Coastal Management, Volume 22, pp. 285–307
0892-0753/94 $10.00 + .00

Policy Considerations for Wetland Wastewater Treatment in the Coastal Zone: A Case Study for Louisiana

A. M. BREAUX
J. W. DAY JR.

Coastal Ecology Institute
Department of Oceanography and Coastal Sciences
Center for Coastal Energy and Environmental Resources
Louisiana State University
Baton Rouge, Louisiana, USA

Two major environmental problems currently affecting the Louisiana coastal zone are a high rate of wetland loss and high levels of surface water pollution. The application of secondarily treated wastewater to wetlands can be a means of dealing with both of these problems. The benefits of wetland wastewater treatment include improved surface water quality, increased accretion rates to balance a high relative water level rise due mainly to subsidence, improved plant productivity and habitat quality, and decreased capital outlays for conventional engineering treatment systems. Wetland treatment systems can, therefore, be designed and operated to restore deteriorating wetlands. Hydrologically altered wetlands, which are common in the Louisiana coastal zone, are appropriate for receiving municipal and some types of industrial effluent. While the U.S. Environmental Protection Agency has determined wetland wastewater treatment is effective in treating municipal effluent, it has discouraged the use of natural wetlands for this purpose. At the same time, funds are being used for the construction of artificial wetlands to treat municipal effluent. In the Louisiana coastal zone, however, wetlands are deteriorating and disappearing due to hydrological alteration and a high rate of relative sea level rise. If no action is taken, these trends will continue. Effluent discharge to existing wetlands should be incorporated into a comprehensive management plan designed to increase sediment and nutrient input into subsiding wetlands in the Louisiana coastal zone, improve water quality, and result in more economical wastewater treatment. The authors believe that the Louisiana example serves as a model for other coastal areas, especially in light of projections of accelerated sea level rise.

Keywords wetland, wastewater, restoration, Louisiana, sea level rise

Received 2 August 1993; accepted 1 February 1994.

This study was supported by the Louisiana Water Resources Research Institute, the Louisiana Department of Environmental Quality, and a fellowship from the Louisiana Board of Regents. We thank the cities of Thibodaux and Breaux Bridge, Zapp's Potato Chip Company, Tom Oswald, John Rybczyk, Irene Hesse, Ron Zappe, and Dugan Sabins for their assistance.

Address correspondence to Dr. Andree M. Breaux, 881 Trestle Glen, Oakland, CA 94610, USA.

Wetlands have been used to treat wastewater for centuries, but only in the past several decades has the response to such use been scientifically analyzed in a comprehensive way (Richardson & Davis, 1987). From an ecological perspective, interest in wetlands to purify effluent is based on a belief that the free energies of the natural system are both capable of and efficient at driving the cycle of production, use, degradation, and reuse (Odum, 1978). The basic principle underlying wetland waste treatment is that the rate of application must balance the rate of decay or immobilization. The primary mechanisms by which this balance is achieved are physical settling and filtration, chemical precipitation and adsorption, and biological metabolic processes resulting in eventual burial, storage in vegetation, and denitrification (Conner et al., 1989; Kadlec & Alvord, 1989; Patrick, 1990).

Both natural and constructed wetlands are used to treat wastewater. Constructed wetlands—those built to treat wastewater on nonwetland sites—can be designed to treat all forms of effluent from primary effluent through tertiary treatment and are designed as either surface or subsurface systems. The latter are used extensively in Europe (Watson et al., 1989) while both systems are used in the United States. Reed (1991) lists 56 surface flow systems and 98 subsurface systems in the United States. There are considerably more systems, however, since the U.S. Environmental Protection Agency (1987) reports more than 100 constructed wetland sites in Ohio, Pennsylvania, Maryland, and West Virginia that are not included in Reed's estimates. Natural wetlands are legally limited to providing only tertiary treatment of secondary waste, and only after approval on a case by case basis. As of 1987, more than 400 natural wetland systems had been approved to receive wastewater discharge in the southeastern United States, with at least 100 more in the Great Lakes states (EPA, 1987).

To a large extent, conventional treatment plants use the same physical and biological processes as those operating in wetland systems. But whereas these processes occur in natural systems by the interaction of soils, water, vegetation, and microorganisms, they occur in conventional plants only with substantially greater amounts of energy and chemical additives to compensate for the reduced space and time required to treat large volumes of effluent.

In any treatment systems—natural, constructed, or conventional—a large number of variables can be manipulated to achieve pollutant-reduction goals. While conventional plants use highly engineered, energy-intensive systems, natural wetland treatment systems are designed to take advantage of existing site and climatic conditions, such as soils, plants, temperatures, precipitation, and flooding regimes. The primary management controls in the natural system are loading rates and residence times, though design of the distribution system can increase the number of outfalls and take advantage of or create gradients or slopes.

Our objective in this article is to discuss the policy considerations for the use of wetland wastewater treatment in the coastal zone using coastal Louisiana as a case study. We first put the issue into a conceptual framework, that of restoration ecology. Then we develop a detailed analysis of the benefits of such treatment, employing examples from Louisiana, followed by a consideration of potential problems. Finally, the current regulatory climate is discussed, along with possible future alternatives for wetland regulation and the impact of those alternatives on wetland wastewater treatment.

Several points are essential to our main hypothesis that wetland wastewater treatment is appropriate in certain circumstances. First, wetlands in the Louisiana coastal plain are deteriorating at the alarming rate of approximately 65 km^2/yr (25 mi^2/yr) (Dunbar et al., 1992). Those that are most amenable to wetland wastewater treatment are generally the most threatened, and we argue that wastewater application will benefit these wetlands. Thus, the nutrients and organic matter in the effluent are used as a resource rather than treated as a pollutant.

Further, coastal wetlands are subsiding, and subsidence is the primary process that leads to the wetland loss cited above (Penland et al., 1988). Subsidence leads to rapid permanent burial of materials, and thus properly operated wetland wastewater treatment systems will not become nutrient saturated. Conversely, effluent application can stimulate accretion, thus helping to offset waterlogging resulting from inundation (Kadlec & Alvord, 1989; Breaux, 1992). Sea level rise is predicted to accelerate in the next century (Warrick & Oerlemans, 1990), resulting in a loss of coastal wetlands. A number of studies indicate that sea level rise is leading to wetland loss in several coastal states: New York (Clark, 1986), Maryland (Stevenson et al., 1985, 1986), North Carolina (Hackney & Cleary, 1987), South Carolina (Kana et al., 1986), and Louisiana (DeLaune et al., 1983; Baumann et al., 1984; Conner et al., 1986; Templet & Meyer-Arendt, 1988; Day & Templet, 1989). Wetland scientists in southern California suggest including projections of sea level rise in plans for creating, restoring, and enhancing wetlands to ensure their permanence over the next century (Pacific Estuarine Research Laboratory, 1990). Outside of the United States, the combined effects of subsidence and sea level rise will lead to considerable losses of land in the Nile delta (Stanley, 1988) and other areas.

The high rates of subsidence in the Louisiana coastal zone combined with eustatic sea level rise result in a relative sea level rise that is about 10 times that of eustatic sea level rise (Gornitz et al., 1982; Baumann et al., 1984; Conner & Day, 1988; Penland et al., 1988). The region can, therefore, serve as a model of how wastewater can be used as a resource to help offset the future impacts of rising water levels in other areas (Figure 1). Wetland restoration attempts through the stimulation of biomass production in the rapidly subsiding Mississippi delta should prove useful in the management of endangered wetlands and the creation of new wetlands beyond the reach of encroaching sea levels.

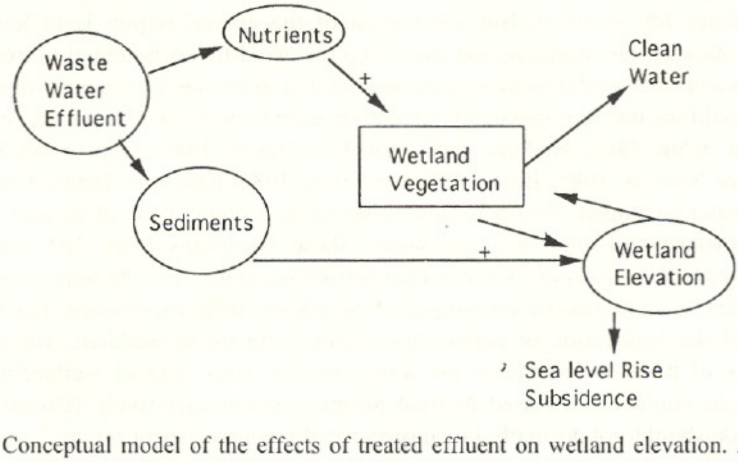

Figure 1. Conceptual model of the effects of treated effluent on wetland elevation. Addition of wastewater effluent stimulates wetland elevation both directly (through deposition of sediments) and indirectly (through increased plant production). In the Louisiana Coastal Zone, wetland elevation is lowered due to sea level rise and subsidence, and thus continual accretion is necessary if plant communities are to be maintained.

Finally, surface water quality deterioration is widespread in coastal Louisiana, mostly due to inputs of high levels of nutrients and nontoxic organic matter (Louisiana Department of Environmental Quality, 1990). Conventional treatment methods alone are often impractical or uneconomical for the widely dispersed small communities and food processors (i.e., seafood and agricultural) that generate much of the wastewater load. Most of these dischargers are located adjacent to large tracts of wetlands so that water does not have to be transported over long distances. Wetland wastewater treatment is often the most cost-effective means of treatment (Breaux, 1992). This is an important issue in light of the financial burdens placed on small municipalities by the current regulatory system, whose standards do not account for the high costs required for conformity.

Restoration Ecology

Restoration ecology has been defined as the reassembly or partial assembly of an ecological system (Jordan et al., 1987). Central to the hypothesis that controlled effluent application to Louisiana wetlands can benefit the receiving systems is the knowledge that a large portion of the state's coastal wetlands have undergone and continue to undergo a severe deprivation of sediments and nutrients that has led, quite literally, to the breakup of the natural system. Impoundments, flood control projects, and oil and gas canals have all contributed to create a large number of hydrologically isolated wetlands (Day et al., 1990). Sediment deprivation combined with regional geologic subsidence, local subsidence in drained wetlands, and rising sea levels and associated problems are responsible for the high wetland loss rates.

In attempting to replace what has been lost, the addition of sediments and nutrients to wetlands through effluent application constitutes a form of wetland restoration. The chief components of a restoration plan would be the selection of an adequate design, effective nutrient loading rates, and hydrologic control to ensure the health of the ecosystem. In a preliminary selection of appropriate sites in the Louisiana coastal region for wastewater treatment, pristine, ecologically sensitive, or highly urbanized areas were avoided (Breaux, 1992). Impounded, hydrologically altered, sediment-starved areas were the primary candidates for selection. But since most of the coastal region is in jeopardy, a much larger area of the coastal region should be reviewed for its potential to treat wastewater. The success of wetlands as tertiary treatment systems has been amply demonstrated under conditions where populations are not large and natural wetland acreage is available (Khalid et al., 1981; Nichols, 1983; Ewel & Odum, 1984; Godfrey et al., 1985; Richardson & Nichols, 1985; Best, 1987; U.S. EPA, 1987; Knight & Ferda, 1989). Wetland wastewater treatment should be incorporated as a component of coastal management in Louisiana and other locations where these conditions exist. The assimilative capacity of wetlands to serve as more than tertiary systems (i.e., to treat effluent less than secondary) should also be investigated through scientific experiment. For example, in a study of the application of potato chip factory effluent to wetlands, we suggested that, because of the low volume of the waste and the large area of wetland receiving area, a system could be designed to treat primary wastes effectively (Breaux, 1992). New wetlands should not normally be constructed if resources spent on artificial systems contribute to the neglect or abandonment of natural but ailing wetlands.

Wastewater application to wetlands does not usually lead to biological communities identical to those either preceding application or surrounding the receiving site. For Louisiana, the objective is both to treat wastewater and to maintain wetlands. In a state with a relative sea level rise four times the average of any other state (Gornitz et al., 1982; Templet & Meyer-Arendt, 1988, from Hicks, 1978), the first problem addressed should be to keep the land above water. Only after succeeding in that attempt will we have the option of determining exactly what type of vegetation is optimal. Ongoing research will help answer critical questions on vegetation, nutrient, and sedimentation dynamics. Monitoring and research should be an integral part of any program that attempts to make use of or enhance the environment. Duplication of wetland functions is the important point. This is emphasized by Jordan et al. (1987) in their discussion of restoration ecology as both environmental technology and ecological technique:

> What is needed . . . is not rote copying, but imitation—the distinction being that copying implies reproducing systems item for item, while imitation implies creating systems that are not identical but that are *similar* in critical ways and that therefore *act* the same.

The authors state further that it is imitation that will ultimately provide the understanding critical for the reproduction of natural systems. Study of wetland treatment systems in Louisiana and elsewhere can help provide this understanding.

The Louisiana Coastal Zone: Some Considerations for Wetland Treatment

Factors favoring efficient removal or transformation of pollutants found in typical municipal or food processor effluent in the Louisiana coastal zone include warm temperatures and a long growing season, which encourage high denitrification rates. Relatively high temperatures also favor high metabolic rates and high plant productivity in general. Most important, however, is the fact that a sediment deficit occurs in Louisiana coastal wetlands because apparent sea level rise is greater than accretion. Annual accretion rates in these coastal wetlands range from 0.7 to 1.3 cm in salt marshes, 0.1 to 0.8 cm in brackish marshes, and 0.2 to 3.0 cm in fresh marshes (Cahoon & Turner, 1989; DeLaune et al., 1989; Knaus & Van Gent, 1989; Cahoon, 1990). These accretion rates are insufficient to balance submergence rates as high as 1 to 3 cm/yr.

A similar accretion deficit is occurring in forested wetlands in Louisiana. Accretion rates in three coastal forested wetlands in Louisiana of 0.3–0.9 cm/yr have been reported (Conner & Day, 1988; I. Hesse, Coastal Ecology Institute, LSU, personal communication). Given the apparent water level rise in these areas (0.8–1.4 cm/yr), the vertical accretion deficits are 0.2–1.1 cm/yr.

Accretion deficits can be balanced only by increased vertical accretion resulting from input of mineral matter and in situ plant production. Vegetation stimulates the formation of mineral as well as organic soil by trapping inorganic sediments (DeLaune et al., 1989). Maintenance of vegetation is crucial to the survival of existing wetlands, and biomass production by vegetation can be as important as mineral sediment input for accretion (Day & Templet, 1989).

Additions of wastewater effluent can stimulate biomass production and subsequent soil formation. For the Houghton Lake, Michigan, natural wetland treatment system that has operated annually from May through September since 1978 to treat secondary effluent, accretion levels increased from 2–3 mm/yr to 10 mm/yr (Kadlec & Alvord, 1989). While increased sedimentation in wetlands might be considered a drawback in some geographic areas due to the filling in and resultant alteration of water levels, for Louisiana wetlands it is an asset in maintaining current land levels against the forces of subsidence.

One way to increase accretion in wetland treatment systems is to increase the sediment content in the effluent. At the present time, however, dischargers are required to reduce total suspended sediment (TSS) discharge to 15 mg/L, whether they discharge to streams or to wetlands. The maximum average TSS load of the three pilot studies described in the following section is 35 mg/L. While the cost for small municipalities in the coastal zone to achieve a 20-mg/L reduction could potentially reach millions of dollars, further millions are being spent on projects to revive sediment-starved wetlands by diverting Mississippi River water, which has an average TSS level of 330 mg/L (Templet & Meyer-Arendt, 1988). It would seem that wetland wastewater treatment systems and river diversion projects could be used for the same ultimate goal.

The entire Mississippi delta, in essence, can be considered as a wetland waste treatment system on a grand scale. Gosselink & Gosselink (1985), for example, emphasized that deposition of riverine sediments leads to the burial of nutrients as well as promoting accretion to offset relative water level rise. They calculated that surface nutrients were effectively removed from the root zone and permanently deposited in deep sediments after approximately 30 years. They concluded that natural wastewater treatment systems in the region must accrete in order to permanently immobilize nutrients not lost by nitrification or plant uptake. This is a central point made in this article.

Pilot Studies

Three wetland treatment pilot projects in the Louisiana coastal region are currently underway to determine the effects of treated secondary effluent discharge on wetlands. The dischargers consist of two municipalities—the cities of Thibodaux and Breaux Bridge—and one food processor—Zapp's potato chip factory in Gramercy (Figure 2). The receiving wetlands for all three dischargers are forested wetlands that have been hydrologically altered, resulting in confinement by canals, spoil banks, highways, oil and gas access roads, or railroad lines. Information on forest structure and productivity and effluent characteristics for the sites are provided in Tables 1A and 3, respectively.

The Thibodaux wetland is characterized by a permanently flooded cypress–tupelo community bordered by a slightly elevated (20–40 cm) ridge consisting of bottomland hardwood vegetation. The high subsidence rate is leading to progressively more flooding and the deterioration of the forest. There can be a high burial rate of nutrients, however, because of the subsidence. Before effluent discharge to the wetland began in 1992, overall vegetative productivity of the flooded area was low compared to the adjacent ridge (Table 1A), and to other southern forested wetland sites (Table 1B). It is important to note that the wetland has been receiving effluent for about one year only. The low productivity value for the treatment area at Thibodaux, therefore, is due not to effluent application but rather to excessive inundation. Since effluent application began, inorganic nitrogen and phosphorus have been reduced to background levels and there are no indications of detrimental impacts (Day et al., 1993b).

At Zapps, data were gathered from two bottomland hardwood zones, one of which has experienced high mortality rates due to elevated water levels resulting from impoundment since the 1950s (Breaux, 1992). Results from 1991–92 indicate assimilation of the secondary effluent (15 mg/L BOD and 20 mg/L TSS) and stimulated vegetative growth (Breaux, 1992). The low productivity of the impounded area (Table 1) results from the long-term waterlogging, which caused the death of most of the trees prior to effluent

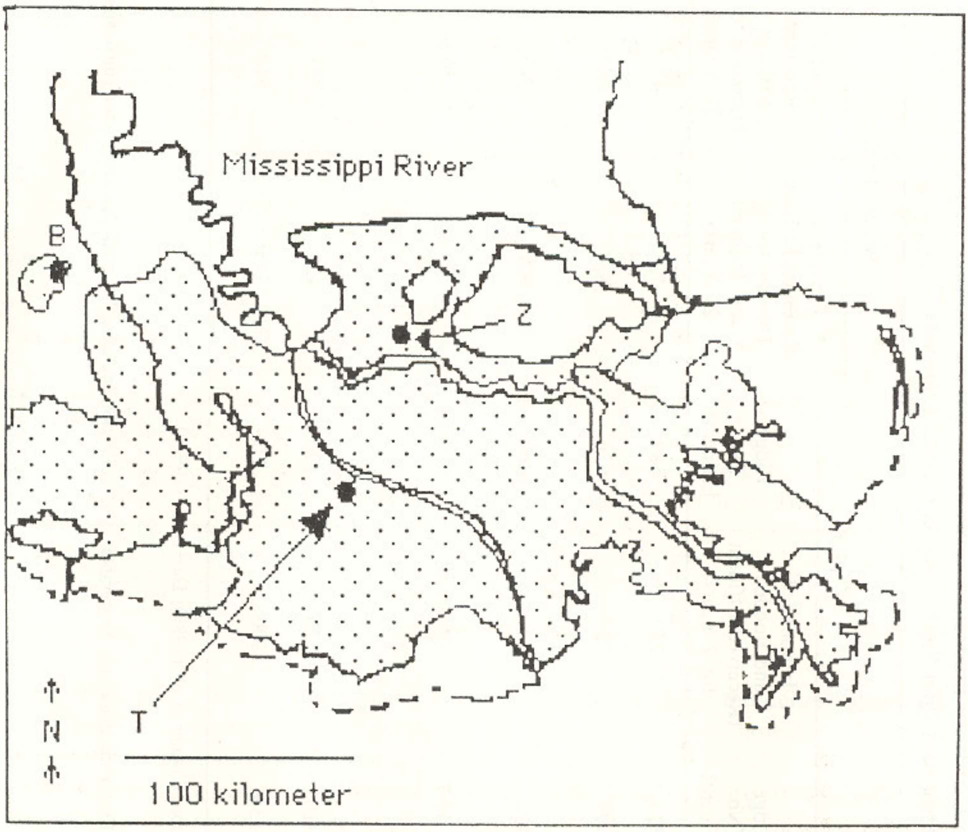

Figure 2. Map of the Louisiana coastal zone (shaded area) showing the location of the three pilot studies: B, Breaux Bridge (municipality); T, Thibodaux (municipality); and Z, Zapp's (food processor).

discharge. The area is recovering, as indicated by the high density of young trees in that area, and productivity will increase as these trees mature. The survival of these young trees is likely due to the high accretion rate (11.5 mm in the impounded area and 2.9 mm on the adjacent higher ridge; subsidence is about 1.0 cm/yr, personal communication from S. Penland, LA Geological Survey, Baton Rouge) which led to a higher elevation and better drainage. Higher accretion rates in the impounded area were probably due to the input of effluent, the lower elevation, and slower decomposition rates compared to the ridge area. Decomposition calculations indicated that 87% and 21% of litterfall deposited in the flooded and ridge areas, respectively, would remain after one year. Thus, while litterfall of the flooded area was less than half that of the ridge, most of the flooded litter is not decomposed and contributes to organic soil formation.

The third pilot study site at Breaux Bridge, Louisiana, is unique in its long history of discharge to the receiving wetland. The town of 6000 has been discharging its effluent (30 mg/L BOD, 35 mg/L TSS) to a forested wetland for almost 40 years with no apparent damage to the cypress/tupelo swamp. Preliminary results show similar basal area for the treatment and control areas (Table 1A). The structural difference between the two zones probably has more to do with past logging in the treatment area than with the effluent discharge. Results indicate complete nutrient assimilation in the 1475-ha

Table 1

Structural Features and Aboveground Net Primary Production of Riverine Forested Wetlands
A. Three Wetland Wastewater Treatment Pilot Study Sites in Coastal Louisiana

	Thibodaux[a]			Zapp's[b]		Breaux Bridge[c]	
Parameter	Treatment (Flooded, has Received Effluent for 1 Year)	Control (Flooded, No Effluent)	Ridge (No Effluent)	Impounded and flooded (Received Effluent for 7 Years)	Ridge (No Effluent)	Treatment (Received Effluent Directly for 13 Years; Indirectly 27 Years)	Control (Received Effluent Indirectly for 27 Years)
Litterfall ($g/m^2\ yr^{-1}$)	405	551	723	219	584	475[d]	475[d]
Wood biomass production ($g/m^2\ yr^{-1}$)	370	643	699	227	676	NA[e]	NA[e]
Total above-ground NPP ($g/m^2\ yr^{-1}$)	775	1194	1422	446	1260	NA[e]	NA[e]
Basal area of trees >10 cm diameter at breast height (dbh) (m^2/ha)	21.3	24.5	30.7	26.8	48.4	29.6	34.6
Density of trees >10 cm dbh (no./ha)	536	576	410	320	520	435	775
Density of trees <10 cm dbh (no./ha)	3202[f]	5001[f]	1134[f]	1900[g]	270[g]	3305[g]	910[g]

[a]John Rybczyk, Coastal Ecology Institute, LSU, personal communication; Conner et al. (1989); Day et al. (1993b).
[b]Breaux (1992).
[c]Preliminary results for September 1992 through March 1993.
[d]Based on 4 months of actual data and remaining months estimated from Thibodaux site. September 1992 collection included litterfall deposited after Hurricane Andrew. January and February 1993 collections prevented by flooding.
[e]Not available until second year of study.
[f]Trees >2.5 cm dbh and <10 cm dbh.
[g]Trees >3.2 cm dbh and <10 cm dbh.

Table 1 (*Continued*)
B. General Means and Ranges for Forested Wetlands

Parameter	Riverine Freshwater Wetlands[h] Mean	Range	Number of Sites	Southeastern U.S. Forested Wetlands[i] Mean	Range	Number of Sites
Litterfall ($g/m^2\ yr^{-1}$)	570	320–1700	16	492	120–678	21
Wood biomass production ($g/m^2\ yr^{-1}$)	694	177–1788	16	558	253–1230	14
Total above-ground NPP ($g/m^2\ yr^{-1}$)	1265	668–2136	16	851	192–1780	20
Basal area (m^2/ha)	37.8	12.0–92.3	32	50.6	15.4–92.3	11
Density (no./ha)	1076	71–2730	29	1732	705–3558	11

[h]Lugo et al. (1988). Tree size >2.5 cm dbh.
[i]Conner and Day (1982). Tree size varies between >2.5 and 10 cm dbh.

swamp (Day et al., l993a). The wetland is on the inland margin of the deltaic plain and is not, therefore, in a high subsidence zone. The large wetland area, however, results in low nutrient loading rates to the site.

Based on these results, we believe that the assimilative capacity of wetlands can serve as a basis for wetland water quality standards. Calculations of permanent nutrient retention via denitrification, plant uptake, and subsidence (Table 2) indicate that all three receiving wetlands should be permanent sinks for nitrogen and phosphorus (Table 3). Stream standards currently applied to wetlands are generally inappropriate for the naturally dystrophic wetlands found in many areas of the coastal plain.

Results from the pilot studies, the literature, and the foregoing considerations indicate that the primary benefits of wetland wastewater treatment in coastal Louisiana are as follows: (1) improved surface water quality in rivers and streams, (2) increased accretion rates to balance subsidence, (3) increased productivity of vegetation and maintenance of wetland function, and (4) the financial savings of capital not invested in conventional tertiary treatment systems.

Potential Problems and Concerns

There are a number of potential concerns about the use of wetlands for wastewater treatment. We believe that proper design and operation of these systems in hydrologically altered areas in coastal Louisiana can overcome these concerns.

The main mechanism of phosphorus removal in wetland treatment systems is the adsorption and precipitation of iron and aluminum complexes (Richardson, 1985; Patrick, 1990). After long periods of effluent application, soils become saturated and phosphorus removal efficiency decreases (Nichols, 1983; Richardson, 1985; Hemond & Benoit, 1988; Faulkner & Richardson, 1989). Phosphorus removal rates in the southeast are variable but potentially high. Nixon and Lee (1986), in a review of field studies of wetlands and

Table 2
Assimilative Capacity of Coastal Forested Wetlands

	Nitrogen ($g/m^2\ yr^{-1}$)	Phosphorus ($g/m^2\ yr^{-1}$)
Removal mechanism		
Denitrification	12.6–134[a]	—
Storage in woody tissue based on 738 $g/m^2\ yr^{-1}$	1.8[b]	0.06[b]
Burial		
Subsidence rate = 1 cm/yr	75	8.3
Subsidence rate = 0.5 cm/yr	37.5	4.2
Subsidence rate = 0.2 cm/yr	15	1.7
Subsidence rate = 0 cm/yr	0	0
Total assimilation range		
No subsidence	14.4	0.06
Low (subsidence = 0.2)	29.4	1.76
Medium (subsidence = 0.5)[c]	100.3	4.26
High (subsidence = 1.0)	210.8	8.4

[a]Estimate includes range from Boustany (1991) for Thibodaux study site of 32.9 to 43.8 g $N/m^2\ yr^{-1}$.
[b]Based on nitrogen content in woody tissue of 0.24% and phosphorus content in woody tissue of 0.009% from Schlesinger (1978).
[c]Uses midrange of 61 g $N/m^2\ yr^{-1}$ for denitrification.
Source: Modified from Conner et al. (1989).

water quality, found overall phosphorus removal rates in the southeast to range from 9% to 98% for a range of loading rates between 0.4 and 46 g $P/m^2\ yr^{-1}$.

Where natural soils do not contain sufficient amounts of iron, aluminum, or calcium to effectively remove phosphorus (Nichols, 1983), other techniques have been employed successfully, such as the addition of an anaerobic zone in an activated sludge system

Table 3
Hydraulic and Nutrient Loading Rates
to Three Wetland Wastewater Treatment Sites

Effluent Characteristics	Thibodaux Wetland (High Subsidence)	Zapp's Wetland (Medium Subsidence)	Breaux Bridge Wetland (Low to No Subsidence)
Type	Domestic	Food processor	Domestic
Total flow (m^3/dy)	15,140	20.0	3,785
Wetland area (ha)	231	2.5	1,475
Nitrogen loading ($g/m^2\ yr^{-1}$)	20	15	1.9
Phosphorus loading ($g/m^2\ yr^{-1}$)	4	3	0.9
BOD (mg/L)	20	15	30
TSS (mg/L)	20	20	35

(Knight et al., 1987). When phosphorus loadings are high or a wetland lacks the assimilative capacity to transform or remove excess phosphorus, retention has been increased by using alum or iron, by aeration to decrease BOD and suspended solids, by the addition of calcium carbonate, and by the prereduction of the soil/plant system (Richardson & Davis, 1987; Khalid et al., 1982). Again, Louisiana wetlands can assimilate much higher levels of phosphorus than elsewhere due to the high rate of burial resulting from the high rate of subsidence. Because of this latter factor, properly designed treatment systems using conservative hydraulic and nutrient loading rates and design criteria to optimize contact time should allow for complete removal of all water quality constituents without saturating the receiving wetland.

Two other commonly voiced concerns over the issue of wetlands used as wastewater treatment systems are the suggestion of incomplete pathogen removal and the implications of treatment to wildlife populations. Questions have been raised by some researchers (e.g., Shiaris, 1985; Grimes, 1985) about the effectiveness of wetland treatment in removing pathogens. At the same time, however, successful pathogen removal by natural die-off has been reported by the U.S. EPA (1987), and measured in the field or lab by Meo et al. (1975) and Gersberg et al. (1987), among others. Kadlec (1989) reports that fecal coliforms are generally reduced to acceptable water quality standards after passage through wetlands, as are viruses and bacterial indicators such as fecal streptococcus. He found no reported incidents of adverse effects to animals or humans resulting from wetland wastewater treatment. Krishnan and Smith (1987) emphasize the greater efficiency of stabilization ponds over activated sludge and trickling filters in removing pathogens including bacteria, viruses, protozoa, and helminths. They state that at least three ponds allowing for a detention time of 20 days will reduce pathogens completely or to very low levels. Municipal dischargers in Louisiana are required to disinfect effluents, so bacteria and other pathogens are not expected to be a problem. Given the expense of disinfection, however, future wetland treatment sites with long residence times and low loading rates should be monitored without disinfection to determine whether standards to protect human health can be met.

Finally, concern for the potentially adverse effects of wastewater treatment to wildlife are sometimes expressed and the suggestion made that more artificial wetlands be built (e.g., Guntenspergen & Stearns, 1985). Others acknowledge, however, that there is no substitute for a natural system, and that species diversity is usually lower in artificial systems (U.S. EPA, 1987). Many believe that the use of properly operated natural wetlands as treatment systems has benefited, and can continue to benefit, wildlife populations (e.g., Best, 1987). Wentz (1987) concluded that wetland waste treatment was not incompatible with wildlife management.

A careful design of wetland treatment systems can combine the techniques of the engineer in terms of flow rates, holding ponds, stormwater diversions, and the pretreatment methodologies described above, with the impoundments, spoil banks, levees, and sheer space available in the "natural" system to produce both effective wastewater treatment systems and productive wetlands. Wentz (1987) explains the benefit of and need for the carefully planned multiple use of wetlands: "We must take people beyond the idea that because wetlands are valuable they cannot and should not be 'managed.' It is very important that people understand that manipulation of wetlands is not necessarily a bad thing." Indeed, manipulation of altered natural systems is essential in order to control the changes brought about by human interference. This is especially the case for Louisiana, where human impacts threaten the very existence of the coastal zone. We believe that effluent application will enhance the long-term survival of coastal wetlands.

Current Political and Regulatory Climate: EPA

The U.S. Environmental Protection Agency (EPA) has recognized the benefits and efficiency of wetland treatment systems. The Agency's report on the *Use of Wetlands for Municipal Wastewater Treatment and Disposal* states: "Wetlands appear to perform, to at least some degree, all of the biochemical transformations of wastewater constituents that take place in conventional wastewater treatment plants, in septic tanks and their drainfields, and in other forms of land treatment." The report further states that both natural and constructed wetland treatment systems have been found to achieve high levels of removal from wastewater for nutrients, BOD, suspended solids, heavy metals, trace organic compounds, and pathogens as well as natural die-off of pathogens from wastewater (U.S. EPA, 1987).

While the Agency acknowledges that constructed wetlands are often more costly "and rarely achieve the same level of biological complexity as natural wetlands systems," its stated policy is that "currently, use of constructed, rather than natural wetlands, is generally preferred by EPA when projects for wastewater treatment are proposed" (U.S. EPA, 1987). One reason for preferring constructed over natural wetland treatment systems is the reluctance to alter biotic communities of natural wetlands when using natural systems as treatment areas. The no action approach to wetland preservation in coastal Louisiana, however, is likely to lead to the elimination of existing wetlands because of increasing inundation. Sediment and nutrient additions to the subsiding wetlands could help reverse the trend toward submergence.

An additional reason for encouraging the use of constructed over natural wetland systems is the presumed greater level of "control" in the former. In the case of Louisiana's, however, the large number of impounded or semi-impounded areas allow for as much control as in constructed wetlands. Second, control in an artificially created environment that lacks the diversity of a natural one is not as instructive scientifically in terms of revealing the functions and processes of the wetland ecosystem. Again, Jordan et al. (1987) describe the situation appropriately with an emphasis on the value of control in natural systems, as opposed to artificial ones:

> The essential idea is control—the ability not only to restore quickly, but to restore at will, controlling speed, decelerating change as well as accelerating it, reversing it, altering its course, *steering* it, even preventing it entirely (which of course is actually a frequent objective of the ecological manager).

The need to control or prevent wetland loss and to deal with surface water pollution in Louisiana suggests that wetland wastewater treatment will be beneficial. The use of hydrologically altered wetlands to treat wastewater will enable the testing of hypotheses regarding ecosystem response and land loss, and will contribute to the overall knowledge of wetland ecosystems.

EPA's preference for constructed over natural wetlands as treatment systems has undoubtedly influenced national policy. In 1987 the Agency itself acknowledged that "the lack of EPA water quality criteria for wetlands and the resulting absence of State water quality standards for wetlands is one of the most serious impediments to a consistent national policy on use of wetlands for wastewater treatment or discharge" (U.S. EPA, 1987). Florida is the only state to have instituted its own regulations for wetland treatment systems. Prior to the institution of those regulations in the mid 1980s, H. T. Odum (1978) used Florida as an example of a state whose regulatory authority lacked an appreciation of the environment's assimilative capacity: "An economy is vital when environment and economic developments are mutually reinforced and protected. Unfortunately, well-meaning efforts to draft laws to protect the environment have not always been made with an understanding of the ecological principles of symbiosis and recycling by which nature and humanity are best combined." The regulations that Florida subsequently adopted allow progressively stricter nutrient loading rates depending on the type of wetland to which effluent is discharged. The Florida plan allows the following applications:

1. Hydrologically altered wetlands are allowed to receive a maximum of 75 g/m^2 yr^{-1} of total nitrogen and 9 g/m^2 yr^{-1} of total phosphorus.
2. Treatment wetlands are used to treat reclaimed water that has gone through secondary treatment with nitrification, and are allowed to receive 25 g N/m^2 yr^{-1} and 3 g P/m^2 yr^{-1}.
3. Receiving wetlands are used to receive reclaimed water that has gone through advanced (tertiary) treatment, and can accept only wastewater treated to 3 mg/L total nitrogen and 1 mg/L total phosphorus. (Harvey, 1988)

Florida's ranking of wetlands to treat wastewater is a response to environmental problems that include a high degree of water level reductions with relatively little subsidence. Discharge to treatment and receiving wetlands is generally prohibited in Class I and II waters and in non-cattail-dominated herbaceous wetlands. Hydrologically altered wetlands in Florida are defined as those where upland vegetation has encroached and where substantial reduction in water levels has occurred. While Louisiana does have altered wetlands that fit this description due to drainage projects or deprivation of flows, the problem of subsidence and rising water levels is a far more serious threat. Effluent with higher sediment and nutrient loads should be considered for discharge to submerging wetlands to increase accretion rates and productivity. While Florida needs to deal with the problem of wetland loss as a result of decreased water levels and the consequent transition to uplands, Louisiana needs to deal with the problem of wetland loss as a result of increased water levels, sediment starvation, and the consequent transition to open water.

An additional factor favoring wetland wastewater treatment in Louisiana is its relatively low population density and available land area. While Florida ranks first in the coterminous United States for total wetland acreage and Louisiana ranks second (Dahl, 1990), Louisiana has a substantially lower population density, with 37 persons per square kilometer of land area compared to 93 for Florida (U.S. Bureau of the Census, 1991). In addition, the general tendency for populations in Louisiana to be distributed along natural levee ridges backed by wetlands facilitates use of those wetlands as treatment systems.

Since 1987, EPA has attempted to design standards that would be more appropriate for wetlands than the aquatic standards developed for surface water bodies and has published suggested numerical or narrative biological standards designed to prevent a decrease in wetland productivity or diversity (U.S. EPA, 1990). While the Agency is still willing to permit the use of wetlands as tertiary treatment systems in some Louisiana cases, it will not allow such use as a form of wetland "enhancement." The term was used in the report on wetlands to treat municipal wastewater (U.S. EPA, 1987) for areas where insufficient water exists to maintain a wetland as occurs in the western United States, not for areas facing the possibility of conversion to open water as occurs in Louisiana. We believe that natural but degraded wetlands can adequately purify wastewater, while benefiting ecologically at the same time.

EPA, however, has discouraged wetland wastewater treatment in Louisiana as a form of "enhancement," and has encouraged the state to approve wetland projects according to the "antidegradation" rule, which requires that the state "provide for the protection of existing uses in wetlands" (U.S. EPA, 1990). In Louisiana's case, where sea level rise is predicted to drown a vast expanse of coastal wetlands (Day & Templet, 1989; Park et al., 1989), such an emphasis on "present uses" is inadequate for long-term protection of these wetlands.

The Louisiana Department of Environmental Quality (DEQ) has granted permission to discharge secondarily treated wastewater to wetlands near Thibodaux and Breaux Bridge, but only as a "naturally dystrophic waters" exception on the premise that dissolved oxygen levels are naturally lower than the EPA standard of 4.0 mg/L in estuarine waters. State DEQ personnel have generally sought to expedite permitting of wetland treatment systems, though working within the framework of EPA policy has been a deterrent. A DEQ internal memo emphasized the need for prompt consideration and processing of wetland treatment system permitting:

> If we are to make wetlands enhancement by wastewater application feasible in Louisiana, we must provide the regulatory structure to allow expedient permitting of such discharges. The establishment of appropriate wetland specific standards is the first step in providing the regulatory structure for permitting. (Knox, no date)

Recently the state has developed a set of tentative standards for the Thibodaux wastewater treatment site, which include the following prohibitions designed to protect wetlands from any adverse effects due to wastewater application:

1. No more than 20% decrease in naturally occurring litterfall or stem growth.
2. No significant decrease in the dominance index or stem density of bald cypress.
3. No significant decrease in faunal species diversity and no more than a 20% decrease in biomass.

Since effluent application to the receiving wetland began in the spring of 1992 these criteria have not been violated. Continued monitoring of the site will further test their validity and serve as a basis for their expansion or refinement.

The EPA has already acknowledged the capability of wetlands to effectively treat wastewater. It remains for the Agency to review the potential for treated effluent to benefit Louisiana's wetlands in light of the unique problems of the state. If effluent can contribute sediment and nutrients to wetlands, then wetland wastewater treatment could be incorporated as a component of an overall comprehensive plan to protect and restore the state's wetlands. Gosselink and Gosselink (1985) suggested that wetland treatment be incorporated into plans to divert Mississippi River water to the coastal plain. Templet and Meyer-Arendt (1988) emphasized that lack of sedimentation is a primary reason for Louisiana's land loss. They suggest the use of river water, sediments, and nutrients to revive and nourish coastal wetlands to maintain surface elevation:

> The greater the number of conduits delivering water, sediments, and nutrients into the wetlands, the greater is the level of restoration of a formerly viable ecosystem. . . . Strategy: Provide maximum distribution of the waters of the Mississippi River across the deltaic plain by using the maximum number of distribution points to move water, sediment, and nutrients into the coastal wetlands.

Because of the dispersed nature of effluent dischargers in the coastal zone, wide distribution to wetlands could easily be achieved. For example, Breaux (1992) identified 147 dischargers suitable for wetland treatment in the Barataria and Terrebonne basins along the central Louisiana coast. These consist of secondary effluent, mainly from sewage treatment plants, oxidation ponds, subdivisions, schools, and trailer parks. Total rural flow in the two basins is about 197,000 m^3/day, of which 144,000 m^3/day was appropriate for wetland discharge in terms of effluent quality and total volume per discharger. Based on typical effluent composition of secondarily treated municipal wastewater of 25 mg/L suspended sediments, 20 mg/L total nitrogen, and 10 mg/L total phosphorus (Richardson & Nichols, 1985), and a total wetland area of approximately 783,000 ha in the study area (Louisiana Department of Environmental Quality, 1990), the following loading rates would be applied to the two basins: 0.17 $g/m^2\ yr^{-1}$ of suspended sediments; 0.13 $g/m^2\ yr^{-1}$ of total nitrogen; and 0.067 $g/m^2\ yr^{-1}$ of total phosphorus. Applied to the total wetland area, these additions of sediments and nutrients would be too small to make much of a difference to accretion. Concentrated at only 148 receiving wetlands, however, they could be distributed in a manner that would help build up the wetland with sediment, and fertilize the vegetation with nutrients.

In sum, water, sediment, and nutrients from small industries and municipalities throughout the coastal region could enhance coastal management by increasing both the total volume and the maximum number of distribution points. Money saved from the construction of conventional or constructed wetland treatment systems could be applied toward preproject review of potential wetland treatment areas and a sophisticated monitoring and modeling system designed to prevent any detrimental impacts to natural areas.

In attempting to restore altered wetlands with added sediment and nutrients, a number of questions arise that pertain to the maintenance of virtually all Louisiana wetlands: What were the historic hydraulic and nutrient levels that formed and nourished the wetland before it was altered? Is the present vegetation identical or similar to previous types, or have different species become established? Are natural rates of succession occurring, or have human alterations changed the natural course? Where human intervention has brought about changes, is the ultimate goal to revert to the previous system, maintain the present one, or manipulate the present one to achieve identified functional goals and aesthetic values? Clearly, a comprehensive management plan is needed to save coastal Louisiana, and wetland wastewater treatment can be an integral part of such a plan. While the primary benefit of wetland treatment will be the improvement of water quality, it can also contribute to the solution of wetland loss. Holding ponds, pretreatment techniques, rotating receiving areas, and multiple outlet distribution systems can be incorporated into wetland treatment systems in order to achieve optimum delivery of effluent to wetlands.

Policy Implications for Wetland Regulation

Several options have been suggested for wetland regulation: (1) retain the present system, with the development or protection of each wetland tract determined on a "parcel by parcel" basis; (2) establish a ranking system designed to protect the most valuable wetlands first (Hayes Bill H.R. 1330; Bingham et al., 1990); or (3) conform to a broader, landscape approach whereby wetlands would be considered according to the role they play in the regional landscape (Gosselink et al., 1990). Wetlands and water quality can benefit from the use of wetlands as treatment systems, regardless of the future regulatory framework. Some forms of wetland management, however, will be more complementary to the widespread use of wetland treatment systems than others. Implications of the different regulatory approaches to wetland treatment svstems are described below.

Continuing the Permit System

The permit review process could hinder an overall wetland wastewater treatment policy, because each permit decision provides grounds for opposition by disgruntled parties. Shabman (1986) describes the susceptibility of the process to political opposition:

> . . . a permit decision, by its nature, is a redistribution of wealth. . . . Thus, assessment is not a neutral technical exercise but is rather an activity closely tied to the process of redistributing the rights to use the environment, and will become part of the political acrimony accompanying that process.

Experience has shown that many denied the right to develop land for the public good are likely to protest. Recognition that the maintenance of water quality or the purification of wastewater is a beneficial function of wetlands will inevitably lead to conflict and debate over those benefits. Under the permit process this conflict could emerge each time a permit is denied or permitted. In addition, the inability to predict whether an adjacent wetland will exist in the future may inhibit the use of certain wetlands as treatment systems.

Ranking Wetlands

If a ranking approach were adopted, treatment wetlands could fall under either a damaged but restorable class or an irreparably damaged class, both of which would require the usual monitoring to ensure conformance with environmental water quality or wetland regulations. Wetlands that would be lost or declassified under plans proposing a classification system (e.g., the Hayes Bill, H.R. 1330), or by proposals extending the inundation period (e.g., the Reilly/Quayle proposal, 56 F.R. 40446), may prove useful as treatment systems. The Zapp's receiving wetland described above is an example of a wetland that would be left unprotected under some of the proposed definitions of wetlands.

Landscape Level Approach

The identification and use of appropriate treatment wetlands would fit well within a landscape level management approach by selecting altered but conterminous wetland tracts that might serve the water treatment needs of a community or small industry within or adjacent to the regional wetland. Gosselink et al. (1990) argued for the use of a landscape approach for bottomland hardwood ecosystem for the following reasons:

1. Management for individual processes or species generally ignores the integrated nature of wetland systems.
2. Wetland systems operate as integrated functional units.
3. The regulatory focus on an individual site ignores the context of that site in the landscape.
4. Important ecological processes occur at landscape scales.
5. A site-specific focus cannot deal adequately with cumulative effects.

Where wetland alteration has produced isolated sections of wetlands within a larger system, effluent application might serve to restore the individual areas themselves, while also contributing to the reunification of the integrated functional unit as a whole. Again, the receiving wetland for Zapp's is an example, but, in this instance, one of a hydrologically isolated wetland where wastewater treatment is being managed to conform to the ecological needs of the specific site in the context of the bottomland hardwood forest of which it is a part. The use of such restored wetland tracts can thus serve as patches or corridors to link healthier intact systems.

A landscape level approach also allows the consideration of broad, non-site-specific factors such as rising water levels. The high subsidence rate in coastal Louisiana makes the region a good model for studying the potential for wetland wastewater treatment systems to alleviate the impacts of rising water levels. Wastewater treatment systems can also be a part of regional water management systems as a way of rational use of fresh water resources.

Hydrologically Altered vs. Constructed Wetlands

Knight et al. (1992) evaluated 127 natural and constructed wetland treatment systems in the United States, one-third of which were natural wetlands and the remainder constructed wetlands. Louisiana has 44% of the constructed wetland waste treatment systems, with the remainder located primarily in other southern states. The mean flow for these constructed wetlands is 1522 m^3/day (0.402 MGD), with a range of 8.0 m^3/day (0.002 MGD) to 13,250 m^3/day (3.5 MGD). The average hydraulic surface area is 0.74 ha/1000 m^3/day (5.8 acres per MGD) (Reed, 1991). The prevalence of constructed wetlands in the southern states is likely due to the favorable climate and vegetation, relatively low populations and available land area, and to EPA's position on natural wetlands.

The costs of constructed wetlands are higher than natural treatment systems. The mean capital cost of subsurface constructed wetlands (the type used almost exclusively in Louisiana) is $215,000/ha ($87,000/ac) and the mean cost of free water surface constructed wetlands is $54,000/ha ($22,000/ac) (Reed, 1991). In general, these costs do not include collection or pumping systems, preliminary treatment, disinfection, or operation and maintenance, and neither phosphorus or ammonia removal is very effective (Reed, in press). Natural treatment systems are designed to make use of existing slopes, soils, and vegetation with a minimal amount of materials transport and site alteration. The cost of rock media for one subsurface flow system in Louisiana, for example, represented almost 60% of the total cost since the media had to be barged and trucked from Arkansas (Reed, in press).

If constructed wetlands had been used at the three Louisiana sites discussed in this report, the cost would have been much higher. Capital cost estimates for constructed wetlands based on flow rates (Reed, in press) to the three sites range from $3200 for the Zapp's potato chip factory (20 m^3/day) to $3.2 million for the City of Thibodaux (15,140 m^3/day) (Table 4). This compares to a range of $3000 to $310,000 for the use of natural wetlands at the sites.

Constructed wetlands can be an excellent means to treat wastewater at all or various stages of the treatment process. Their expense, however, in addition to the deteriorating condition of Louisiana's natural wetlands, which could benefit from the replacement of sediments and nutrients, calls for a consideration of natural wetlands as tertiary treatment systems proportionate to, if not greater than, artificial wetlands.

Table 4
Capital Cost Estimates for Constructed Wetlands and Natural Wetland Treatment Systems for Three Study Sites in Coastal Louisiana

Location	Total Flow (m^3/day)	Constructed Subsurface Wetland \$0.16/L[a]	Constructed Free Water Surface Wetland \$0.21/L[a]	Existing Natural Wetland Systems[b]
Breaux Bridge, LA (primary treatment in place)	3,785	\$606,000	\$795,000	\$125,000[c] (for monitoring)
Thibodaux, LA (secondary treatment in place)	15,140	\$2.4 M	\$3.2 M	\$310,000[c] (for monitoring, property lease, and survey)
Zapp's Potato Chip Factory, Gramercy, LA (primary treatment in place)	20	\$3,200	\$4,200	\$3,000[d] (for sprinklers, pipe, labor)

[a]Based on estimates from Reed (in press).
[b]Breaux (1992).
[c]Capitalized costs are discounted at 9% for 30 years.
[d]Capital costs, excluding operation and maintenance.

Summary

Wetland wastewater treatment systems are widely used and have proven to be especially effective in warm temperate regions such as the southern United States. When combined with careful designs and monitoring programs, wetland treatment systems show great promise in meeting the needs of both Louisiana's deteriorating wetlands and of the state's water pollution problems, especially for small isolated communities. Specific benefits include improved surface water quality, increased accretion rates to balance subsidence, increased productivity as a result of the additions of nitrogen and phosphorus, and decreased financial outlays on conventional tertiary treatment components. Because of the high rate of relative sea level rise, the Louisiana coast is a good model for other coastal areas where accelerated sea level rise is predicted to become a more serious problem.

While the U.S. EPA has acknowledged the effectiveness of wetland wastewater treatment, it has encouraged the use of constructed over natural wetlands. Consequently, constructed wetlands are taking precedence over natural wetlands to treat wastewater in Louisiana, despite the fact that coastal wetlands are suffering from high subsidence rates and deprivation of sediments and nutrients. The sediments and nutrients contained in secondarily treated municipal effluent and in some types of industrial effluent (e.g., food processors) can be beneficially applied to subsiding wetlands in the coastal zone. The warm temperatures, relatively low population density, and abundance of hydrologically altered wetlands make the Louisiana coastal zone an especially appropriate region for wetland wastewater treatment. The use of natural wetlands as treatment systems conforms to the general principle of ecological engineering described by H.T. Odum (1978) who emphasized the challenge to modern culture as "recognizing the high values in existing landscapes and finding ways to fit man's further developments without waste of the previous landscape values."

References

Baumann, R. H., J. W. Day, Jr., and C. A. Miller. 1984. Mississippi deltaic wetlands survival: Sedimentation vs. coastal submergence. *Science* 224:1093–1095.

Best, G. R. 1987. Natural wetlands—southern environment: Wastewater to wetlands, where do we go from here? In *Aquatic plants for water treatment and resource recovery,* eds. K. R. Reddy and W. H. Smith, 99–120. Orlando, FL: Magnolia.

Bingham, G., E. H. Clark, III, L. V. Haygood, and M. Leslie, eds. 1990. *Issues in wetlands protection.* Washington, DC: Conservation Foundation.

Boustany, R. G. 1991. *Factors that influence denitrification in a forested wetland: Implications to tertiary treatment of wastewater.* Thesis, University of Southwestern Louisiana, Lafayette.

Breaux, A. M. 1992. *The use of hydrologically altered wetlands to treat wastewater in coastal Louisiana.* Thesis, Louisiana State University, Baton Rouge.

Cahoon, D. R. 1990. Soil accretion in managed and unmanaged marshes. In *A study of marsh management practice in coastal Louisiana,* Vol. 3, *Ecological evaluation,* eds. D. R. Cahoon and C. G. Groat, 409–428. Final Report submitted to Minerals Management Services, New Orleans, LA, Contract No. 14-12-0001-30410, OCS Study/MMS 90-0077.

Cahoon, D. R., and R. E. Turner. 1989. Accretion and canal impacts in a rapidly subsiding wetland, II: Feldspar marker horizon technique. *Estuaries* 12(4):260–268.

Clark, J. S. 1986. Coastal forest tree populations in a changing environment, southeastern Long Island, New York. *Ecological Monographs* 56(3):259–277.

Conner, W. H., and J. W. Day, Jr. 1982. The ecology of forested wetlands in the southeastern United States. In *Wetlands ecology and management,* eds. B. Gopal, R. Turner, R. Wetzel, and D. Whigham, 69–87. Jaipur, India: National Institute of Ecology and International Scientific Publications.

Conner, W. H., and J. W. Day, Jr. 1988. Rising water levels in coastal Louisiana: Implications for two coastal forested wetland areas in Louisiana. *Journal of Coastal Research* 4(4):589–596.

Conner, W., W. Slater, K. McKee, K. Flynn, I. Mendelssohn, and J. Day. 1986. *Factors controlling the growth and vigor of commercial wetland forests subject to increased flooding in the Lake Verret, Louisiana watershed.* Final Report to the LA Board of Regents, Baton Rouge.

Conner, W. H., J. W. Day, Jr., and J. D. Bergeron. 1989. *A use attainability analysis of forested wetlands for receiving treated municipal wastewater.* Baton Rouge: Center for Wetland Resources, Louisiana State University.

Dahl, T. E. 1990. *Wetlands losses in the United States, 1780's to 1980's.* Washington, DC: U.S. Department of the Interior, Fish and Wildlife Service.

Day, J. D., A. M. Breaux, S. Feagley, P. Kemp, and C. Courville. 1993a. *Effects of longterm wastewater discharge on the Cyprière Perdue Forested Wetland at Breaux Bridge, LA.* First annual use attainability analysis report presented to the City of Breaux Bridge, Louisiana. Baton Rouge: Coastal Ecology Institute, Louisiana State University.

Day, J. D., S. Feagley, I. Hesse, J. Rybczyk, and X. Zhang. 1993b. *The use of swamp forests near Thibodaux, Louisiana for application of treated municipal wastewater: Monitoring the effects of the discharge.* Annual report submitted to the City of Thibodaux, Louisiana, and the Louisiana Department of Environmental Quality. Baton Rouge: Coastal Ecology Institute, Louisiana State University.

Day, J. W., Jr., and P. H. Templet. 1989. Consequences of sea level rise: Implications from the Mississippi delta. *Coastal Management* 17:241–257.

Day, R. D., R. K. Holz, and J. W. Day, Jr. 1990. An inventory of wetland impoundments in the coastal zone of Louisiana, USA: Historical trends. *Environmental Management* 14(2):229–240.

DeLaune, R. D., R. H. Baumann, and J. G. Gosselink. 1983. Relationships among vertical accretion, apparent sea level rise and land loss in a Louisiana Gulf Coast marsh. *Journal of Sedimentary Petrology* 53:147–157.

DeLaune, R. D., J. H. Whitcomb, W. H. Patrick, Jr., J. H. Pardue, and S. R. Pezeshki. 1989. Accretion and canal impacts in a rapidly subsiding wetland, I: ^{137}Cs and ^{210}Pb techniques. *Estuaries* 12(4)247–259.

Dunbar, J. B., L. D. Britsch, and E. B. Kemp. 1992. *Land loss rates*, Report 3, *Louisiana coastal plain.* Technical Report GL-90-2 prepared for US Army Engineer District, New Orleans, LA.

Ewel, K. C., and H. T. Odum, eds. 1984. *Cypress swamps.* Gainesville: University of Florida Press.

Faulkner, S. P., and C. J. Richardson. 1989. Physical and chemical characteristics of freshwater wetland soils. In *Constructed wetlands for wastewater treatment,* ed. D. A. Hammer, 41–72. Chelsea MI: Lewis.

Gersberg R. M., R. Brenner, S. R. Lyon, and B. V. Elkins. 1987. Survival of bacteria and viruses in municipal wastewaters applied to artificial wetlands. In *Aquatic plants for water treatment and resource recovery,* eds. K. R. Reddy and W. H. Smith, 237–245. Orlando, FL: Magnolia.

Godfrey, P. J., E. R. Kaynor, S. Pelczarski, and J. Benforado, eds. 1985. *Ecological considerations in wetlands treatment of municipal wastewaters.* New York: Van Nostrand Reinhold.

Gornitz, V., S. Lebedoff, and J. Hansen. 1982. Global sea level trend in the past century. *Science* 215:1611–1614.

Gosselink, J. G., and L. Gosselink. 1985. The Mississippi River delta: A natural wastewater treatment system. In *Ecological considerations in wetlands treatment of municipal wastewaters,* eds. P. J. Godfrey, E. R. Kaynor, S. Pelczarski, J. Benforado, 327–337. New York: Van Nostrand Reinhold.

Gosselink, J. G., L. C. Lee, and T. A. Muir. 1990. The regulation and management of bottomland hardwood forest wetlands: Implications of the EPA-sponsored workshops. In *Ecological processes and cumulative impacts,* eds. J. G. Gosselink, L. C. Lee, and T. A. Muir, 638–671. Chelsea, MI: Lewis.

Grimes, D. J. 1985. Microbial studies of municipal waste release to aquatic environments. In *Ecological considerations in wetlands treatment of municipal wastewaters,* eds. P. J. Godfrey, E. R. Kaynor, S. Pelczarski, and J. Benforado, 270–276. New York: Van Nostrand Reinhold.

Guntenspergen, G. R., and F. Stearns. 1985. Ecological perspectives on wetland systems. In *Ecological considerations in wetlands treatment of municipal wastewaters,* eds. P. J. Godfrey, E. R. Kaynor, S. Pelczarski, J. Benforado, 69–97. New York: Van Nostrand Reinhold.

Hackney, C. T., and W. J. Cleary. 1987. Salt marsh loss in southeastern North Carolina lagoons: Importance of sea level rise and inlet dredging. *Journal of Coastal Research* 3(10):93–97.

Harvey, R. 1988. Interoffice memorandum. Re: Revisions to Chapter 17-6 pursuant to wetland application, 9/28/88; Reclaimed water to wetlands rule, 17-6.030. State of Florida, Department of Environmental Regulations.

Hemond, H. F., and J. Benoit. 1988. Cumulative impacts on water quality functions of wetlands. *Environmental Management* 12(5):639–653.

Hicks, S. D. 1978. An average geopotential sea level series for the U.S. *Journal of Geophysical Research* 83:1377–1379.

Jordan, W. R., III, M. E. Gilpin, and J. D. Aber. 1987. Restoration ecology: Ecological restoration as a technique for basic research. In *Restoration ecology,* eds. W. R. Jordan, III, M. E. Gilpin, and J. D. Aber, 3–21. Cambridge, UK: Cambridge University Press.

Kadlec, R. H. 1989. Wetlands for treatment of municipal wastewater. In *Wetlands ecology and conservation: Emphasis in Pennsylvania,* eds. S. K. Majumdar, R. P. Brooks, F. J. Brenner, and R. W. Tiner, Jr., 300–314. The Pennsylvania Academy of Science.

Kadlec, R. H., and H. Alvord, Jr. 1989. Mechanisms of water quality improvement in wetland treatment systems. In *Wetlands: Concerns and successes,* ed. D. W. Fisk, 489–498. Proceedings sponsored by American Water Resources Association, 17–22 September 1989, Tampa, FL.

Kana, T. W., B. J. Baca, and M. L. Williams. 1986. *Potential impacts of sea level rise on wetlands around South Carolina.* Washington, DC: U.S. Environmental Protection Agency, EPA 230-10-85-014.

Khalid, R. A., R. P. Gambrell, and W. H. Patrick, Jr. 1981. An overview of the utilization of wetlands for wastewater organic carbon removal. In *Progress in wetlands utilization and management,* 405–423. Proceedings of a Symposium: 9–12 June 1981, Orlando, Florida. Sponsored by Coordinating Council on the Restoration of the Kissimmee River Valley and Taylor Creek Nubbin Slough Basin.

Khalid, R. A., W. H. Patrick, Jr., and M. N. Nixon. 1982. Phosphorus removal processes from overland flow treatment of simulated wastewater. *Journal of Water Pollution Control Federation* 54(1):61–69.

Knaus, R. M., and D. V. Van Gent. 1989. Accretion and canal impacts in a rapidly subsiding wetland, III: A new soil horizon marker method for measuring recent accretion. *Estuaries* 12(4):269–283.

Knight, R. L., and K. A. Ferda. 1989. Performance of the Boggy Gut wetland treatment system, Hilton Head, South Carolina. In *Wetlands: Concerns and successes,* ed. D. W. Fisk, 439–450. Proceedings sponsored by American Water Resources Association, 17–22 September 1989, Tampa, FL.

Knight, R. L., T. W. McKim, and H. R. Kohl. 1987. Performance of a natural wetland treatment system for wastewater management. *Journal of Water Pollution Control Federation* 59(8):746–754.

Knight, R. L., R. H. Kadlec, and S. Reed. 1992. *Wetlands treatment data base.* Water Environment Federation, 65th Annual Conference & Exposition, New Orleans, LA, 20–24 September 1992.

Knox, R. No date. Louisiana Department of Environmental Quality memo to the Secretary.

Krishnan, S. B., and J. E. Smith. 1987. Public health issues of aquatic systems used for wastewater treatment. In *Aquatic plants for water treatment and resource recovery,* eds. K. R. Reddy and W. H. Smith, 855–878. Orlando, FL: Magnolia.

Louisiana Department of Environmental Quality. 1990. *Water quality management plan, nonpoint source pollution assessment report,* Vol. 6, Part A, Office of Water Resources.

Lugo, A. E., S. Brown, and M. M. Brinson. 1988. Forested wetlands in freshwater and saltwater environments. *Limnology and Oceanography* 33(4, part 2):894–909.

Meo, M., J. W. Day, Jr., and T. B. Ford. 1975. *Overland flow in the Louisiana coastal zone.* Publication No. LSUSG-T-75-04, Office of Sea Grant Development, Center for Wetland Resources, Louisiana State University, Baton Rouge.

Nichols, D. S. 1983. Capacity of natural wetlands to remove nutrients from wastewater. *Journal of Water Pollution Control Federation* 55(5):495–505.

Nixon, S. W., and V. Lee. 1986. *Wetlands and water quality.* Prepared for the U.S. Army Corps of Engineers, Washington, DC, Technical Report Y-86-2.

Odum, H. T. 1978. Value of wetlands as domestic ecosystems. In *Cypress wetlands for water management, recycling, and conservation,* eds. H. T. Odum and K. C. Ewel, 910–930. Fourth Annual Report to National Science Foundation and the Rockefeller Foundation.

Pacific Estuarine Research Laboratory. 1990. *A manual for assessing restored and natural coastal wetlands with examples from southern California.* California Sea Grant Report No. T-CSGCP-021, La Jolla.

Park, R. A., M. S. Trehan, P. W. Mausel, and R. C. Howe. 1989. Coastal wetlands in the twenty-first century: Profound alterations due to rising sea level. In *Wetlands: Concerns and successes,* ed. D. W. Fisk, 71–80. Proceedings sponsored by American Water Resources Association, 17–22 September 1989, Tampa FL.

Patrick, W. H., Jr. 1990. Microbial reactions of nitrogen and phosphorus in wetlands. In *The Utrecht plant ecology news report,* 52–63. Utrecht, The Netherlands.

Penland, S. K. E. Ramsey, R. A. McBride, J. T. Mestayer, and K. A. Westphal. 1988. *Relative sea level rise and delta-plain development in the Terrebonne Parish region.* Coastal Geology Technical Report No. 4, Louisiana Geological Survey, Baton Rouge.

Reed, S. C. 1991. Constructed wetlands for wastewater treatment. *Biocycle* 44–49.

Reed, S. C. In press. Design of subsurface flow constructed wetlands for wastewater treatment. In *Natural systems for waste management & treatment*, 2d ed., eds. S. C. Reed, E. J. Middlebrooks, and R. W. Crites. New York: McGraw Hill.

Richardson, C. J. 1985. Mechanisms controlling phosphorus retention capacity in freshwater wetlands. *Science* 228:1425–1427.

Richardson, C. J., and J. A. Davis. 1987. Natural and artificial wetland ecosystems: Ecological opportunity and limitations. In *Aquatic plants for water treatment and resource recovery,* eds. K. R. Reddy and W. H. Smith, 819–854. Orlando, FL: Magnolia.

Richardson, C. J., and D. S. Nichols. 1985. Ecological analysis of wastewater management criteria in wetland ecosystems. In *Ecological considerations in wetlands treatment of municipal wastewaters,* eds. P. J. Godfrey, E. R. Kaynor, S. Pelczarski, and J. Benforado, 351–391. New York: Van Nostrand Reinhold.

Schlesinger, W. H. 1978. Community structure, dynamics, and nutrient cycling in the Okefenokee cypress swamp forest. *Ecological Monographs* 48:43–65.

Shabman, L. 1986. The contribution of economics to wetlands valuation and management. In *Proceedings of the National Wetland Assessment Symposium, 17–20 June 1985, Portland, Maine,* eds. J. A. Kusler and P. Riexinger, 9–13. Sponsored by the Association of State Wetland Managers, Technical Report 1, February 1986.

Shiaris, M. P. 1985. Public health implications of sewage applications on wetlands: Microbiological aspects. In *Ecological considerations in wetlands treatment of municipal wastewaters,* eds. P. J. Godfrey, E. R. Kaynor, S. Pelczarski, and J. Benforado, 243–261. New York: Van Nostrand Reinhold.

Stanley, D., 1988. Subsidence in the northeastern Nile Delta: Rapid rates, possible causes, and consequences. *Science* 240:497–500.

Stevenson, J. C., L. G. Ward, M. S. Kearney, and T. E. Jordan. 1985. Sedimentary processes and sea level rise in tidal marsh systems of Chesapeake Bay. In *Wetlands of the Chesapeake,* eds. H. A. Groman et al., 37–62. Washington, DC: Environmental Law Institute.

Stevenson, J. C., L. G. Ward, and M. S. Kearney. 1986. Vertical accretion in marshes with varying rates of sea level rise. In *Estuarine variability,* ed. D. A. Wolfe, 241–259. New York: Academic.

Templet, P. H., and K. J. Meyer-Arendt. 1988. Louisiana wetland loss: A regional water management approach to the problem. *Environmental Management* 12(2):181–192.

U.S. Bureau of the Census. 1991. *Statistical abstracts of the United States,* 111th ed. Washington, DC: U.S. Government Printing Office.

U.S. Environmental Protection Agency. 1987. *Report on the use of wetlands for municipal wastewater treatment and disposal.* Office of Water, Office of Municipal Pollution Control. Submitted to Senator Quentin N. Burdick, Chairman of Committee on Environmental and Public Works. EPA 430/09-88-005.

U.S. Environmental Protection Agency. 1990. *Water quality standards for wetlands: National guidance.* Washington, DC: Office of Water, Regulations and Standards, EPA 440/S-90-001.

Warrick, R., and J. Oerlemans. 1990. Sea level rise. In *Climate change: The IPCC scientific assessment.* eds. J. Houghton, G. Jenkins, and J. Ephraums, 257–281. Cambridge, UK: Cambridge University Press.

Watson, J. T., S. C. Reed, R. H. Kadlec, R. L. Knight, and A. E. Whitehouse. 1989. Performance expectations and loading rates for constructed wetlands. In *Constructed wetlands for wastewater treatment,* ed. D. A. Hammer, 319–351. Chelsea, MI: Lewis.

Wentz, W. A. 1987. Ecological/environmental perspectives on the use of wetlands in water treatment. In *Aquatic plants for water treatment and resource recovery,* eds. K. R. Reddy and W. H. Smith, 17–25. Orlando, FL: Magnolia.