ELSEVIER

Ecological Engineering 11 (1998) 291–302

ECOLOGICAL ENGINEERING

Ecological–economic evaluation of wetland management alternatives[1]

Shanshin Ton [a,*], Howard T. Odum [b], Joseph J. Delfino [b]

[a] *Department of Environmental Engineering and Science, Feng-Chia University, Taichung 407, Taiwan, ROC*

[b] *Department of Environmental Engineering Sciences, University of Florida, Gainesville, FL 32611-2013, USA*

Received 2 January 1997; received in revised form 2 September 1997; accepted 15 September 1997

Abstract

A heavily impacted wetland in Jackson County, FL, USA was selected for this study. Several approaches involving different perspectives were initiated to postulate and test possible mechanisms of transport and transformation of Pb in the wetland environment. A macroscopic system analysis was conducted as well to evaluate the benefits of wetland ecosystem restoration. Microcosms containing cypress *(Taxodium ascendens)* and black gum *(Nyssa sylvatica)* seedlings were used as a wetland surrogate to assess the ecological effects of Pb and acidity on the wetland community. Three wetland management alternatives were proposed. These included land control, sediment excavation, and wetland restoration by replanting. An 'emergy'-based ecological–economic evaluation revealed that restoration of the wetland was the most beneficial option, with a net benefit of 15.2×10^{17} and 57.4×10^{17} solar emjoules (sej) for 20- and 62-year recovery times, respectively. The net benefit of this alternative is calculated to be \$756 000 and \$2 870 000 for the 20- and 62-year recovery periods, respectively, based on macroeconomic values for the US economy in 1990 of 2.0×10^{12} sej/\$. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: Wetland; Restoration; Management; Emergy; Ecological–economic evaluation; Florida

* Corresponding author.

[1] Paper presented at ICEE 96—International Conference of Ecological Engineering, Beijing, China, 7–11 October 1996.

PII S0925-8574(98)00039-1

1. Introduction

The Steele City Bay wetlands in Jackson County of western Florida were heavily impacted by inputs of acidic battery wastewater discharge from Sapp Battery Service, from 1970 to 1980. Wetland structures and functions were altered by the associated ecotoxicity effects. Devastation of the wetland community was observed with respect to the predominant species, pond cypress *(Taxodium ascendens)* and black gum *(Nyssa sylvatica)* (Ton et al., 1993). However, a field study and the microcosm studies suggested a gradual recovery of the damaged wetland ecosystem and showed that there were no significant effects on seedling growth under simulated field conditions, respectively (Ton, 1993). A related simulation study extrapolated into the future also suggested some recovery of the ecosystem (Ton et al., 1996). Therefore, a macroscopic view of wetland management then served to combine the above efforts.

The complexity of interactions between human activities and the natural environment has increased due to the rapid development of urban areas and associated economic systems. Many studies have been conducted to aid in incorporating environmental values into planning and decision-making processes (Odum, 1983, 1988a; Odum et al., 1988; Keller, 1992; Pritchard, 1992). The major effort of most such evaluations has been focused on measuring the impacts of development and the benefits from preserving the environment.

Environmental systems analysis seeks to develop a package of basic principles that govern the interactions between natural and human systems. The package is then used to analyze the structure of the system and to predict its performance under different conditions (Odum, 1983, 1988a). Starting in 1983, the concept of embodied energy was renamed 'EMERGY' and given the unit, emjoule (Odum, 1983; Scienceman, 1987). EMERGY is the energy of one form directly and indirectly required to do environmental work (Odum, 1986). Therefore, emergy is used as the principal conceptual tool for expressing the inter-relationship of energetic flows and resource quality, and for linking together systems of the natural environment and human economy (Odum, 1971, 1988a).

As a result, emergy analysis is a type of embodied energy analysis that can provide common units (emergy) for comparison of environmental and economic goods by summing the energy of one type required directly or indirectly for production of goods (Odum, 1988a). Different energy forms contribute in turn to the ecological processes and to economic activities. The actual energy of various kinds which is used for production processes is said to be 'embodied' in the product.

In emergy analysis, the quality of each form of energy is taken into account by multiplying each quantity of energy by its solar transformity. Solar transformity is defined as solar emergy per unit energy (sej/j) (Odum, 1988a,b). Energy of high transformity has more emergy and is high in its quality of effect. For clarification, Table 1 provides a summary of definitions embodied in the concept and emergy evaluation terms.

'Price' is the amount of money needed to buy a certain unit of goods or services. It reflects the relationship between the flow of goods and the flow of money. Commonly it is referred to as market value, defined in terms of what people are willing to pay (Baumol and Blinder, 1985). Natural inputs and human services are each considered to contribute to economic growth. However, it is difficult to place a market value on natural services. This is because money is paid only for human services, with nature never getting paid (Odum et al., 1988). To evaluate the contribution of natural services, solar emergy is considered as a common measure. All energy sources that contribute to the economy are calculated in terms of solar emergy. By dividing the total solar emergy of the economy by the gross national product (GNP), the emergy–money ratio is obtained (Odum et al., 1988). In other words,

$$\text{Emergy} - \text{money ratio (sej/\$)} = \frac{\text{(Total solar emergy of the economy (sej)}}{\text{Gross national product (\$))}}$$

By dividing the solar emergy of any environmental inputs by the emergy–money ratio, the amount of natural contributions, in terms of macroeconomic value, can be estimated as

$$\text{Macroeconomic value (\$)} = \frac{\text{Energy (sej)}}{\text{Emergy} - \text{money ratio (sej/\$)}}$$

Decision on the use of resources in ecological management cannot be made correctly using money because money is only paid for services, but an emergy comparison can be prepared for choosing among environmental alternatives. The net emergy yield of an energy resource and/or an ecological process are their

Table 1
Definitions of emergy evaluation concepts

Emergy	Energy of a single type required directly and indirectly for transformations in order to generate a product or service.
Solar emergy	Solar energy required directly and indirectly to produce a product or service (units of solar emjoules, sej).
Transformity	Emergy per unit energy required for a given product or service in a system.
Solar transformity	Solar emergy per unit energy, units are solar emjoules/joule (sej/J).
Emergy per unit mass	Emergy of a single type required to generate a flow or storage of a unit mass of a material (units of sej/g).
Empower	Emergy flow per unit time, usually per year (units of sej/yr).
Emergy/money ratio	Ratio of emergy flow to money flow, commonly for a state or nation, calculated as annual emergy use divided by the value of the gross national product (units of sej/$).
Net emergy yield ratio	Ratio of the emergy yield divided by the emergy used for processing, served as an indication of contribution to the economy.
Emergy investment ratio	Ratio of emergy brought into an area from the economy and from environmental resources, served as a measure of economic loading of the environment.

Sources: Odum, 1988a,b, 1991; Odum et al., 1988.

emergy yield after subtracting the emergy for processing. Primary sources and/or ecological processes can be evaluated with the net emergy yield ratio, which is the ratio of the emergy yield divided by the emergy used for processing. In other words,

$$\text{Net emergy yield ratio} = \frac{\text{Yield emergy}}{\text{Feedback emergy}}$$

Typical net emergy yield ratios of fuels and environmental products ranged from 1.06 to 12.0 (Odum, 1996). A higher net emergy yield of energy resources and ecological processes indicated more contribution to the economy; therefore, more economically competitive than the lower ones. The ratio of emergy brought into an area from the economy and from the environmental resources, which are used in the interaction, is the emergy investment ratio (Odum, 1996). It can be obtained as

$$\text{Emergy investment ratio} = \frac{\text{Purchased emergy}}{\text{Environmental emergy}}$$

This index is a measure of economic loading of environment and can also be used for determining the competitive of an ecological process. Lower emergy investment ratio of a proposed project usually means that it requires less purchase costs from economy and more support from environment. Environmental processes with higher emergy investment ratios usually have less environment to support each unit for economic activities. Thus, the impacts on them are heavier and more of their emergy is used up without being reinforced.

2. Systems analysis

Several work plans were prepared in response to the US EPA and FDER (Florida Department of Environmental Regulation) requests for a remedial investigation and feasibility study (RI/FS) at the Steele City Bay wetlands (Watts, 1984; Ecology and Environment, 1989; CH2M HILL, 1991). Remedial alternatives were also developed and proposed to the US EPA and the FDER (Trnovsky et al., 1988; Bechtel Environmental, 1991). Two alternatives proposed in the aforementioned reports and restoration of the wetland ecosystem by replanting, as proposed herein, are evaluated by using the ecological–economic method for wetland management. These alternatives include the following.

(A) Planting: to restore the wetland ecosystem by providing seedlings. Such revegetation efforts would promote gross primary production (GPP) by the wetland ecosystem. It would therefore enhance the biogeochemical processes for Pb, and consequently reduce the toxicity effects of Pb in the wetland ecosystem. According to the sediment quality criteria (Bonnevie et al., 1992) and the contaminant clean-up criteria (Trnovsky et al., 1988), a fence is needed for the Steele City Bay West wetland to protect human health.

(B) Land control: to restore the wetland ecosystem by natural processes. In this case, no treatment is applied to the contaminated site. A fence for the Steele City Bay West wetland, to protect human health, is the only requirement. This is one of the alternatives being suggested to the FDER and EPA. It is intended to serve as a baseline against which other alternatives can be measured.

(C) Sediment excavation: to remove and dispose of the contaminated sediment. Removal of contaminated sediment for disposal in an off-site, secure landfill is considered in this alternative. This action provides a high level of clean-up and prevents any further migration of contaminants. Cost for this alternative is estimated for the excavation action only; off-site disposal is not evaluated.

A system diagram, with energy circuit language symbol, of three alternative wetland management systems is shown in Fig. 1. By estimating energy flows in terms of solar emergy (solar emjoules, sej), an emergy table can be established to evaluate alternative wetland management strategies. The net emergy, or emergy yield, of an ecological process and/or the cost of wetland management can be calculated with respect to macroeconomic value. The emergy investment ratio and the net emergy yield ratio are therefore used to determine the economic competitiveness of an ecological process and the benefit of an ecological process to society or the economy, respectively (Odum, 1996).

3. Results and discussion

To characterize emergy values for the environmental work, an emergy evaluation table with an itemized list of energy flows from natural resources, imported resources, exports, and storage has been prepared. The emergy evaluation of energy flows for three alternative strategies of wetland management is shown in Table 2.

Energy inflows of renewable resources are estimated as a natural input received by a defined area. Thus, the natural input for the three alternatives is kept constant, which has a value of 50.3×10^{15} sej. The different wetland management strategies also involve various goods and services. The emergy for each energy input is calculated by multiplying the energy of the material by its solar transformity. The transformity of human service, which usually is embodied in equipment and fuel used, can be obtained by dividing the total emergy used in the US economy by the GNP. The value is calculated as 2.0×10^{12} sej/$, according to US economic figures for 1990.

Nonrenewable resources applied to the system for wetland restoration include fence construction, seedling supply, and operation and maintenance costs (items 5, 6, and 7). The emergy of seedlings and annual operations costs also are calculated according to their transformities. The summation of these nonrenewable resources is 152.6×10^{15} sej.

It is believed that replanting, the first alternative considered, will promote wetland production. After 20 years of revegetation, the Steele City Bay wetlands are assumed to gradually recover to normal conditions. Thus, the GPP of this wetland ecosystem is based on the production of a normal forest wetland ecosystem. The transformity of GPP in this study is obtained by dividing the total solar emergy of the wetland ecosystem by the energy of a forest wetland in primary production. The value is calculated to be 1091 sej/j. Thus, the emergy of a well-functioning wetland ecosystem (item 8) is estimated at 50.3×10^{15} sej.

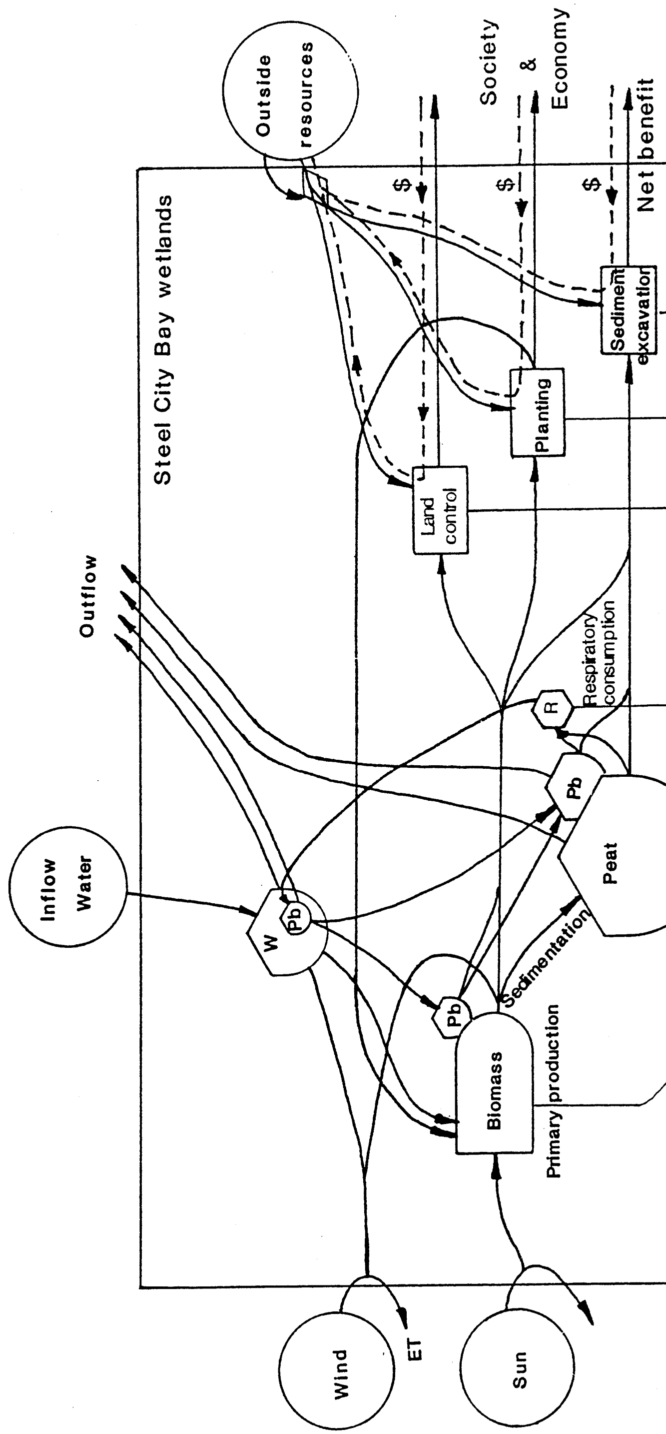

Fig. 1. System diagram of three alternative wetland managements.

Table 2
Emergy evaluation of emergy flows of alternative wetland management strategies

Item	Raw units	Transformity or emergy/unit	Solar emergy ($\times 10^{15}$ sej)
Energy inflows (renewable source)			
Sunlight[1]	1.07×10^{15} J/yr	1.00×10^{0} sej/J	1.1
Wind[2]	7.85×10^{10} J/yr	1.50×10^{3} sej/J	0.1
Rain, chemical[3]	9.10×10^{11} J/yr	1.82×10^{4} sej/J	16.6
Runoff[4]	8.22×10^{11} J/yr	4.11×10^{4} sej/J	33.7
Planting			
Energy inflows (nonrenewable source)			
Good and services (fence)[5]	7.20×10^{4}\$	2.00×10^{12} sej/\$	144.0
Good and services (seedlings)[6]	3.01×10^{9} J	1.20×10^{5} sej/J	0.4
Good and services (O/M costs)[7]	4.10×10^{3}\$	2.00×10^{12} sej/\$	8.2
Subtotal			152.6 sej
Ecosystem processes			
GPP[8]	4.61×10^{13} J/yr	1.09×10^{3} sej/J	50.3
Land control			
Energy inflows (nonrenewable source)			
Goods and services (fence)[9]	7.20×10^{4} \$	2.00×10^{12} sej/\$	144.0
Ecosystem processes			
GPP[10]	1.43×10^{13} J/yr	1.09×10^{3} sej/J	15.6
Sediment excavation			
Energy inflows (nonrenewable source)			
Goods and services (excavation)[11]	1.53×10^{5}\$	2.00×10^{12} sej/\$	306.9
Energy export			
Peat, sediment[12]	9.50×10^{13} J	4.42×10^{3} sej/J	420.0
Ecosystem processes			
GPP[13]	1.43×10^{13} J/yr	1.09×10^{3} sej/J	15.6

Total emergy used/GNP (1990 US) = 2.00×10^{12} sej/\$ (Odum, 1996).

[1] Area (m^2) = 2.49×10^{5}; insolation (kcal/cm^2/yr) = 1.46×10^{3} (Odum et al., 1987); Albedo (= 30%) = 3.00×10^{-01} (Odum et al., 1987); energy (J/yr) = (area)*(ave insolation)*(1 − albedo)*(1000 cm^2/m^2)*(4186 J/kcal) = 1.07×10^{15}.

[2] Height (m) = 1.00×10^{3} (Odum et al., 1987); air density (kg/m^3) = 1.23×10^{0} (Odum et al., 1987); diffusion coefficient (m^2/s) = 2.25×10^{0} (Odum et al., 1987); wind gradient (l/s) = 1.90×10^{-3} (Odum et al., 1987); surface wind (J/yr) = (height)*(density)*(diffusion coefficient)*(wind gradient)^2*(area)*(1 J/s/W)*(3.154×10^{7} s/y) = 7.85×10^{10}.

[3] Gibbs free energy (J/g) = 4.94; rainfall (m/yr) = 1.48×10^{0} (US Soil survey Jackson County, FL, 1979); evapotrans rate (m/yr) = 7.40×10^{-1} (assume 50% ET rate) (Ewel and Odum, 1984); energy of rain (J/yr) = (area)*(rainfall)*(ET rate)*(G)*($\times10^{6}$ g/m^3) = 9.10×10^{11}.

[4] Annual runoff rate (m/yr) = 6.68×10^{-1} (calculated from Soil Conservation Service method); energy (J/yr) = (area)*(annual runoff rate)*(l000 kg/m^3)*(4.94×10^{3} J/kg) = 8.22×10^{11}.

For the second alternative, the wetland itself is assumed to be preserved without any treatments. Concerns for elevated Pb concentrations in sediments to human health dictate adding a fence in this option (item 9). The emergy value for the fence is 144.0×10^{15} sej. Since Sapp Battery Service has ceased operation, field measurements have revealed a slow recovery of wetland production (Pritchard, 1992). Because of this slow recovery, the GPP for the emergy calculations is based on field measurements for the damaged wetland ecosystem in 1991 (Pritchard, 1992), which are estimated at 1.43×10^{13} J/yr. The energy value of the GPP for a damaged wetland ecosystem (item 10) is then estimated as 15.6×10^{15} sej.

The third alternative, sediment excavation, is considered to be a highly effective alternative for cleaning up contamination; however, the high cost makes this option less acceptable (Trnovsky et al., 1988). Estimation of the cost of this operation (item 11) is based on two earlier reports (Trnovsky et al., 1988; Bechtel Environmental, 1991). The ratio of the off-site contaminated sediment volume to total contaminated soil/sediment volume is 1.74×10^{-2} (Trnovsky et al., 1988). By multiplying this ratio by the total cost for excavation, the costs embodied in equipment and fuel are obtained. The emergy for sediment excavation is estimated at 306.9×10^{15} sej.

The excavation action not only requires outside energy inputs but also exports the energy of the peat stored in the ecosystem. Therefore, the energy of sediment excavation (item 12) is calculated by multiplying the mass of the excavated sediment by its energy content. The emergy value is then estimated to be 420.0×10^{15} sej.

Several assumptions are necessary for the GPP estimation of the sediment-excavation alternative. First, the excavation action may disturb the ecosystem or even create a different ecosystem, such as development of a deep pond ecosystem. Second, the removal of sediment from the wetland area may reduce future nutrient: supply for wetland production. Third, without proper management the production

[5] Length (ft) = 4.80×10^3; unit price (\$/ft) = 1.50×10^1 (Bechtel Environmental, 1991); human services embodied in equipment and fuel used (\$) = (length)*(unit price) = 7.20×10^4.

[6] Seedlings = 4.00×10^3; biomass (g) = 4.00×10^1; energy contents of biomass (J/g) = 1.88×10^1 (Odum et al., 1987) Seedlings (J) = (seedlings)*(biomass)*(energy content of biomass) = 3.01×10^9.

[7] (Operation and maintenance costs): human services embodied in equipment and fuel (\$) = 4.10×10^3 (Lahors, misc.).

[8] GPP calculation based on the control forest wetland ecosystem (Pritchard, 1992): gross primary production = 1.85×10^8 (J/m^2/yr); energy (J) = (area)*(GPP) = 4.61×10^{13}.

[9] Length (ft) = 4.80×10^3; unit price (\$/ft) = 1.50×10^1 (Bechtel Environmental, 1991); human services embodied in equipment and fuel used (\$) = (length)*(unit price) = 7.20×10^4.

[10] GPP calculation based on the damaged wetland ecosystem: gross primary production = 5.73×10^7 (J/m^2/yr) (Pritchard, 1992); energy (J) = (area)*(GPP) = 1.43×10^{13}.

[11] Excavation costs (\$) = 8.67×10^5 (Bechtel Environmental, 1991); total soil/sediment excavation (m^3) = 9.65×10^5 (Trnovsky et al., 1988); off-site sediment excavation (m^3) = 1.68×10^4 (Trnovsky et al., 1988) Costs embodied in equipment and fuel used (\$) = (Excavation costs)*(off-site excavation ratio) = 1.53×10^5.

[12] Peat (J) = (total volume)*(bulk density)*(energy content of peat) = 9.50×10^{13} (Odum et al., 1987).

[13] GPP calculation based on the damaged wetland ecosystem: gross primary production = 5.73×10^7 (J/m^2/yr) (Pritchard, 1992); energy (J) = (area)*(GPP) = 1.43×10^{13}.

recovery may cease or progress at only a slow rate. Thus, the GPP for this alternative (item 13) is estimated as that for an ordinary pond system, and not very different from that for a damaged wetland ecosystem.

Based on the emergy analysis, an empower graph for wetland production is shown in Fig. 2. The recovery rates from this graph provide a database for the emergy evaluation of the various wetland management strategies. Recovery rates for the three alternatives are projected as 20 years, 62 years, and infinite from 1991, shown as (a), (b), and (c), respectively. Wetland production over time is calculated by estimating the associated areas; i.e. wetland empower (sej/yr) = wetland production (sej)/time (yr).

The emergy evaluation of alternative management strategies with different recovery rates is summarized in Table 3. Emergy values for different works are listed for each alternative. Ecosystem processes, i.e. wetland production, and clean surface water being filtered and passed downstream are the major benefits provided to the society by a wetland ecosystem. By subtracting the emergy input for wetland management from the benefit of natural work, a net benefit can be obtained for each specific wetland management strategy. For the purpose of comparison, a monetary unit (macroeconomic value, 1990 US$) is used.

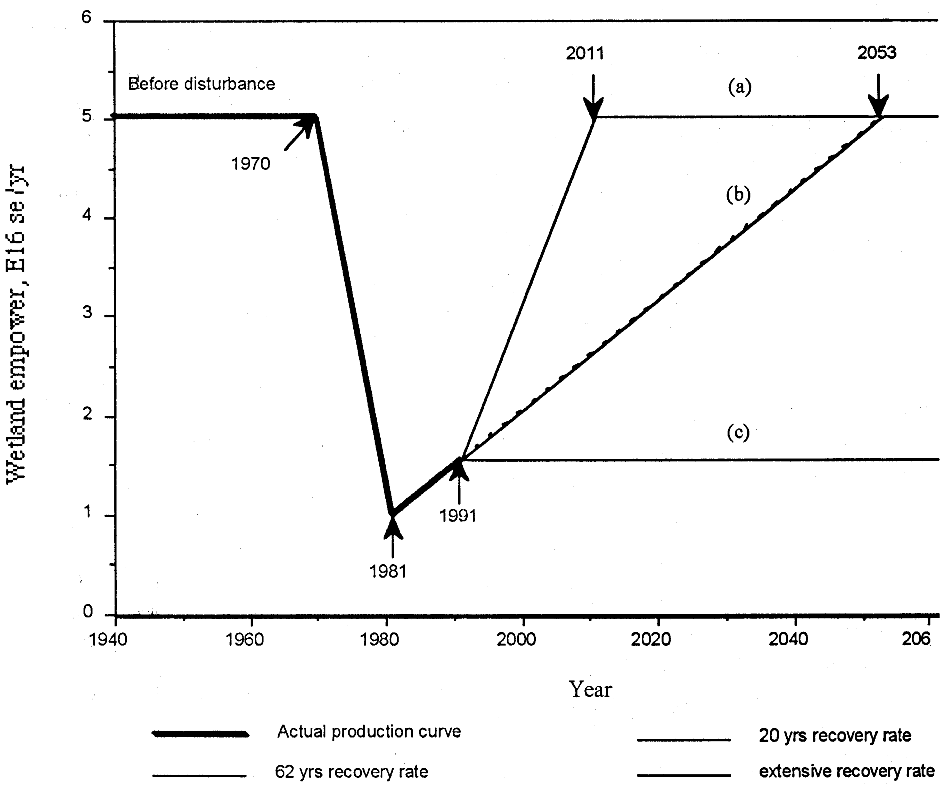

Fig. 2. Empower graph of wetland production with three alternatives: (a) planting, (b) land control, and (c) sediment excavation.

Table 3
Emergy evaluation of alternative management strategies with different recovery rates

Item	Emergy ($\times 10^{17}$ sej)		Macroeconomic value[a] ($\times 10^{6}$ 1990 US$)		Emergy investment	Emergy yield
	20 years	62 years	20 years	62 years	ratio[11]	ratio[12]
Planting					3.03	9.92
1. Ecosystem processes[1]	6.6	27.7				
2. Water filtered and passed downstream[2]	10.1	31.2				
3. Management cost[3]	1.5	1.5				
Net benefit (item 1+2−3)	15.2	57.4	0.756	2.87		
Land control					2.86	8.93
4. Ecosystem processes[4]	4.2	25.4				
5. Water filtered and passed downstream[5]	10.1	31.2				
6. Management cost[6]	1.4	1.4				
Net benefit (item 4+5−6)	12.9	55.1	0.643	2.76		
Sediment excavation					6.10	1.93
7. Ecosystem processes[7]	3.1	9.7				
8. Water filtered and passed downstream[8]	10.1	31.2				
9. Peat storages loss[9]	4.2	4.2				
10. Management cost[10]	3.1	3.1				
Net benefit (item 7+8−9−10)	5.9	33.6	0.296	1.68		

[a] Solar emergy, 2.0×10^{12} sej/$.
[1] Calculated from empower graph of wetland production (Figure 2): emergy (20 years) $= 6.6\times10^{17}$ sej; emergy (62 years) $= 27.7\times10^{17}$ sej.
[2] Calculated from Table 2 (item 3+4) $= 50.3\times10^{15}$ sej/yr: emergy (20 years) $= 10.1\times10^{17}$ sej; emergy (62 years) $= 31.2\times10^{17}$ sej.
[3] Calculated from Table 2 (item 5+6+7) $= 152.6\times10^{15}$ sej/yr.
[4] Calculated from empower graph of wetland production (Figure 2): emergy (20 years) $= 4.2\times10^{17}$ sej; emergy (62 years) $= 25.4\times10^{17}$ sej.
[5] Same as note 2.
[6] Datum from Table 2 (note 9) $= 144.0\times10^{15}$ sej/yr.
[7] Calculated from empower graph of wetland production (Figure 2): emergy (20 years) $= 3.1\times10^{17}$ sej; emergy (62 years) $= 9.7\times10^{17}$ sej.
[8] Same as note 2.
[9] Calculated from Table 2 (note 12) $= 420.0\times10^{15}$ sej/yr.
[10] Datum from Table 2 (note 11) $= 306.9\times10^{15}$ sej/yr.
[11] Emergy of management cost/emergy of environmental inputs (0.5 rain and run off, Table 2).
[12] Emergy of net benefit/emergy of management cost.

The net benefit emergy for wetland restoration by planting, alternative A, is 15.2×10^{17} and 57.4×10^{17} sej for 20- and 62-year recovery rates, respectively. Land control, alternative B, has a net benefit from 12.9×10^{17} to 55.1×10^{17} sej after 20 to 62 years of recovery. Due to the low productivity in pond systems and the lack of sediment to filter the pollutants, alternative C (sediment excavation) has the lowest benefit from natural input. The loss of sediment storage further reduces the net benefit for this option.

To apply the macroeconomic values to estimate the benefit to society after 20 years, \$756000, \$643000, and \$296000 are obtained for alternatives A, B, and C, respectively. The figures for 62 years are increased to \$2870000, \$2760000, and \$1680000 for A, B, and C, respectively. Results of emergy investment ratio are 3.03, 2.86, and 6.10 for alternatives A, B, and C, respectively. The net emergy yield ratio, which is the ratio of the emergy yield divided by the emergy used for processing, are obtained for alternatives A, B, and C as 9.92, 8.93, and 1.93, respectively.

The result of the net benefit calculations, i.e. macroeconomic values, suggest that alternative A is a better management strategy than the other two strategies for this impacted wetland ecosystem. Results of the emergy investment ratio calculations suggest that alternative C requires too much investment and cost from society, which would make this process economically uncompetitive. Results of net emergy yield ratio calculations were compared with some typical values of fuels and environmental products in an earlier report (Odum, 1996), ranging from 1.06 for palm oil to 12.0 for naturally grown rainforest wood. Alternative A evidenced a higher net emergy yield, i.e. 9.92, than for the most environmental products, and was even greater than for oil production, i.e. 7.9. Comparison of restoration of the wetland by planting (alternative A) with reclamation of a phosphate mine by succession (phosphate reclamation) showed that the net emergy yield of alternative A was greater than the net emergy yield of phosphate reclamation (found to be 1.61 by Brown, personal communication).

Since a good public policy for a nation or a state is to pursue resources and/or invest in processes with the highest net emergy yield ratio (Odum, 1996), the emergy evaluation practice in this study suggests that alternative A is the most appropriate management strategy for this impacted wetland ecosystem. Emergy evaluation proved to be a better way to value the nonmarketed goods and services which nature provides for our society.

References

Baumol, W.J., Blinder, A.S., 1985. Economics: principles and policy, 3rd edn. Harcourt Brace Jovanovich, New York, 893 pp.

Bechtel Environmental, 1991. Final Design Report for the Remedial Design at the Sapp Battery site, Vols. I, II, III. Oak Ridge, TN, 59 pp.

Bonnevie, N.L., Gunster, D.G., Wenning, R.J., 1992. Lead contamination in surficial sediments from Newark Bay, New Jersey. Environ. Int. 18, 497–508.

CH_2M HILL, 1991. Work plan for Ecological RI/FS Steel City Bay Operable Unit Sapp Battery Project, Jackson County, Florida. CH2M HILL, Gainesville, FL, 63 pp..

Ecology and Environment, 1989. Remedial Design Field Investigation Report Sapp Battery site, Jackson County, Florida. Ecology and Environment, Buffalo, New York, 166 pp.

Ewel, K.C., Odum, H.T., 1984. Cypress Swamps. University Presses of Florida, Gainesville, FL, 472 pp.

Keller, P.A., 1992. Perspectives on interfacing paper mill wastewaters and wetlands. M.S. Thesis, University of Florida, Gainesville, FL, 133 pp.

Odum, H.T., 1971. Environment Power and Society. Wiley, New York.

Odum, H.T., 1983. System Ecology: an introduction. Wiley, New York, 644 pp.

Odum, H.T., 1986. Emergy in ecosystems. In: Polunin, N. (Ed.), Ecosystem theory and applications. Wiley, New York, pp. 337-369.

Odum, H.T., 1988a. Emergy, Environmental and Public Policy: a guide to the analysis of system. Regional Seas Reports and Studies No. 95, United Nations Environment Programme, 109 pp.

Odum, H.T., 1988b. Self-organization, transformity, and information. Science 242, 1132–1139.

Odum, H.T., 1991. Emergy and biogeochemical cycles. In: Rossi, C., Tiezzi, E. (Eds.), Ecological Physical Chemistry: Proceedings of an International Workshop, 8–12 November 1990, Siena, Italy. Elsevier Science, Amsterdam, Netherlands, pp. 25–56.

Odum, H.T., 1996. Environmental accounting — Emergy and decision making. Wiley, New York.

Odum, H.T., Odum, E.C., Brown, M.T., LaHart, D., Bersok, C., Sendzimir, J., 1988. Environmental systems and public policy. Center for Wetlands, University of Florida, Gainesville, FL, 253 pp.

Odum, H.T., Wang, F.C., Alexander, J.F., Jr., Gilliland, M., Miller, M., Sendzimer, J., 1987. Energy analysis of environmental value. Center for Wetlands, University of Florida, Gainesville, FL.

Pritchard, L., Jr., 1992. The ecological economics of natural wetland retention of lead. M.S. Thesis, University of Florida, Gainesville, FL, 139 pp.

Scienceman, D.M., 1987. Energy and emergy. In: Pillet, G., Murota, T. (Eds.), Environmental economics: the analysis of a major interface. Leimgruber, Geneva, Switzerland, pp. 257–276.

Ton, S., 1993. Lead cycling through a hazardous waste-impacted wetland. Ph.D. Dissertation, University of Florida, Gainesville, Florida, 149 pp.

Ton, S., Odum, H.T., Delfino, J.J., 1996. Simulation studies of lead cycling through a natural wetland ecosystem, International Conference on Ecological Engineering, October 7–11, Beijing, China.

Ton, S., Delfino, J.J., Odum, H.T., 1993. Wetland retention of lead from a hazardous waste site. Bull. Environ. Contam. Toxicol. 53, 430–437.

Trnovsky, M., Oxer, J.P., Rudy, R.J., Hanchak, M.J., Hartsfield, B., 1988. Site remediation of heavy metals contaminated soils and groundwater at a fomer battery reclamation site in Florida. In: Abbou, R. (Ed.), Hazardous Waste: detection, control, treatment. Elsevier Science, Amsterdam, pp. 1581–1590.

Watts, G.B., 1984. The Sapp battery site, Jackson County, Florida remedial investigation. FDER, Tallahassee, FL, 302 pp.