ELSEVIER

Ecological Modelling 91 (1996) 105–130

ECOLOGICAL MODELLING

EMergy analysis perspectives of Thailand and Mekong River dam proposals

M.T. Brown [a,*], T.R. McClanahan [b]

[a] Center for Wetlands and Water Resources, Phelps Lab, University of Florida, Gainesville, FL 32611, USA
[b] Coral Reef Conservation Project, P.O. 99470, Mombasa, Kenya

Received 10 February 1995; accepted 14 September 1995

Abstract

Methods of EMergy analysis (a scientifically based measure of wealth with units of solar emjoules [sej]) are explained and illustrated, using the economy of Thailand and two proposed dams on the Mekong River. Thailand's EMergy/$ ratio is near the world average ($3.46 \cdot 10^{12}$ sej/$), its EMergy per capita ratio ($2.98 \cdot 10^{15}$ sej/capita) is low compared to developed economies (that of the United States is $29.3 \cdot 10^{15}$ sej/capita), and its EMergy balance of payments is negative (the EMergy in exports is almost twice the EMergy in imports). The calculated net yield ratios of the proposed dams were sensitive to the treatment of sediments. The analysis yielded high net yield ratios (12.3/1 and 20.3/1) if sediments were not included, but yielded ratios of only 1.4/1 and 1.3/1 if sediments were included. If the two dams were constructed as a cascade, the combined net yield ratio was 2.5/1 (sediments included). If compared to conventional fossil fuels as a primary source of energy to the economy, the net yield ratio of the electricity generated from the two-dam cascade expressed as fossil fuels was 7.4/1.

Keywords: EMergy; Environmental impacts; Hydroelectricity; Energy

1. Introduction

This study of Thailand's economy and proposals for Hydroelectric Dams on the Mekong River was one in a series of studies of the interface between humanity and nature in various regions of the world, where questions of public policy were quantitatively explored and suggestions made for sustainable patterns of development. A new measure of value, called EMergy [1] (which stands for *e*nergy *m*emory), was used to quantitatively determine how to best manage resources, populations and regional

* Corresponding author. Fax: (1) (904) 392-3624.

[1] EMergy (spelled with an "m") is a scientifically based measure of wealth. It expresses all types of resources (energy, raw materials, finished goods, and human services) on a common basis: the energy it took to generate them. EMergy is a measure of value that is independent of human preferences, and therefore does not fluctuate with changing tastes. So as not to confuse EMergy with energy, the first two letters of the word EMergy are capitalized in this paper. For a more complete discussion of EMergy, see Odum (1988, 1995).

SSDI 0304-3800(95)00183-2

economies. The methodology is useful where growth has generated controversy over economic development and environmental protection. Past analyses of world regions have shown that both development and environmental protection are possible and, in fact, necessary if a sustainable economy is to prevail (Odum et al., 1986; Brown et al., 1988; Doherty et al., 1992).

EMergy analysis is a technique which determines the value of nature to the human economy (Odum, 1988). This technique is based on the principles of energetics (Lotka, 1922), systems theory (von Bertalanffy, 1968), and systems ecology (Odum, 1983). Its fundamental assumption is that the value of a resource is proportional to the energy required to produce the resource. EMergy evaluation can make comparisons of alternative uses of resources to develop policies which maximize the total EMergy flow in an economy. In the following evaluation, an EMergy overview of Thailand and specific evaluation of two alternative dam sites proposed for the Mekong River are illustrated.

First the EMergy basis for the economy of Thailand was evaluated. And second, net EMergy and environmental impacts of the two alternative hydroelectric dam proposals were evaluated to determine their potential contribution to the economy of Thailand.

1.1. EMergy, trade, and sustainability

Net EMergy, as measured with an EMergy yield ratio, is the ratio of the EMergy yield from a process to the EMergy costs. The ratio is a measure of how much a process will contribute to an economy and thus is an index of sustainability. Net EMergy can be calculated for energy sources, commodities, and processes like foreign trade. Primary energy sources typically have yield ratios in the range of 5/1 to 15/1, thus they can contribute much to the wealth of

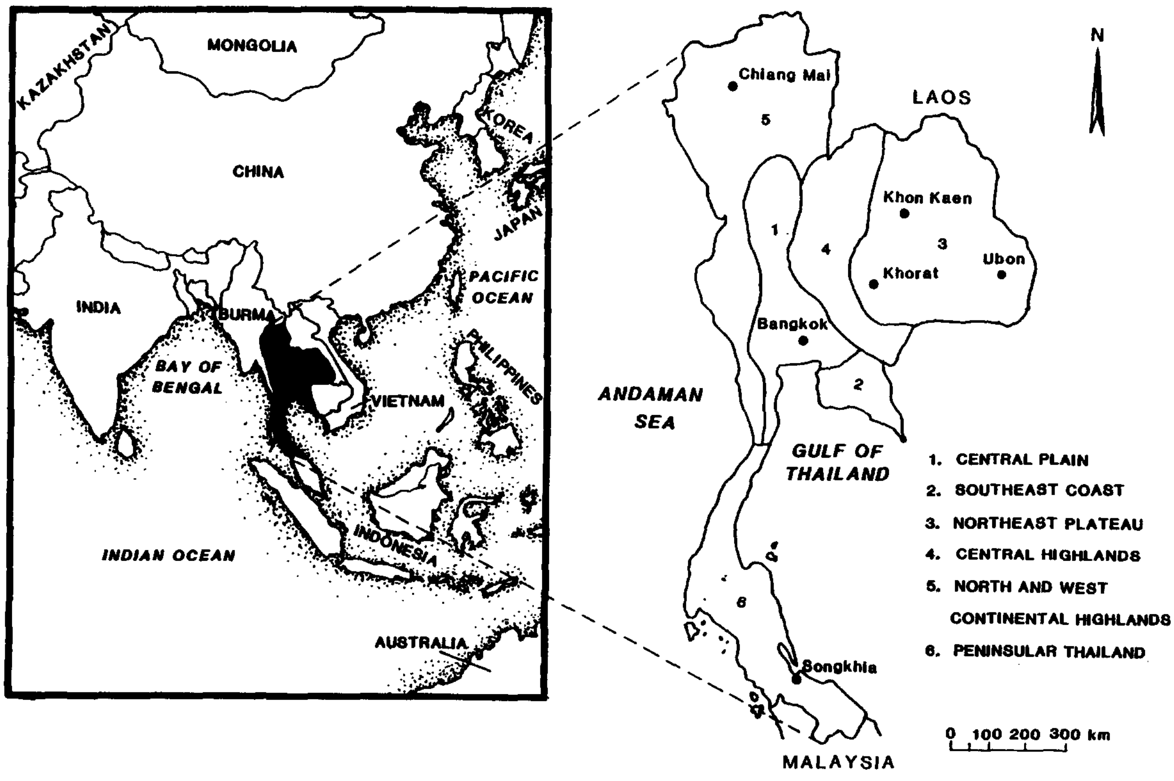


Fig. 1. Location and physigraphic regions of Thailand (after Moormann and Rojanasoonthorn, 1968).

an economy. Secondary energy sources have yield ratios less than 5/1, but greater than 1/1, and consumer products often have ratios less than 1/1.

Throughout the developing world, uneven balances of trade are fostered at the expense of both the ecological and economic well being of local populations and their economies. Previous studies of world regions (Odum et al., 1986; Brown et al., 1988; Odum and Arding, 1991; Doherty et al., 1992) have shown that the export of raw resources from developing countries in exchange for finished goods and services drains the economy of the exporting region, while fostering continued economic growth of the developed world. Frequently, the balance of monetary payments is positive for developing economies, yet their EMergy balance is negative. Where these conditions prevail, public policy based solely on monetary concerns often encourages continued sale of resources. Under these conditions, populations may suffer because more total value (measured in EMergy terms) leaves the country than is imported. In the case of Thailand, a moderately developed nation, the issue is both a negative EMergy balance of payments and questions of internal resource use and population carrying capacity. Consequently, it is important to develop policies for the future which will accommodate Thailand's people and the long-term viability of its economy.

1.2. The environment of Thailand

Thailand, like many developing countries, lies at the crossroads between the past's reliance on low-energy technology and an uncertain future based on fossil fuels and high-energy technology. Reduced mortality, associated with improved health standards, and immigration have resulted in a steady and exponential increase in the population from 8.26 million in 1910 to more than 50 million in 1984 (TDRI, 1987). Population expansion has resulted in a 2.4% annual rate of deforestation, while revenue from timber exports have declined from $46.8 million in 1973 to $2 million in 1984 (UNEP, 1988).

Located north of the equator (6° to 20°N, see Fig. 1), Thailand is highly affected by monsoon seasons typical of the Indian Ocean region. Lacking much seasonal variation in temperature, Thailand's seasons are marked by a period of abundant rainfall and a period of drought, which correspond to the shifting intertropical convergence zone. The wet season begins in May and extends until October, and the dry season lasts from October through April. Rainfall throughout many parts of the country is relatively high (from 1000 to 4000 mm/yr), but seasonal.

Thailand contains a number of physiographic regions which differ in their geology and climate (Moormann and Rojanasoonthorn, 1968) as shown in Fig. 1. Briefly, the southeast coast of Thailand is a lowland area affected by the marine environment, and has the highest and least seasonal rainfall. The original vegetation was tropical rainforest, but extensive deforestation in many areas has replaced the forest with agriculture and rubber plantations. The central plain area has low rainfall but is an alluvial floodplain region that maintains its productivity through constant alluvial inputs, which result from the seasonal flooding of the Chao Praya River and its tributaries. The central region has long been utilized for paddy rice and fruit and vegetable cultivation, which supplies the Bangkok markets. The northern continental highlands region is mountainous, cooler and has less predictable rainfall in its lower elevations; however, rainfall increases with elevation. The highlands areas are vegetated by coniferous forests, dry forests and savannas where human encroachment has not occurred. Within this region, productive alluvial soils occur within river basins but, cultivation has expanded onto steeper slopes and decreased forest cover in many regions. The Khorat Plateau of northeastern Thailand is the nation's driest region, and has unproductive saline soils which appear to become more saline following deforestation (UNEP, 1988).

1.3. The Mekong River System

The Mekong River ranks sixth in the world in terms of mean annual discharge (approximately 475 $\cdot 10^9$ m^3/yr). Its headwaters are located in the Himalayas and receive drainage from China, Burma, Laos, Kampuchea, Thailand and Vietnam. The uppermost tributaries reach an elevation of 5000 m, but the Mekong is only approximately 355 m above sea level once it enters Thailand. Sediment load is relatively low compared to other major Asian rivers, carrying 6.2 million t/yr. The Lower Mekong Basin fisheries contribute approximately 500 000 t/yr, or 4.5% of the GNP of the Lower Basin (Pantulu, 1986).

The Mekong River forms the northern boundary between Thailand and Laos until it flows eastward through Cambodia. As part of the UN-sponsored initiative to develop the hydroelectric potential throughout the Mekong Basin, several proposals for dams along the main reaches in the upper basin have been made. One of the first of these proposals involved two sites in northern Thailand known as the Upper Chiang Khan and Lower Pa Mong dams. Numerous studies evaluating both sites have been conducted over the past decade as the governments involved have tried to reconcile costs and benefits of the two locations. An EMergy analysis of both dams was conducted to lend additional insight and to provide a practical demonstration of the EMergy analysis technique.

2. Methods

This analysis was conducted to demonstrate the EMergy analysis methodology, and to provide fresh insight on proposals for constructing dams on the Mekong River. Previous analysis of the dams used standard economic and engineering methods for evaluating benefits and costs. Of greatest concern was the net effect of the two alternate dam proposals and which was the better proposal when all costs and benefits were taken into account. In order to evaluate the dams and their contribution to the economy, it was necessary to evaluate Thailand's economy and the EMergy and accompanying money flows that support it. Thus prior to the detailed analysis of the dams, an EMergy analysis of the economy was conducted. Then the EMergy benefits and costs of each dam were evaluated, comparing one to the other, and finally their net contributions to the economy of Thailand were evaluated.

The general methodology for EMergy analysis is a 'top-down' systems approach (Odum, 1988, 1995). The first step is to construct systems diagrams that are means of organizing thinking and relationships between components and pathways of exchange and resource flow. The second step is to construct EMergy analysis tables directly from the diagrams. The third step involves calculating several EMergy indices that relate EMergy flows of the economy with those of the environment to predict economic viability and carrying capacity and to suggest public policy options.

Definitions for several key words and concept are given next:

Energy: sometimes referred to as the ability to do work. Energy is a property of all things which can be turned into heat, and is measured in heat units (BTU, calories, or joules).

EMergy: an expression of all the energy used in the work processes that generate a product or service in units of one type of energy. Solar EMergy of a product is the EMergy of the product expressed in equivalent solar energy required to generate it.

EMjoule: the unit of measure of EMergy, 'EMergy joule.' It is expressed in the units of energy previously used to generate the product; for instance, the solar EMergy of wood is expressed as joules of solar energy that were required to produce the wood.

Maximum EMergy principle: systems that prevail are those that take maximum advantage of the EMergy that is available, by reinforcing productive processes, drawing more resources, and overcoming more limitations through effective system organization. Patterns that maximize EMergy contribute to the most wealth.

Macroeconomic dollar (Emdollar): a measure of the money that circulates in an economy as the result of an EMergy flow. In practice, to obtain the macroeconomic dollar value of an EMergy flow or storage, the EMergy is divided by the ratio of total EMergy to gross national product (GNP) for the national economy.

Transformity: the ratio obtained by dividing the total EMergy that was used in a process by the energy yielded by the process. Transformities have the dimensions of EMergy/energy. A transformity for a product is calculated by summing all of the EMergy inflows to the process and dividing by the energy of the product. Transformities are used to convert energies of different types to EMergy of the same type. Transformities for many types of energy, resources, and goods have been calculated in previous studies (Arding and Brown, 1991).

2.1. Solar EMergy and transformities

To derive solar EMergy of a resource or commodity, it is necessary to trace back through all the resources and energy that are used to produce it and express each in the amount of solar energy that went into their production. This has been done previously for the renewable energies driving the biogeochemical process of the earth and a wide variety of resources and commodities (Arding and Brown, 1991). When expressed as a ratio of the total EMergy used to the *energy* produced, a transformity results (dimensions are sej/J). As its name implies, the transformity can be used to 'transform' a given energy into EMergy, by multiplying the energy by the transformity. For convenience, so as to avoid recalculating the EMergy in input resources and commodities every time a process is evaluated, transformities that have been previously calculated are used (Arding and Brown, 1991).

Uncertainities surrounding transformities are related to the resource in question. For instance, transformities for renewable energies like wind, rain, tides and so forth were calculated using global inputs from sunlight, deep heat, and tidal momentum. The best estimates of the total energy in global winds, total amount of global rainfall, and global tidal energy, were divided by the total EMergy in sunlight, deep heat and tidal momentum to obtain their transformities. These renewable energy transformities are the basis for most other transformities, since all 'higher-order' processes and commodities include some proportion of renewable energy. The uncertainty then becomes relative, since if the transformities for renewable energies are off, then the EMergy in higher-order products are off as well, but by equal amounts.

The use of transformities calculated for processes that are spatially and temporally separated appears to have its limitations and to add some uncertainty. In fact, it is quite well known that there is no single transformity for most commodities, but a range of transformities. There is probably a lower limit, below which the commodity cannot be made, and there is some upper limit (although in theory, one could make corn, for instance, with an infinite amount of wasted fuel and thus have an infinitely high transformity). For some commodities several transformities have been calculated in different parts of the globe and for different ways of making them. Electricity is an example. The transformity of electricity generated in a conventional natural gas fired plant is about 167 000 sej/J (Odum, 1995), while the transformity of electricity generated in a hydroelectric plant in Brazil, is 150 000 sej/J (Brown, 1986). Electricity produced in a nuclear power plant has a transformity of 200 000 sej/J (Lapp, 1991). For other energies and commodities, processes have been chosen that are representative of relatively efficient means of production. Average transformities are used whenever the exact origin of a resource or commodity is not known.

2.2. Data and EMergy evaluation

Two scales of evaluation were conducted in this study, first the economy of Thailand and then the proposed hydroelectric dams on the Mekong River. Evaluations were conducted by listing all sources of materials and energy, calculating the energy associated with each flow, and then applying transformities to each flow. Data for energy and material flows in and out of the economy of Thailand were obtained from statistical abstracts. Data for the material and energy requirements of dam construction, environmental and economic impacts, and benefits from irrigation and electricity produced were obtained from a variety of studies done previously.

Conversion of energy to EMergy units required that transformities be applied to each flow of resources, labor, or energy. Transformities previously calculated in other studies were used, for the most part, although several transformities were calculated for this study: two processes for rice production, and the transformities for concrete and labor (Brown and McClanahan, 1992). In addition, the transformity, or ratio of money to EMergy was calculated from the analysis of total EMergy flow and money circulation within the economy of Thailand.

2.3. Step-by-step procedure

Given next is further elaboration on the methods used for EMergy analysis in general, and for this study of Thailand in particular.

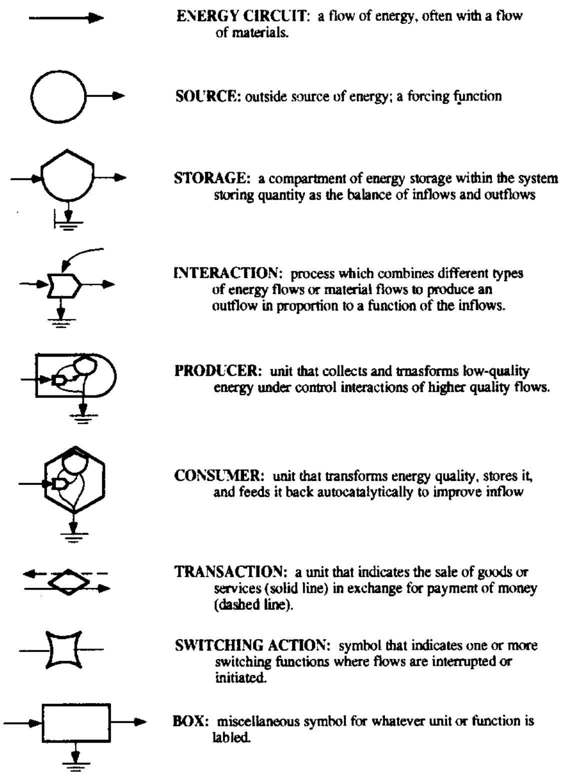


Fig. 2. Energy language symbols.

Step 1: Overview system diagrams

A system diagram in 'overview', using the energy language symbols illustrated in Fig. 2, is drawn first to put the system of interest in perspective, combine information about the system from various sources, and to organize data gathering efforts. The process of diagramming the system of interest in overview ensures that all driving energies and interactions are included. Since the diagram includes both the economy and environment of the system it is like an impact diagram, showing all relevant interactions.

The diagram of the system is used to construct a table of data requirements for the EMergy analysis. Each pathway that crosses the system boundary is evaluated.

Step 2: EMergy analysis tables

EMergy analysis of a system of interest is usually conducted at two scales. First the larger system, within which the system of interest is embedded, is analyzed and indices generated that are necessary for evaluation and comparative purposes. Second, the system of interest is analyzed and comparisons made between it and other comparable systems, and between it and the larger system.

The analysis is conducted using an EMergy Analysis Table organized with the following headings:

1	2	3	4	5	6
Note	Item	Raw units	Trans-formity	Solar EMergy	Macro-economic $

Each row in the table is an inflow or outflow pathway in the diagram of the system of interest, therefore pathways are evaluated as fluxes in units per year. An explanation of each column is given next.

1. the line number and footnote number that contains sources and calculations for the item.
2. the item name that corresponds to the name of the pathway in the aggregated diagram.
3. the actual units of the flow, usually evaluated as flux per year. Most often the units are energy (joules/year), but sometimes are given in grams/year.
4. transformity of the item, usually derived from previous studies.
5. Solar EMergy is the product of the raw units in Column 3 with the transformity in Column 4.
6. the result of dividing solar EMergy in Column 5 by the EMergy-to-money ratio (calculated independently) for the economy of the nation within which the system of interest is embedded.

Step 3: Calculation of EMergy indices

Once the EMergy analysis tables are completed, several indices using data from the tables are calculated to gain perspective and aid in public policy decision-making. The criteria used in judging alternatives differ depending upon whether two systems are being compared or whether a single system is being analyzed for its contributions to the economy. When two alternative systems are compared, the one which contributes the most EMergy to the public economy and minimizes environmental losses is considered best. When a single system is analyzed, it is judged to be successful in relation to the economy in which it is embedded by determining how closely its EMergy intensity matches that of the local economy, and whether it minimizes environmental losses. To accomplish these, two ratios are calculated: EMergy investment ratio (IR), and the Environmental loading ratio (ELR). Several other indices help in gaining perspective about processes and economies, and are necessary precursors to the IR and ELR; they are: EMergy-to-money ratio, EMergy per capita, EMergy density, EMergy exchange ratio, EMergy yield ratio, and solar transformity. Fig. 3 illustrates several of these ratios.

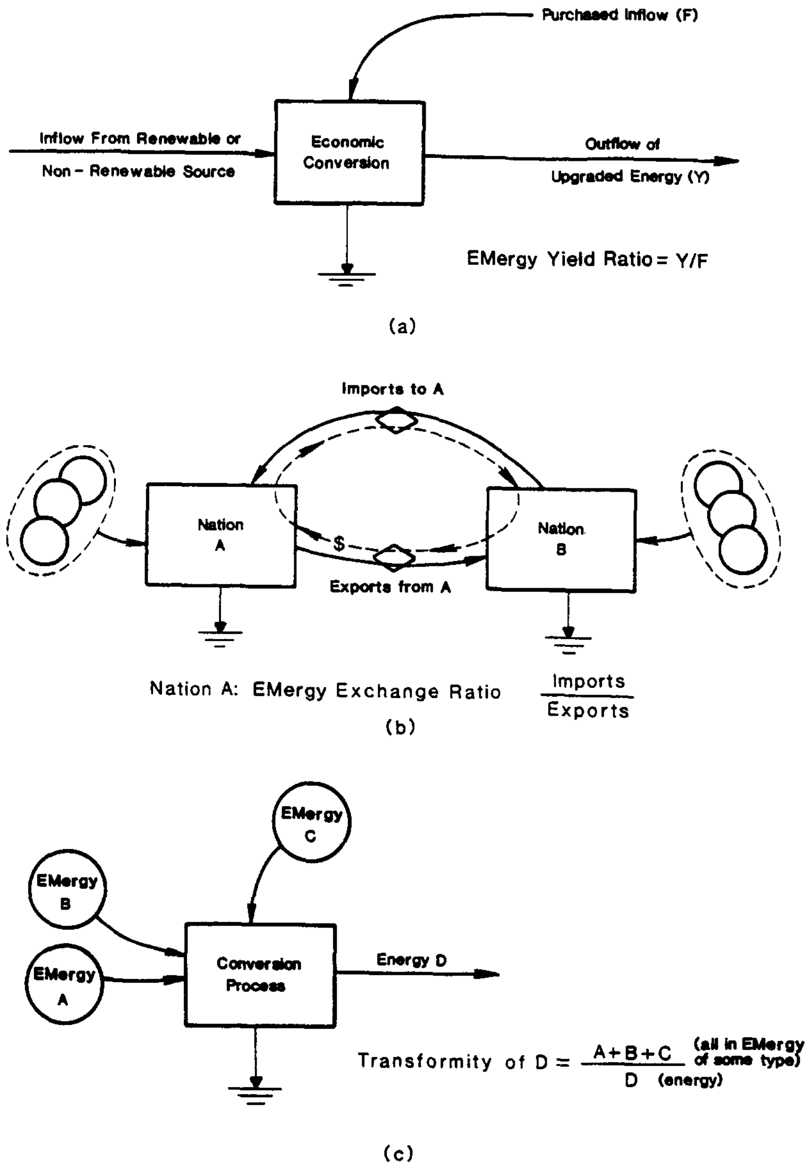


Fig. 3. Simplified diagrams illustrating (a) the calculation of net EMergy yield ratio for an economic conversion where purchased energy is used to upgrade a lower grade resource, (b) the calculation of EMergy exchange ratio for trade between two nations, and (c) the calculation of a transformity for the flow D that is a product of the process that requires the input of three different sources of EMergy (A, B, and C).

2.4. Determining the intensity of development and economic competitiveness: EMergy investment ratio

A diagram illustrating the use of nonrenewable and renewable EMergies in a regional economy is given in Fig. 4. The interaction of nonrenewable EMergies (both purchased from outside [F] and transformed from within [N]) with renewable EMergies (I) is the primary process by which humans interface with their environment.

The investment ratio (IR) is the ratio of purchased inputs (F) to all EMergies derived from local sources (the sum of I and N) as follows:

$$IR = F/(I+N) \quad (1)$$

The name is derived from the fact that it is a ratio of 'invested' EMergy to resident EMergy. A dimensionless number, the bigger the investment ratio the greater the intensity of development. Regional or country wide IRs are useful for comparison with the IR of individual developments or processes. Investment ratios for nations that have been studied vary from as high as 7/1 for the United States (Odum et al., 1987a) to as low as 0.045/1 for Papua New Guinea (Doherty et al., 1992).

Comparison between regional investment ratios and the ratio for proposed or existing developments may be used as an indicator of the intensiveness of the development within the local economy. When the ratios of two developments of like kind are compared, an indication of their economic competitiveness is derived. The investment ratio can also be used to indicate if a process is economical in its utilization of purchased inputs in comparison with other alternative investments within the same economy.

2.5. Determining environmental impact: environmental loading ratio

Nearly all productive processes of humanity involve the interaction of nonrenewable EMergies with the renewable EMergies of the environment, and in so doing the environment is 'loaded' (meaning to strain, stress, or pressure). Fig. 4 shows environmental loading as the interaction of purchased EMergy and nonrenewable storages of EMergy from within the system with the renewable EMergy pathway through environmental work. An index of environmental loading, the environmental loading ratio (ELR) is the ratio of nonrenewable EMergy ($N+F$) to renewable EMergy (I) as follows:

$$ELR = (N+F)/I \quad (2)$$

Low ELRs reflect relatively small environmental loading, while high ELRs suggest greater loading.

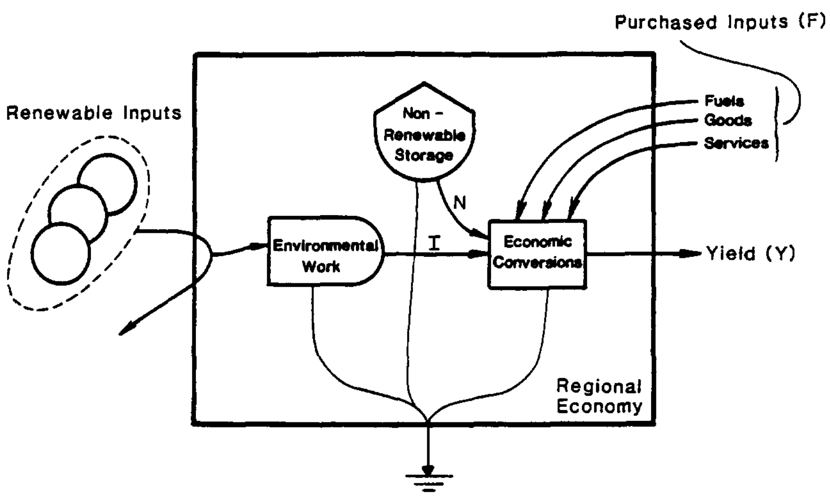


Fig. 4. Diagram illustrating a regional economy that imports (F) and uses resident renewable inputs (I) and nonrenewable storages (N). Several ratios used for comparisons between systems are given below the diagram and explained in the text. The letters on pathways refer to flows of EMergy per unit time, thus ratios of flows are dynamic and changing over time.

The ELR reflects the potential environmental strain or stress of a development when compared to the same ratio for the region, and can be used to calculate carrying capacity.

3. Results

3.1. Country overview

The aggregated country diagram in Fig. 5 emphasizes the inputs of sun, rain, rivers, geologic uplift, and imported goods and services. Production within the country included the forests, agriculture and aquaculture; industry and commerce utilize natural resources while supporting and being managed by the urban population.

EMergy and the macroeconomic value of annual flows of energy in Thailand are presented in Table 1. The chemical potential of rain was the single most important renewable resource. Agriculture, animal husbandry (livestock) and fisheries were the most important forms of renewable production. Important indigenous nonrenewable resources include top soil, which was used at a high rate, and natural gas, oil, lignite and limestone. Among the important imported EMergies were oil, phosphorus, nitrogen, food, wood, pesticides and mechanical equipment and vehicles. Associated with these goods was very high EMergy imported as foreign services; in other words, the EMergy of imported products that results from human service involved in the production of those resources. Among the most important exports were cash crops, fisheries and limestone. Exported services associated with exported goods were also high, but were about 65% of the imported EMergy in goods and services.

Summary diagrams of EMergy flows supporting Thailand's economy are given in Fig. 6. The top diagram (Fig. 6a) is an aggregate of all the EMergy

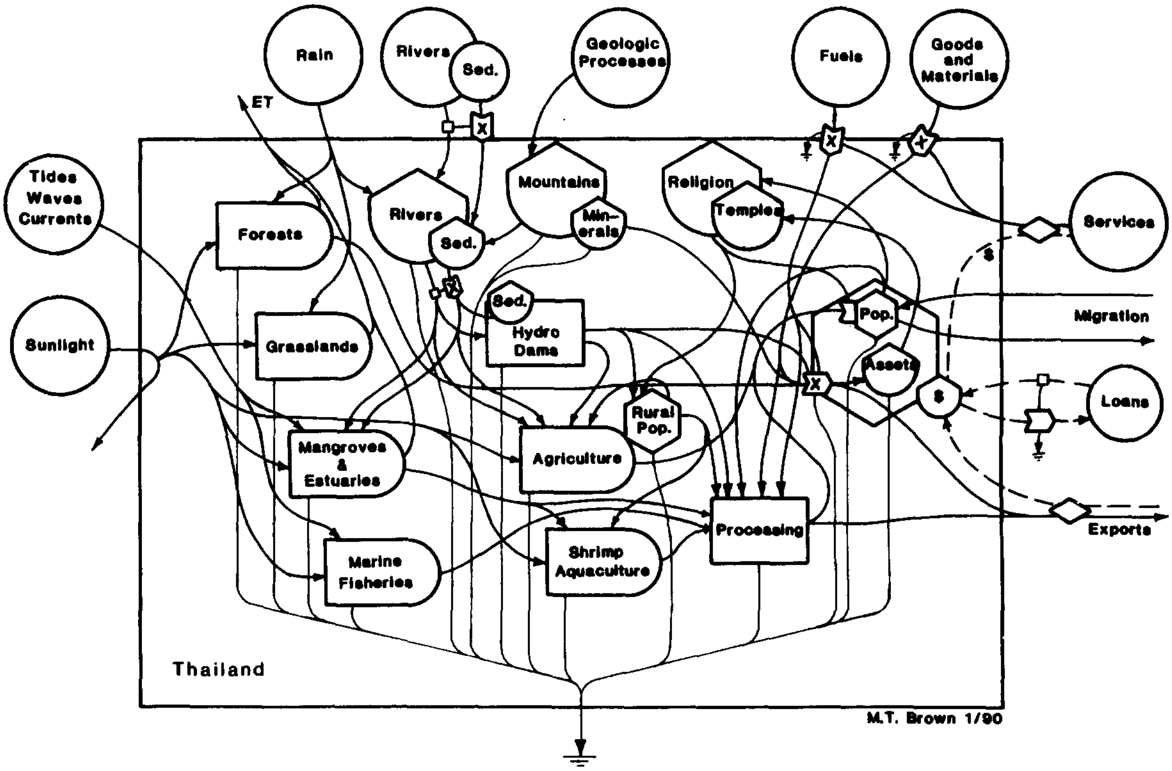


Fig. 5. Energy diagram of Thailand showing rural populations and their relationship to forested and agricultural lands, and the importance of religion. ET = evapotranspiration, Pop. = population, Sed. = sediments.

inputs including: imported fuels and goods (F and G), imported services ($P_2 I$), renewable resources (R), and nonrenewable resources derived from within the country (N_0, N_1, and N_2). Exports from the economy are composed of three flows: direct export of non-renewable resources (N_2), exports of eco-

Table 1
EMergy evaluation of resource basis for Thailand, 1984

No.	Item	Raw units	Transformity (sej/unit)	Solar EMergy (10^{20} sej)	Macroeconomic value (10^9 1984 US$)
RENEWABLE RESOURCES:					
1.	Sunlight	$2.88 \cdot 10^{21}$ J	1	28.84	1.20
2.	Rain, chemical	$4.77 \cdot 10^{18}$ J	15444	737.27	30.72
3.	Rain, geopotential	$2.16 \cdot 10^{18}$ J	8888	191.89	8.00
4.	Wind, kinetic	$2.38 \cdot 10^{18}$ J	623	14.83	0.62
5.	Waves	$4.20 \cdot 10^{17}$ J	25889	108.73	4.53
6.	Tide	$4.42 \cdot 10^{16}$ J	23564	10.42	0.43
7.	River geopotential	$1.31 \cdot 10^{17}$ J	23564	30.87	1.28
INDIGENOUS RENEWABLE ENERGY:					
8.	Hydroelectricity	$5.05 \cdot 10^{16}$ J	$1.59 \cdot 10^5$	80.25	3.34
9.	Agriculture prod.	$9.96 \cdot 10^{17}$ J	$2.00 \cdot 10^5$	1992.54	83.02
10.	Livestock prod.	$6.28 \cdot 10^{16}$ J	$2.00 \cdot 10^6$	1255.80	52.33
11.	Fisheries	$3.68 \cdot 10^{16}$ J	$2.00 \cdot 10^6$	736.74	30.70
12.	Fuelwood prod.	$9.35 \cdot 10^{15}$ J	$3.49 \cdot 10^4$	3.26	0.14
13.	Forest extraction	$1.47 \cdot 10^{16}$ J	$3.49 \cdot 10^4$	5.13	0.21
NONRENEWABLE SOURCES FROM WITHIN SYSTEM:					
14.	Natural gas	$9.41 \cdot 10^{16}$ J	$4.80 \cdot 10^4$	45.14	1.88
15.	Oil	$8.42 \cdot 10^{16}$ J	$5.30 \cdot 10^4$	44.64	1.86
16.	Lignite	$5.42 \cdot 10^{16}$ J	$3.74 \cdot 10^4$	20.28	0.84
17.	Gypsum	$3.40 \cdot 10^{11}$ g	$1.00 \cdot 10^9$	3.40	0.14
18.	Limestone	$8.70 \cdot 10^{12}$ g	$1.00 \cdot 10^9$	87.00	3.63
19.	Top soil	$7.24 \cdot 10^{16}$ J	$6.30 \cdot 10^4$	45.60	1.90
IMPORTS AND OUTSIDE SOURCES:					
20.	Oil	$5.00 \cdot 10^{16}$ J	$5.30 \cdot 10^4$	26.51	1.10
21.	Steel	$5.84 \cdot 10^{11}$ J	$1.97 \cdot 10^7$	0.12	0.00
22.	Phosphorus	$8.29 \cdot 10^{12}$ J	$4.14 \cdot 10^7$	3.43	0.14
23.	Nitrogen	$1.28 \cdot 10^{14}$ J	$1.69 \cdot 10^6$	2.17	0.09
24.	Potash	$8.63 \cdot 10^{12}$ J	$2.62 \cdot 10^6$	0.23	0.01
25.	Food	$7.24 \cdot 10^{15}$ J	$8.50 \cdot 10^4$	6.15	0.26
26.	Plastics	$1.84 \cdot 10^{13}$ J	$6.60 \cdot 10^4$	0.01	0.00
27.	Pesticides	$1.85 \cdot 10^{14}$ J	$1.97 \cdot 10^7$	36.53	1.52
28.	Wood, paper, textiles	$1.04 \cdot 10^{16}$ J	$3.49 \cdot 10^4$	3.60	0.15
29.	Mech. and trans. eqp.	$3.75 \cdot 10^{11}$ J	$1.40 \cdot 10^9$	5.25	0.22
30.	Services	$1.06 \cdot 10^{10}$ $	$3.80 \cdot 10^{12}$	402.80	16.78
31.	Net migration	$-9.33 \cdot 10^4$ p/yr	$3.15 \cdot 10^{15}$	−2.94	−0.12
EXPORTS:					
32.	Cash crops	$2.48 \cdot 10^{17}$ J	$2.00 \cdot 10^5$	496.71	20.70
33.	Fishery products	$5.68 \cdot 10^{15}$ J	$2.00 \cdot 10^6$	113.55	4.73
34.	Forest products	$1.28 \cdot 10^{15}$ J	$3.49 \cdot 10^4$	0.45	0.02
35.	Fluorite	$2.04 \cdot 10^{11}$ g	$1.00 \cdot 10^9$	2.04	0.09
36.	Gypsum	$8.70 \cdot 10^{11}$ g	$1.00 \cdot 10^9$	8.70	0.36
37.	Limestone	$1.10 \cdot 10^{12}$ g	$1.00 \cdot 10^9$	11.00	0.46
38.	Barite	$2.13 \cdot 10^{11}$ g	$1.00 \cdot 10^9$	2.13	0.09
39.	Service in exports	$7.15 \cdot 10^9$ $	$3.46 \cdot 10^{12}$	247.40	10.30
40.	Tourist service	$1.00 \cdot 10^9$ $	$3.46 \cdot 10^{12}$	34.60	1.44

Data sources and calculations are given in Appendix A.

nomic products (E) and exports of services derived from the dollar income from exported goods ($P_1 E$). The GNP (X) was equal to $4.3 · 10^10. The bottom diagram (Fig. 6b) further summarizes Thailand's economy by summing EMergy flows from indigenous sources ($R + N_0 + N_1 + N_2$), imports ($F + G + P_2 I$), and exports ($N_2 + E + P_1 E$). $P_1 E$ is defined as EMergy-to-money ratio for Thailand (P_1) multiplied by total exports (E). $P_2 I$ is defined as the world EMergy-to-money ratio ($P_2 = 3.8 \cdot 10^{12}$ sej/$) multiplied by imports ($F + G = I$).

Overview indices of the EMergy analysis of Thailand are given in Table 2. Some of the more striking of the overview indices are as follows: Thailand's EMergy-to-money ratio ($3.46 \cdot 10^{12}$ sej/$) was close to the world average ($3.8 \cdot 10^{12}$ sej/$). About 67% of the EMergy basis for Thailand's economy was derived from within the country (line 7), 33% was

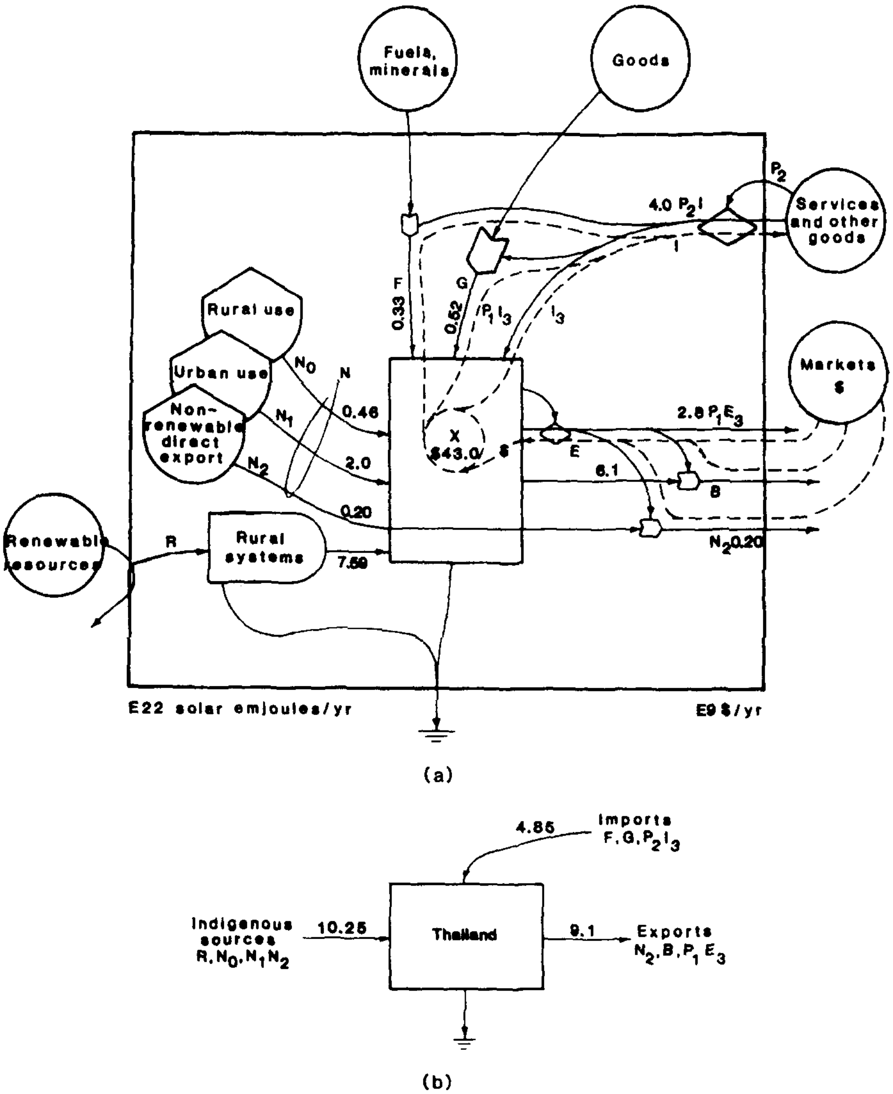


Fig. 6. Summary diagram of EMergy flows in Thailand's economy. An aggregation of all EMergy flows is given in the top diagram (a). The inflows and exports are further aggregated into a three-flow diagram at the bottom (b). All EMergy flows are 10^{22} sej/yr, all dollar flows are 10^9 $/yr.

imported (line 12), while 61% of the total EMergy of the economy (line 10) was exported. Fifty-two percent of EMergy use was locally renewable (line 14). Thailand had a net EMergy deficit from trade (425 · 10^{20} sej/yr). The portion of exports that are derived from storages of raw resources was relatively small, only about 2% ($N_2/N_2 + B + P_1E$). The ratio of imported EMergy to exported EMergy is 0.53/1 (line 9). Twenty-seven percent of the country's EMergy came from imported service (line 13).

The ratio of concentrated EMergy to rural resources used (line 15) is a ratio that relates the percent of EMergy use that flows through urbanized areas to the renewable EMergy that is derived primarily from the rural landscape. In Thailand the ratio was about 0.85/1 or about 85% of the total EMergy of the economy is derived from concentrated sources that flow through urban centers.

A measure of long-term, sustainable carrying capacity for humans of Thailand's landscape is the *renewable EMergy carrying capacity* at present living standard (line 18). It is derived by calculating the percent of total EMergy that is from rural sources (49%) and multiplying by the present population (50 million people). It is a measure of the number of people that could be supported by renewable sources alone, if they maintained today's living standard. The renewable carrying capacity of Thailand was 25.4 million people or about 50% of today's population. Line 19 gives the carrying capacity assuming development of Thailand's economy to that which is characteristic of developed nations like the United States, but using Thailand's present living standard. Developed carrying capacity is calculated by multiplying renewable EMergy flow (R) by 8.0 (the ratio of concentrated to renewable EMergy in developed economies) and dividing by the current EMergy use per capita (2.98 · 10^{15} sej/person; line 17). The developed carrying capacity was 203 million people, but assumes that world energy supplies are of suffi-

Table 2
Overview indices of Thailand, 1985

No.	Description	Expression	Quantity
1.	Renewable EMergy flow	R	779 · 10^{20} sej/yr
2.	Flow from indigenous nonrenewable reserves	N	266 · 10^{20} sej/yr
3.	Flow of imported EMergy	$F+G+P_2I$	485 · 10^{20} sej/yr
4.	Total EMergy inflows	$R+N+F+G+P_2I$	1530 · 10^{20} sej/yr
5.	Total EMergy used (U)	$N_0+N_1+R+F+G+P_2I$	1510 · 10^{20} sej/yr
6.	Total exported EMergy	N_2+E+P_1E	910 · 10^{20} sej/yr
7.	Fraction of EMergy use derived from home sources	$(N_0+N_1+R)/U$	67%
8.	Imports minus exports	$(F+G+P_2I)-(N_2+B+P_1E)$	−425 · 10^{20} sej/yr
9.	Ratio of imports to exports	$(F+G+P_2I)/(N_2+B+P_1E)$	0.53
10.	Fraction of EMergy that is exported	$(N_2+B+P_1E)/U$	61%
11.	Fraction used, locally renewable	R/U	51%
12.	Fraction of EMergy use purchased (imports)	$(F+G+P_2I)/U$	33%
13.	Fraction imported service	P_2I/U	27%
14.	Fraction of use that is free	$(R+N_0)/U$	52%
15.	Ratio of concentrated to rural EMergy sources	$(F+G+P_2I+N_1)/(R+N_0)$	85%
16.	EMergy density	U/(area)	2.9 · 10^{11} sej/m^2
17.	EMergy per capita	U/(population)	2.98 · 10^{15} sej/person
18.	Renewable carrying capacity at present living standard	(R/U) (population)	25.4 · 10^6 people
19.	Developed carrying capacity at present living standard	$8R/(U$/pop.)	203 · 10^6 people
20.	EMergy-to-money ratio	$P_1 = U$/GNP	3.46 · 10^{12} sej/$
21.	Electricity use as fraction of total EMergy use	(electric)/U	8.2%
22.	Fuel use per person	fuel/population	1.80 · 10^{14} sej/person
23.	Environmental loading ratio	$(N_0+N_1+F+G+P_2I)/R$	1.0/1

Letters refer to letters on pathways and storages given in Fig. 7.

cient size that this may be accomplished, and that the present living standard would be maintained in the future.

3.2. EMergy analysis of the Mekong River Dam proposals

An overview diagram of the proposed dam on the Mekong (Fig. 7) shows that the main loss from the proposed dam was the loss of area for agricultural production and the displacement of rural households. The primary benefits were electricity generated for use in urban and rural households and manufacturing and water for irrigation.

EMergy analyses of both dams (Tables 3 and 4) included the potential dam benefits (electricity, aquatic productivity, and irrigation supporting farm production) and costs (operation and maintenance, the direct costs of dam and irrigation system construction, and losses of agricultural productivity, as well as losses associated with human population resettlement and social disruption). Also included was the loss of river sediments (these were treated separately in the analysis of benefits and costs). The dam was assumed to have a 50-year life span, thus construction costs were divided by 50 to present data on a yearly basis.

The analysis indicates that electricity production, by far, was the major EMergy benefit of dam construction. Irrigation and aquatic productivity were relatively unimportant. The analysis assumes that irrigation has the effect of doubling the annual yield of crops through dry season irrigation. Irrigation had a very high benefit/cost ratio but its inclusion in the development project seemed not to be important in determining the net EMergy of the project, since the

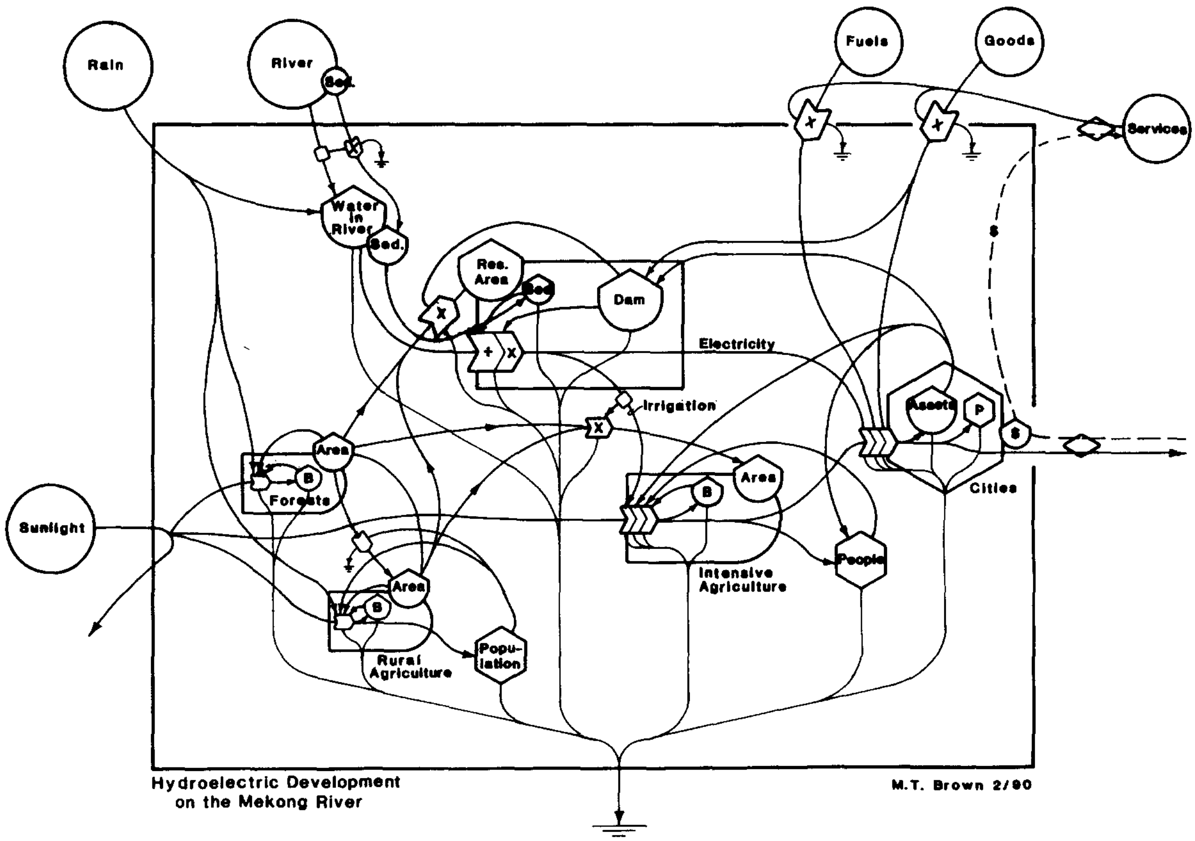


Fig. 7. Energy diagram of relationships between urban and rural populations and the proposed hydroelectric dams on the Mekong River. B = Biomass, P = People, Sed. = Sediments.

Table 3
EMergy evaluation of Low Pa Mong dam

No.	Item	Raw units	Transformity (sej/unit)	Solar EMergy (10^{18} sej/yr)
1.	River geopotential	$5.68 \cdot 10^{16.5}$	23564	1338.5
EMERGY BENEFITS				
2.	Electricity	$3.62 \cdot 10^{16}$ J	159000	5755.8
3.	Aquatic productivity	$9.30 \cdot 10^{14}$ J	440	0.4
4.	Irrigation (Agric.)	$1.15 \cdot 10^{11}$ g	$9.70 \cdot 10^{8}$	112.1
	Total			5868.3
EMERGY COSTS				
5.	Operation and maintenance	$2.04 \cdot 10^{7}$ $	$3.46 \cdot 10^{12}$	70.6
6.	Concrete	$1.35 \cdot 10^{11}$ g	$7.00 \cdot 10^{7}$	9.5
7.	Steel	$2.31 \cdot 10^{8}$ g	$1.80 \cdot 10^{9}$	0.4
8.	Machinery	$6.66 \cdot 10^{8}$ g	$6.70 \cdot 10^{9}$	4.5
9.	Services	$3.78 \cdot 10^{7}$ $	$3.46 \cdot 10^{12}$	130.8
10.	Agric. prod. (rice)	$1.23 \cdot 10^{11}$ g	$9.70 \cdot 10^{8}$	119.3
11.	Agric. prod. (maize)	$7.42 \cdot 10^{14}$ J	$4.75 \cdot 10^{4}$	35.2
12.	Resettlement	$4.00 \cdot 10^{6}$ $	$3.46 \cdot 10^{12}$	13.7
13.	Irrigation (services)	$4.80 \cdot 10^{6}$ $	$3.46 \cdot 10^{12}$	16.6
14.	Social disruption	$2.56 \cdot 10^{4}$ p/yr	$2.98 \cdot 10^{15}$	76.2
15.	Sediments	$5.91 \cdot 10^{16}$ J	$6.30 \cdot 10^{4}$	3759.6
	Total			4236.4
EMERGY YIELD RATIO WITHOUT SEDIMENT: $58.7 \cdot 10^{20}/4.8 \cdot 10^{20} = 12.3/1$				
EMERGY YIELD RATIO WITH SEDIMENT: $58.7 \cdot 10^{20}/42.4 \cdot 10^{20} = 1.39/1$				

Data sources and calculations are given in Appendix B.

Table 4
EMergy evaluation of Upper Chiang Khan dam

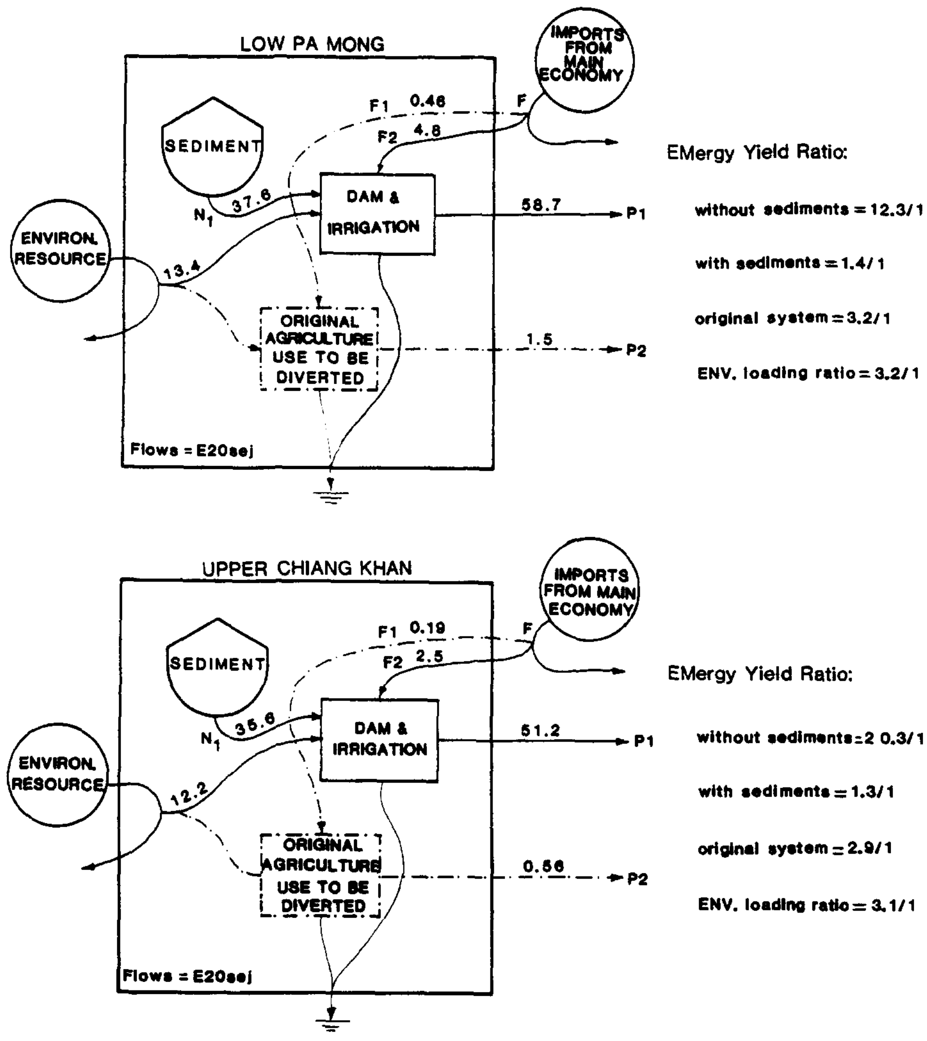
No.	Item	Raw units	Transformity (sej/unit)	Solar EMergy (10^{18} sej/yr)
1.	River geopotential	$5.19 \cdot 10^{16}$ J	23564	1222.1
EMERGY BENEFITS				
2.	Electricity	$3.20 \cdot 10^{16}$ J	159000	5088.0
3.	Aquatic productivity	$6.10 \cdot 10^{14}$ J	440	0.3
4.	Irrigation (Agric.)	$3.68 \cdot 10^{10}$ g	$9.7 \cdot 10^{8}$	35.7
	Total			5124.0
EMERGY COSTS				
5.	Operation and maintenance	$7.40 \cdot 10^{6}$ $	$3.46 \cdot 10^{12}$	25.6
6.	Concrete	$1.10 \cdot 10^{11}$ g	$7.00 \cdot 10^{7}$	7.7
7.	Steel	$1.91 \cdot 10^{8}$ g	$1.80 \cdot 10^{9}$	.3
8.	Machinery	$4.16 \cdot 10^{8}$ g	$6.70 \cdot 10^{9}$	2.8
9.	Services	$2.77 \cdot 10^{7}$ $	$3.46 \cdot 10^{12}$	95.8
10.	Agric. prod. (rice)	$2.30 \cdot 10^{9}$ g	$9.70 \cdot 10^{8}$	2.2
11.	Agric. prod. (maize)	$1.14 \cdot 10^{15}$ J	$4.75 \cdot 10^{4}$	54.2
12.	Resettlement	$2.63 \cdot 10^{6}$ $	$3.46 \cdot 10^{12}$	9.1
13.	Irrigation (services)	$1.54 \cdot 10^{6}$ $	$3.46 \cdot 10^{12}$	5.3
14.	Social disruption	$1.68 \cdot 10^{4}$ p/yr	$2.98 \cdot 10^{15}$	50.1
15.	Sediments	$5.65 \cdot 10^{16}$ J	$6.30 \cdot 10^{4}$	3559.5
	Total			3812.6
EMERGY YIELD RATIO WITHOUT SEDIMENTS: $51.24 \cdot 10^{20}/2.53 \cdot 10^{20} = 20.3/1$				
EMERGY YIELD RATIO WITH SEDIMENTS: $51.24 \cdot 10^{20}/38.12 \cdot 10^{20} = 1.34/1$				

Data sources and calculations are given in Appendix C.

EMergy value of electricity produced was more than an order of magnitude greater than the expected agricultural production.

The most significant costs associated with the dam construction were services (the dollar project costs), followed by lost agricultural production. The lost agricultural production was nearly made up for with increased production resulting from irrigation of other lands. Social disruption was the third largest cost. Overall, both dams had positive EMergy yield ratios. When sediments were not included, the Upper Chiang Khan option had a better ratio (20.3/1) than the Low Pa Mong option (12.3/1). While electrical production is relatively similar between the two sites, costs at the Upper Chiang Khan site were proportionately lower.

The EMergy analysis suggests that, in either case, the development of irrigation is necessary to offset losses of agricultural production resulting from inundation. Development of irrigation schemes and hy-



37

Fig. 8. Summary diagrams of the EMergy analysis of the proposed Low Pa Mong (top) and Upper Chiang Khan dam sites.

droelectric potential may cause increased population density near the dam sites which could reverse some out migration trends and alleviate some of the potential problems associated with population resettlement. However, increased population pressure and resulting soil erosion could easily reduce the useful lifespan of either of the dams, which is one of the single most critical factors affecting their success.

Fig. 8 summarizes the EMergy evaluations and policy options related to the proposed dams. The Low Pa Mong option is illustrated in the top portion of the figure and the Upper Chiang Khan in the lower portion. Three EMergy yield ratios and the environmental loading ratio are given for each dam. The EMergy yield ratio without sediments is derived from the diagram by dividing P_1 by F_2, and is 12.3/1 and 20.3/1 for Low Pa Mong and Upper Chiang Khan dams, respectively. If sediments are included as a cost, the EMergy yield ratio is calculated by dividing the yield (P_1) by $N_1 + F_2$. Under these conditions, the EMergy yield ratios are 1.41 and 1.31 for Low Pa Mong and Upper Chiang Khan dams, respectively. The environmental loading ratio for each dam can be determined by dividing $N_1 + F_2$ by I (the inflow of environmental resources). The ELRs of the Upper Chiang Khan and Low Pa Mong were 3.1/1 and 3.2/1, respectively. These ratios are relatively larger than the corresponding ratio for Thailand (1.0/1, see Table 2), indicating that, on the average, they place a larger 'load' on the environment. This is to be expected since they are facilities that produce concentrated economic resources.

The diagrams also show the original systems that will be diverted (lost) should either of the dams be built (dashed box) and their EMergy yield ratios. The total production (P_2) from either of the original systems is considerably smaller than the production resulting from the dams. Comparison of the yield ratios of the new systems versus the original systems reveals that, in both cases, if sediments are included in the evaluation, the original systems have higher yield ratios than the new (Low Pa Mong = 3.2/1 versus 1.4/1; and Upper Chiang Khan = 2.9/1 versus 1.3/1). Higher yield ratios suggest a more sustainable pattern, all other things being equal, however the larger total EMergy flow that results from the dams contributes more to the economy in the short run.

4. Discussion

4.1. Country overview

The EMergy analysis is indicative of the transitional state of Thailand's economy. Thailand's EMergy/$ ratio is near the world average, indicating its position at the boundary between developed and less developed countries. Yet, its EMergy/capita ($2.98 \cdot 10^{15}$ sej/person) is relatively low. India's ratio is $1.0 \cdot 10^{15}$ sej/person and the United States' is $29 \cdot 10^{15}$ sej/person (Odum, 1987). This may represent an abundant population in relationship to resources. The country has an agricultural base, and has the potential for increased production of natural gas and hydroelectricity. Of great environmental concern is the rate of top soil loss that is nearly equal to natural gas or oil production (Table 1). Thailand presently has a net EMergy loss from its trade despite a small deficit in its balance of payments (TIC, 1987) due, in part, to the fact that much value is exported in agricultural and fisheries products. However, the imbalance is not the result of exports of raw materials (which make up only about 2% of the total exports).

Analysis of the economies of other nations has led to a broad classification of national economies based on their imports and exports: 'consumer' nations and 'producer' nations. If a nation imports more EMergy than it exports, it is a 'consumer' nation; on the other hand, it if exports more than it imports, it is considered a 'producer' nation. Further, producer nations can be classed based on the makeup of their exports. Nations whose exports are composed largely of raw resources (i.e., greater than 50%) are considered resource producers, while those whose exports are composed mostly of upgraded, intermediate, or finished products are considered commodity producers. The fact that Thailand exports more than it imports (almost 2/1) and that 98% of its exports are finished or intermediate products suggests that it is a commodity producer.

4.2. Mekong Dam proposal

Sediments (and their accompanying organic matter and nutrients) brought from the upper reaches of the Mekong River are a major input to the economy of Thailand when they are allowed to deposit freely in floodplain and estuarine systems. Stockpiled and buried in one location their effect in stimulating productivity is diminished since, to be a source, an energy must be used. The EMergy analysis of the two proposed dam sites was calculated in two different ways: with and without sediments as an environmental 'cost'. The loss of sediments can be considered a negative impact resulting from hydroelectric development since their deposition and burial in the reservoir precludes their deposition in downstream locations. Thus, their input to downstream wetlands, agricultural lands, and estuarine systems is curtailed and, presumably, the productivity of these systems is lowered. When they are included in the EMergy analysis, the results were quite different. The EMergy yield ratio with and without sediments for each of the dams was 1.4/1 and 12.3/1 (Low Pa Mong) and 1.3/1 and 20.3/1 (Upper Chiang Kahn), respectively. The difference illustrates the value of sediments. In both cases, their value was equal to nearly 2/3 of the electricity produced (Tables 3 and 4).

It can be argued that the burial of sediments within the reservoir is an EMergy cost from two perspectives. First, burial 'locks' them up, removing them from the system (i.e., as a driving energy), and second, the net effect of trapping sediments at one location is often increased erosion downstream, since depositional and erosional forces are no longer in balance. Thus a measure of the loss of soils eroded from downstream locations might be the volume trapped in the reservoir. Add to this the potential for increased erosion and scouring of the river channel resulting from increased velocities and the net effect may be greater soil loss. Erosion at the Pa Mong site was suggested to extend for a length of 200 km downstream (IMC, 1987), at an estimated cost of $200 million (although no quantitative evaluation of actual erosion rates or magnitude was attempted). Floodplain vegetation, and near-river agriculture will be seriously affected by the loss. In light of the potential for increased erosion, the estimates of environmental costs using sediments trapped may be an underestimate of the actual costs to the economy.

If both dams are built as a cascade, the inclusion of sediments as an environmental cost would be halved since sediments trapped in one location could not be doubled counted in the second location. Summing EMergy costs and benefits for both dams (but including only the sediments of the Pa Mong site) gives an overall EMergy yield ratio of 2.45/1.

EMergy yield ratios for primary energy sources (e.g., oil or natural gas) calculated in previous studies have been between 6/1 (coal) and 14/1 (Alaska North Slope). Thus, to compete, alternative primary sources of energy should have comparable yields. A yield ratio calculated as electricity cannot be compared directly with primary energies, since electricity is a higher quality energy that includes the necessary second law losses associated with the conversion from fuels. An EMergy yield ratio, as electricity, of 2.45/1 for a hydroelectric facility can be expressed in equivalent fossil fuel energy by multiplying its yield ratio by the ratio of the transformities of electricity and fossil fuels (159000/53000, or 3/1). In this way, the yield ratio can be compared with other primary energies. The EMergy yield ratio for the combined Chiang Kahn/Low Pa Mong cascade, then, becomes 7.35/1, and the ratios for the either of the dams constructed individually are 4.2/1 (Pa Mong) and 3.9/1 (Chiang Kahn).

The converted yield ratios suggest that if either of the dams were built individually without the second facility, its net contribution to the economy would be questionable when compared with conventional fossil fuel plants. In other words, the yields are such that if only one or the other of the dams is built, it would not be competitive at the present time. On the other hand, if both are constructed as a cascade, the combined yield (7.35/1) is high enough to suggest that they will compete with conventional fossil fuel plants.

Often, when comparing conventional fossil fuel plants with hydroelectric facilities, the argument of nonrenewable versus renewable energy sources is posited, suggesting that it is better to rely on renewable energy sources (even though they may have lower yields) than it is to rely on nonrenewable sources. However, this argument ignores two facts. First, the EMergy analysis takes into account the lifetime yields of the dam. With low net yields, it 'consumes' energy (some of which will presumably be fossil fuel energy) at a ratio that is lower than conventional fuels over its lifetime. Second, for a source of energy to be competitive, its yield must be comparable with those characteristic of other sources, otherwise it will drain away energy from other productive activities.

The yield ratios calculated for the dam proposals are extremely sensitive to the costs associated with the loss of sediments. In conventional economic analysis, costs associated with such things as sediment loss are accounted for only as economic costs incurred, and not as the potential productivity (especially to natural systems) that may be lost. Since an underlying principle of EMergy analysis is that loss of any EMergy, regardless of its 'form', will result in lowered overall system performance, the loss of sediments is a cost to the overall economy. Lowered productivity of floodplain swamps, river aquatic production, and estuarine fisheries will ultimately show up as decreased economic performance. Accounting for these potential losses using EMergy analysis may provide additional insight upon which decisions can be based.

4.3. Summary comments

Hydro-electric dams commonly have high yields when their costs of construction are compared to the electricity generated. Other benefits from dams such as increased irrigation are added benefits that often make dams even more attractive. Yet long-term ecological costs are not easily factored in using conventional accounting methods. In this analysis the benefits of irrigation about equaled the environmental losses resulting from terrestrial systems being inundated. The large yields of electricity are almost offset by the loss of sediments and the down stream productivity they support.

Overall the net benefits of dam proposals to economies should be measured taking into account their net contribution to the larger economy. Probably, if many present dam facilities were evaluated after the fact, and such things as lost fisheries, negative impacts on nutrient balances, and increased soil erosion in surrounding areas were included, numerous dam projects may have had much lower net yields.

There is a trade-off between using the geopotential energy of rivers to generate electricity and thus not having it to spread organic matter, nutrients, and sediments in its lower reaches and delta. The trade-off appears to be one of high quality energy for urban and industrial applications, at the expense of rural and environmental systems that rely on the geopotential and chemical energy spread over floodplains and river deltas.

Acknowledgements

This research was supported by funds from The Cousteau Society. Captain Jacques Cousteau and his son Jean-Michel Cousteau have worked closely with our group over the past decade, providing research funds and logistical support throughout the world. Our friend and colleague Dr. Richard Murphy was project manager, and made many pertinent comments on earlier drafts. Our thanks to two anonymous reviewers for their comments and criticisms.

Appendix A. Footnotes to Table 1

1. SOLAR ENERGY

Cont. shlf area	$= 2.27 \cdot 10^{11}$ m^2 (Tennenbaum and Brown, 1989)
Land area	$= 5.13 \cdot 10^{11}$ m^2 (TDRI, 1987)
Insolation	$= 1.33 \cdot 10^{2}$ kcal/cm^2/yr (Tennenbaum and Brown, 1989)
Albedo	= 0.30 (% given as decimal)
Energy (J)	= (area incl shelf) * (avg insolation) * (1 − albedo)
	$= (\text{—m}^2) * (\text{—cal/cm}^2/\text{yr}) * (1 \cdot 10^4\ \text{cm}^2/\text{m}^2) * (1 - 0.30) * (4186\ \text{J/kcal})$
	$= 2.88 \cdot 10^{21}$

2. RAIN, CHEMICAL POTENTIAL ENERGY:

Land area	$= 5.13 \cdot 10^{11}$ m^2

	Cont. shlf area	$= 2.27 \cdot 10^{11}$ m^2
	Rain (land)	= 1.56 m/yr (TDRI, 1987)
	Rain (shelf)	= 1.50 m/yr (est. from TDRI, 1987)
	Evapotrans. rate	= 1.22 m/yr
	Energy (land)	= (area)(evapotrans)(rainfall)(Gibbs no.)
		= (—m^2) * (—m)(1000 kg/m^3) * ($4.94 \cdot 10^3$ J/kg)
		$= 3.09 \cdot 10^{18}$
	Energy (shelf) (J)	= (area of shelf)(rainfall)(Gibbs no.)
		$= 1.68 \cdot 10^{18}$
	Total energy (J)	$= 4.77 \cdot 10^{18}$
3.	RAIN, GEOPOTENTIAL ENERGY	
	Area	$= 5.14 \cdot 10^{11}$ m^2
	Rainfall	= 1.56 m
	Avg. elev.	= 350 m
	Runoff rate	= 0.79 (1.0 − ET)
	Energy (J)	= (area)(%runoff)(rainfall)(avg elevation)(gravity)
		= (—m^2) * (—m) * (1000 kg/m^3) * (—m) * (9.8 m/s^2)
		$= 2.16 \cdot 10^{18}$
4.	WIND ENERGY:	
	Energy (J)	$= 2.38 \cdot 10^{18}$ J/yr (Tennenbaum and Brown, 1989)
5.	WAVE ENERGY:	
	Energy (J)	$= 4.20 \cdot 10^{17}$ J/yr (Tennenbaum and Brown, 1989)
6.	TIDAL ENERGY:	
	Cont. shlf area	$= 2.27 \cdot 10^{11}$ m^2
	Avg. tide range	= 0.33 m
	Density	$= 1.03 \cdot 10^3$ kg/m^3 (Odum et al., 1987b)
	Tides/year	$= 3.65 \cdot 10^2$
	Energy (J)	= (shelf)(0.5)(tides/yr)(mean tidal range)^2(density of seawater)(gravity)
		= (—m^2) * (0.5) * (—m)^2 * (—kg/m^3) * (9.8 m/s^2)
		$= 4.42 \cdot 10^{16}$
7.	RIVER GEOPOTENTIAL (MEKONG)	
	Flow	$= 1.70 \cdot 10^4$ m^3/s
	Elevation change	$= 5.00 \cdot 10^1$ m
	Energy (J)	= (flow)(elevation change)(gravity)(seconds/year)(water weight)(0.5 energy available to Thailand)
		= (—m^3/s)(—m)(9.8 m/s^2)(1000 kg/m^3)($3.1 \cdot 10^7$ s/yr)(0.5)
		$= 1.31 \cdot 10^{17}$
8.	HYDROELECTRICITY:	
	Hydro. prod.	$= 2.00 \cdot 10^3$ MW/yr (TDRI, 1987)
	Efficiency	$= 8.00 \cdot 10^{-1}$
	Energy (J)	= (—MW) * (eff) * (8760 hr/yr) * (100 kWh.MW) * (860 cal/kWh)(4187 J/cal)
		$= 5.05 \cdot 10^{16}$
9.	AGRICULTURAL PRODUCTION:	
	Agric. prod.	$= 6.08 \cdot 10^7$ Mt (TDRI, 1987)
	Energy (J)	= (6.87 Mt) * ($1.06 \cdot 10^6$ g/Mt) * (3.5 cal/g) * (4186 J/cal)
		$= 9.96 \cdot 10^{17}$

10. LIVESTOCK PRODUCTION:
Livestock prod. $= 3.75 \cdot 10^6$ Mt (TDRI, 1987)
Energy (J) $= (3.75 \cdot 10^6\ \text{Mt}) * (\cdot 10^6\ \text{g/Mt}) * (4\ \text{cal/g}) * (4187\ \text{J/cal})$
$= 6.28 \cdot 10^{16}$

11. FISHERIES PRODUCTION:
Fish catch $= 2.20 \cdot 10^6$ Mt (TDRI, 1987)
Energy (J) $= (2.2 \cdot 10^6\ \text{Mt}) * (1 \cdot 10^6\ \text{g/Mt}) * (4\ \text{cal/g}) * (4186\ \text{J/cal})(\%\ \text{protein})$
$= 3.68 \cdot 10^{16}$

12. FUELWOOD PRODUCTION:
Fuelwood prod. $= 1.24 \cdot 10^6\ \text{m}^3/\text{yr}$ (TDRI, 1987)
Energy (J) $= (1.24 \cdot 10^6\ \text{m}^3/\text{yr}) * (0.5 \cdot 10^6\ \text{g/m}^3) * (3.6\ \text{cal/g}) * (4187\ \text{J/cal})$
$= 9.35 \cdot 10^{15}$ (Tennenbaum and Brown, 1989)

13. FOREST EXTRACTION:
Harvest $= 1.95 \cdot 10^6\ \text{m}^3$ (TDRI, 1987)
Energy (J) $= (1.95 \cdot 10^6\ \text{m}^3)(0.5 \cdot 10^6\ \text{g/m}^3)(3.6\ \text{cal/g})(4186\ \text{J/cal})$
$= 1.47 \cdot 10^{16}$

14. NATURAL GAS:
$= 1.1 \cdot 10^6\ \text{J}/1000\ \text{ft}^3$
Consumption $= 8.55 \cdot 10^{10}\ \text{ft}^3$ (TDRI, 1987)
Energy (J) $= (8.55 \cdot 10^{10}\ \text{ft}^3) * (1.1 \cdot 10^6\ \text{J}/1000\ \text{ft}^3)$
$= 9.41 \cdot 10^{16}$

15. OIL:
Consumption $= 1.29 \cdot 10^7$ BBL (TDRI, 1987)
Energy (J) $= (1.29 \cdot 10^7\ \text{BBL}) * (42\ \text{gal/BBL}) * (3.8\ \text{l/gal}) * (9800\ \text{cal/l}) * (4187\ \text{J/cal})$

16. LIGNITE:
Consumption $= 5.18 \cdot 10^6$ Mt (TDRI, 1987)
Energy (J) $= (5.18 \cdot 10^6\ \text{Mt}) * (1 \cdot 10^3\ \text{kg/Mt}) * (2500\ \text{cal/kg}) * (4187\ \text{J/cal})$
$= 5.42 \cdot 10^{16}$

17. GYPSUM:
Consumption $= 3.40 \cdot 10^5$ Mt (TDRI, 1987)
Energy (g) $= (3.4 \cdot 10^5\ \text{Mt}) * (1 \cdot 10^6\ \text{g/Mt})$
$= 3.40 \cdot 10^{11}$

18. LIMESTONE:
Consumption $= 8.70 \cdot 10^6$ Mt (TDRI, 1987)
Energy (g) $= (8.7 \cdot 10^6\ \text{Mt}) * (1 \cdot 10^6\ \text{g/Mt})$
$= 8.70 \cdot 10^{12}$

19. TOPSOIL:
Soil loss $= 6.86 \cdot 10^7$ Mt/yr (Pantulu, 1986; TDRI, 1987)
Energy (J) $= 6.86 \cdot 10^7\ \text{Mt/yr}) * (1 \cdot 10^6\ \text{g/Mt}) * (0.07\ \text{g OM/g sed}) * (3.6\ \text{cal/g}) * (4187\ \text{J/cal})$
$= 7.24 \cdot 10^{16}$

20. OIL:
Imports $= 1.22 \cdot 10^9$ l (TIC, 1987)
Energy (J) $= (1.22 \cdot 10^9\ \text{l}) * (41 \cdot 10^6\ \text{J/l})$
$= 5.00 \cdot 10^{16}$

21. STEEL:
Imports $= 5.84 \cdot 10^5$ Mt (TIC, 1987)

	Energy (J)	$= (5.85 \cdot 10^5$ Mt$) * (1 \cdot 10^6$ g/Mt)
		$= 5.84 \cdot 10^{11}$
22.	PHOSPHORUS:	
	Imports	$= 7.22 \cdot 10^5$ Mt (TIC, 1987)
	% P by atomic wt.	$= 3.30 \cdot 10^{-1}$
	% PO_4 in fert.	$= 1.00 \cdot 10^{-1}$
	Energy (J)	$= (7.22 \cdot 10^5$ Mt$) * (0.33) * (0.1) * (1 \cdot 10^6$ g/Mt$) * (348$ J/g)
		$= 8.29 \cdot 10^{12}$
23.	NITROGEN:	
	Imports	$= 7.22 \cdot 10^5$ Mt (TIC, 1987)
	% N by atomic wt.	$= 8.20 \cdot 10^{-1}$
	% NH_3 in fert.	$= 1.00 \cdot 10^{-1}$
	Energy (J)	$= (7.22 \cdot 10^5$ Mt$) * (0.82) * (0.1) * (1 \cdot 10^6$ g/Mt$) * (2.17 \cdot 10^3$ J/g)
		$= 1.28 \cdot 10^{14}$
24.	POTASH:	
	Imports	$= 3.07 \cdot 10^5$ (TIC, 1987)
	% K by atomic wt.	$= 4.00 \cdot 10^{-1}$
	% KCl in fert.	$= 1.00 \cdot 10^{-1}$
	Energy (J)	$= (3.07 \cdot 10^5$ Mt$) * (0.4) * (0.1) * (1 \cdot 10^6$ g/Mt$) * (702$ J/g)
		$= 8.63 \cdot 10^{12}$
25.	FOODS:	
	Imports	$= 4.79 \cdot 10^5$ Mt (TIC, 1987)
	Energy (J)	$= (1 \cdot 10^6$ g/Mt$) * (15.1 \cdot 10^3$ J/g)
		$= 7.24 \cdot 10^{15}$
26.	PLASTICS:	
	Imports	$= 1.96 \cdot 10^3$ Mt (TIC, 1987)
	Energy (J)	$= (1.9 \cdot 10^3$ kg/Mt$) * (1000$ kg/Mt$) * (9.4 \cdot 10^6$ J/kg)
		$= 1.84 \cdot 10^{13}$
27.	PESTICIDES:	
	Imports	$= 1.96 \cdot 10^4$ Mt (TIC, 1987)
	Energy (J)	$= (1 \cdot 10^3$ kg/Mt$) * (9.4 \cdot 10^6$ J/kg)
		$= 1.85 \cdot 10^{14}$
28.	WOOD, PAPER, TEXTILES:	
	Imports	$= 6.93 \cdot 10^5$ Mt (TIC, 1987)
	Energy (J)	$= (6.93 \cdot 10^5$ Mt$) * (1 \cdot 10^6$ g/Mt$) * (15 \cdot 10^3$ J/g)
		$= 1.04 \cdot 10^{16}$
29.	MACHINERY, TRANSPORTATION, EQUIPMENT:	
	Imports:	
	Mach. and	
	Trans. equip.	$= 3.75 \cdot 10^5$ Mt (TIC, 1987)
	Total wt. (g)	$= (3.75 \cdot 10^5$ Mt$) * (1 \cdot 10^6$ g/Mt)
		$= 3.75 \cdot 10^{11}$
30.	SERVICES:	
	Dollar value	$= 1.06 \cdot 10^{10}$ \$US (TIC, 1987)
31.	NET MIGRATION:	
	Net migration	$= -9.33 \cdot 10^4$ people/yr
32.	CASH CROPS:	
	Exports:	(BOT, 1987)

	Rice	$= 4.50 \cdot 10^6$ Mt
	Maize	$= 3.10 \cdot 10^6$ Mt
	Cassava	$= 6.60 \cdot 10^6$ Mt
	Sugar cane	$= 1.20 \cdot 10^6$ Mt
	Fruit	$= 1.86 \cdot 10^5$ Mt
	Molasses	$= 7.74 \cdot 10^5$ Mt
	Rubber	$= 5.91 \cdot 10^5$ Mt
	TOTAL	$= 1.70 \cdot 10^7$ Mt
	Energy (J)	$= 1.7 \cdot 10^7$ Mt)$*$(1 $\cdot 10^6$ g/Mt)$*$(3.5 cal/g)$*$(4186 J/cal)
		$= 2.48 \cdot 10^{17}$
33.	FISHERY PRODUCTION:	
	Exports	$= 3.39 \cdot 10^5$ Mt (BOT, 1987)
	Energy (J)	$= (3.39 \cdot 10^5$ Mt)(1 $\cdot 10^6$ g/Mt)(4 cal/g)(4187 J/cal)
		$= 5.68 \cdot 10^{15}$
34.	FOREST PRODUCTS:	
	Exports:	(TIC, 1987)
	Logs	$= 4.00 \cdot 10^3$ m^3
	Lumber	$= 1.40 \cdot 10^4$ m^3
	Misc. wood prod.	$= 1.52 \cdot 10^5$ m^3
	Energy (J)	$= (1.7 \cdot 10^5$ m^3)(0.5 $\cdot 10^6$ g/m^3)(3.6 cal/g)(4187 J/cal)
		$= 1.28 \cdot 10^{15}$
35.	FLUORITE:	
	Exports	$= 2.04 \cdot 10^5$ Mt (TDRI, 1987)
	Energy (g)	$= (2.04 \cdot 10^5$ Mt)$*$(1 $\cdot 10^6$ g/Mt)
		$= 2.04 \cdot 10^{11}$
36.	GYPSUM:	
	Exports	$= 8.70 \cdot 10^5$ Mt (TDRI, 1987)
	Energy (g)	$= (8.7 \cdot 10^5$ Mt)$*$(1 $\cdot 10^6$ g/Mt)
		$= 8.7 \cdot 10^{11}$
37.	LIMESTONE:	
	Exports	$= 1.10 \cdot 10^6$ Mt (TDRI, 1987)
	Energy (g)	$= (1.1 \cdot 10^6$ Mt)$*$(1 $\cdot 10^6$ g/Mt)
		$= 1.10 \cdot 10^{12}$
38.	BARITE:	
	Exports	$= 2.13 \cdot 10^5$ Mt (TDRI, 1987)
	Energy (g)	$= (2.13 \cdot 10^5$ Mt)$*$(1 $\cdot 10^6$ g/Mt)
		$= 2.13 \cdot 10^{11}$
39.	SERVICES IN EXPORTS:	
	Value (Baht)	$= 1.93 \cdot 10^{11}$ Baht (TDRI, 1987)
	Dollar value	$= (1.93 \cdot 10^{11}$ Baht)/(27 Baht/$US)
		$= 7.15 \cdot 10^9$
40.	TOURISM SERVICES:	
	Value (Baht)	$= 2.73 \cdot 10^{10}$ (TDRI, 1987)
	Dollar value	$= (2.7 \cdot 10^{10}$ Baht)/(27 Baht/$US)
		$= 1.0 \cdot 10^9$

Appendix B. Footnotes to Table 3

1. RIVER GEOPOTENTIAL
Avg. discharge = 4600 m^3/s (Pantulu, 1986)
Energy (J) = (4600 m^3/s)∗(31.5 · 10^6 s/yr)∗(1.0 · 10^3 kg/m^3)∗(9.8 m/s^2)∗(40 m)
= 5.68 · 10^{16} J/yr
2. ELECTRICITY (assumes installed capacity = 2250 MW)
Avg. power = 1.01 · 10^4 GWh/yr (IMC, 1987)
Energy (J) = (1.01 · 10^4 GWh)∗(3.6 · 10^{12} J/GWh)
= 3.62 · 10^{16} J
3. AQUATIC PRODUCTIVITY
Reservoir area = 6.09 · 10^2 km^2
Productivity = 1 g C/m^2/day
Energy (J) = (1 g C/m^2/day)∗(2.5 g OM/g C)∗(1674 J/g OM)∗(365 day/yr)∗(6.09 · 10^2 km^2)∗(1.0 · 10^6 m^2/km^2)
= 9.3 · 10^{14} J/yr
4. IRRIGATION (assumes 2 crops per year and half yield attributable to irrigation)
Irrigated area = 4.0 · 10^4 ha (IMC, 1987)
Rice yield = 5.75 · 10^3 kg/ha
Tot. yield = (5.75 · 10^3 kg/ha)∗(0.5)∗(1.0 · 10^3 g/kg)∗(4.0 · 10^4 ha)
= 1.15 · 10^{11} g
5. OPERATION and MAINTENANCE (assumes O and M costs include downstream erosion control)
Yearly US$ costs = $10.4 · 10^6 (IMC, 1987)
Erosion costs = $10 · 10^6/yr (assume 1/2 estimated costs for first 10 years)
Tot. $ costs = $20.4 · 10^6/yr
6. CONCRETE (assumes a useful dam life = 50 years)
Volume = 2.7 · 10^6 m^3 (estimate)
Tot. weight = (2.7 · 10^6 m^3)∗(2.5 · 10^6 g/m^3)/(50 years)
= 1.35 · 10^{11} g
7. STEEL (assumes a useful dam life = 50 years)
Weight = 1.16 · 10^4 t (estimate)
Tot. weight = (1.16 · 10^4 t)∗(1.0 · 10^6 g/t)(50 years)
= 2.31 · 10^8 g
8. MACHINERY (assumes a useful dam life = 50 years)
Weight = 3.33 · 10^4 t (estimate)
Tot. weight = (3.33 · 10^4 t)∗(1.0 · 10^6 g/t)/(50 years)
= 6.66 · 10^8 g
9. CONSTRUCTION SERVICES (assumes a useful dam life = 50 years)
US$ costs = $1.89 · 10^9 (IMC, 1987)
Tot. $ costs = (1.89 · 10^9)/(50 years)
= $3.78 · 10^7/year
10. LOST AGRIC. PRODUCTION (rice) (assumes 70% of agricultural land in rice)
Agric. area = 60 900 ha (based on reservoir area)
Yield = 2.88 · 10^3 kg/ha
Tot. yield = (2.88 · 10^3 kg/ha)∗(1.0 · 10^3 g/kg)∗(60 900 ha)∗(0.70)
= 1.23 · 10^{11} g
11. LOST AGRIC. PRODUCTION (maize) (assumes 30% of agricultural land in maize)
Agric. area = 60 900 ha (based on reservoir area)

Yield	$= 2.43 \cdot 10^3$ kg/ha
Energy/g	= 16744 J/g
Energy (J)	$= (2.43 \cdot 10^3$ kg/ha)*(1.0 $\cdot 10^3$ g/kg)(60900 ha)*(0.30)*(16744 J/g)
	$= 7.42 \cdot 10^{14}$ J

12. RESETTLEMENT (assumes a useful dam life = 50 years)

Number of people	$= 4.26 \cdot 10^4$ people (IMC, 1987)
Per capita $ costs	= $4.7 $\cdot 10^3$ (IMC, 1987)
Tot. costs	$= (4.26 \cdot 10^4$ people)*($4.7 $\cdot 10^3$)/(50 years)
	= $4.0 $\cdot 10^6$

13. IRRIGATION (services)

US$ costs	= $6.0 $\cdot 10^3$/ha (IMC, 1987)
Area	$= 4.0 \cdot 10^4$ ha (IMC, 1987)
Tot. $ costs	= ($6.0 $\cdot 10^3$/ha)*(4.0 $\cdot 10^4$ ha)/(50 years)
	= $4.8 $\cdot 10^6$

14. SOCIAL DISRUPTION (assumes social disruption is equal to the EMergy value of the population over a 30-year generation)

Number of people	$= 4.26 \cdot 10^4$ people (IMC, 1987)
EMergy per capita	$= 2.98 \cdot 10^{15}$ sej/yr
Ppl yrs lost	$= (4.26 \cdot 10^4)$*(30 years)/(50 years)
	$= 2.56 \cdot 10^4$ people years

15. SEDIMENTS

Volume	$= 132 \cdot 10^6$ m^3/yr (SMEC, 1979)
Energy (J)	$= (132 \cdot 10^6$ m^3)*(2.0 $\cdot 10^6$ g/m^3)*(1% OM)*(5.4 cal/g)*(4186 J/cal)
	$= 5.97 \cdot 10^{16}$ J

Appendix C. Footnotes to Table 4

1. RIVER GEOPOTENTIAL

Avg. discharge	= 4200 m^3/s (estimate based on Pantulu, 1986)
Energy (J)	= (4200 m^3/s)*(31.5 $\cdot 10^6$ s/yr)*(1.0 $\cdot 10^3$ kg/m^3)*(9.8 m/s^2)*(40 m)
	$= 5.19 \cdot 10^{16}$ J/yr

2. ELECTRICITY (assumes installed capacity = 1500 MW)

Avg. power	$= 8.9 \cdot 10^3$ GWh/yr (Mekong Secretariat, 1989)
Energy (J)	$= (8.9 \cdot 10^3$ GWh)*(3.6 $\cdot 10^{12}$ J/GWh)
	$= 3.2 \cdot 10^{16}$ J

3. AQUATIC PRODUCTIVITY

Reservoir area	$= 4.0 \cdot 10^2$ km^2 (Mekong Secretariat, 1989)
Productivity	= 1 g C/m^2/day
Energy (J)	= (1 g C/m^2/day)*(2.5 g OM/g C)*(1674 J/g OM)*(365 day/yr)*(4.0 $\cdot 10^2$ km^2)*(1.0 $\cdot 10^6$ m^2/km^2)
	$= 6.1 \cdot 10^{14}$ J/yr

4. IRRIGATION (assumes 2 crops per year and half yield attributable to irrigation)

Irrigated area	$= 1.28 \cdot 10^4$ ha (Mekong Secretariat, 1989)
Rice yield	$= 5.75 \cdot 10^3$ kg/ha
Tot. yield	$= (5.75 \cdot 10^3$ kg/ha)*(0.5)*(1.0 $\cdot 10^3$ g/kg)*(1.28 $\cdot 10^4$ ha)
	$= 3.68 \cdot 10^{11}$ g

5. OPERATION and MAINTENANCE
Yearly US$ costs = $7.4 \cdot 10^6$ (IMC, 1987)
Tot. $ costs = $7.4 \cdot 10^6$/yr
6. CONCRETE (assumes a useful dam life = 50 years)
Volume = $2.2 \cdot 10^6$ m^3 (estimate)
Tot. weight = $(2.2 \cdot 10^6\ m^3) * (2.5 \cdot 10^6\ g/m^3)/(50\ years)$
= $1.1 \cdot 10^{11}$ g
7. STEEL (assumes a useful dam life = 50 years)
Weight = $9.56 \cdot 10^3$ t (estimate)
Tot. weight = $(9.56 \cdot 10^3\ t) * (1.0 \cdot 10^6\ g/t)(50\ years)$
= $1.91 \cdot 10^8$ g
8. MACHINERY (assumes a useful dam life = 50 years)
Weight = $2.08 \cdot 10^4$ t (estimate)
Tot. weight = $(2.08 \cdot 10^4\ t) * (1.0 \cdot 10^6\ g/t)/(50\ years)$
= $4.16 \cdot 10^8$ g
9. CONSTRUCTION SERVICES (assumes a useful dam life = 50 years)
US$ costs = $1.385 \cdot 10^9$ (Table 5, IMC, 1987)
Tot. $ costs = $(1.385 \cdot 10^9)/(50\ years)$
= $2.77 \cdot 10^7$/year)
10. LOST AGRIC. PRODUCTION (rice) (assumes 30% of agricultural land in rice)
Agric. area = $4.0 \cdot 10^4$ ha (based on reservoir area)
Yield = $2.88 \cdot 10^3$ kg/ha
Tot. yield = $(2.88 \cdot 10^3\ kg/ha) * (1.0 \cdot 10^3\ g/kg) * (4.0 \cdot 10^4\ ha) * (0.30)$
= $2.3 \cdot 10^9$ g
11. LOST AGRIC. PRODUCTION (maize) (assumes 70% of agricultural land in maize)
Agric. area = $4.0 \cdot 10^4$ ha (based on reservoir area)
Yield = $2.43 \cdot 10^3$ kg/ha
Energy/g = 16744 J/g
Energy (J) = $(2.43 \cdot 10^3\ kg/ha) * (1.0 \cdot 10^3\ g/kg) * (4.0 \cdot 10^4\ ha) * (0.70) * (16744\ J/g)$
= $1.14 \cdot 10^{15}$ J
12. RESETTLEMENT (assumes a useful dam life = 50 years)
Number of people = $2.8 \cdot 10^4$ people (IMC, 1987)
Per capita $ costs = $4.7 \cdot 10^3$ (IMC, 1987)
Tot. costs = $(2.8 \cdot 10^4\ people) * (\$4.7 \cdot 10^3)/(50\ years)$
= $2.63 \cdot 10^6$
13. IRRIGATION (services)
US$ costs = $6.0 \cdot 10^3$/ha (IMC, 1987)
Area = $1.28 \cdot 10^4$ ha (IMC, 1987)
Tot. $ costs = $(\$6.0 \cdot 10^3/ha) * (1.28 \cdot 10^4\ ha)/(50\ years)$
= $1.54 \cdot 10^6$
14. SOCIAL DISRUPTION = (assumes social disruption is equal to the EMergy value of the population over a 30-year generation)
Number of people = $2.8 \cdot 10^4$ people (IMC, 1987)
EMergy per capita = $2.98 \cdot 10^{15}$ sej/yr
Ppl yrs lost = $(2.8 \cdot 10^4) * (30\ years)/(50\ years)$
= $1.68 \cdot 10^4$ people years)
15. SEDIMENTS
Volume = $125 \cdot 10^6$ m^3/yr (SMEC, 1979)

$$\text{Energy (J)} = (125 \cdot 10^6 \text{ m3}) * (2.0 \cdot 10^6 \text{ g/m3}) * (1\% \text{ OM}) * (5.4 \text{ cal/g}) * (4186 \text{ J/cal}) = 5.65 \cdot 10^{16} \text{ J}$$

References

Arding, J. and Brown, M.T., 1991. Collected and recalculated transformities: a working paper. Center for Wetlands, University of Florida, Gainesville, FL, 73 pp.

Bank of Thailand (BOT), 1987. Annual Economic Report. Bank of Thailand, Bangkok.

Brown, M.T., 1986. Energy analysis of the hydroelectric dam near Tucurui. In: H.T. Odum, M.T. Brown and R.A. Christianson (Editors), Energy Systems Overview of the Amazon Basin. Final Report to the Cousteau Society (CFWWR-86-04). Center for Wetlands and Water Resources, University of Florida, Gainesville, FL, 188 pp.

Brown, M.T. and McClanahan, T.R., 1992. Emergy Analysis Perspectives of Thailand and Mekong River Dam Proposals. Final Report to The Cousteau Society (CFWWR-92-03). Center for Wetlands and Water Resources, University of Florida, Gainesville, FL, 56 pp.

Brown, M.T., Tennenbaum, S.E. and Odum, H.T., 1988. Emergy Analysis and Policy Perspectives for the Sea of Cortez, Mexico. Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville, FL, 58 pp.

Doherty, S.J., Brown, M.T., Odum, H.T. and Murphy, R.C., 1992. Emergy Analysis and Policy Perspectives for Papua New Guinea. Report to the Cousteau Society. Center for Wetlands and Water Resources, University of Florida, Gainesville, FL.

Interim Mekong Committee for Coordination of Investigations of the Lower Mekong Basin (IMC), 1987. Assessment of the viability of a Low Pa Mong multi-purpose project. IMC, Bangkok, Thailand.

Lapp, C.W., 1991. Emergy analysis of the nuclear power system in the United States. MS Paper, Department of Environmental Engineering Sciences, University of Florida, 64 pp.

Lotka, A.J., 1922. Contributions to the energetics of evolution. Proc. Natl. Acad. Sci. USA, 8: 147–151.

Mekong Secretariat, 1989. Development of the Mekong Mainstream Low Pa Mong or Upper Chaing Khan Project. Interim Committee for Coordination of Investigations of the Lower Mekong Basin, Bangkok.

Moormann, F.R. and Rojanasoonthorn, S., 1968. Soils of Thailand. SSR No. 72, Land Development Department, Bangkok, Thailand.

Odum, H.T., 1983. Systems Ecology: An Introduction. John Wiley, New York.

Odum, H.T., 1987. Models for national, international and global systems policy. In: L.C. Braat and W.F.J. VanLierup (Editors), Economic-Ecologic Modeling. Elsevier, New York.

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

Odum, H.T., 1995. Environmental Accounting: Emergy and Decision Making. John Wiley, New York, 400 pp.

Odum, H.T. and Arding, J.E., 1991. Emergy analysis of shrimp mariculture in Ecuador. Working paper prepared for Coastal Resources Center, University of Rhode Island, Narragansett, RI, 124 pp.

Odum, H.T., Brown, M.T. and Christianson, R.A., 1986. Energy Systems Overview of the amazon Basin. Report to the Cousteau Society. Center for Wetlands, University of Florida, Gainesville, FL, 190 pp.

Odum, H.T., Odum, E.C. and Blissett, 1987a. Ecology and economy: Emergy analysis and public policy in Texas. Policy Research Project report No. 78, Office of Natural Resources and Texas Department of Agriculture, Austin, TX.

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

Pantulu, V.R., 1986. The Mekong river system. In: B.R. Davies and K.F. Walker (Editors), The Ecology of Rivers. Dr. W. Junk Publishers, Dordrecht.

Snowy Mountain Engineering Corps (SMEC), 1979. Pa Mong multi-purpose project summary of engineering and economic feasibility studies. Interim Committee for Coordination of Investigations of the Lower Mekong Basin, Bangkok.

Tennenbaum, S.E. and Brown, M.T., 1989. Global Emergency Data Filed. Working paper, Systems Ecology Group, Center for Wetlands, University of Florida, Gainesville, FL.

Tera International Company (TIC), 1987. Thai Trade Monitor 1987–1988. Tera International Company, Bangkok, Thailand.

Thailand Development Research Institute (TDRI), 1987. Thailand natural resource profile. Thailand Development Research Institute, Bangkok, Thailand.

United Nations Environmental Program (UNEP), 1988. Sustainable Development of Natural Resources. United Nations Environmental Program, New York.

von Bertalanffy, L., 1968. General System Theory. George Braziller, New York.