A Review of Recent Studies of the Ecological and Economic Aspects of the Application of Secondarily Treated Municipal Effluent to Wetlands in Southern Louisiana

J. W. Day, Jr.[1], J. M. Rybczyk[2], L. Cardoch[3], W. H. Conner[4], P. Delgado-Sanchez[5], R. I. Pratt[6], A. Westphal[7]

1 Coastal Ecology Institute, Louisiana State University, South Stadium Rd., Baton Rouge, LA 70803, TEL: 225-388-6508; FAX: 225-388-6326; email: ceiday @lsuvm.sncc. lsu. edu
2 Department of Biological and Environmental Sciences, California University, 250 University Avenue, California, PA 15419; email: ryhczyk@cup.edu
3 Coastal Ecology Institute, Louisiana State University, South Stadium Rd., Baton Rouge, LA 70803; email: cardoch @lsu.edu
4 Baruch Forest Science Institute, Clemson University, Box 596, Georgetown, SC 29442
5 Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA 70803
6 Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA 70803
7 Coastal Ecology Institute, Louisiana State University, South Stadium Rd., Baton Rouge, LA 70803; email: awestph@lsuvm.sncc.lsu.edu

From the Symposium Recent Research in Coastal Louisiana: Natural System Function and Response to Human Influence. Rozas L. P., J. A. Nyman, C. E. Proffitt, N. N. Rabalais, D. J. Reed, and R. E.Turner (editors). 1999. Published by Louisiana Sea Grant College Program.

ABSTRACT: Insufficient sedimentaffon, coupled with high rates of relative sea level rise (RSLR), are two important factors contributing to wetland loss in coastal Louisiana. We hypothesized that adding nutrient-rich treated wastewater effluent to selected coastal wetlands results in four benefits: (1) improved effluent water quality; (2) increased accretion rates to help offset subsidence; (3) increased productivity of vegetation; and (4) financial savings of capital not invested in conventional tertiary treatment systems. To test these hypotheses, we are currently monitoring several forested wetlands that are receiving secondarily treated wastewater in coastal Louisiana. At one site where sedimentation accumulation was measured, rates of accretion increased significantly after wastewater application began in the treatment site (from 7.8 to 11.4 mm yr^{-1}), and approached the estimated rate of regional RSLR (12.0 mm yr^{-1}). No corresponding increase was observed in an adjacent control site. In the same site, surface water nutrient reduction, from the effluent inflow to outflow (1600 m), ranged from 100% for NO_3^-N to 66% for total P. At another site, a forested wetland that has been receiving wastewater effluent for 40 years, dendrochronological analysis revealed that stem growth increased significantly in the treatment site after wastewater water applicaffons began, and was significantly greater than an adjacent control. Preliminary results indicate that these sites have the potential to assimilate all effluent nitrogen and varying percentages of phosphorus. Results of avoided costs analyses to evaluate the economic implications between conventional treatment and wetland treatment at three sites indicate savings range from $500,000 to $1.5 million.

Introduction

Numerous studies have shown that wetlands can be effective tertiary processors of wastewater effluent (Kadlec and Knight 1996). Previous studies indicate that both natural and constructed wetlands have been successfully used to purify effluent (Richardson and Davis 1987; Conner et al. 1989; Reed 1991; Kadlec and Knight 1996). Wetlands are efficient at removing excess nutrients and pollutants by physical settling and filtration, chemical precipitation and adsorption, and biological metabolic processes that result in burial, storage in vegetation, and denitrification (Conner et al.1989; Kadlec and Alvord 1989; Patrick 1990). These wetland functions can be especially critical for the coastal regions in Louisiana affected by degraded water quality caused, in part, by inadequate sewage treatment (Louisiana DEQ 1988).

Wastewater effluent may also serve as a restoration tool in coastal wetlands impacted by high rates of relative sea level rise (RSLR). Wetlands have been shown to persist in the face of RSLR when vertical accretion and elevation gain equals or exceeds the rate of subsidence (Delaune et al.1983; Cahoon et al. 1995). Historically, seasonal overbank flooding of Mississippi river deposited sediments and nutrients into the wetlands of the delta plain. Not only did these floods provide an allochthonous source of mineral sediments, which contributed directly to vertical accretion, but the nutrients associated with these sediments promoted vertical accretion through organic matter production as well as deposition (Nyman and Delaune 1991). This sediment and nutrient source to most forested wetlands in coastal Louisiana has been eliminated since the 1930s with the completion of levees along the entire course of the lower Mississippi River, resulting in vertical accretion deficits (accretion < RSLR), prolonged periods of inundation, lowered productivity and a lack of regeneration (Conner and Day 1988).

In these stressed systems, we hypothesize four primary benefits derived from wetlands wastewater treatment in Louisiana: (1) improved effluent water quality; (2) increased accretion rates; (3) increased productivity of vegetation; and (4) the financial savings of capital not invested in conventional tertiary treatment systems (Breaux 1992; Breaux and Day l994). The high rate of burial due to subsidence and higher than national average rates of denitrification due to warm temperatures are additional reasons for the use of wetland treatment in Louisiana. Increasing vegetative productivity is especially crucial in many parts of Louisiana where coastal subsidence intheMississippi Delta results in a relative sea level rise nearly ten times greater than eustatic sea level rise (Conner and Day 1988; Penland et al.1988). Increasing productivity results in greater root production leading to organic soil formation which can enhance the accretion necessary to offset the subsidence that is contributing to wetland loss.

Since 1988, the Coastal Ecology Institute at Louisiana State University has been working with the U.S. Environmental Protection Agency (EPA), the Louisiana Department of Environmental Quality (DEQ), and several dischargers to assess the impact of forested and marsh wetland wastewater assimilation projects in coastal Louisiana (for a general policy review see Breaux and Day 1994). The dischargers include two municipalities, Thibodaux and Breaux Bridge, and one food processor, Zapp's potato chip factory in Gramercy (Fig. l). Two additional municipalities (Amelia and St. Bernard) are in the final stages of the EPA-mandated Use Attainability Analyses prior to formal discharge permitting. A feasibility study was recently conducted for wetland treatment of shrimp processing effluent in Dulac, Louisiana. All of the potential and actual receiving wetlands have been hydrologically altered by some combination of levees, spoil banks, highways, oil and gas access roads, or railroad lines. In addition, prior to wetland treatment, all effluent was discharged directly into open water bodies. Wetland discharge provides additional treatment by removing further nutrients from the effluent before entering open water bodies.

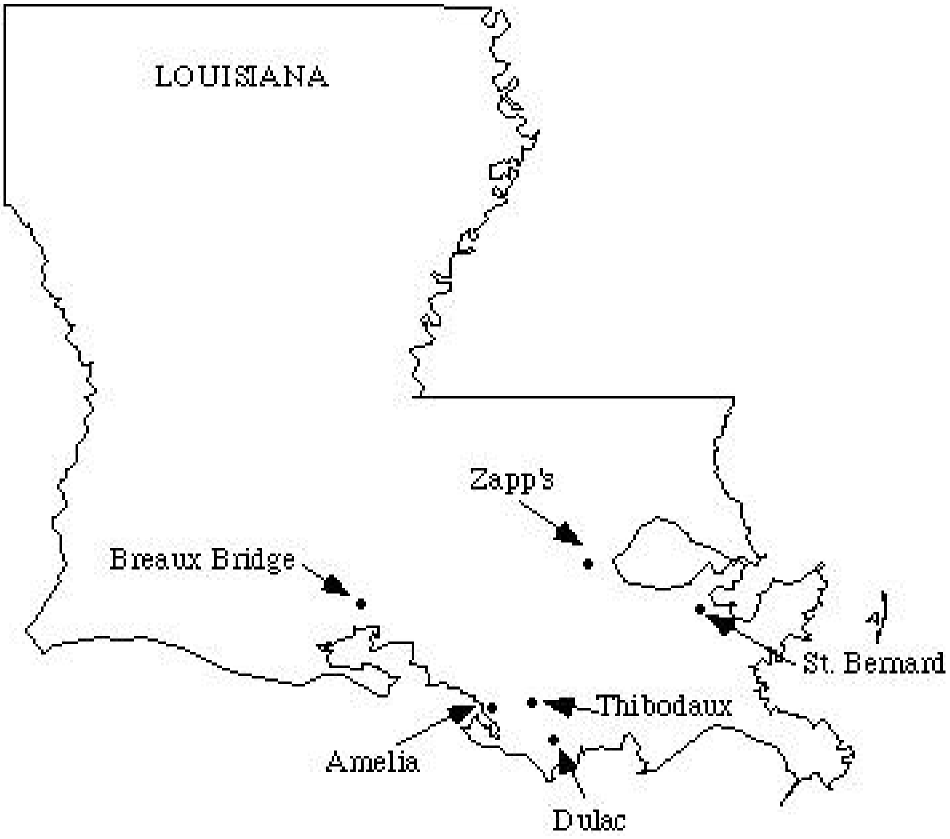

Fig. 1. Wetlands treatment study sites studied by the Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA.

To examine the effect of wetland treatment on effluent water quality, sediment accretion, productivity, and economic savings, we review results of studies conducted at Amelia, Breaux Bridge, Dulac, Thibodaux and St. Bernard (Conner and Day 1989; Day et al. 1994; Day et al. 1997a,b; Day et al. 1998; Cardoch et al. 2000). Throughout this review, when we use the term significant, it implies a statistical significance which is documented in the references. Sampling of benthic invertebrate and nekton communities did not indicate any clear effects due to wastewater discharge and results are not presented here. For more information, refer to Conner and Day (1989), Breaux and Day (1994), Day et al. (1994), Day et al. (1997a), Day et al. (1997b) and Pratt (1998). Additional project information can be found in Breaux (1992), Hesse (1994), Delgado-Sanchez (1995), Zhang X. 1995, Blanick (1997), Boustany et al. (1997), Rybczyk (1997).

Improved Effluent Water Quality

We hypothesized that effluent water quality will be improved through efficient nutrient uptake and removal pathways within forested wetlands. Loading rates and percent nutrient reductions for municipal wastewater treatment wetlands are listed in Table 1. Data from the Point au Chene treatment wetland for the City of Thibodaux offers an example for the impact of effluent on water quality.

The Thibodaux site consists of two almost permanently flooded, subsiding, forested wetlands, separated by a slightly elevated bottomland hard-wood ridge. Since 1992, the 231 ha wetland on the western side of the ridge has received secondarily treated municipal wastewater at the average rate of 15,140 m^3 d^{-1}. The wetland on the eastern side of the ridge, which is not impacted by the effluent, serves as a control site. Baseline monitoring of vegetation, soils, surface water, hydrology, and fauna, at both sites, began in 1988. Extended inundation was documented during the baseline studies (Conner and Day 1989). A comprehensive site description is provided by Breaux and Day (1994) and Rybczyk et al. (1995).

Measurements taken at Thibodaux by Zhang (1995) indicate that effluent water quality was improved as nutrients were significantly reduced and assimilated. The effluent stream was highly nitrified, with NO_3^-N being the dominant form of N and soluble PO_4^-P accounting for about 77% of the total P in the effluent. After passage through the treatment swamp the concentrations of many water quality parameters at the output station were significantly reduced compared with the influent concentrations. From 1992 through 1996, the mean annual reduction (from inflow to outflow) of NO_3^-N the dominant form of nitrogen in the effluent, ranged from 96% to 99% (Fig. 2). At the output station, the NO_3^-N concentration was below the detection limit (<0.1 mg l^{-1}) during most sampling periods, indicating that the swamp system was removing NO3-N. Figure 3 illustrates reductions of NO_3^-N concentrations as a function of distanced traveled in the swamp. Within 800 m, concentrations were comparable to those found in the control site. NO_3^-N was taken up by growing plants, immobilized to organic N, or removed by denitrification (Boustany et al.1997). Concentrations of total P in the treatment site varied during the study period. From l992 through l994, the mean annual reduction of total P in the treatment site ranged from 33% to 71 % from inflow to outflow (Fig. 4, Zhang 1995).

Zhang (1995) described the effects of wastewater effluent on effluent water quality, sediment nutrient concentrations, and the chemical composition of floating aquatic vegetation at the Pointe au Chene site. This study assessed the long term ability of the swamp to treat secondarily treated wastewater effluent from the city of Thibodaux. In general Zhang found that, within the immediate 231 ha treatment zone, N and P concentrations in the water were reduced 100% and 66%, respectively, From effluent inflow to outflow Table 1. In a related review, Rybczyk et al. (1996) concluded that the effective tertiary processing of effluent at this site could be attributed to the following: (1) The dominant species of N in the effluent was the oxidized NO3-N form and not the reduced species, NH4-N. These naturally dystrophic wetlands readily denitrify NO3-N, resulting in a net loss of N to the system as N2 or N2O gas (see Boustany et al.1997); (2) Loading rates are low compared to other wetlands treatment sites. For example, the State of Florida has adopted regulations for wetland wastewater management that established maximum P loading rates of 9 gm^{-2} yr^{-1} for hydrologically altered wetlands (Harvey 1988), an order of magnitude higher that at most of our sites, and; (3) High rates of accretion and burial of sediments in these subsiding systems provide a permanent sink for phosphorus. Two other studies also documented the high rates of denitrification at this site (Crozier et al. 1996; Boustany et al. 1997).

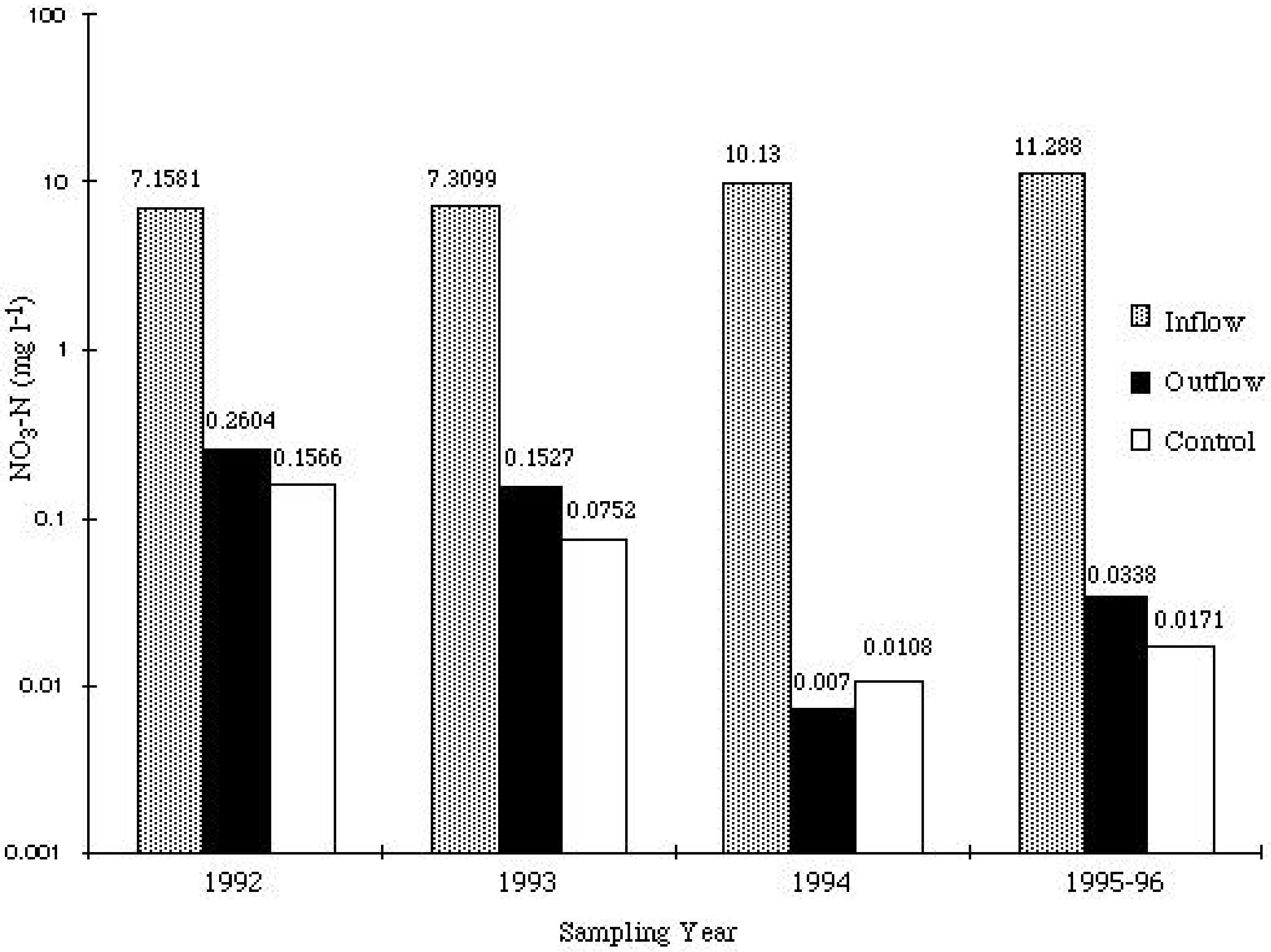

Fig. 2. Mean annual concentrations of NO_3 for the effluent inflow pipe, the treatment outflow, and within the first 100 m of the control site at Thibodaux. Inflow concentrations are reduced 96-99%. Note: Logarithmic scale.

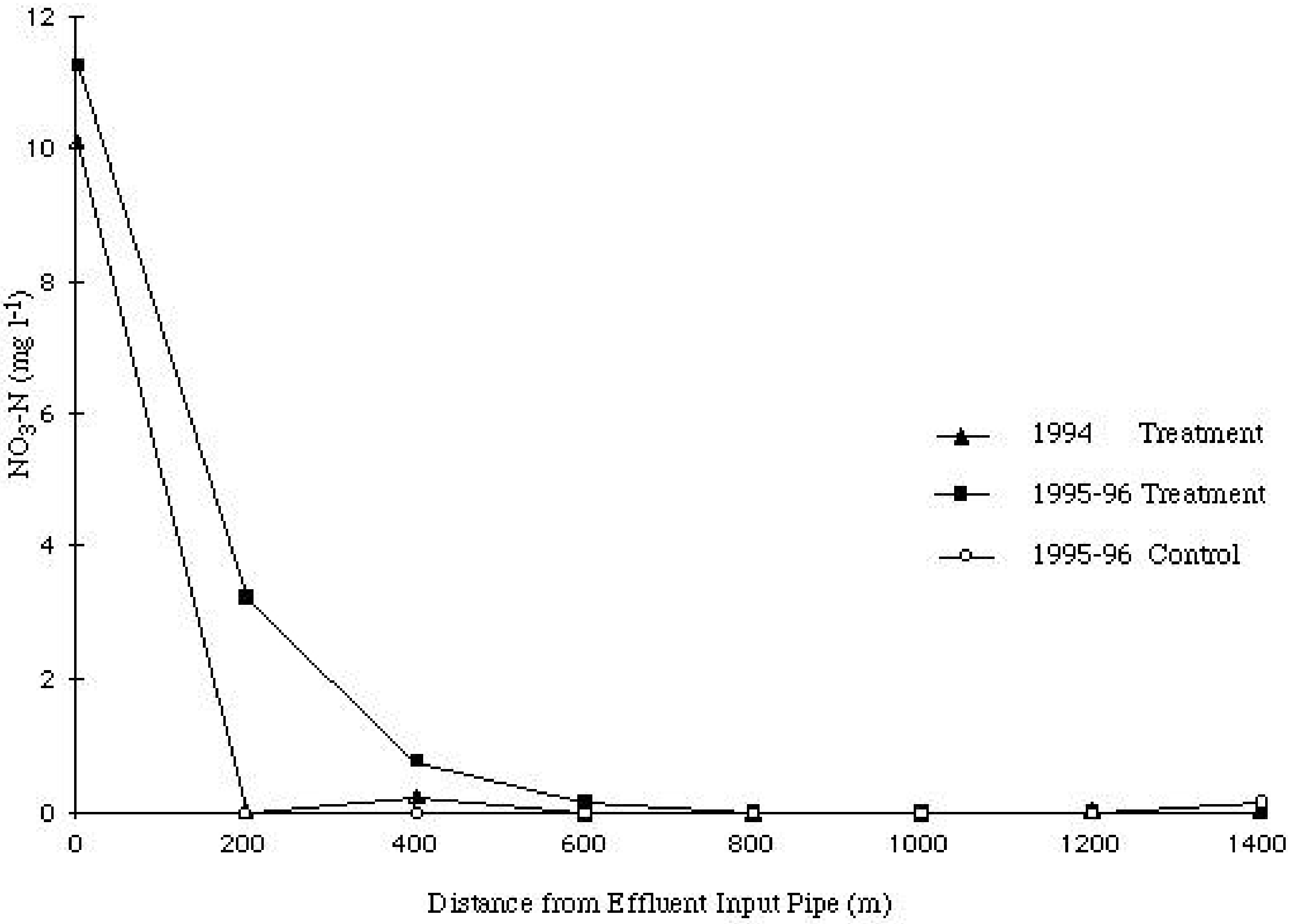

Fig.3. Mean concentrations of NO_3-N along sample transects in the treatment site during sample years 1994 and 1995, and in the control site at Thibodaux for sample year 1995. Nitrate concentrations are reduced 99%.

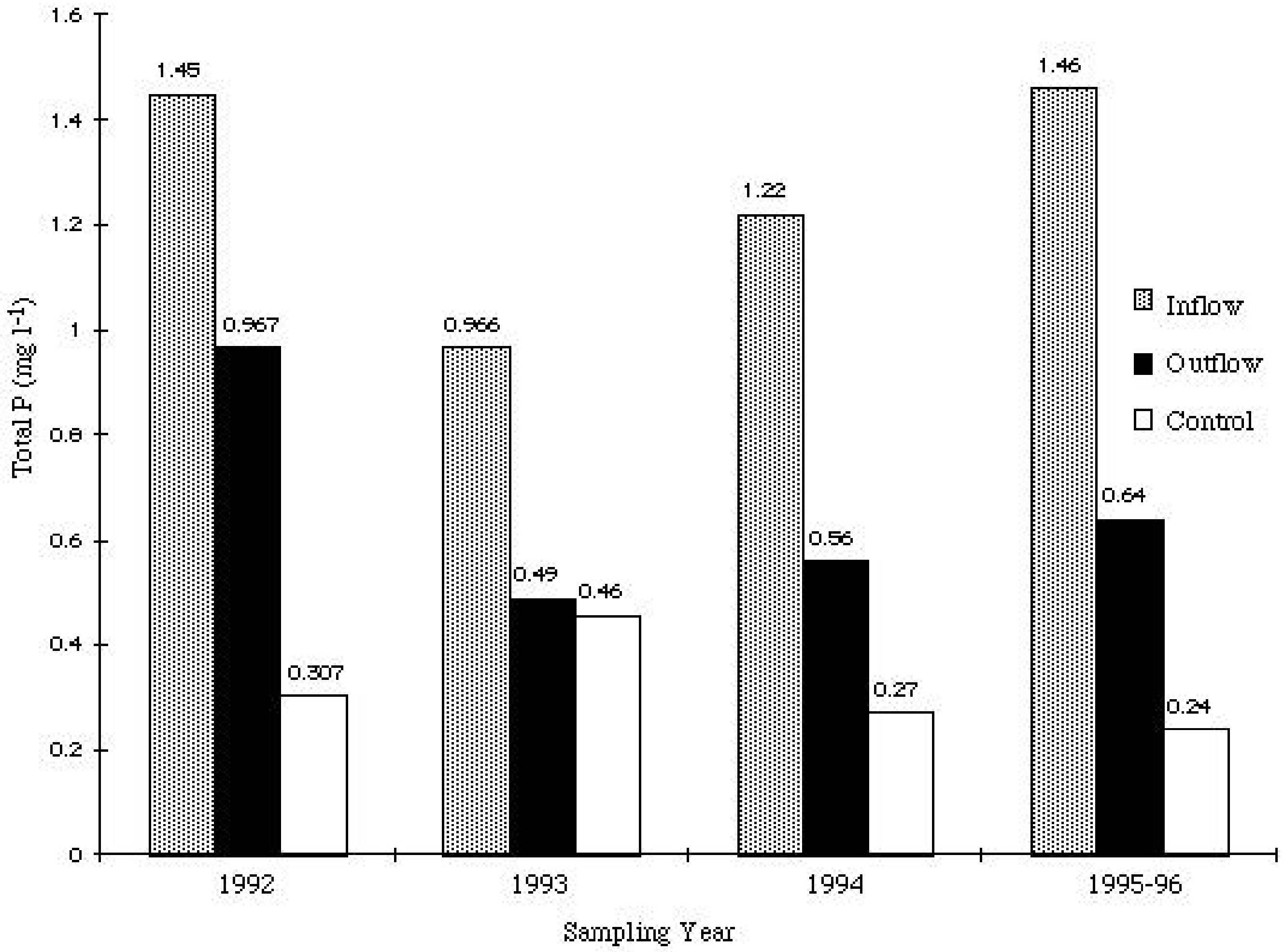

Fig. 4. Mean annual concentrations of Total P for the effluent inflow pipe, the treatment outflow, and within the first 100 m of the control site at Thibodaux. Inflow concentrations are reduced 33-56 %.

Similar water quality improvements have been documented for the treatment wetlands at Amelia, Breaux Bridge, and St. Bernard (Table 1). High reduction rates of N and P indicate that the wetlands there act as a net nutrient sink and that the sites are effective providers of tertiary treatment. For comparison, in Florida, the tertiary advanced waste treatment (AWT) standards for total N and total P are 3 mg l^{-1} and 1 mg l^{-1}, respectively. For many of these sites, nutrient concentrations have been well below that limit, indicating that tertiary treatment was achieved.

Increased Sediment Accretion

Current evidence indicates that rising water levels are leading to wetland loss, coastal erosion, and salt water intrusion in a number of coastal areas (Stevenson et al. 1988; Sestini 1992). If coastal wetlands, especially those 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 disappear (Mendelssohn and McKee 1988). Many wetlands in Louisiana suffer from accretion deficits; that is, they are not keeping pace with RLSR. Discharge of secondarily treated effluent can stimulate biomass production and enhance sediment accretion rates. Maintaining vegetation is crucial to wetlands survival.

Subsidence in deltas leads to a relative sea level rise (RSLR} rate that is often much greater than eustatic rise. For example, while the current rate of eustatic rise is between 1-2 mm yr^{-1} (Gornitz et al. 1982), RSLR in the Mississippi delta is in excess of 10 mm yr^{-1}, thus eustatic sea level increase accounts for only 10-15% of total RSLR in this delta. We hypothesized that adding nutrient rich effluent can increase rates of sediment accretion by promoting production of organic matter and trapping of mineral matter. Evidence from the Pointe au Chene treatment wetland at Thibodaux supports this hypothesis.

The relative sea level rise (RSLR) rate at the Thibodaux treatment wetland (Fig.5) derived from tidal gauge analysis (Penland et al. 1988), is 1.23 cm yr^{-1} for the period 1962 through 1982. To maintain elevation, soil accretion must equal this rate of RSLR. However, by analyzing ^{137}Cs activity in the soil profile (see Delaune 1978 for a description of methods), it was estimated that background accretion rates in the Thibodaux site averaged only 0.44 ± 0.04 cm yr^{-1} for the same period, leading to an accretion deficit of O.79 cm yr^{-1} (Rybczyk l997).

To determine whether wastewater applications stimulated accretion, a feldspar horizon marker technique (Cahoon and Turner 1989) was utilized to estimate accretion rates in the site receiving effluent and in an adjacent control site, both before (1988 - 1991) and after (1992 - 1994) wastewater applications began in the treatment site. Pre-effluent accretion rates averaged 0.78 cm yr^{-1} in the treatment site and 0.52 cm yr^{-1} in the control site and were not significantly different (Fig. 1). After application began, accretion rates in the treatment site (1.1 cm yr^{-1}) were significantly higher than accretion rates measured at the control site (0.14 cm yr^{-1}).

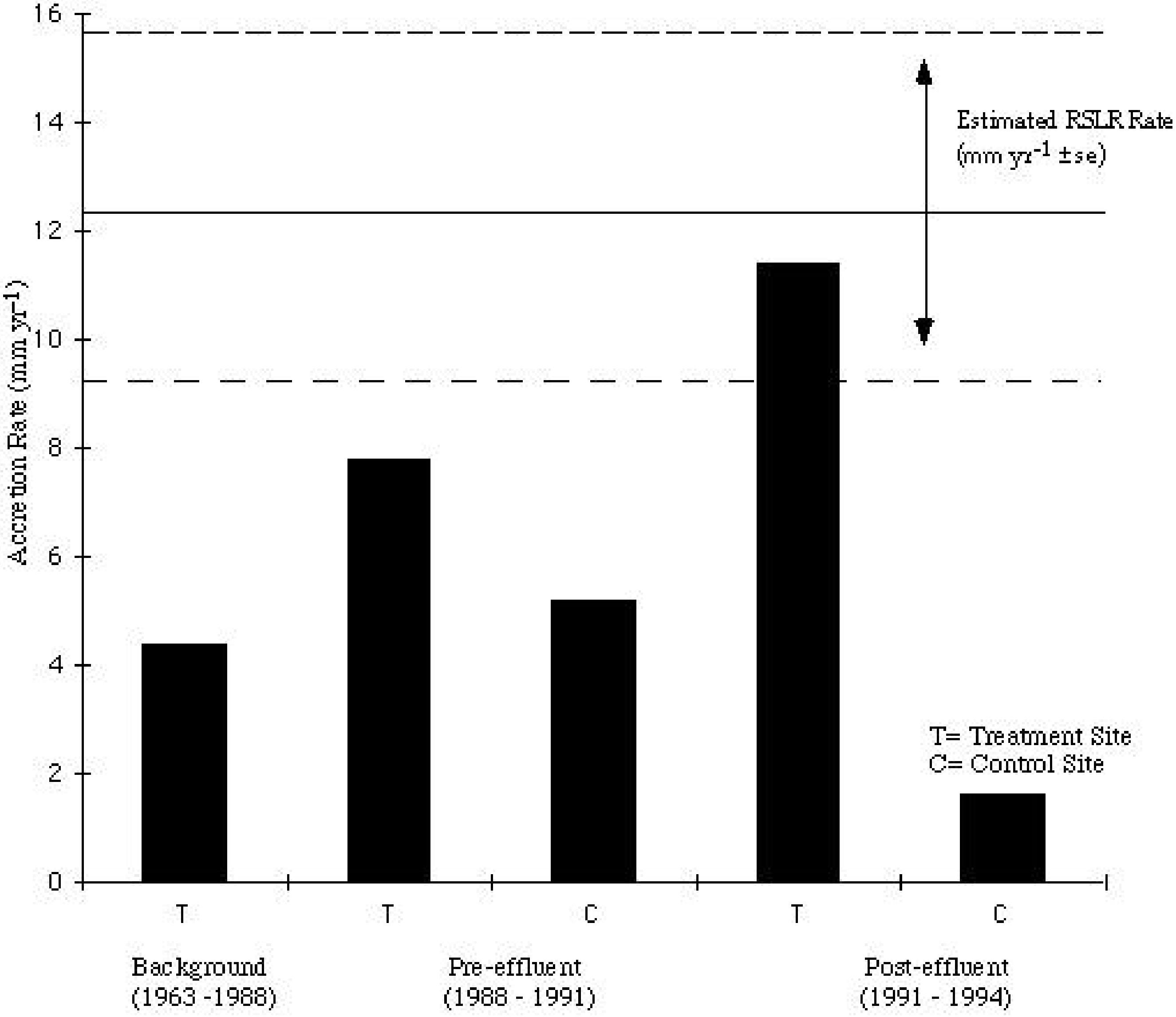

Fig. 5. Background (from ^{137}Cs measurements), pre-effluent, and post-effluent accretion rates, relative sea level rise (RSLR) and accretion balance deficits for treatment (T) and control (C) at the Thibodaux site. T and C were not significantly different during the pre-treatment period, but T was significantly greater during the post-effluent period.

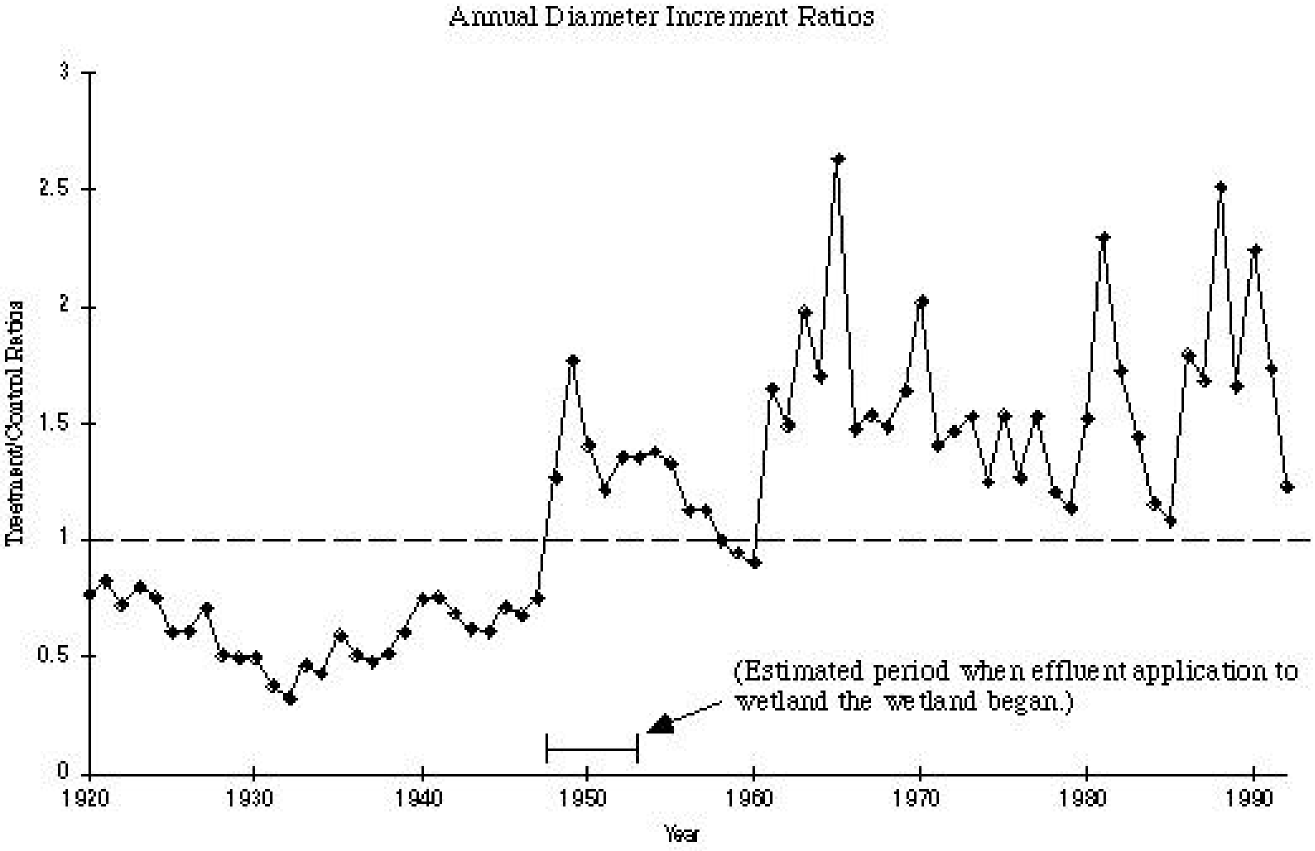

Fig. 6. The ratio (treatment/control) of annual wood stem growth (measured as growth in diameter) for bald cypress trees at Breaux Bridge. Before wastewater applications to the treatment site began in the late 1940's or early 1950's, growth in the control site was significantly higher than growth in the treatment site ($P < 0.05$). After wastewater applications began, stem growth was significantly higher in the treatment site. Both sites were similar in size and structure (Hesse et al. 1997).

Additionally, estimated accretion rates in the treatment site fell within one standard deviation of the estimated rate of RSLR in the region (Rybczyk 1997).

Using an integrated field and modeling approach, Rybczyk et al. (1996), Rybczyk (1997) and Rybczyk et al. (1998) focused on the use of wastewater effluent at Pointe au Chene for wetland enhancement and restoration. Their studies revealed that neither aboveground tree production nor annual rates of decomposition were affected by wastewater effluent. Because of increased floating aquatic vegetation production, however, rates of sediment accretion increased significantly after wastewater applications began and fell within one standard error of the estimated rate of relative sea level rise. A site- specific wetland elevation model revealed that wetland elevation in this subsiding region was more sensitive to the uncertainty surrounding estimates of eustatic sea level rise and deep subsidence than to possible effluent-related changes in autogenic processes such as decomposition and primary production (Rybczyk 1997). The model also indicated that nutrient addition alone was not sufficient to lead to long term restoration of the forested wetland and that some mineral sediment input was necessary.

Increased Productivity

Secondarily reated effluent delivers nutrient-rich water to wetlands, stimulating vegetative productivity. Long term impacts on forested wetlands can be assessed by evaluating data from the Breaux Bridge treatment wetland. The treatment wetland at Breaux Bridge is unique because of its long history of discharge to the receiving wetland. The town of 6,000 has been discharging its effluent from an oxidation pond (3,785 m^3 d^{-1}) to a 1475-ha cypress-tupelo wetland for almost 50 years (Breaux and Day 1994). Monitoring of the effluent impact site and an adjacent reference site began in 1992. A comprehensive site description is provided by Day et al. (1993).

A dendroecological analysis was conducted (Hesse 1994; Hesse et al. 1997) to determine the long term impacts of wastewater effluent on aboveground productivity (Fig. 6). Stem wood growth from 1920 to 1992 was measured at the treatment site and an adjacent control site. An annual diarneter increment ratio was calculated by comparing stem wood growth from the treatment site versus the stem wood growth at the control site. Records indicate that the city began discharging into the forested wetland between 1948 and 1953. Before wastewater application began, Hesse et al. (1997) found statistically significant higher growth in the control site than at the treatment site. However, after onset of treatment, there was increased growth in the treatment site, resulting in statistically significant higher annual diameter incrementratios (Hesse et al. 1997). A spike in the annual diameter increment ratios coincides with the onset of treatment. The sustained elevated trend of ratios in the treatment site illustrates the long term benefits of wetland treatment in this site.

Short term records at this site also confirm these findings. In January 1994, the effluent discharge was switched from the historic wetland (old treatment site), to a new site that had not previously received effluent (new treatment site). In 1992, permanent plots were established at both sites to measure annual litterfall and stem growth (Table 2). There was no statistically significant difference in the total aboveground production between the old treatment site and the new treatment site during 1993 (Delgado-Sanchez 1995). However, during 1994 and 1995, when effluent discharge was switched to the new treatment site, total production was significantly higher at the new treatment site compared to the old treatment site (Delgado-Sanchez 1995). Most of this difference was due to increases in stem wood biomass in the new treatment site and not leaf production.

Similar results have been reported for the other treatment wetlands. For example, a study conducted at Amelia also indicates an increase of primary productivity. The City of Amelia is investigating the ecological feasibility of incorporating the Ramos et al. (1993).forested wetland as part of its treatment system to polish secondarily treated sewage effluent (Day et al. 1997a). A year long study on primary productivity indicates enhanced growth in the treatment sites (Table 3). Productivity, as expressed in mean litterfall for one year, was statistically significantly higher in the treatment site than in one of the control sites (Day et al. 1997a).

Economic Savings

Conventional wastewater treatment is often very expensive for the loads generated from many of the small communities in southern Louisiana. Wetland assimilation can providean affordable and effective waste treatment option. In a series of papers, Breaux (1992), Breaux and Day (1994) and Breaux et al. (1995), conducted economic cost bene fit analyses of the wastewater treatment operation at Breaux Bridge and Thibodaux (Table 4). They conservatively estimated a capitalized cost savings, using natural wetland wastewater treatment rather than conventional tertiary treatment. At Breaux Bridge, the estimated costs savings was approximately $1.4 million, over a 30-year period. At Thibodaux, there is a potential savings of approximately $500,000. However, it is further noted that capitalized savings could be as high as $1,300,000 over a 30-year period, depending upon the disinfection system employed prior to wetland discharge.

Non-toxic, industrial processors, such as shrimp processors, can benefit from using wetlands for their highly seasonal loads. A study was recently conducted to determine the feasibility of using wetlands for treatment of shrimp processing waste water in Dulac, Louisiana (Cardoch et al. 2000). The avoided cost estimate approach was used to compare costs from conventional on-site treatment of the shrimp processing effluent with costs for wetlands treatment. Conventional treatment would cost approximately $200,000 per year for 25 years, as compared to wetland treatment costs of $64,000 per year for 25 years. This is a potential cost savings of $1.5 million dollars over 25 years (Table 4).

Much wetland treatment has focused on constructed wetlands primarily to provide a high degree of control for treatment. In Louisiana, the dense network of canals and levees have left many wetlands hydrologically isolated and confer the same degree of control as constructed wetlands. With many natural systems plentiful, it is unnecessary to build artificial wetlands in Louisiana, although many have been built. These isolated wetlands provide a practical economic solution for the small communities that are widely dispersed in the coastal zone.

Conclusions

Results from several ongoing and completed studies of wastewater treatement in wetlands indicate that they are achieving the ecological goals of enhancing effluent water quality, stimulating vertical accretion, and increasing productivity. Economically, the savings are substantial for small communities and non-toxic industrial processors. Calculations of nutrient retention and loss via denitrification, plant uptake, and burial indicate that the receiving wetlands should assimilate all of the NO3-N and more than 50% of the phosphorus given the current loading rates. As water quality regulations become more stringent, and federal grants for sewage treatement improvements become less available, it will be increasingly difficult for small coastal communities to meet the water quality standards. Wetland wastewater treatment could provide an economically viable and effective alternative to expensive conventional tertiary treatment. Additionally, it potentially serves as a means for wetland restoration in the subsiding coastal zone.

LITERATURE CITED

BLAHNIK, T. P.1997. Effects of varied hydraulic and nutrient loading rates on water quality and hydrologic distributions in a natural forested wetland receiving waste water. Masters Thesis. Department of Oceanography and Coastal Sciences. Louisiana State University, Baton Rouge, Louisiana.

BOUSTANY, R. G., C. R. CROZIER, J. M. RYBCZYK, AND R. R. TWILLEY.1997. Denitrif~cation in a South Louisiana wetland forest receiving treated sewage effluent. Wetlands Ecology and Management 4: 273-283.

BREAUX, A. M. 1992. The use of hydrologically altered wetlands to treat wastewater in coastal Louisiana. Ph.D. Dissertation, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana.

BREAUX, A. M., AND J. W. DAY, JR. 1994. Policy considerations for wetland wastewater treatment in the coastal zone: a case study for Louisiana. Coastal Management 22: 285-307.

BREAUX, A., S. FARBER, AND J. DAY. 1995. Using natural coastal wetlands systems for wastewater treatment: an economic benefit analysis. Journal of Environmental Management 44: 285-291.

CAHOON, D. R. AND R .E. TURNER. 1989. Accretion and canal impacts in a rapidly subsiding wetland II. Feldspar marker horizon technique. Estuaries 12: 260-268.

CAHOON, D., D. REED AND J. DAY.1995. Estimating shallow subsidence in microtidal salt marshes of the southeastern United States: Kaye and Barghoorn revisited. Marine Geology 130: 1-9.

CARDOCH, L., J. W. DAY, JR., J. M. RYBCZYK, AND G. P. KEMP. 2000. An economic analysis of using wetlands for treatment of shrimp processing wastewater: A case study in Dulac, Louisiana. Ecological Economics, in press.

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: 589-596.

CONNER, W. H. AND J. W. DAY, JR. 1989. A use attainability analysis of wetlands for receiving treated municipal and small industry wastewater: a feasibility study using baseline data from Thibodaux, LA. Center for Wetlands Resources, Louisiana State University, Baton Rouge, Louisiana.

CONNER, W. H., J. W. DAY JR., AND J. D. BERGERON. 1989. A use attainability analysis of forested wetlands for receiving treated municipal wastewater. Report to the City of Thibodaux, Louisiana.

CROZIER, C. R., J. M. RYBCZYK, AND W. H. PATRICK, JR. 1996. Spatial gradients of dissolved nitrate and nitrous oxide in a wetland forest receiving treated sewage effluent, p. 65-68. In Kathryn Flynn (ed.), Proceedings of the Southern Forested Wetlands Ecology and Management Conference. Clemson University, South Carolina.

DAY, J. W., A. M. BREAUX, S. FEAGLEY, P. KEMP, AND C. COURVILLE.1994. A use attainability analysis of longterm wastewater discharge on the Cypriere Perdue Forested Wetland at Breaux Bridge, LA. Coastal Ecology Institute, Lousiana State University, Baton Rouge, Louisiana.

DAY, J. W., J. RYBCZYK, R. PRATT, A. WESTPHAL, T. BLAHNIK, G. GARSON, AND P. KEMP. 1997a. A use attainability analysis for longterm wastewater discharge on the Ramos Forested Wetland at Amelia, LA. Coastal Ecology Institute, Louisiana State University, Baton Rouge, Louisiana.

DAY, J. W., J. RYBCZYK, R. PRArr, M. SUTULA, A. WESTPHAL, T. BLAHNIK, P. DELGADO, P. KEMP, A. J. ENGLANDE, C.Y. Hu, G. JIN, AND H.W. JENG. 1997b. A use attainability analysis for longterm wastewater discharge to the Poydras-Verret Wetland in St. Bernard Parish, LA. Coastal Ecology Institute, Louisiana State University, Baton Rouge, Louisiana.

DAY, JR., J. W., L. CARDOCH, J. M. RYBCZYK, AND G. P. KEMP. 1998. Food Processor and Community Development of Rural Coastal Areas through the Application of Wetland Wastewater Treatment Systems. Report submitted to National Coastal Resources Research and Development Institute. Coastal Ecology Institute, Louisiana State University, Baton Rouge, LA 70803.

DELAUNE, R. D., W. H. JR. PATRICK, AND R. J. BURESH. 1978. Sedimentation rates determined by Cs dating in a rapidly 4ccreting salt marsh. Nature 275:532-533.

DELAUNE, R. D., R. H. BAUMANN, AND J. G. GOSSELINK.1983. Relationship among vertical accretion, coastal submergence, and erosion in a Louisiana gulf coastal marsh. Journal of SedimentaryPetrolog,53:147-157.

DELGADO-SANCHEZ, P. 1995. Effects of longterm wastewater discharge into the Cypiere Perdue forested wetland at Breaux Bridge, Louisiana. Maste's Thesis, Department of Oceanography and Coastal Sciences, Louisiana State University, Baton Rouge, Louisiana.

GORNITZ, V., S. LEBEDEFF, AND J. HANSEN. 1982. Global sea level trend in the past century. Science215:1611-1614.

HARVEY, R. 1988. Interoffice memo. Re: Revisions to Chapter 17-6 pursuant to wetland application.9/28188,5 pages. And Reclaimed Water to Wetlands Rule. 17-6.030. 19 pages. State of Florida, Department of Environmental Regulations.

HESSE, I., T. DOYLE, AND J. DAY. 1997. Long-term growth enhancement of baldcypress (Taxodium distichum) from municipal wastewater application. Environmental Management22:119-127.

HESSE, I. D. 1994. Dendroecological determination of municipal wastewater effects on Taxodium distichum (L.) rich productivity in a Louisiana swamp. Masters Thesis. Department of Oceanography and Coastal Sciences Louisiana State University, Baton Rouge, Louisiana.

KADLEC, R. H. AND H. ALVORD, JR. 1989. Mechanisms of water quailty imporvements in wetland treatment systems, p. 489-498. In D.W. Fisk (ed.), Wetlands: Concerns and Successes. Proceeding sponsored by American Water Resources Association, September 17-22, 1989, Tampa, Florida.

KADLEC, R. H. AND R. L. KNIGHT. 1996. Treatment Wetlands. Lewis Publishers, New York.

LOUISIANA DEPARTMENT OF ENVIRONMENTAL QUALITY. 1988. Water Quality Management Plan, Volume 5 Part A.

MENDELSSHON, I. AND K. McKEE. 1988. Spartina alternifltora die-back in Louisiana: time-course investigation of soil waterlogging effects. J. Ecology 76: 509-521.
NYMAN, J. A. AND R. D. DELAUNE. 1991. Mineral and organic matter accumulation rates in deltaic coastal marshes and their importance to landscape stability. GCSSEPM Foundation 12th Annual Research Conference. Program and Abstract: 166-170.
PATRICK, W. H., JR. 1990. Microbial reactions of nitrogen and phosphorus in wetlands, p. 52-63. In Utrecht Plant Ecology News Report, Utrecht, 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, Louisiana.
PRATT, R. I. 1998. The use of benthic macro invertebrates for monitoring the discharge of municipal effluent into a forested wetland at Amelia, Louisiana. Masters Thesis. Department of Oceanography and Coastal Sciences. Louisiana State University, Baton Rogue, Louisiana.
REED, S. C. 1991. Constructed wetlands for wastewater treatment. Biocycle: pp. 44-49.
RICHARDSON, C. J. AND D. S. DAVIS. 1987. Natural and artificial wetland ecosystems: ecological opportunities and limitations, p. 819-854. In K. R. Reddy and W. H. Smith (eds.), Aquatic Plants for Water Treatment and Resource Recovery. Magnolia Publishing Inc., Orlando, Florida.
RYBCZYK, J. M., CALLAWAY, J. C. AND DAY, JR. J. W. 1998. A relative elevation model (REM) for a subsiding coastal forested wetland receiving wastewater effluent. Ecological Modeling. Accepted for publication.
RYBCZYK, J. M., J. W. DAY, I. D. HESSE, AND P. DELGADO SANCHEZ. l996. An overview of forested wetland wastewater treatment projects in the Mississippi River delta region, p. 78 -82. In Kathryn Flynn (ed.), Proceedings of the Southern Forested Wetlands Ecology and Management Conference. Clemson University, South Carolina.
RYBCZYK, J. M.1997. The use of secondarily treated wastewater effluent for forested wetland restoration in a subsiding coastal zone. Ph. D. Dissertation. Louisiana State University, Baton Rouge, Louisiana.
SESTINI, G. 1992. Implications of climatic changes for the Po Delta and the Venice Lagoon, p. 429-495. In L. Jeftic, J. Milliman and G. Sestini (eds.), Climate Change and the Mediterranean. E. Arnold, London.
STEVENsON, J. C., L. WARD, AND M. KEARNEY. 1988. Sediment transport and trapping in marsh systems: implications of tidal flux studies. Marine Geology 80:37-59.
ZHANG, X. 1995. Use of a natural swamp for wastewater treatement. Masters Thesis, Department of Agronomy, Lousiana State University, Baton Rouge, Louisiana.

Legends

Fig. 1. Wetlands treatment study sites.

Fig. 2. Mean annual concentrations of NO3 for the effluent inflow pipe, the treatment outflow, and within the first 100 m of the control site. Inflow concentrations are reduced 96-99%. Note: Logarithmic scale.

Fig. 3. Mean concentrations of NO3-N along sample transects in the treatment site during sa~nple years 1994 and 1995, and in the control site for sample year 1995. Nitrate concentrations are reduced 99%.

Fig. 4. Mean annual concentrations of Total P for the effluent inflow pipe, the treatment outflow, and within the first lOO m of the control site. Inflow concentrations are reduced 35-71%.

Fig. 5. Background (from t37Cs measurements), pre-effluent, and post-effluent accretion rates, relative sea level rise (RSLR) and accretion balance deficits for treatment (T) and control (C) at the Thibodaux site. T and C were not significantly different during the pre-treatment period, but T was significantly greater during the post-effluent period.

Fig. 6. The ratio (treatment/control) of annual wood stem growth (measured as growth in diameter) for bald cypress trees at Breaux Bridge. Before wastewater applications to the treatment site began in the late 1940s or early l950s, growth in the control site was significantly higher than growth in the treatment site (P>0.05). After wastewater applications began, stem growth was significantly higher in the treatment site. Both sites were similar in size and structure (Hesse et al. 1997).

Table 1. Loading rates and percent nutrient reductions in at four wastewater treatment forested wetlands in coastal Louisiana. All concentrations are reported as mg l^{-1}.

Table 2. Aboveground production (g m-2yr-1 ±se) measured at Breaux Bridge treatment site.1

Table 3. Total mean litterfall (g m-2) collect at the Amelia treatment wetland from Sept. 1995-Sept. 1996. Those means with different letter are statistically different (Day et al. 1997a).

1 The treatment site is adjacent to Lake Palourde. Lake Site 2 is connected directly to the treatment site by a small channel. Thus measurements were taken at the lake edge where there is potential influence from the effluent.

Table 4. Cost comparisons for three wetlands treatment projects.

1 Costs reported in 1992 dollars as per Breaux and Day (1994) and Breaux et al. (1995). Capitalized costs are discounted at 9% for 30 years.

2 Costs reported in 1995 dollars as per Cardoch et al. (2000). Capitalized costs are discounted at 8% for 25 years.