EMERGY SYNTHESIS:
Theory and Applications of the Emergy Methodology

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16

Embodied Energy And Emergy Analysis Of Wastewater Treatment Using Wetlands

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ABSTRACT

In the Mississippi delta of Louisiana, wetlands have been used to provide tertiary treatment to municipal wastewater as an alternative to more energy- and capital- intensive conventional methods. In addition to providing the same services as conventional methods, i.e., removal of nutrients and suspended solids, wetland utilization generates economic savings, and ecological benefits such as increased primary productivity and sediment accretion. Increased input of mineral matter and increased organic soil formation by in situ plant production reduce the sediment accretion deficit: a major focus of coastal management in Louisiana. We used a cost-benefit analysis and two energy analysis techniques: embodied energy and emergy, to assess the holistic impacts of treating municipal wastewater using wetlands. Using these three accounting techniques we compared a wetland treatment system with a conventional sand filtration system for the tertiary treatment of municipal wastewater. Characteristics of a typical tertiary wetland treatment facility were based on averages of multiple sites in Louisiana. The benefit-cost ratio favored the wetland method by two times following the cost-benefit method, 6.19 times using the embodied energy approach, and 10.73 times using the emergy analysis. This case study identifies similarities and the differences of these accounting techniques. Embodied energy analysis emphasizes material and energy flows from the human economy, while emergy analysis identifies and quantifies the inputs from natural ecosystems, in addition to flows from the human economy.

INTRODUCTION

In this paper, we compare three different accounting techniques: cost-benefit analysis, embodied energy analysis and emergy analysis to account for natural services relative to the human economy. Using these three techniques we compare the cost effectiveness and energy efficiency of wetland treatment systems versus conventional tertiary treatment systems in removing nutrients and suspended solids from municipal wastewater. The wetland treatment systems are located within the Louisiana coastal zone, where state guidelines have been established for the use of hydrologically isolated natural wetlands for municipal wastewater treatment. Data were averaged from the four sites to calculate characteristics for an average wetland treatment system (Figure 1).

Both wetland and conventional treatment systems rely on biological and physical processes to treat wastewater. However, natural energies drive the multiple functions in wetlands including physical settling, chemical precipitation, adsorption, and biological processes (Nichols 1983; Ewel and Odum 1984). Specifically, the nutrients of inflowing wastewater can be taken up in several different pathways: 1) plant uptake, 2) burial in bottom sediment, 3) nitrification and denitrification, and 4) the residue in the treated water. Suspended solids in wastewater follow two different pathways: 1) burial, and 2) the residue in the treated water (Figure 2). The benefits of using natural wetlands for treating municipal wastewater include improved effluent water quality, increased productivity of vegetation, increased sediment accretion rates to compensate for subsidence, and financial and energy savings (Breaux and Day1994; Day et al. 2000).

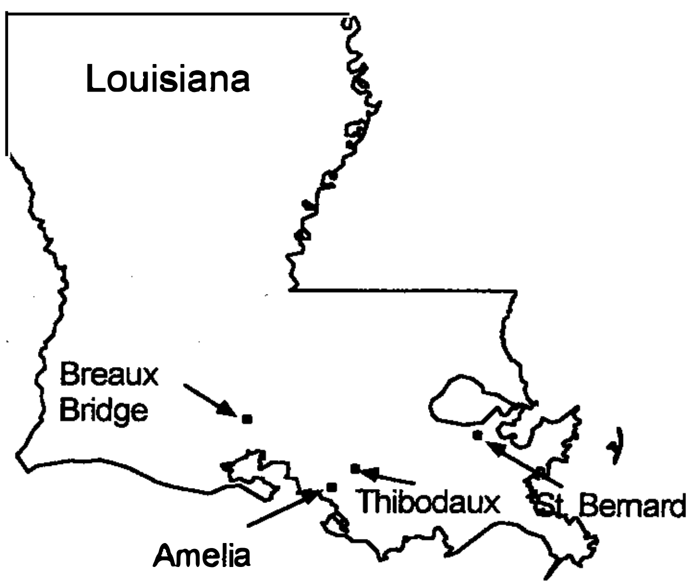

Figure 1. *Data were averaged from these four wetland wastewater treatment systems for a typical town in the coastal Louisiana zone.*

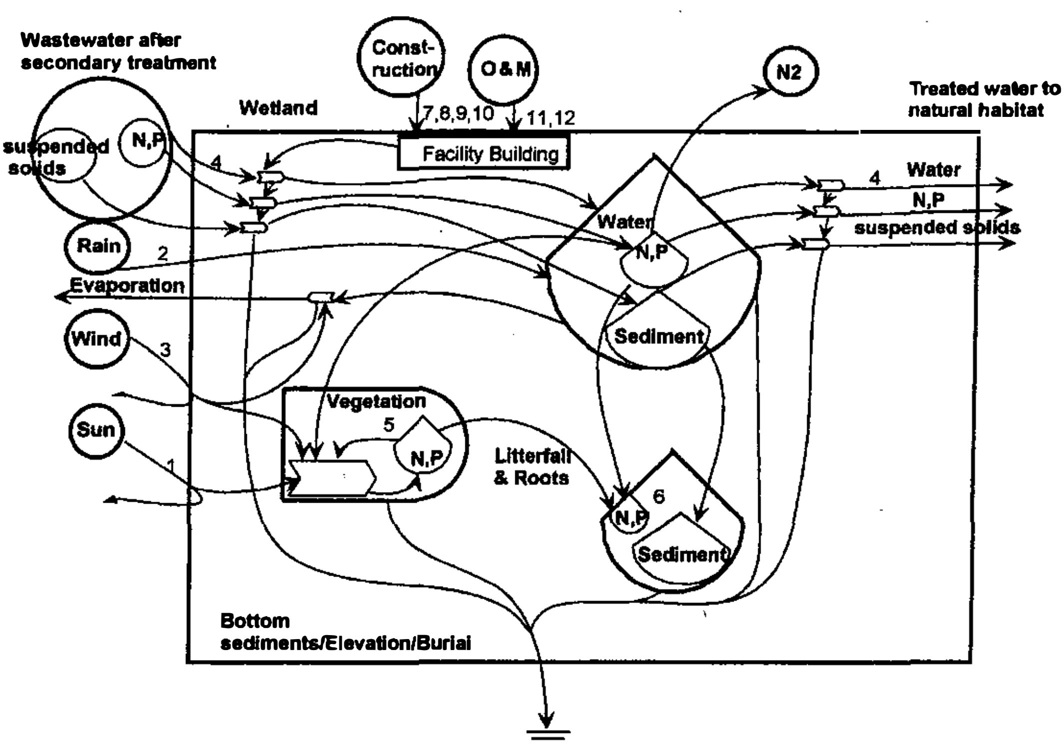

Figure 2. *Energy systems diagram of wastewater treatment using wetlands. Wetlands remove nutrients and retain suspended solids by physical settling, chemical precipitation and adsorption, and biological metabolism. The processes are controlled by natural energies such as sunlight, wind, and rain. Numbers refer to the note numbers of Table 5.*

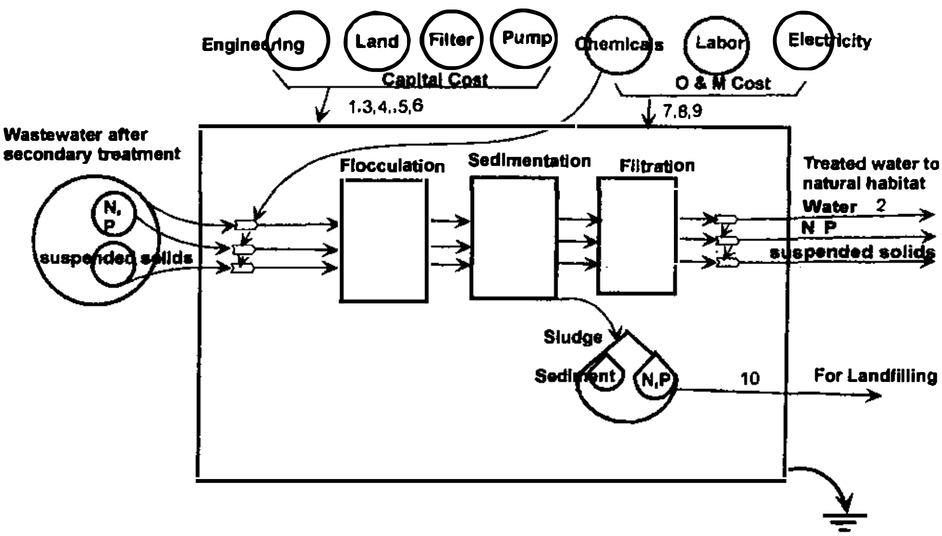

Figure 3. Energy systems diagram of the sand filtration method. Chemicals are added to increase flocculation of suspended solids for increased efficiency of sedimentation and filtration. The process is operated by electrical energy. Numbers refer to the note numbers of Table 4.

Locally land loss in the coastal zone, principally due to lack of sedimentation, is one of the major environmental problems in Louisiana (Bauman et al. 1984; Day and Templet 1989;Day et al. 1997; Kesel 1988; Templet and Meyer-Arendt 1988). The addition of wastewater effluent was found to increase the accretion rate enough to maintain wetlands (Day et al. 2000; Rybczyk et al. 1998).

Conventional treatment systems depend on imported, non-renewable inputs including chemicals and other capital investment. The sand filtration method, one of major conventional treatment options, consists of three major steps of treatment: flocculation, sedimentation, and filtration (Figure 3). Thus, in this paper, we compare sand filtration and wetland treatment for improving municipal wastewater quality with different benefits and costs.

This paper is an effort to account for different benefits and costs of these two treatment systems in a holistic manner using three different accounting techniques. Each of these three techniques has its own common unit to value system flows. Cost-benefit analysis uses money, while embodied energy uses fossil fuel-based embodied energy (usually as Btu) and emergy analysis uses solar power-based embodied energy (usually as solar emjoules(sej)). The project allowed us to compare procedures and identify the strengths and weaknesses of the three accounting techniques.

METHODS

The four wetland sites in coastal Louisiana vary in population served, treatment capacity, nutrient loading rate, wetland size, and the distance between existing secondary wastewater treatment facilities and the receiving wetlands. From these four sites we derived characteristics of a typical wetland treatment facility in coastal Louisiana (Table 1). We used the three techniques mentioned to assess the environmental benefits and financial costs of the wetland treatment systems. Using these same three techniques, we also calculated the benefits and costs of a conventional sand filtration system designed for tertiary treatment of municipal wastewater in treating the same amount of municipal wastewater (Viessman and Hammer 1998).

Table 1. A Typical Wastewater System Was Derived From Data Collected For The Four Sites Within Coastal Louisiana.

Town	Amelia	Breaux Bridge	St. Bernard	Thibodaux	Typical Town
Serving population	2,500	6,500		17,000	8,700
Wastewater generation (MGD)	1.00	1.00	1.44	4.001.86	
Total nitrogen loading ($g/m^2/yr$)	0.96	1.87	2.03	7.76	2.14
Total phosphorus loading ($g/m^2/yr$)	0.11	0.94	0.43	3.88	0.38
Total wetlands (ha)	1,012	1,475	1,536	1,425	1,362
Distance between plant & wetlands (meters)	0	0	40	2,520	640

Cost-Benefit Analysis

Cost-benefit analysis has been frequently used for environmental impact analysis (Hanley, et, al 1997), and is required for federally funded environmental projects in the United States. Market price is used to account for costs and benefits of projects in consideration. This technique is based on the "willingness-to-pay" principle, which implies that the values of environmental projects depend on human perceptions, rather than a biophysical basis.

Conventional tertiary treatment system: We estimated capital and annual costs of operation and maintenance (O&M) for a typical sand filtration facility with a capacity of 1.86 million-gallons-per-day (MGD) (Table 3). We used two different cost functions: 1) capital cost per MGD = $a*(MGD)^{0.68}$ (where a = constant) and 2) O&M cost per MGD = $b*(MGD)^{(-0.12)}$ (where b = constant) (Smith 1978).

We included the costs of land acquisition, a transfer pump, filter & equipment, and construction of the facility in capital costs, which were adjusted from the analysis done by Breaux (1992) using the cost function of capital cost. Costs of electricity, labor, chemicals, and sludge disposal were considered as O&M costs and we derived from the existing literature (Hernandez 1978; Kibby and Hernandez 1976; Letterman and Cullen 1985; Rogers 1999; Sedlak 1991). Detailed information is given in Appendix A. The present values of annual costs for O&M were calculated assuming 1) the life span of the plant is 30 years, and 2) a discount rate of 9 percent (Breaux 1992).

Wetland treatment system: Treated wastewater and wetland maintenance were included as benefits of the wetland treatment system. The financial benefits of treating wastewater using wetlands was assumed to be the same as the wastewater treatment cost of the conventional system. The benefit of wetland maintenance was calculated by multiplying the area of wetland affected by the median value of annual state-wide wetland maintenance costs (e.g., transporting dredged soils from other places), $65, in Louisiana (Suhayda et al. 1991). We did not include the benefit of additional net primary production (NPP), because the cost-benefit analysis is based on the willingness-to-pay principle, in which the value depends on how much a person is willing to pay for the benefit. People in general may not want to spend money to make trees grow a little faster, even though the increased NPP is important from ecological standpoint.

We considered the costs of a pump station, force main, and a baseline ecological characterization, as capital investments. O&M costs included property lease payments (only true in one case), wetland monitoring work, and other costs such as electricity costs of pumping, and wetland maintenance (Table 3). We estimated those costs by adjusting the costs for a 4 MGD-wetland treatment facility (Breaux 1992) using the cost functions. The present values of annual costs for O&M were calculated using the same assumptions as the conventional wastewater treatment system.

Embodied Energy Analysis

Embodied energy (EE) analysis is "the process of determining the energy required directly and indirectly to allow a system (usually an economic system) to produce a specified good or service" (Brown and Herendeen 1996, p.220). The major objective of the embodied energy analysis is to minimize conventional (fossil) energy inputs per unit of desired system output. This technique has been used for a biophysical analysis of the US economic activities (e.g., Costanza 1980) and a comparative assessment between new power plant construction and a community insulation program (Hall et al. 1979).

For this project, we used the energy intensity values of services and goods published by the U.S. Congress, Office of Technology Assessment (1990). We applied the linear best fit trend line to extrapolate the values to reflect changes for 1992, which is the base year for this study. Financial costs were multiplied by the extrapolated energy intensity values to estimate the embodied energies for the costs. The annual embodied energy costs for O&M were multiplied by thirty to calculate the embodied energies for thirty years, the life span of facilities. The biophysical flow cannot be discounted.

Conventional tertiary treatment system: The financial costs for capital investments were multiplied by the extrapolated energy intensity values to calculate embodied energies for the capital investments. We used the extrapolated median energy intensity of economic outputs for land cost of the sand filtration plant, the extrapolated intensity of general industrial machinery and equipment for the transfer pump, the extrapolated value of stone and clay products for filter and equipment, and the value of new construction for engineering.

We adjusted the electricity consumed by multiplying by 3.37 to estimate the embodied energy for the electricity, because 3.37 Btu of oil is required to produce 1 Btu of electricity (US OTA 1990), due to the thermodynamic inefficiency. The extrapolated energy intensity of maintenance and repair construction was used for labor input, and the extrapolated value of chemicals was applied for polymer and lime. Sludge disposal was considered as maintenance and repair work. The benefit of the conventional tertiary treatment method is assumed to be equal to the cost of the treatment method, because the primary objective of the treatment is to meet the water quality standard mandated by the National Pollutant Discharge Elimination System(NPDES) permit.

Wetland treatment system: We assumed that the embodied energy savings using wetlands would be equal to the embodied energy required for mandated conventional treatment standards, because 1) the primary objective of the treatment is to meet the water quality, and 2) the wetland system can meet the water quality criteria as the conventional system does. We estimated the environmental benefit of maintaining wetlands by multiplying the extrapolated energy intensity of maintenance and repair construction by the median cost of maintaining wetlands. The following procedure was utilized to calculate the benefit of increased NPP: 1) the mean additional above-ground net primary productivity, which is the sum of stem growth and litterfall, was determined from field data; 2) the additional productivity was then extrapolated to the typical size of wetland (Table 1); 3) the estimated additional net productivity was converted to gross primary productivity by multiplying by a factor of 1.42 (Turner et al. 1988); 4) the additional biomass was converted to fossil fuel-based energy value by multiplying by an energy quality factor of 0.05 (Turner et al. 1988).

We multiplied the financial costs by the extrapolated energy intensities to calculate embodied energies for the corresponding financial costs. We used the extrapolated intensity of general industrial machinery and equipment for the cost of the pump station. The energy intensity of pipeline was used for the force main. We used the energy intensity of state and local government enterprise to estimate the embodied energy of survey and monitoring costs. Wetlands were assumed to be privately-owned. We used the median energy intensity of non-energy products for the land lease and used the extrapolated energy intensity of maintenance and repair construction to estimate the embodied energy for other O&M costs in operating the wetland system. The annual embodied energy cost was multiplied by thirty to estimate the accumulated embodied energy of O&M for the life span of the wetland system.

Emergy Analysis

Emergy analysis is a "technique of quantitative analysis which determines the values of non-monied and monied resources, services, and commodities in common units of the solar energy it took to make them (Brown and Herendeen 1996, p.220)." Emergy analysis has been used for a holistic cost-effectiveness analysis of building a dam (e.g., Brown and McClanahan 1996) and energy and material dependence of the Italian national economy (Ulgiati et al. 1994).

The sand filtration facility requires inputs of imported chemicals and other human-made factors, while the wetland system depends on natural free energies. Thus we assumed that the environmental input for the sand filtration system is the land to be used for the facility building (Table 4). We included sunlight, rain, and wind as environmental inputs for the wetland system (Table 5). We used the transformity values from the existing literature (Odum 1996, Odum and Odum 1987).

Conventional tertiary treatment system: We calculated the emergy value of the benefits of treated wastewater using the following procedure: 1) the volume of treated wastewater was converted to mass units; 2) the mass of treated wastewater was converted to an energy unit by multiplying by the Gibbs free energy (4.94 J/g); and 4) the energy of wastewater was multiplied by the transformity of wastewater.

Land was included as an environmental input for conventional treatment. Like the cost-benefit analysis, and embodied energy analysis, we included expenditures for land acquisition, transfer pump, filter&equipment, and engineering for capital costs. We multiplied the financial cost of those capital items by the ratio of solar emergy to the US gross national product, which was 1.43E+12 sej/$ for 1992 (Odum 1996,p.314).

Electricity consumed was multiplied by the transformity of electricity to calculate the emergy value of electrical energy. The required amount of lime was multiplied by the solar emergy per mass for limestone to estimate the emergy value of lime. The costs of labor, polymer, and sludge disposal were converted to emergy values by multiplying by the solar emergy to dollar ratio for the US national economy.

Table 2. Cost-benefit analysis and embodied energy analysis of a conventional sand-filtration tertiary treatment method

Item	Raw unit	(unit)	Cost (US $)	Energy intensity/quality	(unit)	Embodied energy (mega Btu)
Capital Cost						
Land	292	US $/MGD	828	11,968	Btu/US '92$	10
Transfer pump	18,018	US $/MGD	51,108	11,496	Btu/US '92$	588
Filter & equipment	74,020	US $/MGD	174,134	30,522	Btu/US '92$	5,315
Engineering	18,992	US $/MGD	44,679	14,088	Btu/US '92$	629
O&M Cost						
Electrical energy	7,461	US $/yr	76,652	3.37	Btu/Btu	36,778
Labor	55,335	US $/yr	568,493	12,773	Btu/US '92$	21,204
Chemicals						
Polymer	1,700	US $/yr	17,465	36,620	Btu/US '92$	1,868
Lime	10,218	US $/yr	104,976	36,620	Btu/US '92$	11,226
Sludge disposal	2,000	US $/yr	20,547	12,773	Btu/US '92$	766
Sub-total	76,714	US $/yr				
Total Cost			1,058,882			78,384

Footnotes given at the end of this chapter.

Wetland treatment system: We included sunlight, rain, and wind energies as environmental inputs to the wetland. We considered the Albedo effect, to estimate the actual sunlight absorbed in the wetlands. The volume of local rain was converted to emergy value after considering evapotraspiration rate and the transformity of rain. Diffusion, vertical wind gradient, and air dentisy were considered to determine the energy of the wind. The wind energy was then multiplied by a wind transformity to quantify the solar emjoules (sej) required to produce the wind energy.

The emergy benefit of treated wastewater in a wetland was assumed to be equivalent to that of the treated water using the conventional system, because the transformities of the treated wastewater from the two systems are assumed to be the same. The increased biomass was converted to emergy by multiplying the trasformity of above-ground live biomass. We used an average accretion rate (Rybczyk et al. 1998), and transformity of peat to calculate the emergy value of maintaining wetlands. The emergy costs of building and operating the wetland system were calculated by multiplying the financial costs by the emergy to dollar ratio for the US economy for 1992.

RESULTS

Cost-Benefit Analysis

The capital cost for a sand filtration facility with a capacity of 1.86 MGD was estimated as $270,750, which is the sum of costs including land acquisition, transfer pump, filter&equipment, and construction. The annual O&M cost of the facility was estimated as $76,714, which includes electricity,

Table 3. Cost-Benefit Analysis And Embodied Energy Analysis Of Wetland Treatment System

Item	Raw unit	(unit)	Cost (US $)	Energy intensity/quality	(unit)	Embodied energy (mega Btu)
Benefits						
Treated water			1,058,882			78,384
Wetland maintenance	65	US $/ha	373,961	12,773	Btu/US '92$	13,948
Additional NPP	207	dry wt. g/m²/yr		0.05	Fossil fuel/ biomass	39,190
Total			1,432,843			131,522
COSTS						
Capital Costs						
Pump station	17,044	US $/MGD	48,345	11,496	Btu/US '92$	556
Force main	2,000	Ft@40$/ft	80,000	12,281	Btu/US '92$	982
Survey	5,000	US $	5,000	10,876	Btu/US '92$	54
Sub-total			133,345			1,592
O&M Costs						
Land lease	6,000	US $/yr	61,642	11,968	Btu/US '92$	2,154
Monitoring	45,000	US $/yr	462,314	10,876	Btu/US '92$	14,683
Other	7,390	US $/yr	75,922	12,773	Btu/US '92$	2,832
Sub-total	58,390	US $/yr				
Total			733,223			21,261
Benefit-Cost Ratio			1.95			6.19

Table 4. Emergy analysis of conventional sand filtration wastewater treatment system

Note	Item	Input	(Unit)	Transformity	(Unit)	Annual emergy (sej)	Cumulative emergy (sej)
	Environmental Input						
1	Land	2,238	Sq meter	6.29E+10	Sej/sq m[1]-yr	1.41E+14	4.22E+15
	Emergy Benefits						
2	Usable water	1.26E+13	J/yr	4.10E+04	Sej/J	5.17E+17	1.55E+19
	Emergy Costs						
	Capital Cost						
3	Land purchase	828	US $	1.43E+12	Sej/ US '92$	1.18E+15	1.18E+15
4	Transfer pump	51,108	US $	1.43E+12	Sej/ US '92$	7.31E+16	7.31E+16
5	Filter&equipment	174,134	US $	1.43E+12	Sej/ US '92$	2.49E+17	2.49E+17
6	Engineering	44,679	US $	1.43E+12	Sej/ US '92$	6.39E+16	6.39E+16
	O&M Cost						
7	Electrical energy	3.84E+11	J/yr	1.59E+05	Sej/J	6.11E+16	1.83E+18
8	Labor	55,335	US $/yr	1.43E+12	Sej/ US '92$	7.91E+16	2.37E+18
9	Chemicals						
	Polymer	1,700	US $	1.43E+12	Sej/ US '92$	2.43E+15	7.29E+16
	Lime	133	Tonne/yr	1.00E+09	Sej/g	1.33E+17	3.99E+18
10	Sludge disposal	2,000	US $/yr	1.43E+12	Sej/ US '92$	2.86E+15	8.58E+16
	Total Cost						8.74E+18
	Benefit-Cost Ratio						1.77

Footnotes given at the end of this chapter.

labor, chemicals, and sludge disposal. The combined cost of capital and present value of the accumulated annual costs was about $1,000,000 (Table 2).

Assuming that the benefit-cost ratio of the conventional system is one, because the primary objective of the treatment is to meet the water quality criteria mandated by the National Pollutant Discharge Elimination System (NPDES) permit. The benefit-cost ratio of the wetland system is about 1.95, due to the additional positive effects of wetlands maintenance and lower cost of the wetland system (Table 3). The capital cost of the wetland system was estimated as $133,345, while the sand filtration system costs $270,750 for treating the same amount of wastewater. The annual O&M cost for the conventional system was estimated as $76,714, while that for the wetland system as $58,390. Thus, the economic savings from using wetlands are estimated as $137,405 for capital cost, and $18, 324 per year for O&M cost. The result of the cost-benefit analysis shows that the wetland system is more cost-effective than the sand filtration system.

Embodied energy analysis

78 giga Btu would be used to treat wastewater over thirty years if the sand filtration system is employed, which includes capital costs and accumulated O&M costs. The embodied energy required for the wetlands system for the same period was estimated as 21 giga Btu. The wetland system is about 3.7 times more energy efficient than the sand filtration system from a biophysical standpoint. In other words, the embodied energy saving of 57 giga Btu over thirty years is equal to 9,800 barrel's of crude oil (1

Table 5. Emergy Analysis Of Wetland Wastewater Treatment System

Note	Item	Input	(Unit)	Transfonnity	(Unit)	Annual emergy (sej)	Cumulative emergy (sej)
	Renewable Resources						
1	Sunlight	2.13E+16	J/yr	1.00E+00	Sej/J	2.13E+16	6.39E+17
2	Rain, chemical	3.26E+13	J/yr	1.82E+04	Sej/J	5.93E+17	1.78E+19
3	Wind, kinetic	6.26E+12	J/yr	1.50E+03	Sej/J	9.39E+15	2.82E+17
	Emergy Benefits						
4	Treated wastewater	1.26E+13	J/yr	4.10E+04	Sej/J	5.17E+17	1.55E+19
5	Additional NPP	1.94E+13	J/yr	6.96E+03	Sej/J	1.35E+17	4.05E+18
6	Organic sediment	4.98E+13	J/yr	1.90E+04	Sej/J	9.46E+17	2.84E+19
	Total						4.80E+19
	Emergy Costs						
7	Pump station	4.83E+04	US '92$	1.43E+12	Sej/US '92$	4.96E+15	4.96E+15
8	Force main	8.00E+04	US '92$	1.43E+12	Sej/US '92$	3.81E+15	3.81E+15
9	Survey of property	5.00E+03	US '92$	1.43E+12	Sej/US '92$	7.15E+15	7.15E+15
	O&M						
10	Land lease	6.00E+03	US '92$/yr	1.43E+12	Sej/US '92$	8.58E+15	2.57E+17
11	Monitoring	4.50E+04	US '92$/yr	1.43E+12	Sej/US '92$	6.44E+16	1.93E+18
12	Other	7.39E+03	US '92$/yr	1.43E+12	Sej/US '92$	1.06E+16	3.17E+17
	Total						2.52E+18
	Benefit-Cost Ratio						19

Footnotes given at the end of this chapter.

barrel of crude oil is equal to 5.8E+06 Btu). After we included the benefits of wetland maintenance and additional NPP growth, the wetland system was 6.19 times more energy efficient than the conventional treatment system (Table 6).

Emergy Analysis

The total emergy cost of the sand filtration system was estimated as 8.74E+18 sej (Table 4). The most significant costs associated with the sand filtration system were lime, labor, followed by electrical energy, all of which are imported resources. Thus, the emergy analysis clearly demonstrated the characteristics of the capital- and labor- intensive conventional system. The total emergy cost of the wetland system was estimated as 2.52E+18 sej. The emergy cost of the wetland system was lower than that of the conventional system, due to environmental contributions including sunlight, rain, and wind (Table 5). The chemical potential of rain was the single most important renewable resource. The emergy benefit-cost ratio (or emergy yield ratio) of the conventional system was estimated as 1.77, while the ratio of the wetland system was 19, due to lower inputs and additional benefits (Table 4&5). The emergy analysis also suggests that the wetland maintenance through organic soil building is more important than treating wastewater.

The monitoring cost for the wetland, which is mandated by state regulation, was the single largest emergy cost in operating the wetland system. The emergy analysis also showed the impact of distance between the secondary treatment facility and the wetland for the wetland treatment system.

Table 6. Integrated benefit-cost table of wastewater treatment and cost-effectiveness ratio for a typical town in Louisiana. The costs are averaged total annual cost, in which capital cost and present value of O&M cost are added and divided by thirty years. The benefits include wastewater treatment and other additional benefits. Cost-effectiveness ratio is the ratio of the wetland system over the sand filtration system with regard to benefit-cost ratio of each method.

System\Analysis		Cost-benefit	Embodied energy	Emergy
Sand filtration	Benefit	35,296 ($)	2,613 (mega Btu)	5.17E+17 (sej)
	Cost	35,296 ($)	2,613 (mega Btu)	2.91E+17 (sej)
Wetlands	Benefit	47,761 ($)	4,384 (mega Btu)	1.60E+18 (sej)
	Cost	24,441 ($)	709 (mega Btu)	8.40E+16 (sej)
Cost-effectiveness Ratio		1.95	6.19	10.73

DISCUSSION

The three accounting techniques demonstrated that the wetland treatment system is more cost-effective and energy-efficient than the sand filtration system in removing nutrients and suspended solids from secondarily treated municipal wastewater and that the wetland system provides additional environment benefits. Thus, the relative cost-effectiveness ratio of the wetland system to the conventional system, which is defined as the benefit-cost ratio of the wetland system divided by that of sand filtration system, was 1.95 by the cost-benefit analysis, 6.19 by the embodied energy analysis, and 10.73 by the emergy analysis (Table 6). If the wetland can be located adjacent to the facility, then the emergy cost for the wetland system will significantly drop. Further, enhancement of wetlands quality using wastewater will generate additional financial benefit through wetland mitigation banks (Edmonds et al. 1997; Keating et al. 1997).

Methodologically, the cost-benefit technique does not consider non-monetary benefits, while it provides the more familiar monetary outputs. The embodied energy technique has a relative strength in showing more detailed energy intensities of human economy and provides benefits and energy savings in relatively easily understandable oil equivalent information, which allows us to quantify the benefits of wetlands in terms of oil savings. The emergy technique quantifies nature's service to human economy and explains why the wetland system is more cost-effective than the conventional system in treating wastewater. However, presently it depends on limited numbers of transformity, which may be resolved by further studies of developing more transformaties for diverse economic sectors.

Non-renewable resources have been more rapidly exhausted than commonly perceived (Campbell and Laherrère 1998). 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). Thus, we argue that cost-benefit analysis, which is based on market price, cannot alone provide a sound accounting technique and that biophysical approaches should be more emphasized. Biophysical approaches provide quantified information of the contribution of renewable resources, and describes physical flows, thermodynamic transformations, and use efficiencies of renewable and non-renewable resources. This information is needed in designing the sustainable development.

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APPENDICES

Appendix A. Variables used for the sand filtration system (Table 2)

1. electricity price : 7 cent per kwh (Sedlak 1991, p.69)
2. labor hours for O&M: 1,190 hours per year for scraping, resanding, and maintenance (Letterman and Cullen 1985, p.4)
3. labor cost: $25 per hour (Sedlak 1991, p.130)
4. polymer input and price: 0.15 mg per liter and $2 per pound (Sedlak 1991, p.130).
5. lime input and price: 275 mg/L for a return activated sludge (RAS) feed, 25 % flow to the stripper, and 75% of elutriation flow. $70 per short ton (Sedlak 1991, p.187). Lime usage (as CaO) = (275 mg/L)*(1.86 MGD)*(0.25)*(0.75)*(365 days/yr)=291,948 lb/yr.
6. sludge volume: TSS of inflowing water = 35 mg/L. Mandated TSS of discharging water = 15 mg/L. V(ft^3(gal))=Ws/[(s/100)rS], where V= volume of sludge, ft^3(gal), Ws=weight of dry solids (lb), s=solid content, %, r=unit weight of water, 62.4lb/ft^3, S=specific gravity of wet sludge (normally assumed as one) (Viessman and Hammer 1998,p.637). Assumption of 20% of concentration, similar to wet clay. Volume of sludge = 1.86 *(35-15)*8.34/(0.20*62.4)=24.84 ft^3/day. 20% of the sludge is solid, which is 4.97 ft^3, and 80% is water, which is 19.87 ft^3, whose weight = 19.87*8.34=165.716 lbs. The total weight of daily sludge = 310.437+165.716=476.153 lbs. For a year 476.153*365=173,796 lbs, which is 87 short tons.
7. tipping fee for landfilling in Louisiana: $23 per short ton (Roger 1999).

Appendix B. Notes to Table 4 (emergy analysis of sand filtration)

1.Land: 2 acres are needed for 4 MGD (Breaux 1992,p.176). The cost function of capital cost is a=(MGD)**0.68. From this information, the land cost for typical case 2,238 square meter. Transformity of land = 6.29E+14 sej/ha-yr (Odum 1996,p.110).
2. Usable water: Energy(J)= (1.86*10^6 gallon)*(365 days/yr)*(3.7853 liter/gallon)*(1 kg/liter* 1000 g/kg)*(4.94 J/g Gibbs)=1.26E+13 J/yr. Tranformity of wastewater is 4.1E4 Sej/J (Odum 1987,p.143).
3. Land purchase: land acquisition cost for 4 MGD = $,3000 (Breaux 1992,p.176). The cost function for capital cost = a*$(MGD)^{0.68}$ Then the land cost for the typical case of 1.86 MGD= $828. The emergy-to-dollar ratio for 1992 is 1.43E+12 sej/$.
4. Transfer pump: the transfer pump cost for 4 MGD is $185,000 (Breaux 1992,p.176). The cost function of capital cost is a*(MGD)**0.68. From this information, the pump cost for the typical case of 1.86 MGD = $51,108.
5. Filter&equipment: the filter&equipment cost for 4MGD is $760,000 (Breaux 1992,p.176). The cost function for capital cost is a*(MGD)**0.68. From the two information, the filter&equipment cost for the typical case is $174,134.
6. Engineering: the engineering cost for 4 MGD is $195,000 (Breaux 1992,p.176). The cost function is a*(MGD)**0.68. From this information, the engineering cost for the typical case is $44,679.
7. Electrical energy: 266.4 kwh of electricity are consumed daily for clarifier operation, sludge pumping, sludge thickener, and filter operation (air compressors, backwashing, etc.) for the tertiary treatment for the capacity of 1.5 MGD (Smith 1978,p.6). The cost function of O&M is a*$(MGD)^{(-0.12)}$ for trickling filter plants. From this information, the typical case will be 106, 587 kwh for a year.

Energy(J)= (106,587 kwh)*(3.606 E+6 J/kwh). Transformity of electricity = 1.59E+5 sej/j (Odum and Odum 1987, p.114)

8. Labor: the labor hours of scraping, resanding, and day-to-day maintenance for 1.5 MGD is 1,833 hours/yr (Letterman and Cullen 1985). The cost function of O&M cost is a*$(MGD)^{(-0.12)}$. From this information, the typical case will be 2,213 hours for a year. The labor cost is $25 (Sedlak 1991, p.130).
9.Chemicals: polymer input = 0.15 mg/L (Kibby and Hernandez 1976, p.14). The price of polymer is $2/lbs (Sedlak 1991,p.130). Polymer cost = (1.86MGD)*(0.15 mg/L)*(3.7853 liter/gallon)*(0.001 g/mg)*(0.001 kg/g)*(2.2046 lbs/kg)*($2.00/lbs)=$1,700.

Lime: from assumptions in which 1). An return activated sludge (RAS) feed, 2). 25 % flow to the stripper, and 3).elutriation water flow of 75 % (Sedlak 1991,p.187). The lime usage (as CaO)=(275 mg/L)*(1.86 MGD)*(0.25)*(0.75)*(1 liter/0.26418 gallon)*(1g/1000 mg)*(1lb/453.59 gramme)*(365 days/yr)*(2000 lb/short ton)*(0.90718 tonne/short ton)= 133 tonnes. Transformity of limestone = 1.0 E+09 sej/g (Odum 1996,p.46).

10.Sludge disposal: For 1.86 MGD, the TSS of inflowing water = 35 mg/L from the average of the four sites. The assumed TSS of discharging water after tertiary treatment is 15 mg/L for average, which is

mandated by the permit. Volume of sludge, V (ft3(gal)) = Ws/[(s/100)rS], where V= volume of sludge, ft3(gal). Ws=weight of dry solids, s=solid content, %, r=unit weight of water, 62.4lb/ft3, S=specific gravity of wet sludge (normally as one) (Viessman and Hammer 1998,.p.637 and 638). 20% of solid, which is similar to wet clay, is assumed. The solids in sludge is 1.86*(35-15)*8.34 = 310.248 lbs/day. The total weight of sludge = 310.248 + 0.8*24.86*8.34= 475.964 lbs/day. For year, 475.964 lbs*365 = 87 short ton. The tipping fee in Louisiana in 1994 is $23/ton (Rogers 1999).
The disposal cost = 87 ton* $23 = $2,000/yr.

***Appendix** C. Notes to Table 5 (emergy analysis of wetland treatment system)*

1. Sunlight: total area = 560 ha = 5.60E+06 square meter. Insolation = 5.94E+9 J/square meter/yr (Costanza et al. 1983). Albedo = 36%(Costanza et al. 1983). Energy(J)= (5.60E+06 square meter)*(5.94E+9 J/ square meter/yr)*(1-0.36) = 2.13E+16 J/yr.
2. Rain, chemical potential energy: total area = 560 ha = 5.60E+06 square meter. Rainfall = 1.51 m/yr (NOAA 1981). Evapotranspiration rate = 1.18 m/yr (Mitsch and Gosselink 1993). Energy (J) = (5.60E+6 squre meter)*(1.18 m/yr)*(1000 kg/cubic meter)*(4.94E+3 J/kg Gibbs) = 3.26E+13 J. Transformity of rain = 1.82E+04 (Odum 1996,p.124).
3. Wind, kinetic: total area = 560 ha = 5.60E+06 square meter. Average eddy diffusion coefficient = 14.74 squre meter/sec. Average vertical wind gradient = 4.42E-3/sec. Height = 100 m. Density of air = 1.23 kg/cubic meter. Energy (J) = (5.60E+06)*(100 m)*(1.23 kg/cubic meter)*(14.74 squre meter/ sec)*(4.42E-3/sec)**2*(3.15E+07 sec/yr) = 6.26E+12 J. Transformity of wind = 1,496 sej/J (Odum 1996,p.309).
4. Treated wastewater: Energy (J) = (1.86E+06 gal/day)*(365 day/yr)*(3.7853 liter/gal)*(1E+03 cubic cm/liter)*(1 gram/1 cubic cm)*(4.94J/gram Gibbs)= 1.26E+13 J/yr. Transformity of wastewater = 4.1E+04 sej/J (Odum 1987,p.143).
5. Additional NPP: From field data, the average additional NPP is 207 dry weight gram/square meter/yr. One tonnne of wood biomass = 4E+06 Cal plant production (Turner et al. 1988). Energy(J)= (207 g/sq meter/yr)*(560 ha)*(10,000 square meter/ha)*(1E-6 tonne/gram)*(4E+6 Cal plant production/ tonne)*(4186 J/kcal) = 1.94E+13 J/yr. Transformity of above-ground live biomass = 6,962 sej/J (Odum 1996, p.116).
6. Organic sediment building: The average accretion rate, due to wastewater effluent is 0.40 cm/yr (Rybczyk, et al. 1998). Dry weight of peat = 10.4 % and heat content of peat is 9.2E+3 Btu/lb dry (Odum 1996,p.86). Energy (J)= (5.60E+06 square meter)*(0.4 cm)*(1 meter/100 cm)*(1E+06 g/cubic meter)*(10.4 percent)*(9.2E+03 Btu/lb dry)*(1054 J/Btu)/(4.5359E+02 gram/lb) = 4.98E+13 J. Transformity of peat = 1.9E+4 sej/J (Odum 1996, p.86).
7, 8, 9,10,11, & 12: Estimated financial costs were multiplied by the emergy to dollar ratio, which is 1.43E+12 sej/$ for 1992.