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ANALYSIS

A comparative evaluation of money-based and energy-based cost–benefit analyses of tertiary municipal wastewater treatment using forested wetlands vs. sand filtration in Louisiana

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Abstract

Forested wetlands have been used to provide advanced secondary and tertiary treatment for municipal wastewater for a number of cities in southern Louisiana. Wetland assimilation provides the same services as conventional methods in improving wastewater quality, while having positive impacts on wetlands. Suspended solids and nutrients in wastewater increase net primary productivity (NPP), which leads to increased organic soil formation. This leads to increased elevation that offsets subsidence, a major cause of coastal wetland loss in Louisiana. The City of Breaux Bridge, LA, has discharged secondarily treated municipal wastewater into a forested wetland since 1950, and wetland assimilation was permitted by the Louisiana Department of Environmental Quality and the US Environmental Protection Agency (US EPA) in 1997. We compared benefits and costs of utilizing forested wetlands and conventional sand treatment using money-based and energy-based cost–benefit analyses (CBA). The wetland method had a higher benefit–cost ratio than conventional treatment by 6.0 times based on dollar-based CBA, and by 21.7 times from the energy analysis. Methodologically, dollar-based CBA is a market price-based assessment, liming to an anthropocentric framework, while embodied energy analysis accounts for monetary and nonmonetary values such as carbon sequestration by wetlands, which contributes a more complete assessment of the interaction between the natural environment and the human economy. Wetlands treat more wastewater per unit of energy and with less financial cost than conventional methods, because the wetland method utilizes natural energies such as sunlight, wind and rain, while conventional treatment methods depend on imported nonrenewable energies and materials such as chemicals and electricity and require additional capital investment. Increasing application of natural energies is becoming more important with depleting fossil fuels. Further, wastewater addition increases NPP and wetland elevation, which has potential for wetland mitigation credit.

Keywords: Wetlands; Energy analysis; Municipal wastewater treatment; Louisiana; Cost–benefit analysis

1. Introduction

Both wetlands and conventional treatment methods rely on biological and physical processes to treat

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wastewater. Natural wetlands improve wastewater quality by utilizing natural energies, which drive the multiple functions and mechanisms of effluent treatment in wetlands including physical settling, chemical precipitation, adsorption, and biological processes such as uptake and denitrification. A number of studies have shown that wetlands provide an efficient means of nutrient and suspended sediment assimilation (Nichols, 1983; Ewel and Odum, 1984; Breaux and Day, 1994; Kadlec and Knight, 1996; Boustany et al., 1997; Zhang et al., 2000; Day et al., 2003) (Fig. 1).

Conventional methods of municipal wastewater treatment (e.g., grit chamber, clarifier, aeration tank, anaerobic digesters, sand filtration, sludge thickener) depend mostly on nonrenewable energy sources (e.g., electricity and chemicals) (Tchobanoglous and Burton, 1991; Viessman and Hammer, 1998). Further, capital investments to build a facility (e.g., reactivator and pump) are required. For example, the sand filtration method consists of the three major steps of treatment: flocculation, sedimentation, and filtration. These functions take place inside reactors, powered by electrical power, and controlled by inputs of chemicals (Fig. 2).

The benefits of using natural wetlands for municipal wastewater treatment include improved effluent water quality, increased vegetation productivity, financial and energy savings, and lower requirements for expensive capital investments (Breaux and Day, 1994; Hesse et al., 1998; Cardoch et al., 2000; Rybczyk et al., 2002; Day et al., 2003). Additionally, land loss in the coastal zone of Louisiana, due largely to lack of nutrients and sediments, is one of the major environmental problems in Louisiana (Baumann et al., 1984; Templet and Meyer-Arendt, 1988; Day et al., 2000a). Settled solids in wetlands and active organic soil formation due to increased root growth enhanced by nutrient uptake increase accretion rates in impacted wetlands to help offset subsidence in wetlands, which prevents or slows down wetland loss (e.g., Rybczyk et al., 2002).

We had two general objectives in this paper. First, we attempted to clarify differences between monetary and biophysical assessments using dollar-based and energy-based cost–benefit analysis (CBA) by applying these two analyses to a case study of wastewater treatment. Additionally, we demonstrated some of the benefits of ecological engineering that employs natural free energies (e.g., sun, wind, rainfall, and tides)

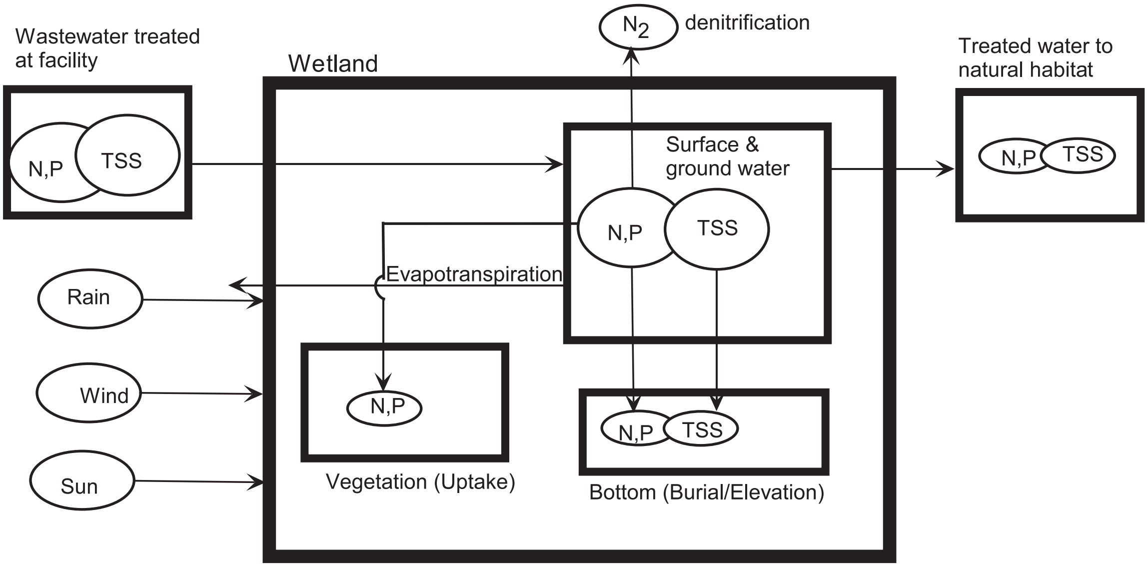

Fig. 1. Diagram of the wetland treatment method. Wetlands remove nutrients and retain suspended solids by physical settling, chemical precipitation, adsorption, and biological metabolism. The processes are controlled by natural energies such as sunlight, wind, and rain. Permanent nutrient pathways are burial, vegetation uptake, and denitrification.

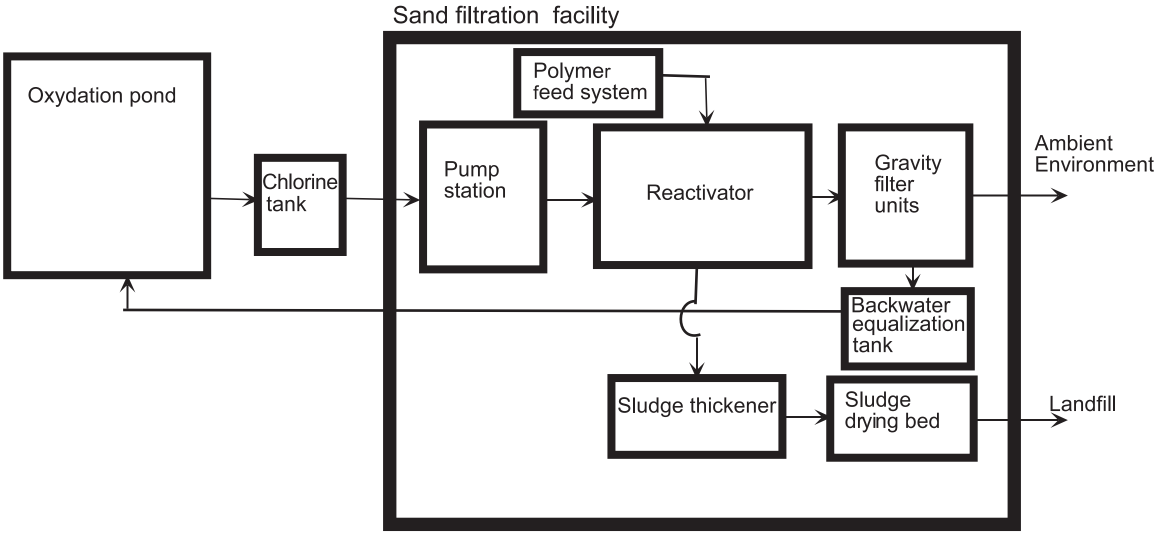

Fig. 2. A diagram of the sand filtration method (modified from Hernandez, 1978, p. 8, fig. 1). Polymer is added to increase flocculation of suspended solids for increased efficiency of sedimentation and filtration. The process is operated by electrical energy.

over conventional engineering for wastewater treatment. Specifically, we compared the cost effectiveness and energy efficiency of using forested wetlands vs. a conventional treatment method, sand filtration, at Breaux Bridge, LA.

2. Background

The wetland under study is part of a municipal wastewater treatment facility for the city of Breaux Bridge, LA. The wetland is located in the Cypriére Perdue Swamp in St. Martin Parish, LA (latitude 30°16′ N, longitude 91°54′ W).

Until about 1950, residents of Breaux Bridge used individually owned septic tanks to treat wastewater. Then, a city-wide centralized treatment system was developed to transport raw sewage to a trickling filter treatment facility, located approximately 2 km southwest of the city, on the edge of the forested wetlands. An oxidation pond was constructed to replace the trickling filter in 1970, and two additional ponds were built by 1980 as the local population grew from 2492 in 1950 to 6694 in 1990, and 7800 in 2000 (Census Demographics for Louisiana, http://www.state.la.us/census/cities/). Since about 1950, treated wastewater at the facility has been discharged to the adjacent forested wetlands, which are owned by the local government and The Nature Conservancy.

During the early and mid-1990s, the facility was cited by the US Environmental Protection Agency (US EPA) for violating the water permit primarily for TSS and BOD_5, with NH_4–N and pH violations less frequently, due to increasingly stringent water quality criteria. The city searched for the most cost-effective method to conduct additional treatment in order to come into compliance. The utilization of natural forested wetlands adjacent to the current wastewater plant was investigated in a series of meetings among city officials, officials of the Louisiana State Department of Environmental Quality (DEQ), the US EPA, civil engineers, and researchers at Louisiana State University. The city also searched for an alternative

Table 1
Municipal wastewater generation and maximum loading rates of the Breaux Bridge site

	Value	Unit
Serving population	7800	person
Wastewater volume	3785 (1.0)	m^3/day (MGD)
Treatment basin	1475 (750*)	ha
Nitrogen loading	1.87 (3.69*)	g/m^2/year
Phosphorus loading	0.94 (1.84*)	g/m^2/year

* Area impacted and following adjusted rates.

Table 2
Mean nutrient removal efficiency and additional net primary production (NPP)

	Unit	Incoming (mean ± S.E.)	Outgoing (mean ± S.E.)	Efficiency (%)
TSS				67.3
NO_3-N	mg/l	0.67 ± 0.33	0.06 ± 0.01	91.0
NH_4-N	mg/l	1.64 ± 0.60	0.14 ± 0.01	91.5
PO_4-P	mg/l	0.95 ± 0.10	0.24 ± 0.10	74.7
Additional NPP	g/m^2/year		344 ± 177	

Sources of nutrient information: Day et al. (1994), p. 65 and 80; Blahnik and Day (2000) for TSS. NPP is averaged from the data from 1993 to 1999.

from conventional methods in improving the facility and selected wetlands after compared wetlands assimilation with sand filtration of conventional method, in upgrading its wastewater facility. After completion of a background ecological study called a 'Use Attainability Analysis (UAA)' in 1994 (Day et al., 1994), the neighboring 1475-ha forested wetland tract was permitted to be utilized for additional treatment of wastewater discharged from the wastewater facility, as a way to meet water quality requirements of tertiary treatment level, under a National Pollutant Discharge Elimination System (NPDES) permit (LA 0033014), effective November 7, 1997.

The present treatment system for Breaux Bridge consists of three oxidation ponds, a chlorination/dechlorination tank, and the adjacent natural wetlands, with a 3785-m^3/day (or 1 million gallons per day, MGD) treatment capacity (Table 1). The wetland treatment method at Breaux Bridge has been successful in nutrient removal and enhancing net primary production in the influenced area (Table 2).

3. Methods

We evaluated the costs and benefits of wetland assimilation at Breaux Bridge compared to sand filtration which was the alternative approach considered by the city to meet permit limits, using the two different evaluation techniques of dollar-based and energy-based CBA.

Aspects of forest structure and productivity, hydrology, water quality, and soils have been measured as part of the required monitoring and scientific study of the site (Day et al., 1994, 2000b; Hesse et al., 1998; Day and Perez, 1999; Blahnik and Day, 2000; Day and Lane, 2000). These results showed that about half of the permitted 1475-ha wetlands have been influenced by the input of secondarily treated wastewater (Tables 1 and 2). The results were used to determine the environmental benefits and financial costs of wetland treatment using dollar-based and energy-based CBA. Using these same techniques, we also calculated the costs of conventional recirculating sand filtration as a reference system for the equivalent additional tertiary (or advanced) treatment (Fig. 2).

For the sand filtration option, we assumed a TSS limit of 10 mg/l for operational goal (the city only must meet 90 mg/l TSS from the oxidation ponds to use wetland method because of wetlands' assimilative capacity). The sludge generated in sand filtration is assumed to be thickened through a sludge thickener and dried on drying beds and transported to local nonhazardous landfills. We mainly used US EPA reports to estimate potential costs of building and operating the sand filtration facility for the additional tertiary treatment, rather than a sand filtration facility for the whole wastewater treatment system, for a fair comparison between wetlands assimilation and sand filtration (Kibby and Hernandez, 1976; Smith, 1978; Letterman and Cullen, 1985; US EPA, 1998, 2001; see Appendices for detailed information).

3.1. Money-based cost–benefit analysis

3.1.1. Conventional tertiary treatment

We estimated capital costs and annual costs of operation and maintenance (O&M) for a typical sand filtration facility, with a capacity of 3785 m^3/day (1 MGD) as a reference system to compare with wetlands assimilation because this is the option that the city considered.

The capital cost of land acquisition was determined using US EPA estimates of land required and prices in Louisiana (US EPA, 1998, pp. 2–36 and 5–12). We used EPA-standardized capital cost of a primary chemical precipitation facility in estimating costs of equipment, holding tank construction, and installation (US EPA, 1998, p. 2–33). Additional capital costs for a sludge treatment facility, including sludge thickener and sludge drying bed, were estimated using cost functions (Qasim, 1985, pp. 678–679 and 684–

685). The cost information was modified for year 2000 using the construction cost index of the Engineering News Record (ENR, http://www.enr.com/cost/costcci.asp). We assumed that the combined engineering and contingency costs were 30% of total construction cost (US EPA, 2001, pp. 11–12).

According to EPA guidelines, the total O&M cost is the sum of costs for maintenance, electricity, labor, chemicals, residuals, taxes, and insurance (US EPA, 2001, p. 11–13). First, the general maintenance cost was assumed as 4% of total capital cost (US EPA, 2001, p. 11–13). Second, we estimated the O&M cost of electricity required to operate the sand filtration facility using a cost function (Smith, 1978) and EPA cost information, 8 cents/kWh (US EPA, 2001, p. 11–13). We used an EPA labor–hour estimation (Letterman and Cullen, 1985), a cost function (Smith, 1978), and a standardized labor cost, $25/h (Sedlak, 1991, p. 130) for labor cost estimation. Chemicals including polymer and lime can be added to improve the operational efficiency of sand filtration, because these chemicals enhance formation of large particles combined with suspended solids (Sedlak, 1991). We included polymer in our analysis, because polymer addition was recommended to improve operation efficiency of an existing sand filtration facility at another wastewater treatment site in Louisiana (Martin, 2000). Estimations for polymer and sludge disposal were done using EPA documents and local information (Kibby and Hernandez, 1976; Rogers, 1999; Martin, 2000; US EPA, 2001). The Breaux Bridge plant is a public facility, which is subject to tax exemption. Thus, we excluded the portion of taxes and insurance in considering O&M costs.

On discounting the future monetary costs and benefits of environmental projects, significant controversies still exist on the proper discount rate and justification of discounting itself (Hall et al., 1979a,b; Hannon, 1982; Norgaard and Howarth, 1991; Markandya and Pearce, 1991; Costanza and Daly, 1992; Peet, 1992; Howarth, 1996). Thus, we provided the dollar-based analyses with and without discounting.

For discounted analysis, the O&M cost for a 20-year lifetime was calculated using the present value (PV) function with a 7% discount rate (US OMB, 1992; US EPA, 2000). After calculating total PV-based cost of conventional treatment including capital and O&M costs, we calculated the annualized cost of the facility over 20 years to compare with that of wetland treatment. Detailed information on calculations and data sources is given in Appendix A.1.

3.1.2. Wetland treatment

Treated wastewater and wetland maintenance were included as monetary benefits of the wetland method, because financial expenditures for conventional wastewater treatment, and dredging costs for wetland maintenance are avoided by adopting the wetland method (see Goulder and Kennedy, 1997 for avoided cost as a valuation method for ecosystem services). The financial benefits of treating wastewater using wetlands were assumed to be the treatment cost of the conventional method.

The benefit of wetland maintenance was calculated by multiplying the area of influenced wetlands by the inflation adjusted, median value of annual statewide wetland maintenance cost (e.g., transporting dredged soils from another place) in Louisiana, $84/ha for 2000 (Suhayda et al., 1991). The data of sediment accretion were from a similar facility using wetlands, in Thibodaux, LA (Rybczyk et al., 2002), and we assumed the sediment accretion rate is equal to local subsidence rate, based on the Thibodaux study.

Wetland treatment also increases biomass growth, because nutrients in wastewater enhance tree growth in affected wetlands (Table 2). Additional vegetation productivity was captured as net primary production (NPP), which is defined as “the amount of energy left after subtracting the respiration of primary producers (mostly plants) from the total amount of energy (mostly solar) that is fixed biologically” (Vitousek et al., 1986, p. 368). The additional NPP was converted into dollar-based value using the price information of crude oil in the US (see below in energy analysis of wetland treatment and Appendix B). Additionally, we also provided cost–benefit analyses excluding the NPP variable, because NPP measurement may be incommensurable with monetary values (Martizez-Alier, 1998).

The wetland method uses natural wetlands adjacent to the oxidation ponds which do not require any construction or maintenance costs. Thus, we considered only the cost for the UAA preparation for capital cost. The UAA analysis is required by the DEQ to obtain a baseline ecological characterization and to conduct a preliminary assessment of the potential for treating wastewater without generating negative environmental impacts (US EPA, 1984). Annual O&M costs included wetland monitoring work and other costs that may be needed. There were some small costs to put in the pipeline with five outlets to control wastewater flows to the wetlands after discharged from the facility, which was within the annual O&M cost range. The discounted O&M cost for a 20-year life was calculated using the PV function with a 7% discount rate, the same period and rate of the sand filtration method. Nondiscounted O&M costs are also provided. Detailed information on calculations and data sources is given in Appendix B-1.

3.2. Energy-based cost–benefit analysis

Embodied energy analysis is “the process of determining the energy required directly and indirectly to allow a system (usually an economic system) to produce goods or services” (Brown and Herendeen, 1996, p. 220). One of the objectives of the analysis is to encourage the minimization of conventional (fossil) energy inputs per unit of desired system output (Brown and Herendeen, 1996, p. 233). The embodied energy approach has the relative strength of accounting for goods and services that are nonmarketable but essential for sustainable development and in providing benefits and energy savings in oil-equivalent information, which allows the quantification of benefits of wetlands in terms of oil savings (Costanza and Farber, 1985).

This technique has been used for a variety of analyses including biophysical analysis of agriculture (Cleveland, 1995), construction engineering (Hannon et al., 1978), community insulation program (Hall et al., 1979a,b), nonmarket values of the Mississippi Delta (Cardoch and Day, 2001), fishery (Mitchell and Cleveland, 1993), national economy (e.g., Costanza, 1980; Cleveland et al., 1984; Costanza and Herendeen, 1984; Hall et al., 1986), oil production (Hall and Cleveland, 1981), power plant (Hall et al., 1979a,b), wetlands (e.g., Odum, 1961; Teal, 1962; Turner et al., 1988), and other areas to explain relations between human economic activities and at least one aspect of the environment.

For this project, we used the energy intensity values, which are the ‘total amount of direct and indirect energy needed to generate a dollar’s worth of product,’ published by the Office of Technology Assessment (US OTA, 1990, p. 30; table on pp. 32–33). We applied the linear best fit trend line to extrapolate the values to reflect changes for 2000, the base year for this study. We multiplied financial costs by extrapolated energy intensities to calculate embodied energy costs, which are energy requirements, for corresponding financial costs.

With regard to discounting energy flows, significant disagreements exist, as for monetary discounting (Hannon et al., 1978; Hannon, 1982; Hall et al., 1986; Faber et al., 1987; Peet, 1992). Thus, we provided energy-based analyses with and without discounting. Furthermore, analyses were done with including and excluding NPP like the dollar-based analyses above. For nondiscounted analyses, the annual embodied energy cost was multiplied by 20 to calculate the embodied energies for the 20-year life span, as for the dollar-based analyses. We used a 7% discount rate and a 20-year life span for discounted analysis, like the dollar-based analysis.

3.2.1. Conventional tertiary treatment

Financial costs for capital investments were multiplied by the extrapolated energy intensity values to calculate embodied energies for the capital investments. We used the linearly extrapolated median energy intensity of real estate and rental for land acquisition cost for building a sand filtration plant. The extrapolated energy intensities of stone and clay products, general industrial machinery, miscellaneous manufacturing, and new construction were used in calculating embodied energy costs of equipment, holding tank, installation, sludge thickener, and sludge drying bed, respectively. Engineering and contingency costs are assumed as 30% of total embodied energy for total construction cost as for the cost–benefit analysis above.

The extrapolated energy intensity of maintenance and repair was used for energy costs of maintenance, labor, and sludge disposal of the annual O&M costs. We also used an extrapolated energy intensity of chemical products for embodied energy of polymers needed in operating the sand filtration facility for tertiary treatment. We adjusted the electricity consumed by multiplying by 3.37 to estimate the annual embodied energy for the electricity, because 3.37 J of oil is required to produce 1 J of electricity (US OTA, 1990). Detailed information on calculations and data sources is given in Appendix A.2.

3.2.2. Wetland treatment

Like dollar-based analyses, we included energy savings by wetlands treatment for treated wastewater, wetland maintenance, and additional vegetation productivity as benefits of wetlands treatment, because energy expenditures for treating wastewater and for wetland maintenance were avoided. We also analyzed the cost–benefit analysis including and excluding NPP.

We assumed that the embodied energy savings for treated water by wetland treatment was equal to the embodied energy required for the conventional treatment method, as we did for the monetary analysis above. We multiplied the extrapolated energy intensity of maintenance and repair construction by the median financial cost of maintaining wetlands and by the impacted area for annual embodied energy savings for the benefit of wetland maintenance.

The following procedure was used to calculate the benefit of increased vegetation productivity from NPP measurements, which is (1) the mean additional NPP was determined from field data (Day et al., 1994 2000b; Day and Perez, 1999; Day and Lane, 2000); (2) estimated additional NPP was converted to gross primary productivity by multiplying by a factor of 3.33 for wetlands (Turner et al., 1988); (3) additional mean gross productivity was then extrapolated to the impacted wetland area, 750 ha (Table 1); (4) the additional gross productivity within the wetlands was converted to energy value by multiplying a conversion factor for plant production, 4×10^6 kcal plant production/tonne (Turner et al., 1988); (5) the quality of biomass energy was adjusted for fossil fuel-based energy by multiplying an energy quality factor of 0.05 (Turner et al., 1988).

We used the linearly extrapolated energy intensity of new construction to estimate energy cost of UAA preparation and the linearly extrapolated energy intensity of state and local government enterprise to estimate the embodied energy of annual monitoring cost. We also used the extrapolated energy intensity of maintenance and repair to estimate the embodied energy for other O&M costs in operating the wetland method. Detailed information on calculations and data sources is given in Appendix B.2.

3.3. Benefit–cost ratio

Potential benefits of treating wastewater include reductions in ocean and bay beach closures, waterborne disease outbreaks, fish and shellfish contamination, disappearing aquatic and water-dependent species, and fish kills in inland and coastal waters (Adler et al., 1993). We did not consider these benefits for this study, because first, the existing data are crude nationwide averages, and no data are available for Breaux Bridge, and secondly, the main objective of this paper was to compare the wetland method with a conventional method as a way to find a more cost-effective method for treating wastewater. Cost-effectiveness analysis may be fit when the benefit is not explicitly defined (US EPA, 2000). However, the wetland method has additional benefits (here, NPP increase and wetlands maintenance cost savings are considered), and we used cost–benefit analysis as an effort to account for these benefits.

We assumed that the benefit–cost ratio of the conventional tertiary treatment method is one, because the primary objective of the treatment is to meet the water quality standard mandated by the NPDES permit. We then calculated the benefit–cost ratio of the wetland method, relative to the conventional tertiary treatment method.

4. Results

The wetland treatment system was more economic than the sand filtration method using both dollar-based and energy-based CBA under multiple scenarios of discounting and NPP inclusion. This was due to lower capital and O&M costs and additional benefits to the influenced wetland ecosystem.

4.1. Dollar-based analysis

4.1.1. Conventional tertiary treatment

The total capital cost for a sand filtration facility with a capacity of 3785 m^3/day (or 1.0 MGD) was estimated as \$1.9 million, which is the sum of costs for land acquisition, equipment (e.g., filter), holding tank, installation, sludge thickener, sludge drying bed, and construction (Table 3). Based on a local engineering company's rough estimate of \$1.5 mil-

Table 3
Cost analysis of sand filtration: dollar and embodied energy

Item	Dollar-based analysis		Energy-based analysis			
		Unit	Energy intensity	Unit	Embodied energy	Unit
Capital cost						
Land acquisition	29,233	$	79	$10^{3}\ \mathrm{J/\$}$	2	10^{9} J
Equipment (e.g., filter)	896,971	$	26,749	$10^{3}\ \mathrm{J/\$}$	23,993	10^{9} J
Holding tank	30,186	$	9,368	$10^{3}\ \mathrm{J/\$}$	283	10^{9} J
Installment	324,505	$	13,085	$10^{3}\ \mathrm{J/\$}$	4,236	10^{9} J
Sludge thickener	72,461	$	9252	$10^{3}\ \mathrm{J/\$}$	670	10^{9} J
Sludge drying beds	137,676	$	13,085	$10^{3}\ \mathrm{J/\$}$	1,832	10^{9} J
Total construction cost	1,491,032	$			30,996	10^{9} J
Engineering and contingency	447,310	$			9,299	10^{9} J
Total capital cost	1,938,342	$			40,295	10^{9} J
O&M cost						
Maintenance	77,534	$/year	11,636	$10^{3}\ \mathrm{J/\$}$	899	10^{9} J/year
Electrical energy	4935	$/year	3.37	J/J	748	10^{9} J/year
Labor	32,050	$/year	11,636	$10^{3}\ \mathrm{J/\$}$	372	10^{9} J/year
Polymer	2084	$/year	26,212	$10^{3}\ \mathrm{J/\$}$	55	10^{9} J/year
Sludge disposal	3513	$/year	11,636	$10^{3}\ \mathrm{J/\$}$	41	10^{9} J/year
Not discounted						
Accumulated O&M cost	2,402,320	$			42,300	10^{9} J
Total cost	4,340,662	$			82,595	10^{9} J
Annual average cost	217,033	$/year			4,130	10^{9} J/year
Discounted with 7% for 20 years						
PV of O&M cost	1,361,586	$			23,975	10^{9} J
Total discounted cost	3,299,928	$			64,270	10^{9} J
Annualized cost	291,112	$/year			5,670	10^{9} J/year

lion in 1992 for upgrading the Breaux Bridge facility (Breaux, 1992, p. 181), our estimate is reasonable. The annual cost for operating and maintaining the facility was estimated as $120,116, which includes general maintenance ($77,534), electricity ($4935), labor ($32,050), polymer ($2084), and sludge disposal ($3513) (Table 3). The PV-based general maintenance cost for 20 years is estimated as $878,894. The total PV-based cost of the conventional treatment method over the 20 years at 7% is $3.3 million, and the annualized cost of that present value over the same 20 years is $291,112 (Table 3). Nondiscounted annual average cost of the sand filtration facility was estimated as $217,033.

4.1.2. Wetland treatment

Assuming the benefit–cost ratio of the conventional method is one, the benefit–cost ratio of the wetland method, without discounting and excluding additional NPP growth, is about 5.2, reflecting the additional positive effects of wetlands maintenance cost savings and lower financial cost of wetland treatment (Table 4a). The capital cost of wetland assimilation was $120,000 for the UAA, while the sand filtration method costs $1,938,342 for treating the same amount of wastewater. The annual O&M cost for sand filtration was estimated as $120,116, while that for wetland method is $48,000, because natural free energies (e.g., sun, rain, wind) replace purchased energies to operate biophysical processes in a sand filtration facility in the form of electricity, chemicals, labor, and sludge disposal.

Economic savings are $1.8 million for capital costs, and $72,116 for annual O&M cost (Tables 3 and 4a). Another factor that increases the benefit–cost ratio of wetland treatment is the avoided costs to maintain wetlands against local subsidence, which was estimated as $1,260,000 for 20 years without discounting

Table 4
Cost-benefit analysis (CBA) of wetland treatment: dollar and embodied energy

Item	Dollar-based		Energy-based			
	Unit	Unit	Energy intensity	Unit	Embodied energy	Unit
(a) Dollar- and energy-based CBA of wetland treatment method without discounting and excluding NPP						
Benefits						
Treated water		4,340,662$			82,595	10^9 J
Wetland maintenance	84$/ha/year	1,260,000$	11,636	10^3 J/$	14,661	10^9 J
Total benefit		5,600,662$			97,256	10^9 J
Costs						
Capital costs						
UAA		120,000$	13,085	10^3 J/$	1,570	10^9 J
Annual O&M cost						
Monitoring	45,000$/year	900,000$	9,826	10^3 J/$	8,843	10^9 J
Other	3,000$/year	60,000$	11,636	10^3 J/$	698	10^9 J
Subtotal	48,000$/year	960,000$			9,541	10^9 J
Total cost		1,080,000$			11,111	10^9 J
Benefit/cost			5.2		8.8	
(b) Dollar- and energy-based CBA of wetland treatment method without discounting and including NPP						
Benefits						
Treated water		4,340,662$			82,595	10^9 J
Wetland maintenance	84$/ha/year	1,260,000$	11,636	10^3 J/$	14,661	10^9 J
Additional NPP	344 dry weight, g/m^2/year	612,167$	0.05	biomass/fossil fuel	143,786	10^9 J
Total benefit		6,212,829$			241,042	10^9 J
Costs						
Capital costs						
UAA		120,000$	13,085	10^3 J/$	1,570	10^9 J
Annual O&M cost						
Monitoring	45,000$/year	900,000$	9,826	10^3 J/$	8,843	10^9 J
Other	3,000$/year	60,000$	11,636	10^3 J/$	698	10^9 J
Subtotal	48,000$/year	960,000$			9,541	10^9 J
Total cost		1,080,000$			11,111	10^9 J
Benefit/cost			5.8		21.7	
(c) Dollar- and energy-based CBA of wetland treatment method with discounting and excluding NPP						
Benefits						
Treated water		3,299,928$			64,270	10^9 J
Wetland maintenance	84$/ha/year	714,143$	11,636	10^3 J/$	8,310	10^9 J
Total benefit		4,014,071$			72,580	10^9 J
Costs						
Capital costs						
UAA		120,000$	13,085	10^3 J/$	1,570	10^9 J
Annual O&M cost						
Monitoring	45,000$/year	510,102$	9,826	10^3 J/$	5,012	10^9 J
Other	3,000$/year	34,007$	11,636	10^3 J/$	396	10^9 J
Subtotal	48,000$/year	544,109$			5,408	10^9 J
Total discounted cost		664,109$			6,978	10^9 J
Annualized cost		58,586$/year			477	10^9 J/year
Benefit/cost			6.0		10.4	
(d) Dollar- and energy-based CBA of wetland treatment method with discounting and including NPP						
Benefits						
Treated water		3,299,928$			64,270	10^9 J
Wetland maintenance	84$/ha/year	714,143$	11,636	10^3 J/$	8,310	10^9 J
Additional NPP	344 dry weight, g/m^2/year	346,964$	0.05	biomass/fossil fuel	81,495	10^9 J

(continued on next page)

Table 4 (*continued*)

Item	Dollar-based		Energy-based			
	Unit	Unit	Energy intensity	Unit	Embodied energy	Unit
Total benefit		4,361,035$			154,075	10^9 J
Costs						
Capital costs						
UAA		120,000$	13,085	10^3 J/$	1,570	10^9 J
Annual O&M cost						
Monitoring	45,000$/year	510,102$	9,826	10^3 J/$	5,012	10^9 J
Other	3,000$/year	34,007$	11,636	10^3 J/$	396	10^9 J
Subtotal	48,000$/year	544,109$	5,408			10^9 J
Total discounted cost		664,109$			6,978	10^9 J
Annualized cost		58,586$/year			477	10^9 J/year
Benefit/cost			6.6		22.1	

The discount rate is 7%; the time length is 20 years.

(Table 4a). The PV of cost savings for wetlands maintenance was estimated as $714,143 (Table 4c). The benefit of additional NPP was estimated as an additional $612,167 for nondiscounted and $346,964 for discounted benefits over 20 years, after converting NPP into crude oil-based market price (Table 4b and d). The range of benefit–cost ratios are 5.2–6.6, depending on discounting and NPP inclusion (Table 4a–d).

4.2. Energy-based analysis

4.2.1. Conventional tertiary treatment

The energy cost of equipment for sand filtration was the highest energy cost, 24 TJ (10^{12} J), among capital costs (Table 3). Annually, 2.1 TJ are consumed in operating the facility through general maintenance, electricity, labor, polymer, and sludge disposal. In total, 82.6 TJ would have been used to treat wastewater over 20 years for capital cost and O&M cost for sand filtration based on a nondiscounted assessment. The discounted amount was estimated as 64.3 TJ (Table 3).

4.2.2. Wetland treatment

By comparison, the wetland method (11.1 TJ) is 7.4 time less energy intensive than that of the conventional sand filtration method (82.6 TJ) for the life span of the facilities (Tables 3 and 4a), because the wetland method is less capital-intensive and utilizes free natural energies.

The combined, nondiscounted benefits of the wetland method are 241 TJ for wastewater treatment, wetland maintenance, and additional NPP during the life span of the wetland method. Thus, the benefit–cost ratio of the wetland method is about 21.7 (Table 4b). The most benefit of wetland method comes from increased NPP, which accounts about 60% of the benefits, followed by avoided costs of treated water (34%) and wetland maintenance (6%).

The range of benefit–cost ratios is 8.8–22.1, depending on discounting and NPP inclusion (Table 4a–d).

5. Sensitivity analysis of electricity cost

Because there is a growing concern that depletion of fossil fuels will lead to increases in the cost of electricity (Campbell and Laherrère, 1998; Deffeyes, 2001), we conducted a sensitivity analysis of increased electricity cost in operating the sand filtration system by applying different electricity prices (Table 5).

Table 5
A sensitivity analysis of electricity cost in operating a sand filtration facility

Cost/kWh ($)	Annual cost ($)	Present value ($)
0.08	4,935	55,939
0.10	6,169	69,924
0.12	7,402	83,908
0.14	8,636	97,893
0.16	9,870	111,878

1.0 MGD-capacity sand filtration facility is assumed to use 169 kWh/day. The discount rate is 7%; the time length is 20 years.

The current annual electricity cost of operating a sand filtration facility was estimated as $4935 at $0.08/kWh (Tables 3 and 5), and the cost for 20 years is $55,939 using the PV function with 7% discount rate (Table 5). If electricity price is doubled, the electricity cost of sand filtration would be $9870 per year and $111,878 for 20 years, while the wetlands treatment method does not result in additional financial burden.

6. Discussion

The two accounting techniques demonstrated that wetland treatment is more cost-effective and energy-efficient than sand filtration in improving water quality and that wetland treatment provides additional benefits to the environment in terms of improved water quality, enhanced primary production, and increased accretion (Ewel and Odum, 1984; Breaux and Day, 1994; Breaux et al., 1995; Daily, 1997; Hesse et al., 1998; Cardoch et al., 2000; Rybczyk et al., 2002).

Wetland enhancement through wastewater assimilation has the potential to generate additional financial benefit through wetland mitigation banks (Edmonds et al., 1997; Keating et al., 1997), carbon sequestration (Smith et al., 1983), and nitrogen credits (Prato, 2003). Further, the real possibility of fossil fuel shortages in the near future (Campbell and Laherrère, 1998; Deffeyes, 2001) and the potential for increasing energy prices will increase the O&M cost of conventional treatment, due to its dependence on direct and indirect industrial energy inputs. Thus, wetland treatment is a strong alternative for local communities that are under pressure to comply with increasingly stringent wastewater standards, often under worsening financial situations.

Money-based CBA has been widely used for assessing the viability of proposed projects. However, significant controversies have existed whether the approach is appropriate for environmental analyses, due to the complexities of natural ecosystems and their relation to the human economy (Peet, 1992; Hanley and Spash, 1993; Goulder and Kennedy, 1997; Turner et al., 2003). Thus, diverse paradigms of ecosystem valuation have been developed: (1) dollar-based valuation (e.g., Woodward and Wui, 2001), (2) energy-based valuation (e.g., Odum, 1961; Teal, 1962), and (3) risk-based valuation (e.g., Nash, 1991). Monetary valuation implies an anthropocentric perspective (Anderson and Rockel, 1991; Kahn, 1995). However the values perceived by humans and the expressed preferences in the market system, or other monetary valuation methods, often do not take into account what is necessary or relevant for ecosystem integrity for the maintenance of natural ecosystems and their associated services (Turner et al., 1988; Bingham et al., 1995; Gustavson et al., 2002). Thus, valuation research should include both anthropocentric and non-anthropocentric values (Turner et al., 2003). One valuation method alone may not capture the complexity of ecosystem services.

In this paper, we compared results from dollar-based and embodied energy-based cost–benefit analyses as a way to value wetland functions, compared with a conventional method for treating municipal wastewater. We believe there are significant methodological differences between dollar-based and energy-based analyses in their ability to capture multiple impacts of environmental projects. For example, assessment of carbon sequestered in the form of NPP is difficult to assess using dollar-based analysis. Willingness-To-Pay (WTP) of monetary valuation may work in accounting for nature's services or enhanced ecosystem health in the form of increased leisure activities. However, carbon sequestration in wetlands does not attract most people's economic attention. Additionally, some of the impacted wetlands area at Breaux Bridge is owned by the local government, which does not change property tax map. Thus, it is difficult to apply monetary valuation techniques of net factor income analysis or hedonic pricing. Further, the area is not conspicuous enough to attract tourist attention; the travel cost technique does not work either. Assessments based on market or surrogate market prices are extremely difficult for this wetland site. We used oil prices and an energy quality factor (one barrel of crude oil $= 1.5 \times 10^6$ kcal) to account for NPP changes for dollar-based analysis. However, the monetary analysis accounted for the wetland maintenance function of the impacted wetlands through the technique of avoided cost which provided more familiar monetary outputs.

The energy analysis showed the additional benefits of wetland maintenance and increased NPP. Energy analysis of biophysical processes accounts for NPP change, through an estimation of carbon sequestered through photosynthesis and converting this into fossil fuel based embodied energy. The energy analysis in this study showed that about 60% of benefits of the wetlands come from carbon sequestered, which was not accounted for in the monetary analysis. Monetary valuation is incommensurable with energy analysis. (Martizez-Alier, 1998), because the former has an exchange value, while the latter illustrates an accumulated value of environmental goods and services. Thus, we believe that the NPP should be excluded from dollar-based analysis but included in energy-based analysis.

There has been considerable controversy over the appropriateness of discounting ecosystem processes. Dollar-based analysis uses discount rates as revealed preference values over time, based on today's value, which reflects an anthropocentric valuation. The question is whether a discount rate is linked to natural growth and decay rates appropriately (Costanza and Daly, 1992). However, energy analysis is a biophysical approach, which views economic activities as physical processes governed by the same physical and ecological constraints such as thermodynamics (Soddy, 1922; Cleveland et al., 1984; Odum, 1996). Thus, we believe that energy cost and benefits should not be discounted over time (Hannon et al., 1978).

Based on the discounted analysis, the city will save \$2.6 million over the 20-year lifetime of the wetlands treatment project (Tables 3 and 4c). Embodied energy saving of wetland treatment over sand filtration, through reduced capital and O&M costs, will be 71.5 TJ over 20 years, which is equivalent to 11,354 barrels of crude oil (1 barrel of crude oil= 1.5×10^6 kcal) based on nondiscounted analysis (Tables 3 and 4a). Additionally, the wetland ecosystem is influenced by the incoming wastewater, which is already treated to a secondary water quality level. The wetland is affected beneficially rather than detrimentally by additional nutrients and suspended solids that contribute to increased NPP and wetlands maintenance.

Market price and economic analyses including the methods of travel cost, hedonic pricing, and contingent valuation analysis have been used in valuing services of natural ecosystems. These three economic analysis techniques assess market prices in indirect ways by measuring extra travel costs for better environmental services, estimating price differences between different regions for better environmental quality and asking the degree of WTP for a specific environmental service, respectively.

However, market price reflects the amount of resources available in a market, not in reserves, and market price is subject to people's short-term self-interest, not a sustainable base (Hall, 1992). In addition, nonrenewable resources are being more rapidly exhausted than commonly perceived (Campbell and Laherrère, 1998; Deffeyes, 2001).

We argue that cost–benefit analysis, which is based on market price alone, cannot provide a sound accounting technique, and that biophysical approach should be done as a complementary measure to value complex and diverse ecosystem functions in a more holistic way including anthropocentric and non-anthropocentric values (Folke, 1992). Energy analysis of biophysical processes allows the quantification of the contribution of renewable resources to the human economy, through analyses of physical flows, thermodynamic transformations, and use efficiencies of renewable and nonrenewable resources. This information is needed in designing a sustainable community.

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Appendix A. Details of cost calculation for the sand filtration method

A.1. Dollar-based analysis

A.1.1. Capital Cost

1. Land acquisition: 0.4474 acres required for a 1.0 MGD facility (US EPA, 1998, pp. 2–36) and land price in Louisiana for below 10 acres is $65,340/acre (US EPA, 1998, pp. 5–12).
2. A standardized cost for equipment was $665,304 (US EPA, 1998, p. 2–33), $22,390 for holding tank (US EPA, 1998, p. 2–33), $240,693 for installation (US EPA, 1998, p. 2–33), for a 1.0 MGD facility for 1989.
3. $30,000 was needed for a sludge thickener using a cost curve (Qasim, 1985, p. 679), and $57,000 for a sludge drying bed, using a cost curve (Qasim, 1985, p. 685), for a 1.0 MGD facility for 1977.
4. Inflation adjustments were done for equipment, holding tank, installation, sludge thickener, and sludge drying bed, using the Engineering News Record (ENR) construction cost index (http://www.enr.com/cost/costfaq.asp, accessed August 6, 2001).
5. Engineering and contingency: 30% of total construction cost (US EPA, 2001, pp. 11–12) (Table 3).

A.1.2. Annual O&M Cost

1. Maintenance: 4% of total capital cost (US EPA, 2001, pp. 11–13).
2. Electricity: Electricity price is 8 cents/kWh (US EPA, 2001, pp. 11–13); 266.4 kWh of electricity was consumed daily in operating a sand filtration facility with 1.5 MGD capacity for tertiary treatment (Hernandez, 1978); adjustment for 1.0 MGD using a cost function (Smith, 1978, p. 6).
3. Labor: Labor cost is $25/h (Sedlak, 1991, p. 130); 1833 labor–hours/year was needed to maintain a 1.5 MGD facility (Letterman and Cullen, 1985, p. 4); adjustment for 1.0 MGD using a cost function (Smith, 1978, p. 6). The labor cost is not inflation adjusted, because the wage level in Louisiana is lower than the national average. We decided the $25/h is more appropriate for Louisiana for 2000, rather than an inflated number.
4. Polymer: Polymer price is $7.45/kg (or $3.38/lb) in 1989 (US EPA, 2001, p. 11–13); inflation adjustment using the ENR index; the mean dosage of a cationic polymer for a tertiary treatment is 0.15 mg/l (Kibby and Hernandez, 1976, p. 14).
5. Sludge disposal.
   (a) The total suspended solid (TSS) of influents = 38 mg/l; an expected managerial goal of TSS for effluents = 10 mg/l.
   (b) The sludge amount from running a 1.0 MGD wastewater plant was 894 tonnes/year (or 985 short tons/year) under condition in which TSS of influents is 202 mg/l, and TSS of effluents is 1.3 mg/l (Kibby and Hernandez, 1976).
   (c) Using a mass balance equation, the sludge volume to be generated is 124 tonnes/year (or 137 short tons/year).
   (d) The tipping fee for landfill in Louisiana is $25/tonne (or $23/short ton) for 1994 (Rogers, 1999).
   (e) Inflation adjustment for 2000 using the BEA implicit price deplator (Source: Department of Commerce, Bureau of Economic Analysis, http://www.bea.doc.gov/bea, accessed October 1, 2001).

A.2. Energy-based analysis

A.2.1. Embodied energy for capital cost

1. Land acquisition: The energy intensity of real estate and rental for 2000, through a linear extrapolation, from an energy intensity table of the US economy is 127×10^3 J per constant 1982$ (US OTA, 1990, p. 33).
2. Equipment: The energy intensity of stone and clay products for 2000, through a linear extrapolation, is $43{,}065 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
3. Holding tank: The energy intensity of general industrial machinery and equipment for 2000, through a linear extrapolation, is $15{,}082 \times 10^3$ J per constant 1982$ (US OTA, 1990, p.32).

4. Installation: The energy intensity of new construction for 2000, through a linear extrapolation, is $21,067 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
5. Sludge thickener: The energy intensity of miscellaneous manufacturing for 2000, through a linear extrapolation, is $14,897 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 33).
6. Sludge drying bed: The energy intensity of new construction for 2000, through a linear extrapolation, is $21,067 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
7. Inflation adjustments were done for land acquisition, equipment, holding tank, installation, sludge thickener, and sludge drying bed, for 2000, using the BEA implicit price deplator.
8. Engineering and contingency: 30% of embodied energy for total construction cost (US EPA, 2001. p. 11–12).

A.2.2. Embodied energy for annual O&M cost

1. Maintenance: The energy intensity of maintenance and repair construction for 2000, through a linear extrapolation, is $18,734 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
2. Electricity: The energy intensity of electric utilities for 2000 is 3.37 J input per 1 J of output, after a linear extrapolation of an energy intensity table (US OTA, 1990, p. 32), and the electricity consumption estimation is from the financial analysis above.
3. Labor: The energy intensity of maintenance and repair construction for 2000, through a linear extrapolation, is $18,734 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
4. Polymer: The energy intensity of chemicals and selected chemical products for 2000, through a linear extrapolation, is $42,220 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
5. Sludge disposal: The energy intensity of maintenance and repair construction for 2000, through a linear extrapolation, is $18,734 \times 10^3$ J per constant 1982$ (US OTA, 1990, p. 32).
6. Inflation adjustments were done for maintenance, labor, polymer, and sludge disposal, for 2000, using the BEA implicit price deplator.

Appendix B. Details of calculations used for the wetland method

B.1. Dollar-based analysis

B.1.1. Benefits

1. Treated water: from Table 3.
2. Wetland maintenance: $65/ha is for the medium cost of maintaining wetlands using conventional engineering methods (Suhayda et al., 1991); inflation adjustment using the ENR construction cost index.
3. Additional net primary production (NPP): from B-2 energy-based analysis,
   (a) 344 g/m^2/year for the mean additional above ground NPP is equal to $143,786 \times 10^9$ J for 20 years.
   (b) 1 kcal = 4,184 J, one barrel of crude oil = 1.5×10^6 kcal; the price of crude oil for 2000 in the US was $26.72/barrel (Energy Information Administration, Petroleum marketing annual 2002 http://www.eia.doe.gov, accessed Nov. 14, 2003).
   (c) $143,786 \times 10^9$ J is equal to 22,910 barrels, which is equal to $612,167.
   (d) The PV of $612, 167 is $346,964 with 7% discount rate and 20 years of time length (Table 4a–d).

B.1.2. Costs

1. Use attainability analysis (UAA): $120,000 (Martin, 2000).
2. Monitoring cost: $45,000 (Day, 1997; Martin, 2000).
3. Other O&M: $3,000 (Martin, 2000).

B.2. Energy-based analysis

B.2.1. Benefits

1. Treated water: from Table 3.
2. Wetland maintenance: The energy intensity of maintenance and repair construction for 2000, through a linear extrapolation, is $18,734 \times 10^3$ J per constant 1982$ (US OTA, 1990, p.32).
3. Additional net primary production (NPP).
   (a) 344 g/m^2/year for the mean additional above ground NPP from 1993 to 1999 field data.

(b) Gross primary production = NPP × 3.33 (Turner et al., 1988, p. 213) for wetlands.
(c) 1 tonne (metric ton) of biomass = 4 × 10^6 kcal.
(d) 1 kcal of biomass = 0.05 kcal of fossil fuel for energy quality adjustment.
(e) Embodied energy accumulated for 20 years = 344 g/m^2/year × 3.33 × 750 ha × 10,000 m^2/ha × 0.000001 tonne/g × 4 × 10^6 kcal plant production/tonne × 0.05 biomass/fossil fuel × 4,184 J/kcal × 20 years = 143,786 × 10^9 J.

4. 7% discount rate and 20 years of life span were used for discounted benefits of additional NPP, while the NPP value was multiplied with 20 to calculate not-discounted values.

B.2.2. Costs

1. Use Attainability Analysis (UAA): The energy intensity of new construction for 2000, through a linear extrapolation, is 21,067 × 10^3 J per constant 1982$ (US OTA, 1990, p. 32).
2. Monitoring: The energy intensity of state and local government enterprises for 2000, through a linear extrapolation, is 15,821 × 10^3 J per constant 1982$ (US OTA, 1990, p. 33).
3. Other O&M: The energy intensity of maintenance and repair construction for 2000, through a linear extrapolation, is 18,734 × 10^3 J per constant 1982$ (US OTA, 1990, p. 32).
4. Inflation adjustments were done for UAA, monitoring, and other O&M cost, for 2000, using the BEA implicit price deplator.
5. 7% discount rate and 20 years of life span were used for discounted O&M energy costs, while the annual O&M energy costs were multiplied with 20 to calculate not-discounted values.

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