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Municipal wastewater treatment costs with an emphasis on assimilation wetlands in the Louisiana coastal zone

Rachael G. Hunter[a,*], John W. Day[a,b], Adrian R. Wiegman[c], Robert R. Lane[a]

[a] Comite Resources, Box 66596, Baton Rouge, LA 70896, USA
[b] Dept. of Oceanography and Coastal Science, Louisiana State University, Baton Rouge, LA 70803, USA[1]
[c] Rubenstein School of Natural Resources, University of Vermont, Burlington, VT 05401, USA

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ABSTRACT

In recent decades, water quality standards for wastewater treatment have become more stringent, increasing costs and energy required to reduce pollutants. Wetland assimilation is a low-cost and low-energy alternative to traditional tertiary wastewater treatment where secondarily treated and disinfected municipal effluent is discharged primarily into freshwater forested wetlands in coastal Louisiana. In this paper, costs per gallon of treatment capacity for conventional secondary and tertiary treatment were compared to those for assimilation wetlands. Cost analysis reports were used to determine costs per gallon of treatment capacity for conventional wastewater treatment facilities, including costs for conveyance between the collection system and the assimilation wetland site, and between the treatment and disposal sites if they could not be co-located. Capital and operation and maintenance costs were considered. Because all wastewater treatment plants are required to treat at least to secondary standards, costs for primary and secondary treatment were combined. If necessary, these costs were adjusted for inflation to 2017 dollars using an average inflation rate of 2.19 percent and a cumulative inflation rate of 50.84 percent. To determine costs per gallon of treatment capacity for assimilation wetlands, actual costs provided by the project engineer were used when available. To simulate the future costs of facility construction and compare the replacement costs of conventional secondary and tertiary wastewater treatment facilities and treatment wetlands in the context of energy prices, U.S. Bureau of Labor and Statistics (BLS) data for the price index for inputs to construction were used, as were the Energy Information Administration (EIA) data for the price of crude oil to model future wastewater treatment plant construction and operation costs. The cost for the Mandeville assimilation wetland included $1 million for the price of the land. Future costs of treatment facility construction and operation were modeled relative to average price of construction inputs between 1998 and 2015 using the projected price of crude oil. When treatment costs were compared among secondary, tertiary, and assimilation wetlands, mean cost for assimilation wetlands was $0.60 per gallon (> 1 MGD capacity) compared to $4.90 and $6.50 per gallon for secondary and tertiary treatment, respectively. The lower total costs and energy requirements for assimilation wetlands result in lower variability in the price of construction and operation. Wetland assimilation is more economical than conventional wastewater treatment, especially compared to advanced secondary and tertiary treatment. It is likely that energy costs will increase significantly in coming decades. Because conventional secondary and tertiary treatment are energy intensive, increases in energy costs will significantly increase the costs of these treatment systems. Treatment systems that combine lower technology (e.g., oxidation ponds) secondary treatment with wetland assimilation are less likely to be impacted by rising energy costs than traditional wastewater treatment.

1. Introduction

Conventional treatment of municipal sewage is energy and capital-intensive. Over the past half-century, water quality standards for effluent discharge have become progressively more stringent to address pervasive water quality problems. More stringent regulations have resulted in improvements in water quality but also increased costs per gallon of treatment capacity, especially for smaller municipalities

* Corresponding author.
E-mail address: rhunter@comiteres.com (R.G. Hunter).
[1] www.comiteres.com.

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where unit treatment costs are higher than for larger ones (USEPA, 2015). Assimilation wetlands are natural wetlands into which secondarily treated and disinfected municipal effluent is discharged (Hunter et al., 2018; Day et al., 2018), removing nutrients at a much lower cost than conventional tertiary treatment (Godfrey et al., 1985; Kadlec and Wallace, 2009; Nagabhatla and Metcalfe, 2017; Ko et al., 2004). Selection of treatment methods for nutrient removal is increasingly important as more stringent discharge limits are placed on municipal and industrial dischargers. In Louisiana, the majority of dischargers with a Louisiana Pollutant Discharge Elimination System (LPDES) permit do not have nutrient limits for their effluent. However, as eutrophic concentrations of water bodies increase, nutrient limits are becoming more common, as well as biological oxygen demand (BOD) and total suspended solids (TSS) limits below the typical limits of 10 and 15 mg L^{-1}, respectively.

There are three levels of municipal wastewater treatment, with each achieving a greater reduction in BOD, TSS, and nutrient concentrations (Hartman and Cleland, 2007). Primary wastewater treatment can reduce BOD by 20–30 percent and suspended solids by up to 60 percent. Secondary treatment incorporates biological processes to further remove dissolved organic matter and additional settling processes to further reduce suspended solids. Secondary treatment can remove up to 85 percent of BOD and TSS. Tertiary treatment reduces nitrogen and phosphorus concentrations of secondarily treated effluent. Tertiary treatment can reduce total nitrogen (TN) and total phosphorus (TP) concentrations to as low as 3 and 0.3 mg L^{-1} or less, respectively, depending on the treatment process utilized (Hartman and Cleland, 2007; Kadlec and Wallace, 2009). These processes rely on microbial activity to reduce nitrogen and phosphorus along with chemical and physical processes.

Nitrogen in secondarily treated municipal effluent is generally in the form of ammonia and organic nitrogen and it is typically not significantly removed by conventional secondary treatment. Secondary treatment with a high degree of aeration can convert ammonia to nitrate. Transformation of nitrogen is achieved through a series of biochemical reactions that transform nitrogen from one form to another, with key transformations being nitrification and denitrification (Reddy and DeLaune, 2008). During conventional wastewater treatment, phosphorus can be removed through chemical precipitation or physical processes using filtration and membranes but removal is generally less than 20 percent. Chemical precipitation produces a sludge, and the cost of disposing of this material can be significant (Keplinger et al., 2004). Enhanced biological phosphorus removal typically involves an activated sludge process modification (alternating aerobic and anoxic conditions) that allows for a high degree of phosphate removal from wastewater, with the potential to achieve very low (< 0.1 mg L^{-1}) TP effluent concentrations (Hartman and Cleland, 2007). Assimilation wetlands can reduce TN and TP to background levels so that there is no net input to open water systems (Day et al., 2004, 2018; Hunter et al., 2018).

Conventional wastewater treatment is very energy intensive and the costs of operations, maintenance and construction are tightly correlated with energy prices (Bodik and Kubaska, 2013). When calculating life cycle costs for wastewater treatment, the initial cost for facility construction must be considered in conjunction with operation and maintenance costs and future replacement costs. Conventional treatment facilities generally have an operational life of 30–40 years and suffer declines in efficiency (and/or increases in costs) during later years due to several factors such as natural wear and tear, equipment type and materials, and lack of preventative maintenance, primarily because of the highly technical and mechanical nature of “concrete and steel” facilities (Vigneswaran, 2009). Assimilation wetlands have essentially unlimited operational lives, and forested wetland sites have the additional benefit of potential selective timber harvesting (Kadlec and Wallace, 2009; Hunter et al., 2018; Day et al., 2018). In this paper, facility wastewater treatment costs and costs for discharging into an assimilation wetland (price per gallon of treatment capacity ($GTC)) are discussed, along with estimated future costs based on rising energy costs.

2. Objectives

The objectives of this paper are to 1) review available information for conventional municipal wastewater treatment costs; 2) calculate costs of adding assimilation wetlands to the treatment system with special emphasis on systems in Louisiana; and 3) consider the potential impact of global change processes such as climate change and increased energy price on the cost of treatment.

3. Methods

To determine costs for conventional wastewater treatment facilities, cost analysis reports were located and the data compiled into a spreadsheet (Appendix Tables A.1 and A.2). Cost estimates in these reports typically included all aspects of wastewater management such as facility construction and wastewater collection, treatment, and disposal. Costs were also included for conveyance between the collection system and the treatment site, and between the treatment and disposal sites if they could not be co-located. Two measures of cost were considered:

1. Capital cost – the cost to design, permit and build the facilities, including land costs.
2. Operation and Maintenance (O&M) costs – the ongoing expenses for labor, power, chemicals, monitoring, sludge disposal, etc.

Because all wastewater treatment plants are required to treat at least to secondary standards, costs for primary and secondary treatment were combined. If necessary, these costs were adjusted for inflation to 2017 dollars using an average inflation rate of 2.19 percent and a cumulative inflation rate of 50.84 percent (www.usinflationcalculator.com). For all treatment levels and wetland assimilation, annual operation and maintenance costs were included in the total costs ($GTC).

To determine costs for assimilation wetlands, design, building and permitting costs provided by the project engineer were used. If these costs were not available, costs were calculated using the following averages (calculated from actual costs provided): wastewater distribution line to the wetland ($23 per meter), directional drilling costs ($24 per meter), distribution valves ($5000 each), and annual operation and maintenance costs ($48,000 annually for wetland monitoring required by the LPDES permit). If available and applicable, costs of any land purchase for wetland assimilation were included in the total project price.

To simulate the future costs of facility construction and compare the replacement costs of conventional secondary and tertiary wastewater treatment facilities and treatment wetlands in the context of energy prices, U.S. Bureau of Labor and Statistics (BLS) data for the price index for inputs to construction were used (https://data.bls.gov/timeseries/NDUBCON-BCON-; Fig. 1, top) and the Energy Information Administration (EIA) data for the price of crude oil (Fig. 1, bottom) to model future wastewater treatment plant construction and operation costs (Fig. 2). Future costs of treatment facility construction and operation were modeled relative to average price of construction inputs between 1998 and 2015 using the projected price of crude oil (Eq. (1)).

$$Cf_{yr} = (0.3439*P_{2050} + 194.47)/(0.3439*P_{1998-2015} + 194.47) \quad (1)$$

where Cf_{yr} is the wastewater treatment plant construction cost factor and P_{yr} is the projected price of petroleum (2017$/bbl) in a future year (set to 2050), $P_{1998\text{-}2015}$ is the average price of petroleum from 1998 to 2015 and is the period over which the wastewater treatment plant cost data were collected.

Estimates of the price of petroleum in 2050 (P_{2050}) came from two

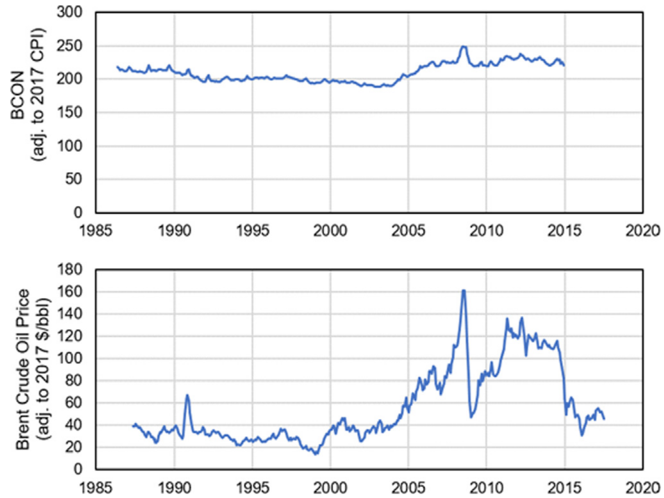

Fig. 1. (top) Monthly data (1987–2014) for price index of construction inputs (BLS code: BCON) and (bottom) real price of Brent crude oil (2017$/bbl).

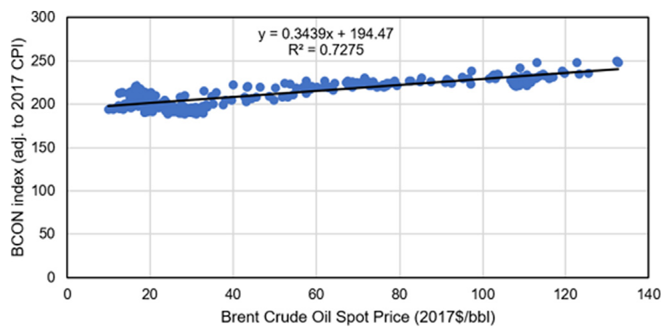

Fig. 2. Real (2017 Adjusted) price index of construction inputs (BCON) as a function of the real price of crude oil.

sources, Wiegman et al. (2017) and EIA's 2017 Annual Energy Outlook (AEO) (https://www.eia.gov/outlooks/aeo/). From EIA (2017) the median ($116), minimum ($48), and maximum ($240) price projected from 10 scenarios in the AEO were used (Fig. 3A). From Wiegman et al. (2017), the price of crude oil projected for low ($108), central ($169) and high ($301) scenarios were used (Fig. 3B).

To obtain a projected cost for wastewater treatment plant operation in 2050, the cost factor for the year 2050 (Cf_{2050} see Eq. (1)) was calculated and multiplied by the average wastewater treatment plant costs (across the data from 1998 to 2015).

4. Results and discussion

4.1. Primary/secondary wastewater treatment costs

Costs for secondary treatment varied with location, type of treatment, and treatment plant design capacity, with a clear trend of decreasing costs with increasing treatment system capacity (Fig. 4). Prices ranged from less than $5 to $45 per gallon.

4.2. Tertiary wastewater treatment costs

Tertiary treatment costs varied based on type of treatment, design capacity, and level of nutrient removal (Fig. 5). Similar to secondary treatment costs, tertiary treatment costs generally declined with increasing treatment system capacity. The dataset for both secondary and tertiary conventional treatment included plants over a wide latitudinal range in the U.S. Prices ranged from less than $5 to nearly $70 per gallon.

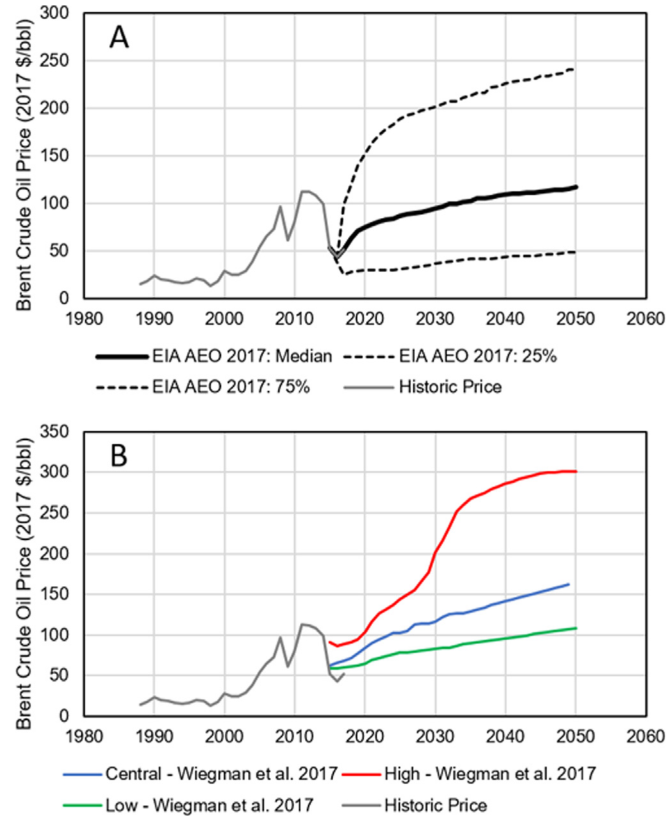

Fig. 3. Historic and projected spot price of Brent crude oil (2017$/bbl). (A) Price projections are median, 25th percentile and 75th percentile of the ten scenarios from the EIA's 2017 AEO (Annual Energy Outlook). (B) Prices are based on the low, central and high scenarios from Wiegman et al. (2017).

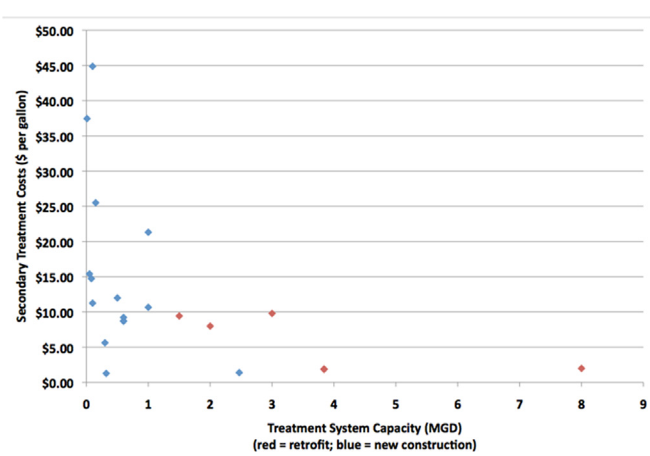

Fig. 4. Costs (2017$) of secondary treatment as a function of treatment system capacity (MGD = million gallons per day (liters per day = MGD*3.785)). Refer to Appendix Table A1 for data sources.

4.3. Assimilation wetland costs

There were less data available for calculating assimilation wetland costs compared secondary and tertiary treatment and, in general, costs were similar among wetlands regardless of treatment system capacity (Fig. 6). This is because the costs for assimilation wetlands are based primarily on the distance between the wetland and the wastewater treatment plant so costs were based more on the amount of distribution line that was needed and the number of distribution valves placed on the line. Prices ranged from less than $0.5 to about $3 per gallon.

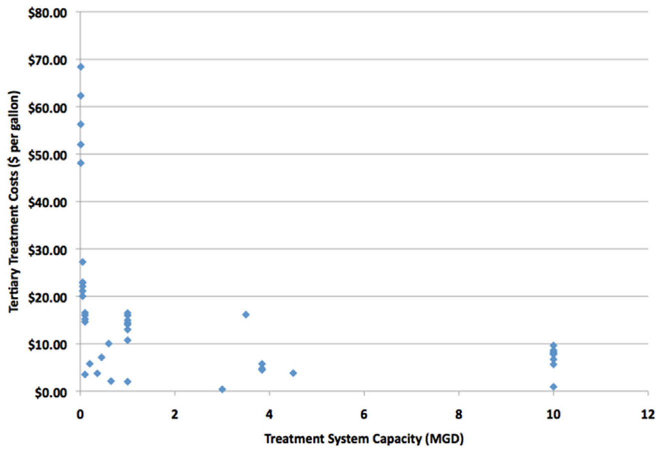

Fig. 5. Costs (2017$) of tertiary treatment as a function of treatment system capacity (MGD = million gallons per day (liters per day = MGD*3.785)). Refer to Appendix Table A2 for data sources.

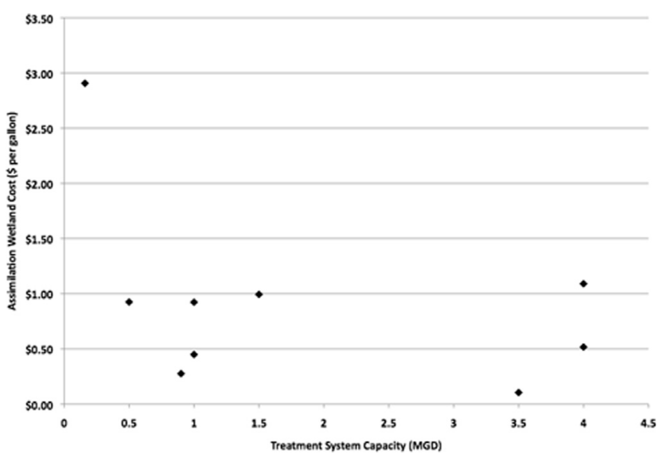

Fig. 6. Costs (2017$) of tertiary treatment using assimilation wetlands as a function of treatment system capacity (MGD = million gallons per day (liters per day = MGD*3.785)). Refer to Appendix Table A3 for data sources.

4.4. Cost comparison

When treatment costs were compared among secondary, tertiary, and wetland assimilation, costs were much lower for assimilation wetlands, generally less than $3 per gallon of treatment capacity (Fig. 7).

4.5. Future energy investment

Based on the data reviewed in this paper, wetland assimilation has a much lower cost ($GTC) than conventional secondary and tertiary treatment (Fig. 8). The lower total costs and energy requirements result in lower variability in the price of construction and operation. This is highlighted when considering the risk of price increases due to increasing energy costs that result from more expensive secondary and tertiary treatment facilities. Continuing secondary and tertiary treatment in the future runs the risk of significant price increases when replacing these facilities (Fig. 8). Considering these results and the longer lifespan of assimilation wetlands (potentially unlimited) compared to conventional facilities (30–40 years; Bodik and Kubaska, 2013), assimilation wetlands are a lower cost and lower risk alternative than conventional wastewater treatment.

There are a number of assimilation wetlands in Louisiana that have functioned for many decades, one for over 70 years, with nutrients still being reduced to background levels (Hunter et al., 2018; Day et al., 2018). The sustainability of these systems makes achieving tertiary treatment levels with assimilation wetlands much more cost effective than highly engineered conventional treatment systems with limited life spans. With assimilation wetlands in place, the secondary phase of treatment can be less expensive. Oxidation ponds or trickling filter secondary treatment can be used with assimilation wetlands to achieve tertiary treatment. The City of Mandeville uses aerated lagoons coupled with a small constructed wetland with a gravel trickling filter to promote nitrification and denitrification to reduce ammonia levels (Ogden, 2007; Brantley et al., 2008). To be under the 10–15 BOD-TSS limits with secondary treatment requires a much more expensive system. Thus, the total costs for wetland assimilation include the added cost to secondary treatment to achieve tertiary treatment. With wetland assimilation, less advanced secondary treatment (e.g., oxidation ponds, aerated lagoons) is needed to achieve tertiary treatment when water flows from an assimilation wetland to an open water body. More advanced secondary treatment includes highly engineered “brick and mortar” approaches including mixed batch reactors, fixed film activated sludge, or membrane bioreactors.

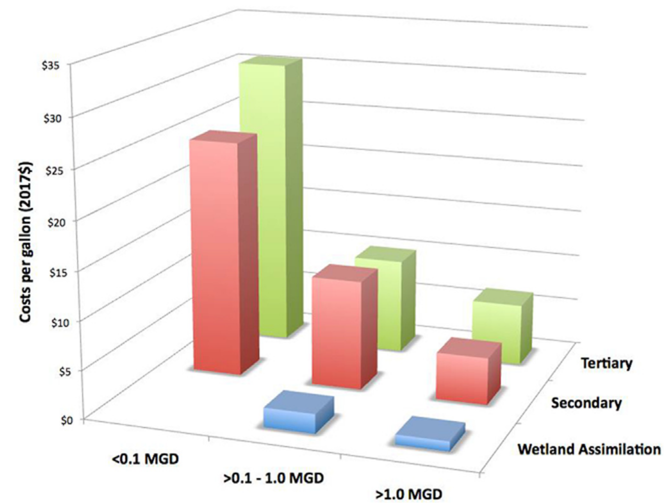

Fig. 7. Comparison of average treatment costs for wetland assimilation (tertiary treatment) and conventional treatment (secondary and tertiary) based on treatment system capacity (MGD = flow in million gallons per day (liters per day = MGD*3.785)).

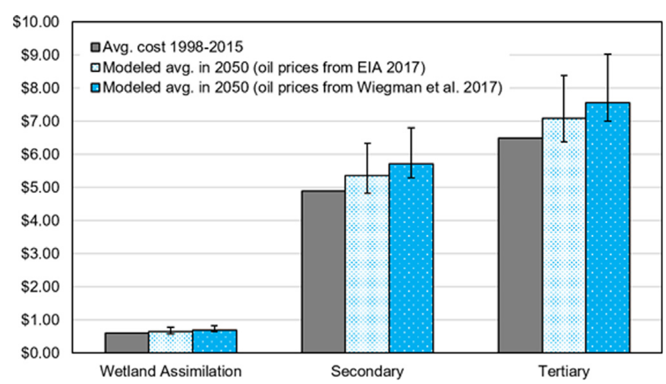

Fig. 8. Average construction and operation costs (1998–2015) of wastewater treatment for 1.0–10 MGD capacity plants (grey bars) verses projected costs of treatment in for plants built in 2050. The error bars show the uncertainty range for the future average cost based on the upper and lower bound for future oil prices (see Fig. 3).

The costs for wetland assimilation presented here include pipeline construction costs to deliver the effluent to the wetland and monitoring costs. Additional costs for some assimilation wetlands include land purchases, flow easements, and tree plantings. Based on our analysis, this could add 20–30 percent to the per gallon costs. On the other hand, assimilation wetlands can provide other economic benefits, especially in coastal areas threatened by sea-level rise. With rising sea levels, there is a greater potential for the burial of sequestered carbon and nutrients (Day et al., 2004; Lane et al., 2017; Hunter et al., 2018). Several studies have shown that accretion is enhanced in assimilation wetlands, enhancing the ability of these wetlands to adjust to sea level rise over wetlands without freshwater discharge (Rybczyk et al., 1998; Brantley et al., 2008; Lane et al., 2017; Hunter et al., 2018; Day et al., 2018). Enhanced productivity of forested wetlands, combined with subsequent accretion and organic matter burial, leads to potentially marketable levels of carbon sequestration. Lane et al. (2017) reported significant increases of carbon sequestration at a freshwater forested assimilation wetland using accepted methods for carbon credits that could be transacted in the carbon markets. Assimilation wetlands are also more resilient to hurricanes. During Hurricane Katrina for example, the 100 MGD treatment plant for New Orleans was damaged and was not repaired for months. By comparison, assimilation wetlands in the coastal zone began functioning as soon as power was restored to conventional plants using aerated lagoons and trickling filters that discharged to the wetlands.

When considering wetland assimilation as part of a treatment system, increased flooding that is detrimental to some freshwater wetland species and herbivory should be considered (Lane et al., 2015; Hunter et al., 2018). At the Hammond assimilation wetland, herbivory by nutria caused considerable damage, but vegetation recovered after nutria were controlled (Shaffer et al., 2015; Weller and Bossart, 2017). Ialeggio and Nyman (2014) reported that nutria preferred fertilized wetland plants with higher nitrogen levels. Thus it is important to develop adaptive management plans that anticipate potential problems and approaches to address these problems

5. Conclusions

Wetland assimilation is more cost effective and less energy intensive than conventional wastewater treatment, especially compared to advanced secondary and tertiary treatment. It is likely that energy costs will increase significantly in coming decades. Because conventional secondary and tertiary treatment are very energy intensive, increases in energy costs will significantly increase operating costs of these systems. Treatment facilities that combine less advanced secondary treatment with wetland assimilation are not as sensitive to future cost increases as conventional systems.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.ecoleng.2018.09.020.

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