to the human economy (H. T. Odum, 1988). Solar EMergy is used to determine the value of environmental and human work within the system on a common basis; namely, the equivalent solar energy required to produce the work. Its fundamental assumption is that the value of a resource is proportional to the energy required to produce the resource. This technique previously was used to quantitatively explore proposals of dam construction on the Mekong River and to make recommendations for sustainable patterns of development (Brown & McClanahan, 1996). The analysis below was performed following the procedure demonstrated in the EMergy analysis concerning the Mekong River, and the reader can refer to this source for a complete explanation of terms and methodology.

Definitions for some of the key concepts related to EMergy analyses follow (Brown & McClanahan, 1996).

EMergy: an expression of all the energy used in the work processes that generate a product or service in one type of energy.

Transformity: the ratio obtained by dividing the total EMergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of EMergy/energy. A transformity for a product is calculated by summing all the EMergy inflows and dividing by the energy of the product. Transformities are used to convert energies of different types to EMergy of the same type. Transformities for many types of energy, resources, and goods have been calculated in previous studies (H. T. Odum, 1996).

Solar EMjoule (sej): The units of solar energy previously used to generate a product; for instance, the solar EMergy of wood is expressed as units of joules of solar energy that were required to generate it. These are usually expressed and recorded as solar EMjoules per year (sej/yr) (Table 8).

Methods. The general methodology for EMergy analysis is a "top-down" systems approach (H. T. Odum, 1988, 1996). The initial step is the construction of systems diagrams that organize relationships among components and pathways of resource flow (Figure 11). In diagramming the system, it is important to include all critical driving energies and relevant interactions. Important energy inputs common to deltas include the sun, rain, river, wind, waves, and imported fuels and goods. Pertinent interactions within these settings are the productivity of natural areas such as wetlands and estuaries, agricultural production, the processing of nonrenewable resources such as oil and natural gas, river management plans such as levees, and the combination of flows involved in industrial activity. The systems diagrams are a prerequisite to EMergy analysis tables, which are constructed directly from the diagrams (Table 8). Each row in Table 8 is an inflow or outflow pathway in the system diagram. The pathways are evaluated as fluxes in units per year. The raw units column gives the total annual flow of each item in units of energy (J, joules), grams, or dollars. Solar EMergy is calculated as the product of raw units and the transformity, and reflects the equivalent annual amount of solar energy for each process. In the final step, several EMergy indexes are calculated using data from the tables (Figure 12; Table 9). These indexes, which relate flows of the economy to flows of the environment, are used to predict economic viability and carrying capacity, and to suggest which management options are more sustainable. When two alternative systems are compared, the one which contributes the most EMergy to the public economy and minimizes environmental losses is considered best (Brown & McClanahan, 1996). With regard to sustainability, the system which relies more heavily on internal sources of energy and renewable energies provided by nature, as opposed to inputs from outside the system, is considered more competitive. Indexes which are helpful in comparing future management alternatives in terms of system functioning and sustainability are the EMergy investment ratio, the environmental loading ratio, and the renewable carrying capacity (Table 9). These are discussed in more detail below.

An EMergy analysis was carried out on four scenarios for the Mississippi delta to demonstrate the manner in which this technique can be used as an aid in management decisions leading to sustainable deltaic functioning. The base case considered the current status of the delta and was based on 1983 conditions. A pristine situation was analyzed to represent predeveloped conditions at the turn of the century. For comparison, the Orinoco and MacKenzie deltas still are largely pristine and representative of what the authors have in mind for the second scenario. Two future scenarios also were evaluated: Future I, a business as usual future where the management of the Mississippi delta continues unchanged, and Future II, a future in which new management approaches are designed to enhance delta survival and sustainability. The business as usual scenario assumed the maintenance of the system of levees, which largely isolates the river from the deltaic plain and continues high rates of land loss. The new management scenario assumed use of the resources of the river (e.g., diversions) to maintain the delta. Parameter values for each of the cases are given in Table 10.

Results. Values for the complete EMergy analysis are given in Table 8 for the base case, and summary values for the three other cases are presented in Table 9. More

Table 8
EMergy evaluation of resource basis for Mississippi delta, base case scenario 1983

No.	Item	Raw units	Transformity (sej/unit)	Solar EMergy (sej/yr) (1E20 sej)
Renewable resources				
1	Sunlight	1.31E + 20 J	1.00E + 0	1.31
2	Rain, chemical	2.01E + 17 J	1.54E + 4	31.06
3	Rain, geopotential	0 J	8.89E + 3	0.00
4	Wind, kinetic	1.11E + 17 J	6.23E + 2	0.69
5	Waves	3.11E + 16 J	2.59E + 4	8.05
6	Tide	6.19E + 15 J	2.36E + 4	1.46
7	Wetland water use	2.00E + 17 J	2.36E + 4	47.23
8	River sediments/nutrients	3.33E + 13 g	1.79E + 9	569.43
9	Offshore sediments	1.66E + 12 g	1.79E + 9	28.47
Indigenous renewable energy				
10	Agriculture/livestock production	1.59E + 16 J	2.00E + 5	31.82
11	Fisheries	3.20E + 15 J	2.00E + 6	64.00
12	Timber (not important)	0	3.50E + 4	0.00
13	Furs, hides, and game	3.25E + 13 J	2.00E + 6	0.65
Nonrenewable sources from within system				
14	Natural gas	2.23E + 15 J	4.80E + 4	1.07
15	Oil	1.48E + 18 J	5.30E + 4	784.40
Imports and outside sources				
16	Oil and natural gas	0	5.30E + 4	0.00
17	Phosphorus	3.70E + 10 J	4.14E + 7	0.02
18	Nitrogen	2.50E + 12 J	1.69E + 6	0.04
19	Pesticides	2.07E + 13 J	1.97E + 7	4.07
20	Food	1.03E + 13 J	8.50E + 4	0.01
21	Mechanical and transportation equipment	1.04E + 12 g	1.40E + 9	14.56
22	Services	7.76E + 8 $	3.80E + 12	29.49
Exports				
23	Oil	3.15E + 18 J	5.30E + 4	1669.50
24	Natural gas	4.79E + 15 J	4.80E + 4	2.30
25	Cash crops	5.04E + 16 J	2.00E + 5	100.77
26	Fisheries	1.18E + 16 J	2.00E + 6	236.00
27	Furs, hides, and game	1.20E + 13 J	2.00E + 6	0.24
28	Service in exports	7.76E + 8 $	3.80E + 12	29.49

For data sources and calculations refer to Martin (1996).
Abbreviations: J, Joules; g, grams; sej, solar EMjoules.

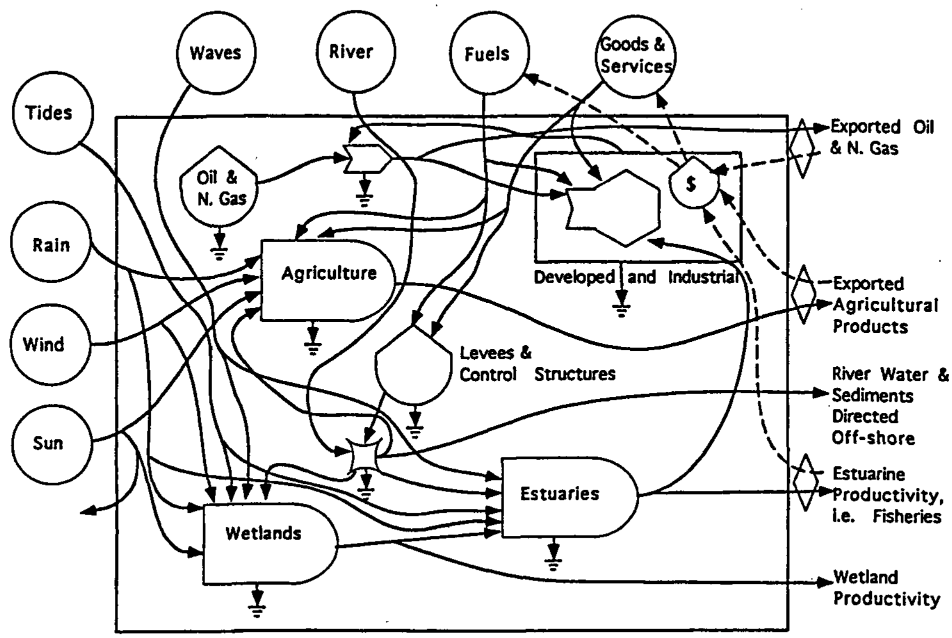

Figure 11. Aggregated energy diagram of the Mississippi delta showing how renewable inputs (waves, wind, river, rain, and sun) interact with imported fuels, goods, services, and nonrenewable resources (NRR) such as oil and natural gas. The importance of levees and control structures in directing riverine inputs is also illustrated. This is a representation of the base case scenario for the EMergy analysis. A diagram without NRR can be used to simulate both future scenarios.

detailed calculations and references corresponding to each pathway, along with variations for the three other cases, may be obtained from the authors (Martin, 1996). An aggregated systems diagram (Figure 12) identifies which pathways were used to calculate the indexes in Table 9.

The EMergy Investment Ratio. The EMergy investment ratio is the quotient of purchased imports (F, G, S; Figure 12) divided by EMergies derived from local sources (N, R). The

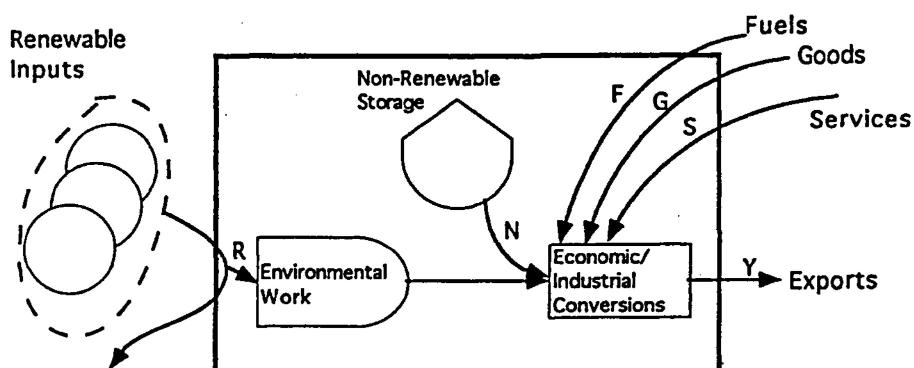

Figure 12. Illustration of a system that imports resources (F, G, S) which interact with renewable inputs (R), and nonrenewable storages (N) to produce outputs (Y). Letters denote pathways used in the calculation of indexes (Table 9).

Table 9
Overview indices of four scenarios for the Mississippi delta[a]

Description	Calculation*	Units	Scenario			
			Base (1983)	Pristine	Future I	Future II
Renewable EMergy flow	R	1E20 sej/yr	635.13	3749.69	642.89	853.93
Flow from indigenous NRR	N	1E20 sej/yr	2457.27	0.00	0.00	0.00
Flow of imported EMergy	F + G + S	1E20 sej/yr	48.19	0.02	832.18	440.31
Total EMergy inflow	R + N + F + G + S	1E20 sej/yr	3150.59	3749.71	1475.07	1294.25
Total exported EMergy	Y	1E20 sej/yr	2010.98	0.08	242.31	377.93
Fraction used that is renewable	R/(R + N + F + G + S)		0.44	1.00	0.44	0.66
EMergy investment ratio	(F + G + S)/(R + N)		0.03	0.00	1.29	0.52
Environmental loading ratio	(N + F + G + S)/R		2.29	1.00	2.29	1.52
Renewable carrying capacity	(R/(R + N + F + G + S))/population	People	8.73E + 5	2.00E + 6	8.72E + 5	1.32E + 6

[a]The base case represents 1983 conditions. The delta during the early 1900s is represented by the pristine case. Future I represents the outcome of unchanged management practices at a time in the future when nonrenewable resources have been exhausted in the delta. Future II represents the system for the same time period resulting from suggested management plans based on system functioning.

*Refer to Figure 12 for explanation of abbreviations.

index measures the degree to which the economic system has invested EMergy from outside sources as compared with internal energy flows. Larger investment ratios indicate a larger investment from the economy which results in decreased efficiency, and possibly increased production. Systems with lower investment ratios receive more of their EMergy free from natural sources, indicative of a more sustainable system, and require less purchased inputs from outside the system. The relatively low investment ratios (overall U.S. investment ratio equals 7.0) for all four scenarios (Table 9) demonstrate large levels of local environmental energies available in deltaic settings, largely accounted for by riverine sediments (Table 8). The extremely low value for the base case (0.03) is due to large amounts of oil, which were withdrawn from the system with little investment from outside the system compared with the high EMergy content of the oil.

Changes in management of local environmental energies result in differences in the two future scenarios. In Future II, 33% more sediments are captured on the landscape compared with Future I (Table 10). This results in greater renewable EMergy flow directly from the sediments, due to land creation leading to increased wetland water use and fisheries production. As a further consequence, less purchased inputs are required from outside the system, and the flow of imported EMergy is reduced. Due to these factors, the investment ratio for Future II (0.52) is less than half of that for Future I (1.29). Although a greater amount of EMergy is exported from Future II, greater than twice the investment from outside the system was required for Future I compared with Future II. Future II requires less inputs from outside the system, relying more on renew-

Table 10
Base case values and assumptions made for parameters which varied during the four EMergy analyses

		Scenario			
Parameter	Units	Base (1983)	Pristine	Future I	Future II
Agricultural area[a]	m^2	3.79E + 9	1.94E + 8	3.61E + 9	1.95E + 9
Water area[a]	m^2	1.68E + 10	1.51E + 10	1.76E + 10	1.60E + 10
Wetland area[a]	m^2	1.32E + 10	1.91E + 10	1.25E + 10	1.58E + 10
Urban/developed area[a]	m^2	7.61E + 8	9.69E + 7	7.25E + 8	7.97E + 8
Captured sediments[b,c]	$g\ yr^{-1}$	3.33E + 13	2.14E + 14	3.33E + 13	4.44E + 13
Agricultural production[a]	$g\ m^{-2}\ yr^{-1}$	1.05E + 3	1.05E + 1	1.05E + 3	1.05E + 3
Phosphorus[a]	$g\ m^{-2}\ yr^{-1}$	8.50E – 1	0.00E + 0	8.50E – 1	8.50E – 1
Nitrogen[a]	$g\ m^{-2}\ yr^{-1}$	3.71E + 0	0.00E + 0	3.71E + 0	3.71E + 0
Pesticides[a]	$g\ m^{-2}\ yr^{-1}$	5.80E – 1	0.00E + 0	5.80E – 1	5.80E – 1
Fishery production[a]	$J\ yr^{-1}$	3.20E + 15	3.20E + 10	1.60E + 15	4.00E + 15
Natural gas	$J\ yr^{-1}$	2.23E + 15	0.00E + 0	2.23E + 15*	2.23E + 15*
Oil	$J\ yr^{-1}$	1.48E + 18	0.00E + 0	1.48E + 18*	7.41E + 17*
Services in[a]	$\$\ m^{-2}\ yr^{-1}$	1.02E + 0	7.61E – 4	1.02E + 0	1.02E + 0
Services out[a]	$\$\ m^{-2}\ yr^{-1}$	1.02E + 0	7.61E – 4	1.02E + 0	1.02E + 0

*Nonrenewable energy sources were assumed to be eliminated in these scenarios, therefore these were contributed from outside the system.

Sources (for base case): [a]Costanza et al. (1983), [b]Kesel (1988), [c]Odum et al. (1987).

able energies supplied by nature. This indicates that the Future II scenario is more sustainable, because it requires less inputs from the larger system. Processes and systems which produce the most EMergy for the least amount of input will be selected for competitiveness over time.

Both Future I and Future II assume that oil and gas resources have been exhausted and that the sustainability of the region will be more dependent on natural resource productivity than it is now. Future II assumes that diversions from the river are used to create and maintain a much larger wetland area which provides a greater steam of natural resource benefits.

Renewable Versus Nonrenewable EMergy: The Environmental Loading Ratio. Most productive human activities depend on the interaction of nonrenewable energies (e.g., fossil fuels) with environmentally supplied renewable energies (e.g., sunlight, wetland productivity, fish production). Through this interaction, the environment is loaded or stressed. The environmental loading ratio quantifies this concept and is the ratio of nonrenewable to renewable EMergy flows. The EMergy yield ratio reflects the importance of natural system processes. However, high environmental loading will disrupt normal system functioning, as exemplified by the many environmental impacts discussed in this paper. The deterioration of Louisiana coastal marshes following levee construction and intense fossil fuel extraction, and the release of concentrated wastewater into water bodies are examples of this phenomena. A value of one for the environmental loading ratio for the pristine case represents low environmental impact. The decreased dependence on outside energy sources and increased reliance on local renewable resources for Future II results in less stress on the environment compared with Future I. A low environmental loading ratio reflects long-term functioning of interactions producing renewable EMergy, and therefore, system sustainability.

The amount of renewable versus nonrenewable inputs has further implications on the sustainability of a system. Nonrenewables, such as oil and natural gas are becoming more scarce, exemplified by drastic production decreases within the Mississippi delta. Greater reliance on renewable energies will be more sustainable in the future. The pristine case is indefinitely sustainable because all of the EMergy used is locally renewable. The fraction of energy which is renewable drops to 0.44 for both the base and Future I scenarios. This indicates that greater than 55% of the inputs are derived from outside the system. The Future II case is more reliant on locally renewable energies, and consequently, has a greater fraction used that is locally renewable (0.66; Table 9). Due to the continued destruction of natural resources, such as wetland loss, more outside energy must be purchased in Future I. The Future II case assumes that the natural functioning of the delta is maintained to a greater extent, which supplements inputs from outside the delta. These natural functions include the use of riverine sediments and nutrients to build and maintain wetlands and a more productive fishery.

Population: Renewable Carrying Capacity. This index provides an estimate of the population which could be sustainable maintained in the system with only renewable inputs. The large renewable EMergy flows of the pristine and Future II cases support the highest sustainable populations. This index clearly shows the importance of maintaining the functioning of the natural system, even during times of heavy reliance on nonrenewable energies. The preservation of the natural system will allow a smooth transition from nonrenewable to renewable energies as fossil fuel resources are depleted, and a quicker approach toward sustainability.

Summary: EMergy Analysis. The EMergy analysis supports the central theme developed in this paper that sustainable management of deltas depends on the utilization of natural renewable energy subsidies such as river floods and storm events. The results also are consistent with other measures of sustainability. During periods of high rates of extraction and utilization of nonrenewable resources such as fossil fuels, part of the energy should be used to ensure the maintenance of renewable energy sources. This is just the opposite of what has happened in most deltas. In the Mississippi delta, huge amounts of energy have been spent to isolate the delta from natural energy inputs. This has resulted in deterioration of the delta and nonsustainable management. This analysis indicates that some of the nonrenewable energies should now be used to implement new management approaches which enhance the effects of the natural pulsing events on the delta.

Summary and Conclusions

In this article, we discussed sustainable management of deltas in a comprehensive and integrated way. Deltas yield enormous economic and ecological values to society. They are sustained by a number of energetic pulses which occur over different spatial and temporal scales, and it is these pulses which support the values of deltas. Many of the environmental problems of deltas stem from a systematic reduction or elimination of these pulses at all pertinent spatial and temporal scales. The elimination of these pulses represents, in economic terms, an externality. Traditional economic analyses generally recognize that, when externalities are large, market failure occurs because prices do not reflect all costs and optimality declines, meaning that allocation of resources is not efficient or equitable. These conditions are not sustainable because the lost natural capital is invisible to market forces and does not enter into decision processes. Yet, the lost natural capital is itself an economic asset on which the market system depends. Under the condition of large externalities, the economic system, in effect, cannibalizes itself.

For deltas to become sustainable once again, management must return to a situation where the natural energy pulses are used to maintain deltas. But, this must be done in a sophisticated return to the natural. It does not mean that human society will have to abandon deltas. There are many activities which can be continued, albeit in a different manner. There are some activities which should not be done, at least not on a large scale. Flood control, navigation, and most development can be achieved in a way that does not significantly reduce important energy pulses. For the most part, levees are continuous along rivers. Changing to a system which emphasizes the use of natural capital by techniques such as ring levees and controlled diversions can allow development to exist with a functioning natural system.

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