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Emergy valuation of diversions of river water to marshes in the Mississippi River Delta

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Abstract

River diversions within the Mississippi Delta deliver river water and associated sediments and nutrients to interior marshes that were previously isolated from river inputs by elevated levees. When isolated from river inputs, the marshes subside and deteriorate to open water, resulting in ecological and economic losses. River diversions are an ecological engineering method to reverse this trend by restoring controlled flows of river water through modified levees. This study compares the cost of constructing and operating the diversions with potential benefits to determine whether the diversions yield a net public benefit. The Caernarvon and Davis Pond river diversions were evaluated using emergy analysis to provide a common basis to quantify and compare economic and ecological costs and benefits. The analysis quantified high concentrations of natural resources inherent to deltas and demonstrated benefits produced by investing economic resources in river diversions to capture and utilize renewable resources. The diversions resulted in large net emergy yield ratios (33.2 and 9.36) that varied depending on the rate of marsh gain produced by the diversions. © 2002 Elsevier Science B.V. All rights reserved.

Keywords: River diversion; River delta; Emergy; Energy analysis; Ecological economics

1. Introduction

Ecological engineering projects operate at the interface between nature and human society, and are created to utilize natural resources to provide societal and environmental benefits. Justifying such projects is often problematic because of the necessity to compare flows from the human economy and flows of environmental resources. This problem is typified by river diversions that restore river inputs to deltaic marshes and require economic investments including labor, materials, and fuels. Do the benefits derived from these projects, including stabilizing and creating coastal marshes, and sustaining and augmenting the production of coastal fisheries, merit the required economic investments? Large capital costs, as high as US$10 million (Table 1), necessitate the comparison of inputs with potential impacts on the system to justify such projects.

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Table 1

A summary of diversion characteristics and projected rates of change used for this study

Diversion	Project area (km^2)[a]	Initial coverages (km^2)[b]		Land gain with diversion (km^2/year)	Land lost without diversion (km^2/year)	% River flow into diversion[d]	Total cost (1×10^6 \$)	Emergy/\$ ratio (1×10^{12} sej/\$)[c]
		Marsh cover	Open water					
Caernarvon	127	52	75	1.29[d]	1.03[e]	1.6	23[f]	2.00
Davis Pond	1158	822	336	–	–	2.1	104[g]	1.55

The emergy analysis for the Davis Pond diversion was performed across a range of land gain and loss rates.

[a] Based on Louisiana Department of Natural Resources (1995), adapted to match initial coverages and allow annual land gain rates for 50 years.

[b] Inital land/water ratio from Barras et al. (1994).

[c] Odum (1996).

[d] Turner and Boyer (1997).

[e] Based on Reed (1995), rates were normalized to account for project area.

[f] United States Army Corps of Engineers (1985).

[g] United States Army Corps of Engineers (1991).

All energy contributions influence an ecosystem's pattern of structure and function (Nixon, 1988). Therefore, it is critical to employ methodologies that properly account for all energy flows of a system including those from economic sectors and natural flows. Emergy analysis, which evaluates system components on a common basis, is an alternative to determine the net value of environmental projects to human society. Using this technique, natural and human contributions required to construct and operate two diversions were expressed in common units of solar energy. The Caernarvon diversion is located downriver of New Orleans and discharges into the Breton Sound estuary (Figs. 1 and 2). The Davis Pond diversion, located upriver of New Orleans, discharges into the Barataria estuary (Figs. 1 and 3). The analyses compare each diversion with the null alternative of no diversion.

1.1. Emergy analysis

Many environmental projects are characterized by the investment of high-quality energies from the human economy to capture and concentrate lower quality natural energies and divert them to the needs of human society. The construction of dams to produce electricity is an example. The value of economic contributions is routinely quantified by economic analyses. However, due to lack of accounting for inputs and outputs that are not directly valued on a monetary basis, such as river sediments and marsh productivity in the case of river diversions, such approaches often underestimate environmental contributions. Economic analyses and the economic market only recognize monetary values, but economies rely on very large inputs from the environment. If these environmental inputs are disregarded, the optimum use of resources may not be achieved and management

Fig. 1. Water flows from the Mississippi River (bottom of photograph), through the Caernarvon diversion, into a channel (top of photograph) that directs the flow to the Breton Sound marshes.

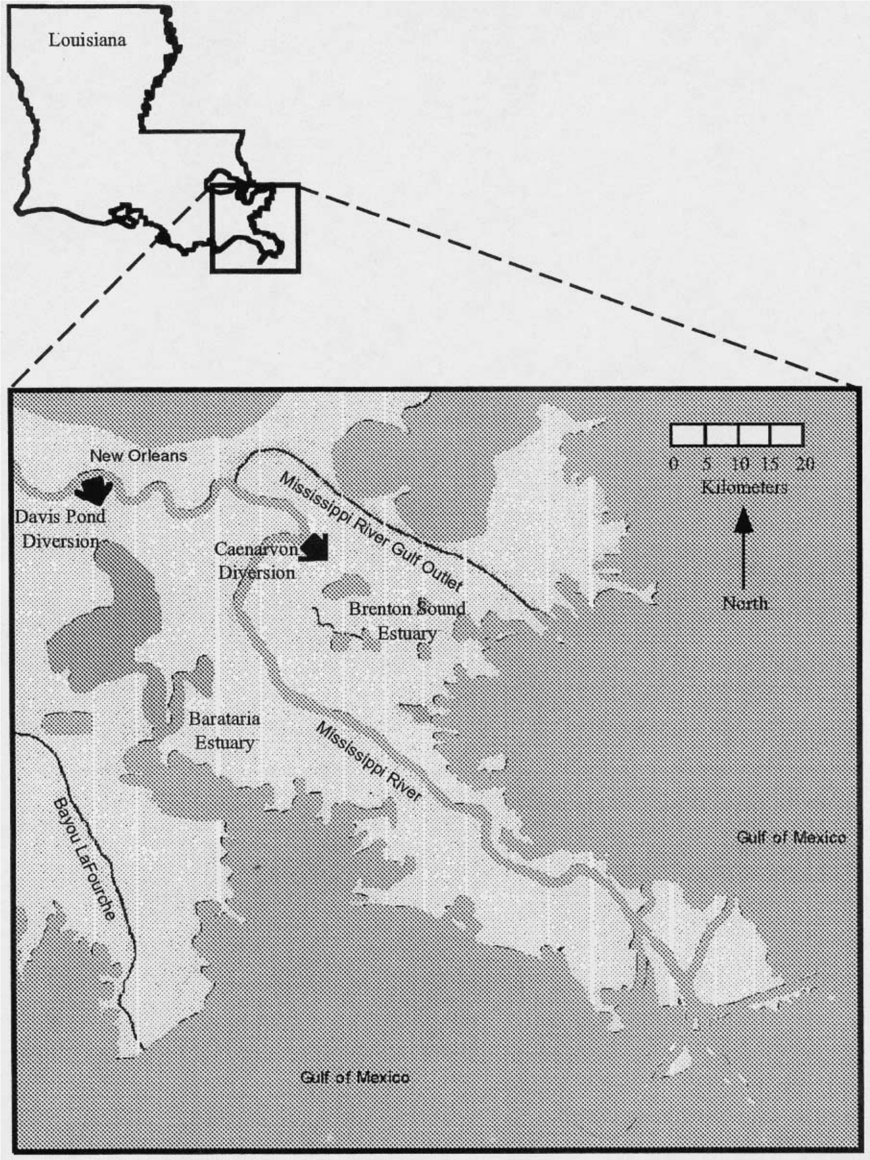

Fig. 2. Located 20 km downriver of New Orleans, the Caernarvon diversion will direct Mississippi River water to the Breton Sound estuary. The Davis Pond diversion, located 15 km upriver of New Orleans, will divert Mississippi River water to the Barataria estuary. The Breton Sound estuary is bounded by the Mississippi River, the Mississippi River Gulf Outlet, and the Gulf of Mexico. The Mississippi River, Bayou LaFourche, and the Gulf of Mexico bound the Barataria estuary.

decisions will be based on incomplete analyses (Ulgiati et al., 1994). Emergy analysis is a form of energy analysis that quantifies values of natural and economic resources on a common basis to derive the value of nature to the human economy (Odum, 1988). Solar emergy is used to determine the value of environmental and human work within a system on a common basis: the equivalent solar energy required to produce each service or product. The fundamental assumption of emergy analysis is that the contribution of a resource is proportional to the available energy of one kind required to produce the resource (Brown and Herendeen, 1996). The solar emergy of products and services is calculated by multiplying units of energy (i.e. joules of oil) by emergy per energy ratios (transformities), units of mass (i.e. grams of river sediment) by emergy per mass ratios, and dollars by emergy per dollar ratios.

Definitions for key terms related to emergy analysis follow (Brown and McClanahan, 1996).

Emergy. An expression in one type of energy of all the available energy used in the work processes, directly and indirectly, that generate a product or service.

Emdollar. The total amount of money flow generated by a given amount of emergy input. It is calculated by dividing the emergy input by the emergy/gross national product ratio (Ulgiati et al., 1994).

Transformity. The ratio obtained by dividing the total emergy that was used in a process by the energy yielded by the process. Transformities are used to convert different energies to emergy of the same type. Emergy per mass and emergy per dollar ratios are used in the same manner to convert mass and dollar values to emergy.

Solar emjoule (sej). The units of solar energy previously used to generate a product.

Transformities quantify the emergy required for the production of a good or service and occupy a central role when performing emergy analyses. Transformities are expressed as the emergy per unit energy. For example, the transformity of corn is 8.3×10^4 sej/J (Odum, 1996). Required inputs for the production of corn on a contemporary farm include the environmental energies of sun, rain, wind and soil, and human inputs of fertilizers, pesticides, machinery, labor, and management. The transformity value indicates that 8.3×10^4 solar joules are necessary to create these

Fig. 3. Construction of the Davis Pond diversion shows the relocated railroad and highway, and the design of the diversion structure. The Mississippi River is flowing towards the top of the photograph to New Orleans.

inputs and, therefore, required to produce each joule of available energy in corn. Tables of calculated transformities facilitate emergy evaluations (Odum, 1996).

Another function of transformities is to position goods and services within a hierarchy of energy quality (Odum, 1988). All forms of energy do not accomplish equivalent amounts of work. Information, human labor, and advanced technological devices have relatively small energy flows, but require large amounts of solar emergy for their formation and maintenance (Brown and Herendeen, 1996). These energy flows have a higher quality with greater transformities and the ability to feedback and amplify flows of lower quality energies (Odum, 1988). Emergy analyses of river diversions were performed to determine whether the amount of low-transformity natural products captured, such as river water and sediments, merited the investment of high-transformity goods and services such as information, labor, and machinery required to construct and maintain the diversions (Martin, 2000a).

Emergy analyses have been used to quantitatively explore public policy options for the Mississippi delta (Day et al., 1997), Italy (Ulgiati et al., 1994), and Taiwan (Huang and Odum, 1991; Huang, 1998), and have been applied to many other smaller scale systems (Odum, 1996). This technique has also been used to evaluate proposals of dam construction on the Mekong river (Brown and McClanahan, 1996). Similar to the Mekong study, the river diversion analysis demonstrates the ability of emergy analysis to quantitatively evaluate specific environmental management options with regards to patterns of sustainable development.

1.2. The delta cycle and river diversions

Over the past 7000 years, the Mississippi Delta has been formed and maintained by a hierarchical series of depositional events. Floods of the Mississippi River historically distributed sediment throughout the delta, resulting in major spatial changes in geomorphology. The natural progression of events that accompanies the prograding and deteriorating phases of delta-building events is referred to as the delta cycle (Roberts, 1997). The operation of this cycle over a range of scales ensures efficient dispersal over the entire deltaic plain, resulting in the extensive interdistributary wetlands that comprise the Mississippi deltaic plain of southeast Louisiana.

During the past two centuries, human activities have had a pervasive impact on delta ecosystems. These actions isolate deltas from the river inputs that formed and sustained them, and now threaten the existence of these systems and the societal benefits they produce. Flood control levees, navigation structures, closure of distributaries, and construction of dikes and canals have interrupted this cycle and eliminated channel switching and development of new depositional areas (Day et al., 1997). Elevated levees along the main channel of the Mississippi have interrupted the annual flooding of deltaic marshes and direct sediments out of the delta system to the Gulf of Mexico, beyond the continental shelf. As a result, marshes within the Mississippi delta succumb to subsidence and experience rapid rates of deterioration (Fig. 4). Land loss rates for the Louisiana coastal plain have ranged from 65 to 109 km^2/year during the past 30 years (Britsch and Dunbar, 1993). Within the Barataria estuary (Fig. 2), reported rates of land loss are 25 km^2/year (Reed, 1995).

The loss of coastal marshes results in negative economic and ecological consequences. As an area of marsh changes to open water, the net primary productivity (NPP) of the area decreases from 6.97×10^7 to 2.33×10^7 J/m^2 per year, a 67% decline (Bahr et al., 1982). Such decreases can lead to dramatic drops of productivity across the delta. For instance, over three decades, the total NPP of the Terrebonne and Barataria basins within the Mississippi Delta has decreased by 26% (Day et al., 1997). The reliance of coastal fishery production on the existence and productivity of surrounding marshes has been established by many studies (Turner, 1977; Nixon, 1982; Deegan, 1993; Houde and Rutherford, 1993; Rozas and Reed, 1993). Using data from 36 marine systems, Nixon (1988) discovered a linear relationship between primary production and fisheries yield. Based on the documented dependence of coastal

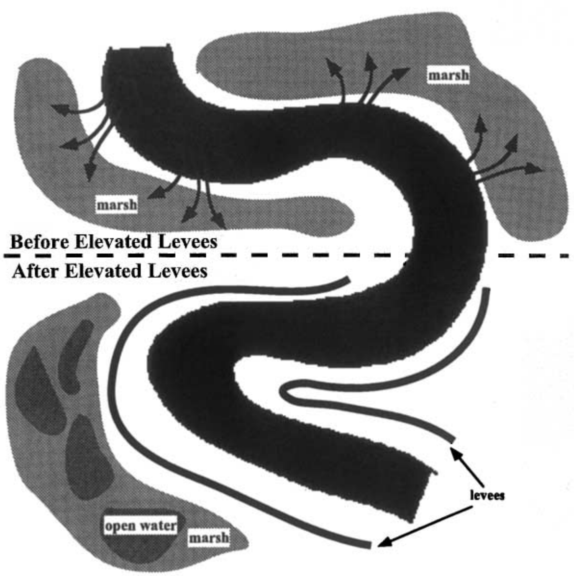

Fig. 4. Before elevated levees, floods delivered sediments and nutrients that stimulated marsh productivity and sustained marsh elevation. After levees were elevated in the Mississippi delta, river inputs to marshes were eliminated. Marshes then subsided and became open water bodies, resulting in decreased productivity. River diversions restore flows of river water to the marshes.

fisheries on the productivity of surrounding marshes, the conversion of deltaic marshes to open water jeopardizes future fishery harvests. Such changes are sure to have a negative impact upon the economy of the delta. Fishing alone contributes over $1 billion dollars to local economies, and other wetland-related activities (hunting, alligator harvest, production of furs) are estimated to contribute another $1 billion (Day et al., 1997). The economies of deltaic societies are dependent on natural resource flows from deltaic marshes.

Since identifying deteriorating deltas throughout the world (Stanley and Warne, 1993; Day et al., 1995; Turner, 1997), a series of remedies have been proposed (Day et al., 1997). River diversions are an alternative that restore natural deltaic functioning through controlled diversions mimicking the natural delta cycle. The ability to manage the flowrate through the diversions provides continued flood protection and navigation. The United States Army Corps of Engineers completed constructed of the Caernarvon river diversion in 1991 (Lane et al., 1999), and began construction of the Davis Pond diversion in 1997. The design of the diversions includes culverts or siphons that run through the levee and a channel to guide the water to the marshes. The large costs (Table 1) are due to the amount of design, construction, equipment, and structure necessary to ensure stability of the levee while at the same time regulating flow through the levee. Relocation costs of railroads, highways, utilities, and pipelines also contribute to the cost of each project (Fig. 3).

Subsequent to the introduction of river water and associated sediments and nutrients, maintenance of existing marsh and building of new marsh is expected. These trends have been observed within the Caernarvon diversion site (Villarrubia, 1998) and are forecast for the Davis Pond project by a landscape simulation model (Martin et al., 2000). The greater productivity of the newly created and sustained marsh compared with open water habitats will continue to provide the basis of a food chain supporting the lucrative coastal fishing industry. The linkages from sustained and newly created marshes evaluated in this study involved changes in marsh and fisheries production. Because of increases in vegetative productivity, more primary production is exported to support higher trophic production in coastal environments (Turner, 1977; Nixon, 1988; Peters and Schaaf, 1991; Houde and Rutherford, 1993). In addition to changes in export of vegetative material, the linear relationship described by Nixon (1988) was used to predict changes in exported fish biomass following changes in marsh coverage.

2. Methods

2.1. Constructing the emergy analysis table

The methodology for the emergy analysis began with the construction of a systems diagram to organize relationships between components and pathways of resource flow (Fig. 5). Important emergy inputs characterizing river diversion projects include the sun, wind, rain, tides, the river, and imported resources and services utilized to construct and maintain the diversion (Fig. 5). Pertinent interactions within these settings are the productivity of coastal marshes and open water areas, the diversion of river inputs to promote marsh productivity and the loss of marsh elevation due to relative sea-level rise (eustatic sea-level rise plus subsidence).

The emergy analysis table (Table 2) was constructed directly from the diagram (Fig. 5) using inflows and outflows crossing the system boundary as row headings. Using the table, the annual amount of input or output of each flow is first quantified in raw units (joules, grams, dollars). Then, by multiplying by the respective transformity, the annual solar emergy of each flow is calculated.

2.1.1. Renewable resources

To avoid double-counting, the environmental inputs (1–3) are not accumulated to calculate the total input of renewable resources. Since these inputs are interdependent on the same initial energies, the largest input is chosen as the sum of these inputs (Odum, 1996); in this case, the chemical emergy of the rain. The emergy of river

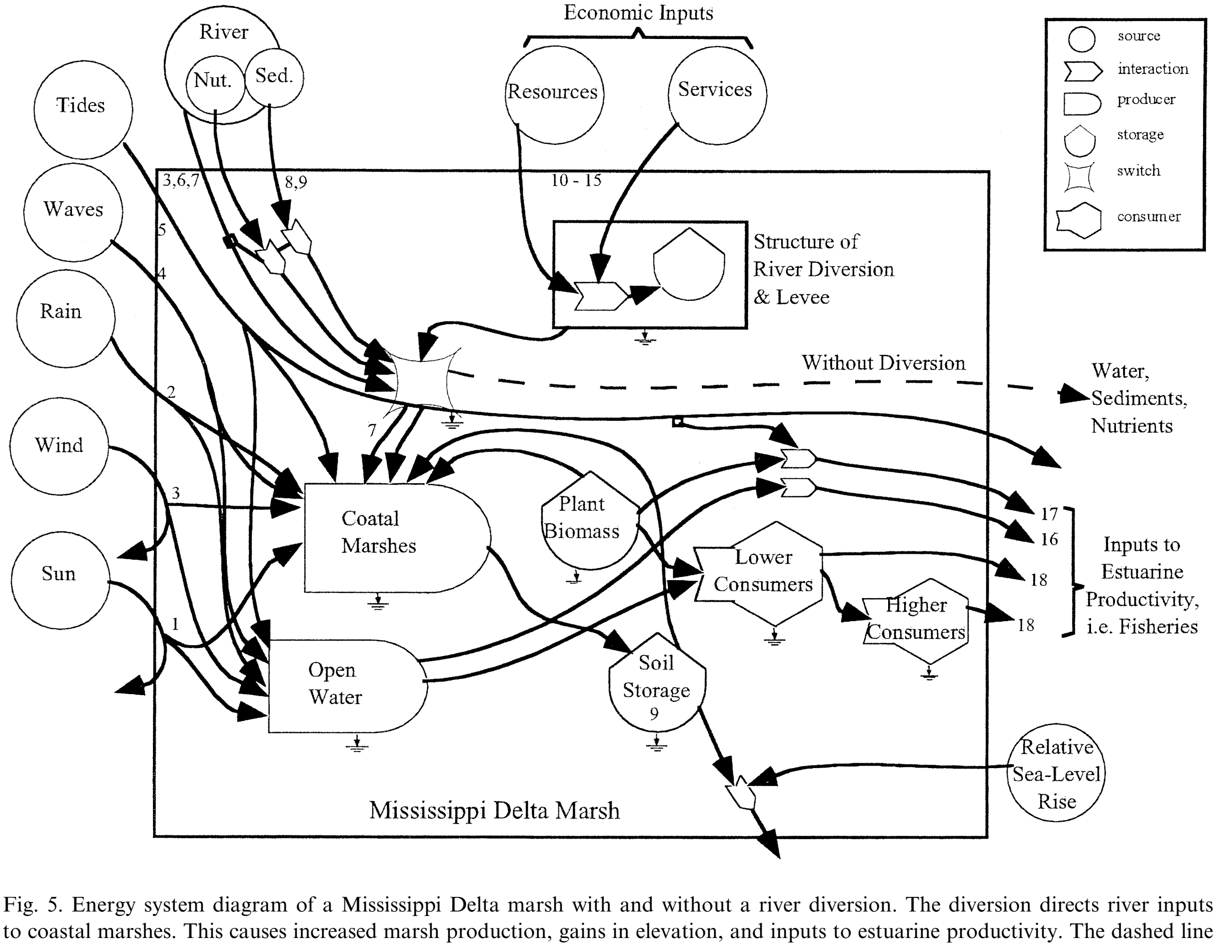

Fig. 5. Energy system diagram of a Mississippi Delta marsh with and without a river diversion. The diversion directs river inputs to coastal marshes. This causes increased marsh production, gains in elevation, and inputs to estuarine productivity. The dashed line illustrates the flow of river freshwater, nutrients, and sediments bypassing the delta without the diversion. Inputs and outputs from the system determined the row categories in the emergy analysis table (numbers refer to the row headings of Table 2).

Table 2
Emergy analysis table in which raw units were multiplied by the emergy per unit to determine the solar emjoules associated with a flow

Item	Raw units	Emergy per unit	Solar emergy (10^{18} sej)				
			Caernarvon			Davis Pond	
			With diversion		Without diversion	With diversion	Without diversion
			Year 1	Years 1–50	Years 1–50	Years 1–50	Years 1–50
Renewable resources							
1 Sunlight	4.84×10^{17} J	1.00×10^{5} sej/J	0.48	24.18	24.18	220.48	220.48
2 Rain-chemical	9.47×10^{14} J	1.82×10^{4} sej/j	17.24	862.08	862.08	7860.57	7860.57
3 River geopotential	2.12×10^{17} J	3.18×10^{4} sej/j	6750.00	338 000.00	0.00	443 000.00	0.00
4 Wind-kinetic	1.42×10^{14} J	1.50×10^{3} sej/J	0.21	10.64	10.64	97.02	97.02
5 Waves	1.49×10^{10} J	3.06×10^{4} sej/J	0.00	0.01	0.03	0.10	0.13
6 Tide	1.22×10^{13} J	1.68×10^{4} sej/j	0.21	5.95	14.03	46.80	57.20
7 Riverine water use—open water	3.64×10^{14} J	4.11×10^{4} sej/J	15.00	434.00	1020.00	3410.00	4170.00
8 Riverine water use—marsh	5.27×10^{14} J	4.11×10^{4} sej/J	21.60	1710.00	533.00	16 700.00	15 200.00
9 Riverine sediments captured	1.57×10^{12} g	6.28×10^{8} sej/g	984.70	49 235.20	0.00	64 621.20	0.00
10 Riverine minerals stored	1.53×10^{12} g	6.28×10^{8} sej/g	962.80	47 482.59	−546.07	47 500.00	−15 500.00
Total renewable resources			6804.05	341 012.04	2429.11	471 017.37	27 287.77
Imports							
11 Land costs	2.24×10^{3} \$	2.00×10^{12} sej/\$	0.00	0.22	0.00	13.20	0.00
12 Relocation	1.78×10^{4} \$	2.00×10^{12} sej/\$	0.04	1.78	0.00	53.32	0.00
13 Construction	2.52×10^{5} \$	2.00×10^{12} sej/\$	0.50	25.20	0.00	68.70	0.00
14 Steel	5.08×10^{7} g	1.80×10^{9} sej/g	0.09	4.57	0.00	20.00	0.00
15 Concrete	3.16×10^{9} g	7.00×10^{7} sej/g	0.22	11.10	0.00	11.50	0.00
16 Operation and maintenance	2.44×10^{5} \$	2.00×10^{12} sej/\$	0.49	5.35	0.00	4.15	0.00
Total imports			1.34	48.22	0.00	170.87	0.00
Exports							
17 Net primary production—open water	1.72×10^{15} J	4.70×10^{3} sej/J	8.07	234.08	551.66	1840.00	2250.00
18 Net primary production—marsh	7.45×10^{14} J	6.96×10^{3} sej/J	5.17	408.71	127.34	3990.00	3620.00
19 Fisheries	3.43×10^{13} J	8.00×10^{6} sej/J	274.00	14 413.05	12 777.40	133 000.00	131 000.00
Total exports			287.24	15 055.84	13 456.0	138 830.00	136 870.00

The raw units correspond to the Caernarvon with diversion scenario for year 1. The final four columns are cumulative over the 50-year analysis period. These cumulative values represent flows entering and exiting the entire area of each project. A land gain rate of 0.0 with diversion and land loss rate of 3.0 km^2/year without diversion were used for Davis Pond. Appendix A contains calculations of raw units and emergy per unit references.

geopotential was calculated by multiplying the flow rate of water into each diversion by the transformity for geopotential specific to the Mississippi Delta (Appendix B). The flow of river sediment was calculated as the sediment inputs via the diversion minus sediment lost through subsidence. Subsidence was assumed to only impact marsh area. Because less than 5% of the particulate matter in the lower Mississippi River is organic matter (Rostad et al., 1997), all sediment was multiplied by the emergy per mass for mineral sediment (6.28×10^8 sej/g) (Martin, 2000b) (Appendix B). River geopotential and river sediments are both generated by rainfall and geologic uplift in the upper reaches of the Mississippi Basin. Therefore, to avoid double-counting, only the greater of these two inputs (river geopotential) was accounted for in the total renewable resources.

2.1.2. Inputs

The inputs were disaggregated to the greatest extent possible from cost estimates provided by the United States Army Corps of Engineers (1991, 1985). However, with the exceptions of steel and concrete, dollar values were used to estimate the emergy of inputs to the system. Previously calculated emergy/dollar ratios were used to convert these monetary values to solar emjoules. This ratio measures the emergy-buying power of the dollar and was calculated by dividing the annual United States inflow of emergy by the Gross National Product (Ulgiati et al., 1994). The solar emergy supporting the United State's currency was 2.00×10^{12} sej/\$ in 1985, the year of construction of the Caernarvon diversion, and 1.55×10^{12} sej/\$ in 1991, the year of the Davis Pond economic analysis (Odum, 1996; Table 1).A discount rate of 9% was used to determine the present value of future operation and maintenance costs.

2.1.3. Exports

It was assumed that 100 and 15.5% of the primary production from open water and marshes, respectively, would be exported from the system, based on a previous study by Bahr et al. (1982). Following Houde and Rutherford (1993), the regression relationship between fish harvest and primary production in coastal systems developed by Nixon (1988) was used to predict catches in the two estuaries impacted by the river diversions (Eq. (1)). Because of higher primary productivity rates for Mississippi delta marshes (1850 g C/m^2 per year) compared with open water areas (445 g C/m^2 per year) (Bahr et al., 1982), the fishery yield increased over time as marsh habitat replaced open water areas. The transformities of the three exports range over three orders of magnitude, and imply that the nekton require almost three times the amount of solar energy to produce a joule of energy then the open water productivity. The order of transformities is indicative of their relative location within the estuarine food chain.

$$\ln \mathrm{FY} = 1.55 \ln \mathrm{PP} - 4.49 \tag{1}$$

where FY is the fishery yield (kg/ha per year), and PP is the primary production (g C/m^2 per year).

2.1.4. Marsh area and rates of change

Differences in the outcomes of the scenarios with and without diversions were driven by changes in areal coverage of marsh and open water. Table 1 denotes the constant rates of marsh loss without diversions and marsh gain with the diversions used for Caernarvon. Marsh loss was based on historical trends (Reed, 1995), and the rate of marsh gain was based on predictions of the Louisiana Department of Natural Resources (Turner and Boyer, 1997). Simulations of a diversion with a landscape model predicted the preservation of 3.76 km^2 marsh annually (Martin et al., 2000). Because this amount was only slightly greater then the annual rate of marsh loss, the Caernarvon diversion, when activated, was assumed to inhibit all future marsh loss. The fact that preservation of existing marsh requires far less sediment inputs than creation of new marsh (Templet and Meyer-Arendt, 1988) further supports this assumption. Due to a range in predicted land gain rates for the Davis Pond diversion (from no growth (United States Army Corps of Engineers, 1991) to 6.72 km^2/year (Turner and Boyer, 1997)), the emergy analysis was performed across a range of land loss and gain rates (from a loss of 3 km^2/year to a gain of 6.72 km^2/year).

The total area of initial marsh and open water coverages was calculated based on marsh to land ratios and predicted rates of change. From a 1990 habitat distribution survey for the Breton Sound and Barataria estuaries (Barras et al., 1994), marsh/open water ratios were calculated (0.412 for Breton Sound, 0.717 for Barataria). Using these ratios as one constraint, and the maximum amount of marsh lost (minimal initial marsh coverage) and the maximum amount of marsh gained (minimal initial water coverage), the initial coverages for both sites were determined (Table 1).

2.2. Calculation of system indices

Emergy indices (Table 3 and Fig. 6) were calculated by aggregating data presented in Table 2. These indices, which relate flows from the economy to flows of the environment, are used to predict net yields and to select sustainable management options. When two alternative systems are compared, the one that exports the most emergy to the public economy and other systems is considered best (Brown and McClanahan, 1996). Systems that rely heavily on renewable energies provided by nature represent more sustainable options. The Emergy Yield Ratio compares units of exported emergy with emergy invested. In river diversions, an investment of emergy from the economy is made in order to capture renewable emergy from the river. The Index of Renewable Emergy Captured was calculated to quantify the emergy captured per emergy invested. These ratios provide a metric of comparison between different choices for the system and allow comparison with other environmental projects.

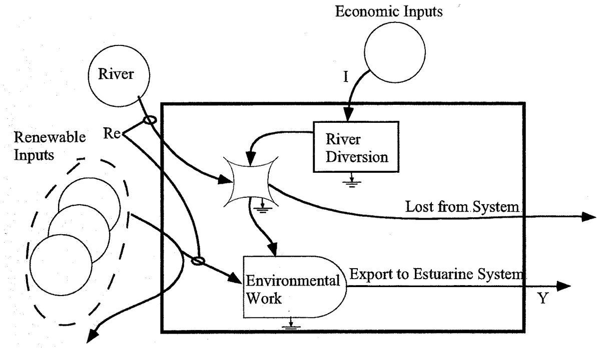

Fig. 6. Aggregated system diagram of a deltaic marsh where resources are imported (I) to build river diversions that direct river inputs to interact with other renewable inputs (Re) to produce exports (Y). Without river diversions, the river energies are input directly to the Gulf of Mexico, which reduces the exports from the marsh to the coastal system. Letters denote pathways used in the calculation of indices (Table 3).

3. Results

3.1. Emergy analysis table

3.1.1. Renewable resources

A substantial gain in renewable energies entering the system occurred with implementation of the river diversions at each location. At Caernarvon and Davis Pond, the contribution of river inputs, calculated as the difference between the with and without scenarios, was 3.17×10^{22} and 4.44×10^{23} sej, respectively (Table 3). River geopotential was the largest renewable resource input in both cases by nearly an order of magnitude (Table 2). This was a consequence of both the quantity of water and the transformity of the water (3.18×10^4 sej/j; Appendix B). River sediments were the second largest renewable resource input in both cases (Table 2). This was due to the quantity of sediments and the large emergy per mass of the sediments (6.28×10^8 sej/g; Appendix B (Martin, 2000b). The change in the sediment storage demonstrated the potential of diversions to sustain and build marsh in subsiding delta areas. Positive sediment budgets for each diversion changed to deficits without the diversions. With the diversions, more productivity shifted to the marshes and away from open water habitats. This trend was reflected by the greater use of river chemopotential emergy over time (Table 2, rows 7 and 8). For Caernarvon without the diversion, open water use of river water constituted an input of 1020×10^{18} sej and the marsh use of river water represented an input of 533×10^{18} sej, for a total of 1550×10^{18} sej. With the diversion at Caernarvon, the total contribution of river water was 2140×10^{18} sej, with marsh use (1710×10^{18} sej) contributing more than open water (434×10^{18} sej). Wave and tidal inputs (Table 2, rows 5 and 6) decreased with the diversions because of a decline in open water area. This difference

Table 3
Emergy indices for the two diversion projects

Description	Calculation (refer to Fig. 4)	Units	Caernarvon		Davis Pond	
			With diversion	Without diversion	With diversion	Without diversion
Renewable emergy flow	Re	10^{18} sej	341 000	2430	471 000	27 300
Inputs	I	10^{18} sej	48.2	0	171	0
	I	10^{7} em$	2.41	0	11.0	0
Exports	Y	10^{18} sej	15 100	13 500	139 000	137 000
Emergy Yield Ratio (EYR)		sej/sej	313	–	813	–
Net Emergy Yield Ratio (NEYR)	Y/I	sej/sej	33.2	–	9.4	–
Renewable Emergy Captured (REC)		em$/em$	7080	–	2750	–
Net Renewable Emergy Captured (NREC)	Re/I	$/$	7020	–	2600	–
REC − NREC		$/$	60	–	150	–

Indices for the ‘without’ scenarios went to infinity because imports from the economy were zero. A land gain rate of 0.0 with diversion and land loss rate of 3.0 km^2/year without diversion were used for Davis Pond.

(8.10×10^{18} sej for Caernarvon, 10.4×10^{18} sej for Davis Pond) was minor when compared with the previously discussed gains.

3.1.2. Inputs and exports

The emergy imported for the construction and maintenance of each project was 48.2×10^{18} and 171×10^{18} sej for Caernarvon and Davis Pond, respectively (Table 3). Expressed in emdollars by dividing by the emergy dollar ratio, these values were 2.41×10^7 and 11.0×10^7 (Table 3). Scenarios without diversions were assumed to have zero imports. Investing emergy to capture more renewable energies resulted in exports increasing from $13\,500 \times 10^{18}$ to $15\,100 \times 10^{18}$ sej for Caernarvon (Table 3). At both sites, the greatest contribution to these increases was from fish exports. The three orders of magnitude difference in transformity between the fish and vegetative exports led to the predominance of fishery exports. Due to land coverage changes, the productivity of the marshes increased while that of open water habitats decreased with the diversions. The declines in the export of open water production were greatly overshadowed by increased exports of marsh production and nekton.

3.2. Emergy indices

3.2.1. Emergy yield ratio

This ratio was calculated by dividing the exported emergy flow by the emergy imported from the economy. This ratio has been referred to as the 'emergy return on investment' and 'net emergy gain' (Odum, 1988) because it quantifies the amount of emergy that is exported due to an economic investment (Fig. 6). Any process with an Emergy Yield Ratio greater than one contributes to the system more than it withdraws, with larger values indicative of greater contributions. The Emergy Yield Ratios for the diversions were 313 for Caernarvon and 813 for Davis Pond (Table 3). Because of the large amount of emergy exported without the diversions, a Net Emergy Yield Ratio was calculated as the difference in exports with and without the diversion divided by the imported emergy. The Net Emergy Yield Ratios were 33.2 for Caernarvon and 9.36 for Davis Pond (Table 3). The greatly reduced net yields for the two projects highlight the importance of calculating net ratios in settings where a substantial amount of export will occur in the null scenario. By accounting for the net yield difference with and without the diversions, the Net Emergy Yield Ratio identifies only the added exports derived from the projects. This index was sensitive to the rate of marsh change due to the diversions. For instance, increasing the rate of land gain to 3.00 km^2/year from 0.0 km^2/year (no loss or gain) increased the Net Emergy Yield Ratio from 9.36 to 18.2 for Davis Pond. A quadratic relationship was found between the Net Emergy Yield Ratio and land gain/loss rates for the Davis Pond diversion (Fig. 7).

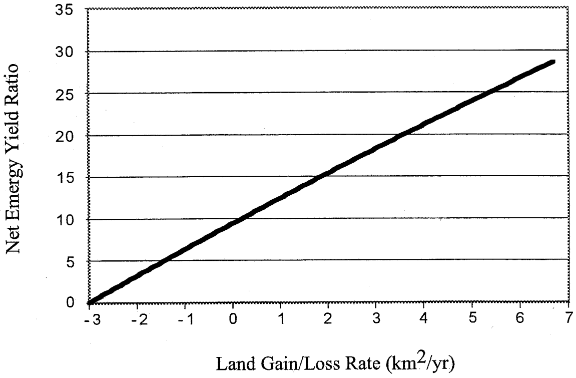

Fig. 7. A sensitivity analysis determined the quadratic relationship between Net Emergy Yield Ratio (NEYR) and Land Gain/Loss Rate (LG) for the Davis Pond Diversion to be: $\text{NEYR} = -0.03\text{LG}^2 + 3.04\text{LG} + 9.36$. The X intercept occurs at a land loss rate of 3 km^2/year because this rate was chosen as the background rate of land loss.

3.2.2. Renewable emergy captured

The Renewable Emergy Captured index quantifies the renewable emergy that was captured and input to the system on an emdollar per emdollar basis (Table 3). For instance, the Renewable Emergy Captured for Caernarvon (7080) indicates that 7080 emdollars of value can be captured by investing 1 emdollar. This ratio was calculated by dividing the input of renewable resources by the total imported emergy from the economic system (Fig. 6). Both of these values were converted to emdollars by dividing each contributing non-dollar flow by the respective emergy-to-dollar ratio for each project (Table 1). To isolate the captured river resources, the Net Renewable Emergy Captured was calculated for each project by determining the difference between renewable resources with and without the diversions and dividing by the imported emergy. The Net Renewable Emergy Captured was 7024 for Caernarvon (Table 3). Subtracting the Net Renewable Emergy Captured from the Renewable Emergy Captured identified the amount of the renewable energies driving each system in the absence of river inputs (Table 3).

4. Discussion

4.1. Assumptions

Several studies have confirmed that coastal fishery production in areas with extensive intertidal zones is largely dependent on energy fixed in estuaries and wetlands (Turner, 1977; Bahr et al., 1982; Nixon, 1982; Deegan, 1993; Houde and Rutherford, 1993; Rozas and Reed, 1993). This is perhaps the most direct impact of river diversions on the economy and demonstrates the importance of sustaining and augmenting current export levels and the potential impacts of increased Emergy Yield Ratios. Because of the greater transformity of fish relative to primary productivity, increases in fishery exports represented nearly 100% of the total increase in exports with diversions. Accordingly, the results of the study were sensitive to the transformity of the fishery exports. Reducing the fish transformity by 50% from 8.00×10^6 to 4.00×10^6 reduced the Net Emergy Yield Ratio by 56 and 52% for Caernarvon and Davis Pond, respectively. During the progradation of the Mississippi Delta, coastal marshes have received large amounts of low-transformity river inputs and exported higher transformity products, such as fish, to the adjacent coastal system. The current hypoxia zone along the Louisiana coastline (Rabalais et al. 1996) illustrates the effect of bypassing marshes and delivering great amounts of lower transformity river inputs directly to coastal waters.

The amount of exports from the system represent a conservative estimate. The 50-year period of evaluation was based on the United States Army Corps of Engineers (1985, 1991) estimated project life. Even if the structures did fail after 50 years, the created marsh and sediment storage will continue to provide system benefits well beyond this period of time. Additional components not included in the analysis were storm protection (Farber, 1987; Stone et al., 1997) and nutrient reduction (Villar et al., 1996; Lane et al., 1999) provided by the marshes and enhancement of higher trophic levels, such as waterfowl, reptiles, and mammals.

The uncertainty and variability of transformities used in emergy analysis have been questioned and criticized (Brown and Herendeen, 1996). Transformities vary through time and space, similar to the inputs and interactions necessary to create any product. The transformities for many components of this study were taken from earlier studies of the Mississippi Delta and Mekong River (Odum et al., 1987b; Brown and McClanahan, 1996). The effects of uncertainty in the transformities of renewable energies driving the biosphere, such as rainfall, wind, and tidal momentum, are relative, since all ‘higher order’ processes include a proportion of renewable energy. If the transformities of renewable energies are too high or low, the emergy in the higher order products is off as well, but by proportional amounts (Brown and Herendeen, 1996).

4.2. Emergy indices

The emergy analyses identified the unique concentration of renewable energies characteristic of river deltas and provided a relative comparison between renewable and imported energies. From diffuse inputs across the drainage basin, the river system concentrates large amounts of renewable emergy that is delivered to the delta. Deltas are characterized by renewable emergy provided by river sources that surpass that provided to other coastal settings (Martin, 2000a). Historic and contemporary high levels of human development and profitable fisheries supported by many river deltas attest to the rich concentration of resources in these environments. This analysis quantifies the contributions leading to increased productivity in coastal regions with river input (Moore et al., 1970; Boyton et al., 1982; Nixon, 1982; Cadee, 1986; Villar et al. 1996). Subtracting the Renewable Emergy Captured from the Net Renewable Emergy Captured for each diversion reveals that the emergy contributed by river sources was nearly an order of magnitude greater than the total contributions of sunlight, rain, wind, tide and waves (Table 3). As a new engineering interface, river diversions use human resources to capture renewable river energies to stimulate marsh productivity.

The Net Renewable Emergy Captured calculated the effectiveness of the diversions in capturing portions of river resources flowing through the delta. In common units of value, emdollars, the ratio quantified the resources captured per resources invested from the economic system. The Caernarvon and Davis Pond diversions captured 7080 and 2750 emdollars of value per emdollar invested, respectively (Table 3). Comparing these ratios with other environmental systems demonstrates the rewards of investing in productive natural systems with concentrated renewable energies.

Agricultural settings are a common example of a system in which imported energies are utilized to capture natural energies to yield exports. In agricultural systems, renewable inputs of sunlight, rain, and wind are dispersed over a large area. Consequently, large imports are required to capture and augment these energies to produce exports. Relatively large imports in relationship to diffuse renewable energies result in lower Renewable Emergy Captured compared with river deltas with large amounts of renewable, concentrated energies requiring relatively small imports. Citrus farming has a Renewable Emergy Captured index of 0.089 and a contemporary farm produces corn with a Renewable Emergy Captured index of 0.080 (Odum, 1996). The fact that these ratios are less than one reflect the current reliance of agriculture on economic resources as opposed to natural energies.

The large ratio of renewable inputs to economic inputs coupled with a highly productive estuarine system (Nixon, 1988) resulted in large exports and beneficial Net Emergy Yield Ratios. The net emergy gain in exports from each diversion was 33.2 and 9.36 times greater than the emergy imported for construction and maintenance (Table 3). Even with large capital cost (Table 1), these values are similar to those from other systems that rely on natural energies to create economic flows, such as pine plantations (4.9), crude oil (7.9), and rainforest wood (12.0) (Odum, 1996). Having yield ratios greater than these established systems interfacing between the environment and the economy indicates that the diversions will be successful in supporting economic activity. The benefits of investing in river environments, where natural energies are highly concentrated, was previously demonstrated by Emergy Yield Ratios (12.3 and 20.3) for dam proposals along the Mekong river (Brown and McClanahan, 1996).

The effects of varying habitat change rates upon the Net Emergy Yield Ratio were tested with a sensitivity analysis of the Davis Pond diversion (Fig. 7). For this analysis, the background rate of land loss assumed to occur without the diversion was 3 km^2/year (Reed, 1995). Therefore, all scenarios with loss rates less than 3 km^2/year and rates of land gain resulted in Net Emergy Yield Ratios greater than 0.0. A Net Emergy Yield Ratio threshold of 6.0 is crossed with a land gain rate of 0.0 km^2/year (Fig. 7). The average Emergy Yield Ratio for domestic oil was approximately 6.0 in 1991 (Odum, 1996). If the Net Emergy Yield Ratio is above this value, it is advantageous to utilize the fuels to construct and maintain the diversion. According to this calculation, if the Davis Pond diversion results in net rates of land loss, other uses of the resources, instead of the diversion, should be considered.

5. Conclusion

Emergy analysis identified the unique concentration of natural energies inherent to delta settings. Since the earliest civilizations, man has recognized the benefits of these energies and coexisted within the delta cycle. Recently, deltaic civilizations have isolated coastal marshes from sustaining river energies, leading to the deterioration of these ecosystems and the benefits they provide. Over the past 7500 years, the Mississippi river has created the delta that currently supports the metropolis of New Orleans, smaller coastal towns, and the richest fishery of the eastern United States. Failing to reinvest in this resource with river diversions while continuing to extract exports is similar to withdrawing from a bank account without depositing. The initial effects of this strategy are revealed by the current land loss rates within the Mississippi delta.

To reach sustainable patterns, ecological engineered systems that rely on renewable energies must be utilized. As evidenced by the large amount of renewable emergy captured (7080 and 2750), river diversions are effective at capturing renewable energies. Large Net Emergy Yield Ratios (33.2 and 9.36) indicate river diversions provide a substantial return on investment and that the amount of emergy exported outweighs the emergy required for the projects. By relying primarily on renewable energies inherent in delta environments to produce societal and ecological benefits, diversions represent an important component of sustainable management plans for deltaic systems. However, land gain rates of diversions should be greater than critical thresholds to merit the economic resources they require.

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Appendix A. Calculations and references for Table 2

Renewable resources

1. Solar energy

Total area water and land: Caernarvon, 1.27×10^8 m^2; Davis Pond, 1.16×10^9 m^2

Insolation: 5.95×10^9 J/m^2 (Costanza et al., 1983)

Albedo: 36% (Costanza et al., 1983)

Caernarvon, 1.27×10^8 m^2 $*$ 5.95×10^9 J/m^2 $*$ $(1-0.36)=4.84\times10^{17}$ J; Davis Pond, 4.41×10^{18} J

Transformity: 1.0 sej/J (by definition)

2. Rain, chemical potential energy

Total area water and land: Caernarvon, 1.27×10^8 m^2; Davis Pond, 1.16×10^9 m^2

Precipitation: 1.51 m/year (National Oceanic and Atmospheric Administration, 1981)

Caernarvon, 1.27×10^8 m^2 $*$ 1.51 m/year $*$ (1000 kg/m^3) $*$ (4940 J/kg) $=9.47\times10^{14}$ J; Davis Pond, 8.64×10^{15} J

Transformity: 1.82×10^4 sej/J (Odum, 1996)

3. River, geopotential
% of Mississippi River into Diversion: Caernarvon, 1.6%; Davis Pond, 2.1%
Average flow Mississippi River: 4.04×10^{11} m^3/year (Kesel, 1988)
Density river water: 1.0×10^6 g/m^3
Average river stage relative to mean sea level: 3.35 m (United States Army Corps of Engineers, 1987)
Caernarvon, $0.016 * 4.04 \times 10^{11}$ m^3/year $* 1.0 \times 10^6$ g/m^3 $*$ 3.35 m $*$ 9.8 m/s^2 $= 2.12 \times 10^{17}$ J; Davis Pond, 2.79×10^{17} J
Transformity: 3.18×10^4 sej/J (Appendix B)

4. Wind, kinetic energy
Total area water and land: Caernarvon, 1.27×10^8 m^2; Davis Pond, 1.16×10^9 m^2
Average eddy diffusion coefficient: 14.74 m^2/s
Average vertical wind gradient: 0.00442/s
Wind height: 100 m
Air density: 1.23 kg/m^3
Caernarvon, 1.27×10^8 m^2 $*$100 m $*$ 1.23 kg/m^3 $*$ 14.74 m^2/s $*$ $(0.0044/s)^2$ $*$ (31 540 000 s/year) $= 1.42 \times 10^{14}$ J; Davis Pond, 1.30×10^{15} J
Transformity: 1.50×10^3 sej/J (Odum, 1996)

5. Waves
Total area open water: Caernarvon, 7.37×10^7 m^2; Davis Pond, 3.92×10^8 m^2
Density of water: 1030 kg/m^3
Wave amplitude: 0.2 m
Caernarvon, (0.5) $* 7.37 \times 10^8$ m^2 $*$ 1030 kg/m^3 $*$ 9.81 m^2/s $*$ $(0.2\ m)^2 = 1.49 \times 10^{10}$ J; Davis Pond, 6.65×10^{10} J
Transformity: 3.06×10^4 sej/J (Odum, 1996)

6. Tide
Total area open water: Caernarvon, 7.37×10^7 m^2; Davis Pond, 3.92×10^8 m^2
Tides per year: 365 (Walker, 1996)
Average tide range: 0.3 m (Walker, 1996)
Density of water, 1030 kg/m^3
Caernarvon, (0.5) $* 7.37 \times 10^8$ m^2 $*$1030 kg/m^3 $*$ 9.81 m^2/s $*$ 365 $*$ $(0.3\ m)^2 = 1.22 \times 10^{13}$ J; Davis Pond, 5.46×10^{13} J
Transformity: 1.68×10^4 sej/J (Odum 1996)

7. Riverine water used—open water
Total area open water: Caernarvon, 7.37×10^7 m; Davis Pond, 3.92×10^8 m^2
Transpiration rate in open water: 1.0 m/year (Abtew and Obeysekera, 1995)
Density of river water: 1.0×10^6 g/m^3
Gibbs free energy: 4.94 J/g
Caernarvon. 7.37×10^7 m^2 $* 1 \times 10^6$ g/m^3 $*$ 1 m/year $*$ 4.94 J/g $= 3.64 \times 10^{14}$ J; Davis Pond, 1.94×10^{15} J
Transformity: 4.11×10^4 sej/J (Odum et al., 1987b)

8. Riverine water used—marsh
Total area marsh: Caernarvon, 5.20×10^7 m^2; Davis Pond, 8.22×10^8 m^2
Transpiration rate in marsh: 2.0 m/year (Abtew and Obeysekera, 1995)
Caernarvon, 5.20×10^7 m^2 $* 1 \times 10^6$ g/m^3 $*$ 2 m/year $*$ 4.94 J/g $= 5.14 \times 10^{14}$ J; Davis Pond, 8.12×10^{15} J
Transformity: 4.11×10^4 sej/J (Odum et al., 1987b)

9. Riverine sediments captured
Annual flow of suspended sediment Mississippi River: 1.40×10^{14} g (Kesel, 1988)
% of Mississippi River into Diversion: Caernarvon, 1.6%; Davis Pond, 2.1%
% Sediment captured in study area: 70%
Caernarvon, 1.40×10^{14} g $*$ 0.016 $*$ 0.70 $=1.57\times10^{12}$ g; Davis Pond, 2.06×10^{12} g
Transformity: 3.18×10^{4} sej/J (Appendix B)

10. River sediments stored
Subsidence rate: 0.005 m/year
Bulk density sediments: 2.65×10^{6} g/m^3
% Soil mineral matter: 5%
Caernarvon, 1.57×10^{12} g$-$(0.005 m/year $*$ 2.65×10^{6} g/m^3 $*$ 0.05) $=1.53\times10^{12}$ g; Davis Pond, 1.51×10^{12} g
Transformity: 3.18×10^{4} sej/J (Appendix B)

Imports

11. Land costs
Life of project: 50 years (United States Army Corps of Engineers, 1985, 1991)
Costs of land acquired: Caernarvon, 1.12×10^{5} 1985\$; Davis Pond, 8.54×10^{6} 1990\$ (United States Army Corps of Engineers, 1985, 1991)
Caernarvon, 1.12×10^{5} 1985\$ $*$ (1/50 years) $=2.24\times10^{3}$ \$; Davis Pond, 1.71×10^{5} \$
Emergy per dollar ratio (1985): 2.00×10^{12} sej/\$ (Odum 1996)

12. Relocation
Life of project: 50 years
Costs of relocations: Caernarvon, 8.88×10^{5} 1985\$; Davis Pond, 3.44×10^{7} 1990\$ (United States Army Corps of Engineers, 1985, 1991)
Caernarvon, 8.88×10^{5} 1985\$ $*$ (1/50 years) $=1.78\times10^{4}$ \$; Davis Pond, 6.88×10^{5} \$
Emergy per dollar ratio (1985): 2.00×10^{12} sej/\$ (Odum 1996)

13. Construction
Life of project: 50 years
Construction costs: Caernarvon, 1.26×10^{7} 1985\$; Davis Pond, 4.43×10^{7} 1990\$ (United States Army Corps of Engineers, 1985, 1991)
Caernarvon, 8.88×10^{5} 1985\$ $*$ (1/50 years) $=2.52\times10^{5}$ \$; Davis Pond, 8.86×10^{5} \$
Emergy per dollar ratio (1985): 2.00×10^{12} sej/\$ (Odum 1996)

14. Steel
Life of project: 50 years
Mass of Steel: Caernarvon, 2.54×10^{9} g; Davis Pond, 1.11×10^{10} g (United States Army Corps of Engineers, 1985, 1991)
Caernarvon, 1.12×10^{9} g $*$ (1/50 years) $=5.08\times10^{7}$ g; Davis Pond, 2.22×10^{8} g
Emergy per mass: 1.80×10^{9} sej/g (Brown and McClanahan, 1996)

15. Concrete
Life of project: 50 years
Mass of concrete: Caernarvon, 3.66×10^{10} g; Davis Pond, 1.65×10^{11} g (United States Army Corps of Engineers, 1985, 1991)
Caernarvon, 2.58×10^{11} g $*$ (1/50 years) $=3.16\times10^{9}$ g; Davis Pond, 3.30×10^{9} g
Emergy per mass: 7.00×10^{7} sej/g (Brown and McClanahan, 1996)

16. Operation and maintenance costs
Life of project 50 years
Annual Operation and Maintenance Costs: Caernarvon 2.44×10^5 1985 \$,
Davis Pond $2.442.44 \times 10^5$ 1990 \$ (United States Army Corps of Engineers, 1985, 1991) Emergy per dollar ratio (1985) = 2.00×10^{12} sej/\$ (Odum 1996)

Exports

17. Net primary production — open water
Total area open water: Caernarvon, 7.37×10^7 m^2; Davis Pond, 3.92×10^8 m^2
Annual primary production water: 2.33×10^7 J/m^2 (Bahr et al., 1982)
Percent water primary production exported: 100% (Bahr et al., 1982)
Caernarvon: 7.37×10^7 m^2 $*$ 2.33×10^7 J/m^2 $*$ $1.00 = 1.72 \times 10^{15}$ J; Davis Pond, 7.67×10^{15} J
Transformity: 4.70×10^3 sej/J (Odum, 1996)

18. Net primary production—marsh
Total area marsh: Caernarvon, 5.20×10^7 m^2; Davis Pond, 8.22×10^8 m^2
Annual primary production marsh: 6.97×10^7 J/m^2 (Bahr et al., 1982)
Percent water marsh production exported: 20% (Bahr et al., 1982; Peters and Schaaf, 1991)
Caernarvon, 5.20×10^7 m^2 $*$ 6.97×10^7 Jm^2 $*$ $0.20 = 7.45 \times 10^{14}$ J; Davis Pond, 1.16×10^{16} J
Transformity: 6.96×10^3 sej/J (Odum, 1996)

19. Fisheries
Total area open water: Caernarvon, 7.37×10^7 m; Davis Pond, 3.92×10^8 m
Total area marsh: Caernarvon, 5.20×10^7 m^2; Davis Pond, 8.22×10^8 m^2
Total area water and land: Caernarvon, 1.27×10^8 m^2; Davis Pond, 1.16×10^9 m^2
Annual primary production open water: 445 g C/m^2 (Bahr et al., 1982)
Annual primary production marsh: 1850 g C/m^2 (Bahr et al., 1982)
Annual total primary production: Caernarvon, (7.37×10^7 m^2 $*$ 445 g C/m^2)+(5.20×10^7 m^2 $*$ 1850 g C/m^2) = 1.29×10^{11} g C; Davis Pond, 1.70×10^{12} g C
Average primary production per m^2: Caernarvon, 1.29×10^{11} g C/1.27×10^8 m^2 = 1.02×10^3 g C/m^2; Davis Pond, 1.47×10^3 g C/m^2
Annual fishery yield: Caernarvon, ($1.55 * \ln(1.02 \times 10^3$ g C/m^2)-4.49) = 6.24 g C/m^2; Davis Pond, 6.81 g C/m^2 (Nixon, 1988)
Assume carbon is 10% total mass (Nixon, 1988)
Annual fishery yield total (g): Caernarvon, 62.4 g/m^2; Davis Pond, 68.1 g/m^2
Assume dry weight is 20% of fresh weight (Odum et al., 1987a)
Annual fishery yield total grams dry weight: Caernarvon, 12.9 g/m^2; Davis Pond, 13.6 g/m^2
Assume 5 kcal/g (Odum et al., 1987a)
Caernarvon, 12.9 g/m^2 $*$ 5 kcal/g $*$ 4186 J/kcal $*$ 1.27×10^8 m^2 = 3.43×10^{13} J; Davis Pond, 3.30×10^{14} J
Transformity (commercial fish): 8.00×10^6 sej/J (Odum et al., 1987a)

Appendix B. Emergy per mass of river geopotential and river sediments

The annual contribution of solar emjoules from rainfall and geologic energies was calculated by multiplying their respective emergy per mass by the grams of each component. The sediment emergy per mass was calculated by summing the rainfall and geologic contributions and dividing by the annual flow of sediments. Similarly, the emergy per joule of river geopotential was calculated by summing the rainfall and geologic contributions and dividing by the annual geopotential energy in the river.

	Annual flow	Emergy per unit	Annual solar emjoules (sej/year)
1. Rainfall	2.67×10^{18} g	8.99×10^{4} sej/g	2.40×10^{23}
2. Uplift	1.83×10^{14} g	1.00×10^{9} sej/g	1.83×10^{23}
3. Total annual solar emjoules			4.23×10^{23}
4. Annual flow of sediments to delta(g)	6.20×10^{14} g		
5. Mississippi delta sediment		6.82×10^{8} sej/g	
6. River potential energy	1.33×10^{19} J		
7. River geopotential		3.18×10^{4} sej/J	

1. Annual rainfall = annual ht. rain (0.799 m) (Odum et al., 1987b) $*$ rain density (1.00×10^6 g/m^3) $*$ basin area (3.34×10^{12} m^2); emergy per mass from Romitelli (1997); 2, annual rock uplifted = uplift rate (10 cm/1000 years (Ruddiman and Kutzback, 1991) $*$ rock density (2.61×10^6 g/m^3) $*$ basin area experiencing uplift (7.01×10^{11} m^2) (Ruddiman et al., 1989); emergy per mass from Odum (1996); 3, sum of row 1 and row 2; 4, Roberts (1997); 5, Row 3 divided by row 4; 6, Annual river flow = 4.04×10^{11} m^3/year $*$ 1×10^6 g/m^3 $*$ 9.81 m/s^2 $*$ average river elevation at diversions relative to mean sea level (3.35 m).

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