Report to

THE COUSTEAU SOCIETY

Emergy Analysis and Policy Perspectives for the Sea of Cortez, Mexico

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PREFACE

Among the most important problems humanity faces today are the sound management of natural resources and the integration of human and natural processes. There is a need to understand both human and natural domains, each in the context of the other, and it is important to develop management strategies which acknowledge and promote the vital interconnections between the two.

Traditionally, a reductionist approach to the study of humanity and nature has been taken. By comparison, very little attention has been given to studying the biosphere at the ecosystem level of organization. It is at the ecosystem level, however, where many of nature's benefits are derived and where the impacts of humanity are being felt.

Neither economics nor ecology alone adequately address the problems society presently faces: a unifying concept or common denominator is needed which embodies both the natural and human domains. Energy flows through and is stored by both systems. Evaluating energy flow, energy quality and embodied energy enables one to quantify and compare various resource uses and to determine which development strategies maximize the energetics of both human and natural systems. The appropriate use will be the one which maximizes the flow and storage of energy for both humanity and nature.

In the Sea of Cortez, it is the upper Gulf where the great forces of nature combine to nurture both nature and humanity. The Colorado River carries sediments and nutrients from the continental heartland to fertilize the upper Gulf. In addition, it is here where tides and upwelling make their contribution, creating the highest rates of productivity found in the Sea of Cortez. This productivity is responsible for Mexico's most important fishery, providing both food and economic benefit to society.

In view of the imprtance of the upper Gulf region to the entire Sea of Cortez, we have invited Dr. H. T. Odum and his team to employ their energy analysis techniques to study this region in conjunction with the Cousteau Sea of Cortez Expedition. The objective of The Cousteau Society is to educate and to communicate on a global scale so as to protect and improve the quality of life for present and future generations. We hope the Odum methods, and the contents of this document, will provide some interesting insights about important processes in the Gulf and will help foster better resource management for the future.

Richard C. Murphy
Vice President for Science and Education
The Cousteau Society

INTRODUCTION

Valuable, unique, and important to the local economies, the Sea of Cortez in Northwestern Mexico (Figure 1) is becoming increasingly joined to the main economy of Mexico and the United States. As a microcosm of international resource use in developing countries, the Sea of Cortez provides an example for application of new methods for determining public policies that maximize sustainable economies symbiotic with the sea. In this study, emergy analysis (spelled with an "M") is used to facilitate the process that may determine which future alternatives maximize public benefit.

Originally, the Colorado River had strong flow into the upper end of the Sea; but starting in 1935, water was diverted, with some flow restored in 1940 and 1984. Figure 2 shows the large changes in the discharge in this century. More recently, there has been expansion of fisheries with larger shrimp trawlers and international markets replacing local fishermen with local markets. In this study emergy analyses are made to evaluate the importance of the changes in the past and anticipated in the future.

Public Policy: The Interface of Ecology and Economics.

The interface of ecology and economics is often in the marketplace where resources are exploited and sold. In the process, the environment sustains some transformations that may or may not lead to long-term stability. As the population expands, it is increasingly important that humans consider the long-term environmental consequences of their economic decisions. A long-term perspective and macroscopic view are needed in order to adequately factor in questions of long-term sustainability in our public policy decision process.

Too often, economics, with its short time horizon and its small, closed value system, is the guiding rationale behind public policy decisions. Its value system is small by virtue of the fact that it considers utility as the means for determining value, and it is closed because it does not extend beyond the marketplace. Thus, public policy decisions made under the assumption of maximizing some monetary value (increased sales, profits, marginal rate of return) are, in reality, basing the decision on individual human utility. Societal needs or environmental concerns are often not factored in because they are generally outside the realm of individual human preferences.

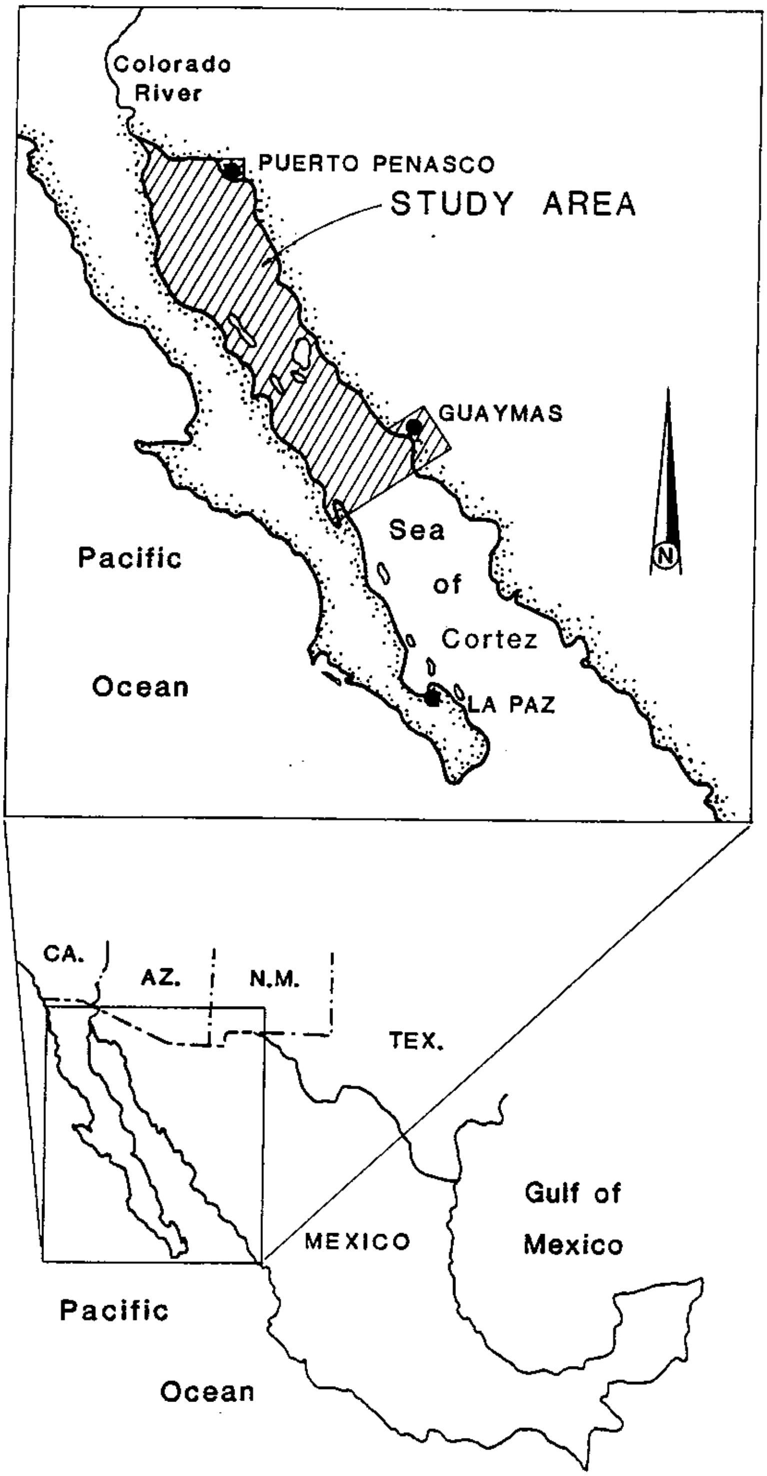


Figure 1. Map of the Sea of Cortez showing the northern study area.

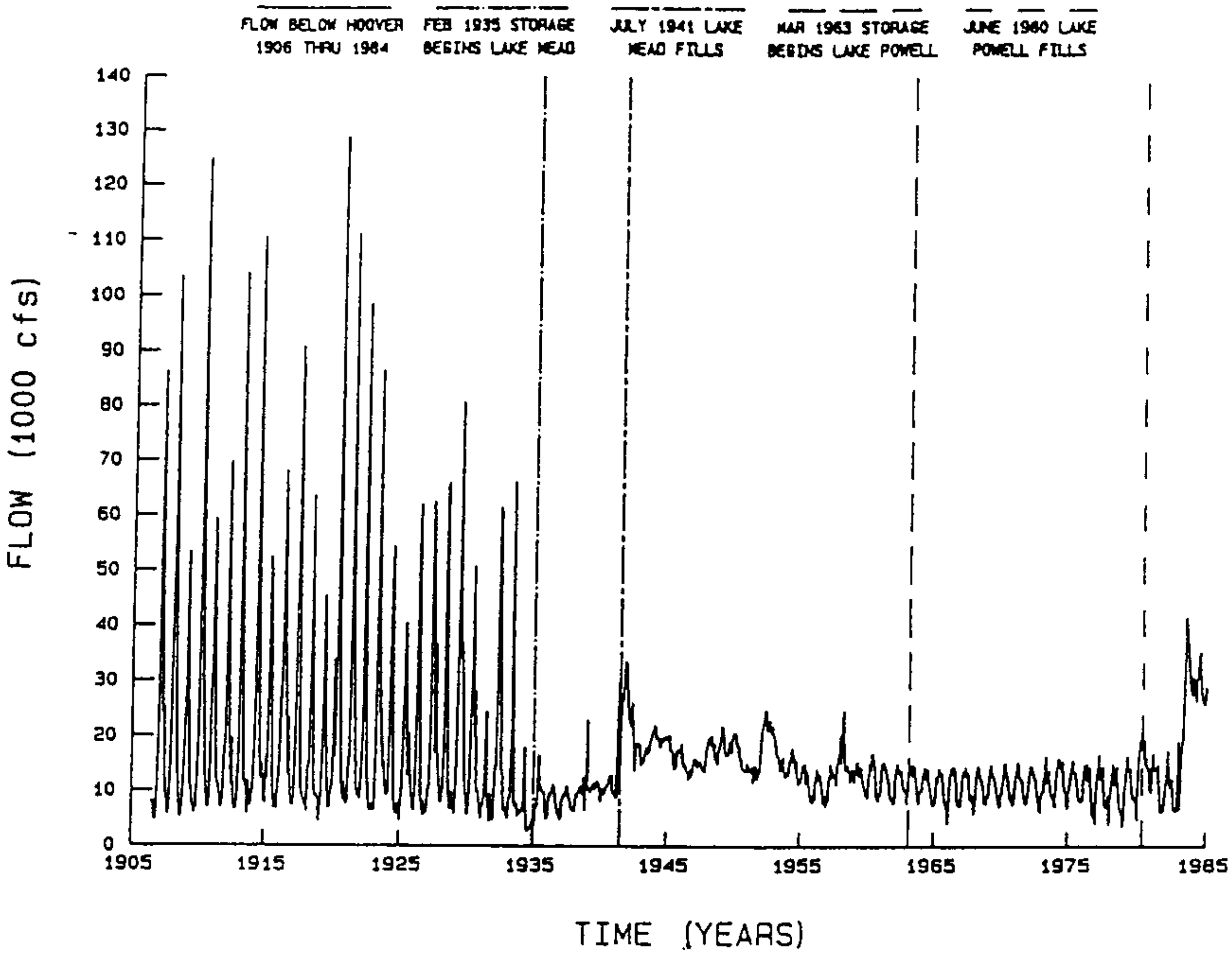


Figure 2. Discharge of the Colorado River below Hoover Dam (from McCleary 1986).

Public policy decisions need to be made on the basis of the value system of the Earth. The new public policy value system used here recognizes the difference between short-term individual human preference and long-term macroscopic well-being and is capable of quantitatively determining value at the macroscopic scale of society and environment. It can equate the value of natural resources, wildlife, and industrial production as a means of determining relative importance and their contributions to overall well-being and long-term sustainability. The system of evaluation used in this report measures value in units of emergy, a relatively new concept, that measures the resources required for a product. Emergy is expressed in units of Solar EmJoules (sej) as a means of expressing the values of diverse products like fishing boats and shrimp on an equivalent scale. In a nutshell, the best system and the one which is eventually successful is one that uses the most emergy.

The emergy system of value is based on concepts of system organization and optimization that have their bases in the early work of Lotka (1922a, 1922b, 1945), in *General System Theory* (von Bertalanffy, 1968), and in Systems Ecology (Odum, 1983). As a result of its foundations in ecology and general system theory, the conceptual framework for an Emergy Theory of Value has longer time horizons and applicability than marketplace economics.

Scope of the Study

As part of The Cousteau Sea of Cortez Expedition, the authors were invited to focus their attention on resource management policy questions facing the people of the United States and Mexico. The productivity of the Sea of Cortez is an important yet little recognized contribution to the economy of Mexico. Local economies are sustained by productive near-shore fisheries, and increasingly the Mexican national economy has been boosted by a highly capitalized export shrimp fishery. Combined, these contributions of natural productivity act to stimulate the economy as the money that is received from exports of shrimp and local sales of fish ripple through the economy "demanding" further exchanges and resource utilization.

While traditional economic "wisdom" would suggest that increasing exports and general exploitation of the Sea of Cortez fishery are to be desired as a means of offsetting a balance of payments deficit and heavy external debt, such economic advice does not consider that the resource base is limited and that overexploitation now may lead to a collapse later. An additional concern is related to the relative value of exported products versus the value of goods received in exchange. Balance of payments measured in dollars and those measured in emergy are two distinctly different concepts and arrive at two distinctly different values. The former is a measure of value to humans, the latter is a measure of value as a contribution to the economy as a whole. The different value systems lead to differing points of view regarding public policy issues and often to opposing solutions to questions of resource management.

Using techniques of emergy analysis that equate the work done in the human domain with work done in domains considered to be outside the human economy, this study evaluates the relative importance of the Sea of Cortez to the economy of Mexico, the possible impact of Colorado River diversions, alternative methods of shrimp fishing, and the equity of foreign trade involving fishery products.

The Northern Sea of Cortez

The Sea of Cortez (also known as the Gulf of California) lies between the arid Baja California Peninsula and the equally arid Mexican mainland States of Sinaloa and Sonora (Figure 3). Many have likened it to a large evaporation basin with a southern opening to the ocean (Roden, 1958, 1964; Alvarez-Borrego, 1983). The Gulf is about 1000 km long and averages about 150 km wide. At its northern end is the Colorado River Delta. Along the western shore the Baja coastline is very steep and flanked by numerous islands; while the northeastern coast (State of Sonora) is less rugged with a wide shelf. Further south, along the Sinaloa coast, the shoreline is characterized by tidal inlets and mangrove swamps with many streams draining the coastal plain.

The bathymetry of the Gulf is quite varied with a number of basins of varying depths throughout. The basins and trenches, separated by transverse ridges, deepen from north to south (Byrne and Emery, 1960). The median depth of the Gulf is about 460 meters, while the deepest basin is over 3300 meters (Shepard, 1950). A shelf borders most of the Gulf that is widest in the northern portions and narrowest approaching the Pacific. In contrast to depths of greater than 3000 meters in the southern extreme of the Gulf, the northern third of the Gulf has depths that average about 250 meters. As shown in Figure 1, the Gulf can be divided by a line running through the southern tip of Angel de la Guarda Island and the northern tip of Tiburon Island. This line separates the northern Gulf, which is more estuarine in character (Zeitzschel, 1969), from the middle and southern Gulf that are more dominated by the Pacific Ocean (Round, 1967). The area north of this line roughly corresponds to two of the four zones identified by Zeitzschel (1969).

The climate of the Sea of Cortez is more continental than oceanic. The Sea is separated from the Pacific Ocean by a chain of mountains from 1 to 3 km high running almost the entire length of the Baja Peninsula greatly reducing the ocean's moderating influence on the climate. Precipitation falls mostly during the summer in the northern Gulf, varying from traces in the northernmost part to 200 mm per year at Guaymas. Evaporation is one of the most important factors affecting the Gulf. High surface salinities in the north, where evaporation far exceeds precipitation, flow south and sink, possibly adding to upwelling through displacement. Hurricanes may play an important role in both circulation and inputs of rain and runoff carrying sediments.

Wind-driven upwelling is one of the most dominant features of the Gulf (Figure 3). Upwelling is most intense along the eastern coast of the Baja Peninsula during the winter's northwesterly winds and during the summer's southeasterly winds along the western coast. Local areas of upwelling are located on the left sides of islands and headlands (Roden, 1958). General circulation of the Gulf is very complex; however, temperature and salinity data suggest that the southern Gulf is more thoroughly mixed with the Pacific while the northern Gulf is somewhat more isolated (Alvarez-Borrego, 1983). Tidal mixing in the north is extensive where mean tidal range is 6.6 meters (Byrne and Emery, 1960) and spring ranges of 10 meters have been reported (Alvarez-Borrego, 1983).

Probably of great significance to the northern Gulf is the discharge of the Colorado River. Historically, average annual discharge was greater than 15 million acre feet (Thompson et al., 1969), transporting an average of 150 to 200 million tonnes of sediments (McCleary, 1986). In its natural state, the river experienced extreme flooding events during spring as a result of mountain snowpack melt and minor base flow during the autumn. Flow varied from spring peaks with daily discharges as high as 250,000 cfs to autumn lows with daily discharges less than 5000 cfs (Thompson et al., 1969). During the years 1905 to 1907 the entire flow of the Colorado was diverted to form the present Salton Sea. The flow was rediverted from the Salton Sea following 1907 until the filling of Lake Meade at Hoover Dam. After 1935, with the construction of the Hoover Dam and other smaller dams along the Colorado, discharge characteristics were greatly altered. Spring peaks were markedly reduced through the storage in reservoirs and the release of waters over the remainder of the year (Figure 2). In addition to the discharge characteristics of the river, the dams have also had a major effect on the Gulf by intercepting sediment loads. While the river used to carry a sediment load of about 180 million tonnes per year (Thompson, 1965), recent measurements of sediment load by the United States Bureau of Reclamation show many years within the last decade where the load is less than 100,000 tonnes per year (McCleary, 1986).

The overall effects of these changes in the discharge characteristics are not well understood. Carlson and Thompson (1969) speculate that the diminished flow of the Colorado into the Gulf has undoubtedly influenced the productivity of its headwaters, but conclude since there are no past and present data available, their speculations have no sound basis. From data collected on three 1968 cruises of the E. B. Scripps, Zeitzschel (1969) reported average integrated primary productivity for two zones in the northern half of the Gulf of 0.53 g C/m^2 day and 0.677 g C/m^2 day and an average integrated rate of primary productivity for all stations within the Gulf of 0.382 g C/m^2 day. He concluded that primary productivity in the Sea of Cortez is comparable to that in other areas of upwelling like those off the coast of North Africa and in the Bay of Bengal, and that productivity in the Gulf is two to three times that found in the open Atlantic or Pacific oceans at similar latitudes.

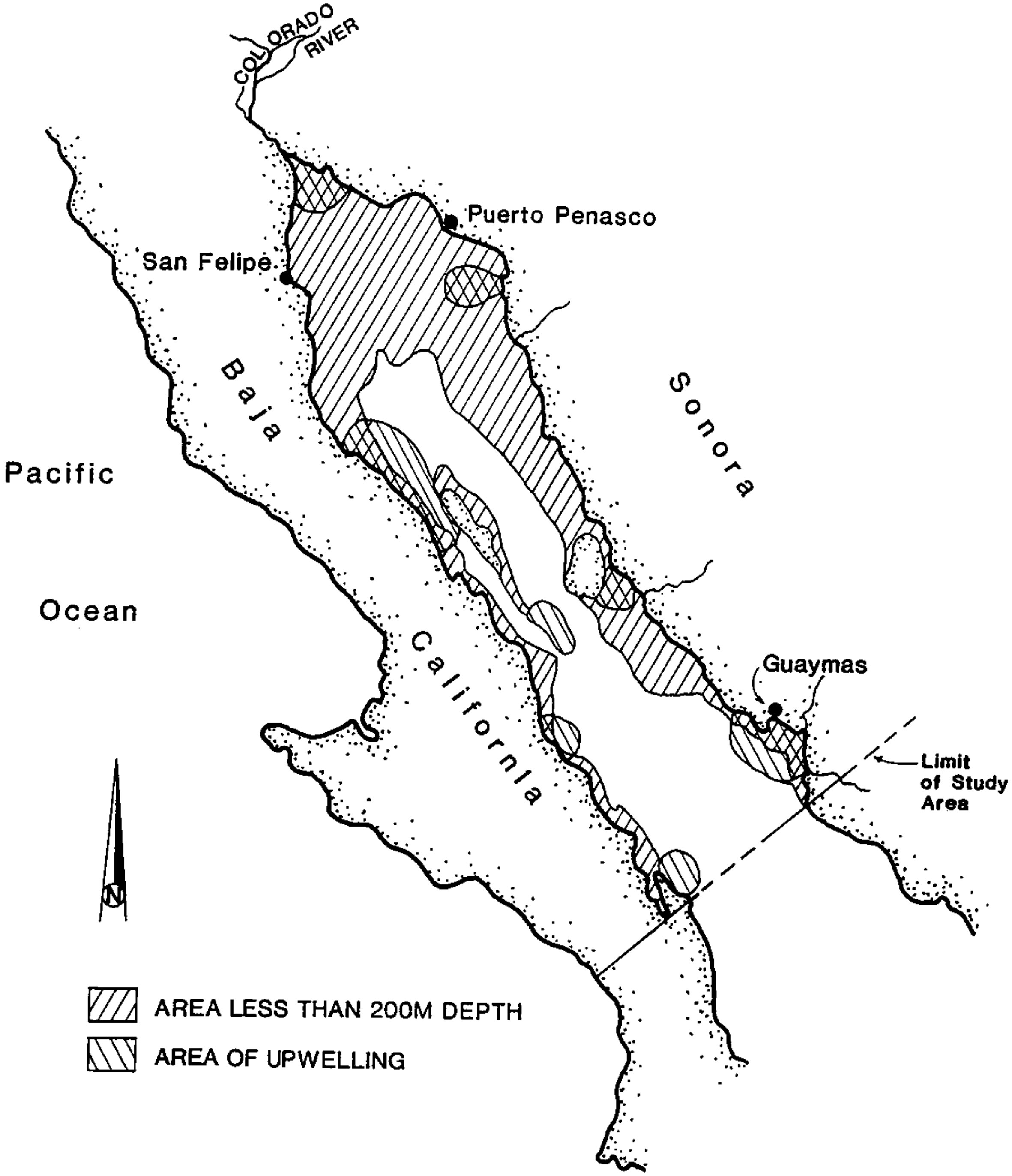


Figure 3. Map of the northern Sea of Cortez showing upwelling areas and areas of less than 200 meter in depth (after Roden 1958, 1964).

By considering the potential importance of the Colorado River to the Sea of Cortez and the importance of the upper Gulf shrimp fishery to Mexico, we have endeavored to address these two subject areas using techniques of energy analysis. Using existing data in the literature, and limited data collection in the field, we have attempted to evaluate the importance of the Colorado River to the whole system of the upper Sea of Cortez. In addition, we use these methods to evaluate the resident shrimp fishery, focusing on differences between panga (small boat), and trawler fisheries and relating this fishery to Mexico's energy/economic situation. Finally, we hope this study will serve to introduce the emergy analysis method to the scientists and resource managers of Mexico and that it may assist them in making important policy decisions fostering sustainable resource use.

METHODS

The method of analysis employed in this study provides an overview of the interactions and resource base of the systems of humanity and nature in the Sea of Cortez. This is accomplished by first gathering as much relevant information about the complete system as one can find. Then the system is diagrammed using the energy language symbols illustrated in Figure 4, creating a visual inventory of components and interactions. Next, aggregate diagrams are created emphasizing the subsystems of interest. Finally, the emergy of the subsystems (the resource base in terms of equivalent solar input) is calculated so that comparisons can be made and indices can be calculated to provide perspective on trends and policy.

This study is organized in a hierarchical manner. First, to place the Sea of Cortez in perspective relative to the overall economy of Mexico, an emergy analysis of the national economy of Mexico is presented. Then, an emergy analysis of the Sea of Cortez for three different time periods (1920s, 1960s, and 1980s) is presented to better understand the changes that have occurred as a result of the manipulation of Colorado River discharge; and finally, emergy analysis of the very productive shrimp fishing that is currently being exploited is presented.

Everything is part of a system and systems are composed of units that are interrelated. As a result of these interrelationships, it is difficult to understand the functions and values of individual units without first having a general idea of how all the units fit together to form the whole. We start with the whole economy in overview. This "top-down" approach facilitates a better understanding of the system and helps to place public policy issues in a broader perspective. Policy decisions regarding the exploitation of natural resources almost invariably require the integration of both economic (bigger scale system) and ecologic (smaller scale system) implications. For instance, resource management decisions regarding the shrimp fishery of the northern Sea of Cortez, while having local implications on the lives of fishermen and their families and on the sustainability of the fishery, simultaneously have an impact on the national economy of Mexico and its balance of payments. All too often policy decisions on the local level are made without sufficient information concerning the implications at the next larger system level. The reverse is also true; decisions made at the regional or national level have serious impacts on local economies and resource systems. The hierarchical systems approach presented in the analysis lends insight and allows for the public policy process to integrate both the economic and ecologic implication of decisions and management alternatives. There are several terms and concepts that are used in this report that are not in common usage or that may be unfamiliar to the reader. They are defined next:

The Maximum Emergy Principle: A main principle that offers some clear criteria for how systems are organized and why some prevail and others do not is the Maximum Emergy Principle.

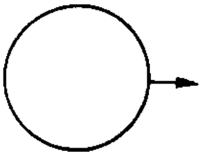
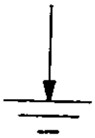
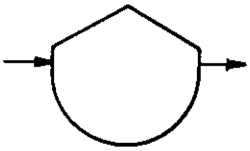
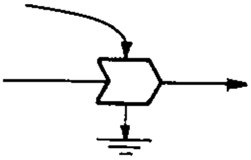
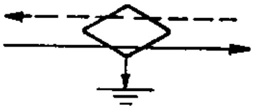
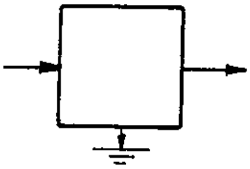
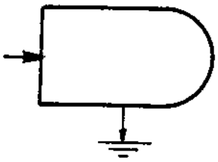
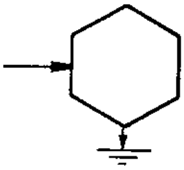
	OUTSIDE ENERGY SOURCE - delivers energy flow from outside the system.
	HEAT SINK - drains out degraded energy after its use in work.
	ENERGY STORAGE TANK - stores and delivers energy flow.
	ENERGY INTERACTION - requires two or more kinds of energy to produce high quality energy flow.
	ENERGY-MONEY TRANSACTION - money flows in exchange for energy.
	GENERAL PURPOSE BOX - for any sub-unit needed, is labeled to indicate use.
	PRODUCER UNIT - converts and concentrates solar energy, self-maintaining; details may be shown inside.
	CONSUMER UNIT - uses high quality energy, self-maintaining; details may be shown inside.

Figure 4. Energy language symbols.

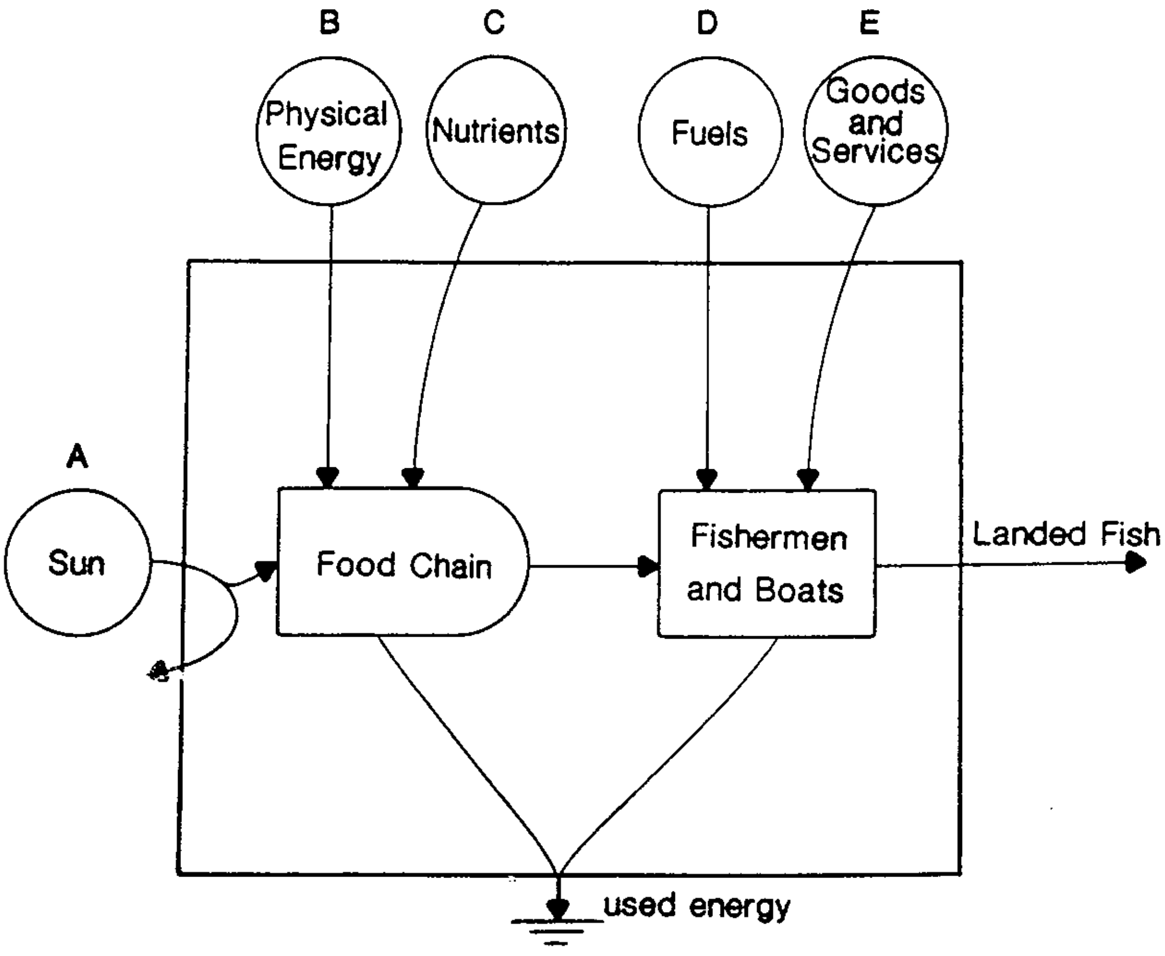
The Maximum Emergy Principle suggests systems which develop and prevail are those that increase and take maximum advantage of the emergy that is available. Generally, this means that the system organization which can develop uses for the most emergy in the shortest time will displace other patterns that do not use resources as effectively. Social, economic, and political systems, as well as ecologic systems, prevail in a competitive environment only if they can develop more emergy inflows and use them more effectively than their competitors. The pattern that prevails links all its parts in a symbiotic array using all by-products.

Emergy (spelled with an "M"): Emergy in a resource, product, or service is the sum of the solar energies that are required both directly and indirectly in its production. In this report, all resources, products, and services are given as solar emergy expressed in solar emjoules. Emjoules are so named to distinguish the units of emergy from units of energy expression in joules. As and example, Figure 5 shows that the emergy of a fish sold at market includes the prorated share of emergy spent for goods and services necessary to run and maintain the fishing vessel, the emergy of the fuel that was burned, the emergy value of goods and services consumed by the fishermen, and all the emergy from direct sunlight and tidal action that was necessary to provide essential ecological support for the fish prior to it being caught.

Attempts to evaluate environmental and economic products or services in units of energy must recognize that all forms of energy do not accomplish equivalent amounts of work. To express the energy value of sunlight and fuel in joules of heat and then to suggest that each joule is equal in its ability to support work is not accurate. The "form" or "quality" of each type of energy is quite different and is capable of supporting very different types of work per unit of energy. To overcome this shortcoming, a measure of work potential based on solar energy equivalence is used to describe all types of energy as solar emergy.

Transformity: Transformity is the emergy of one type required to generate one unit of another type. Its units are solar emjoules per joule (sej/J). To convert energy of one type to solar emergy, units of energy are multiplied by the SOLAR TRANSFORMITY, converting them to solar emergy equivalents (see Figure 5).

The solar transformity of an object or resource is the equivalent solar energy that would be required to generate a unit of that object or resource efficiently and rapidly. A solar transformity of a resource is the ratio of the total amount of solar energy required to create it (solar emergy) to the energy of that resource. It is obtained by dividing the total solar emergy of the system that "creates" the resource by the energy in the resource output. As an example, the transformity for a fish would be calculated by dividing the solar emergy required to support the environmental system that "produces" the fish by the energy of the fish (measured as caloric value) (see Figure 5).



$$\textbf{Solar Emergy of Landed Fish} = \begin{array}{c}\textbf{Sum of Emergy of}\\ \mathbf{A + B + C + D + E}\end{array}$$

$$\begin{array}{c}\textbf{Solar Transformity of Landed Fish}\\ \textbf{in sej/J}\end{array} = \frac{\textbf{Solar Emergy of Landed Fish}}{\textbf{energy of Landed Fish}}$$

Figure 5. Diagram illustrating the methodology for calculating EMERGY and transformity.

RESULTS

The data and calculations upon which this report is based are given in Figures 6 through 13, Tables 1 through 7 and supporting Appendices. The plan was to evaluate the resource base of the national economy of Mexico and the resource base of the northern Sea of Cortez study area, to investigate the implications of the Colorado River diversion, and, using emergy analysis, to evaluate the shrimp fishery of the northern Gulf.

National Emergy Table. A cursory evaluation of the overall resource base of the Mexican economy in 1983 is given in emergy Table 1. The main inputs to the economy of the country are listed including exports and imports. The total annual emergy use is given in line 10, which is then used to evaluate an emergy ratio to the U.S. International Dollar for 1983. Almost 16% of the emergy use was imported goods and services. Counting the very large oil and gas export (item 8), twice as much emergy was exported as imported.

With a 1983 population of 72 million people, per capita emergy utilization was approximately 5 E15 sej/person. The per capita emergy in the United States in the same year was 34 E15 sej/person. Emergy per capita is a measure of standard of living. Comparison with the U.S. average suggests that Mexico's standard is about 1/9 that of the United States.

The ratio of emergy to dollars (a measure of buying power) was 2.86 E12 sej/$ in Mexico, while in the same year the ratio in the U.S. was 2.4 E12 sej/$ (both expressed in U.S. dollars).

Overview Systems Diagram. The systems diagram in Figure 6 was developed to summarize what items and relationships are important, based on written papers and local interviews. Items are arranged from left to right in order of the solar transformity. This means that items on the left are abundant. Those on the right are less in quantity but more important per unit, requiring more resources and having more controlling effects on the items to the left. The many energy flows of the Sea of Cortez develop the food chain that ends on the right in marketable shrimp and fish. The dashed lines on the right are the flows of money at the interface of the economy with the ecosystem.

Water Budget and the Sea. In order to evaluate components and inflows, budgets were developed for the Sea of Cortez including water in Figure 7 (top), organic matter in Figure 7 (bottom), phosphate-phosphorus in Figure 8 (top), and nitrate-nitrogen in Figure 8 (bottom). These are for the period in the 1920s before water from the Colorado River was diverted. Respectively, Figures 9 and 10, show average annual emergy inflowing to the sea and to primary production in the sea. At the lower end of the study area marked in Figure 1, a substantial tide slides water northward and then southward with each tide, about twice a day. This exchange is

Table 1. Emergy Evaluation of the Annual Resource Basis for Mexico in 1983 (from Odum et al., 1987).

Note[a]	Item	Raw Units	Transformity (sej/unit)	Solar Emergy (E22 sej)	Macroeconomic Value* (E9 1983 US$)
1	Rain	7.97 E18 J	8888/J	7.1	29.5
2	Tides	3.00 E17 J	23564/J	0.7	2.9
3	Waves	1.37 E18 J	25889/J	3.5	14.7
4	Oil use	2.75 E18 J	53000/J	14.6	60.7
5	Natural gas use	1.39 E18 J	48000/J	6.7	27.8
6	Imported goods & services	23.1 E9 $	2.4 E12/$	5.5	23.1
7	Exported goods & services	19.3 E9 $	2.86 E12/$	5.5	23.0
8	Exported fuels		8.8	36.6	
9	Hydroelectricity	2.4 E17 J	4 E4 SEJ/j	1.0	4.0
10	Total input			34.6	144.2
11	Gross Nat'l Product	1.21 E11 $	2.86 E12/$	34.6	144.2

sej = Solar equivalent joules

* Solar emergy flow (column 5) divided by 2.4 E12 solar emjoules/$ for U.S. in 1983.

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[a] Refer to numbered notes and calculations given in the appendix.

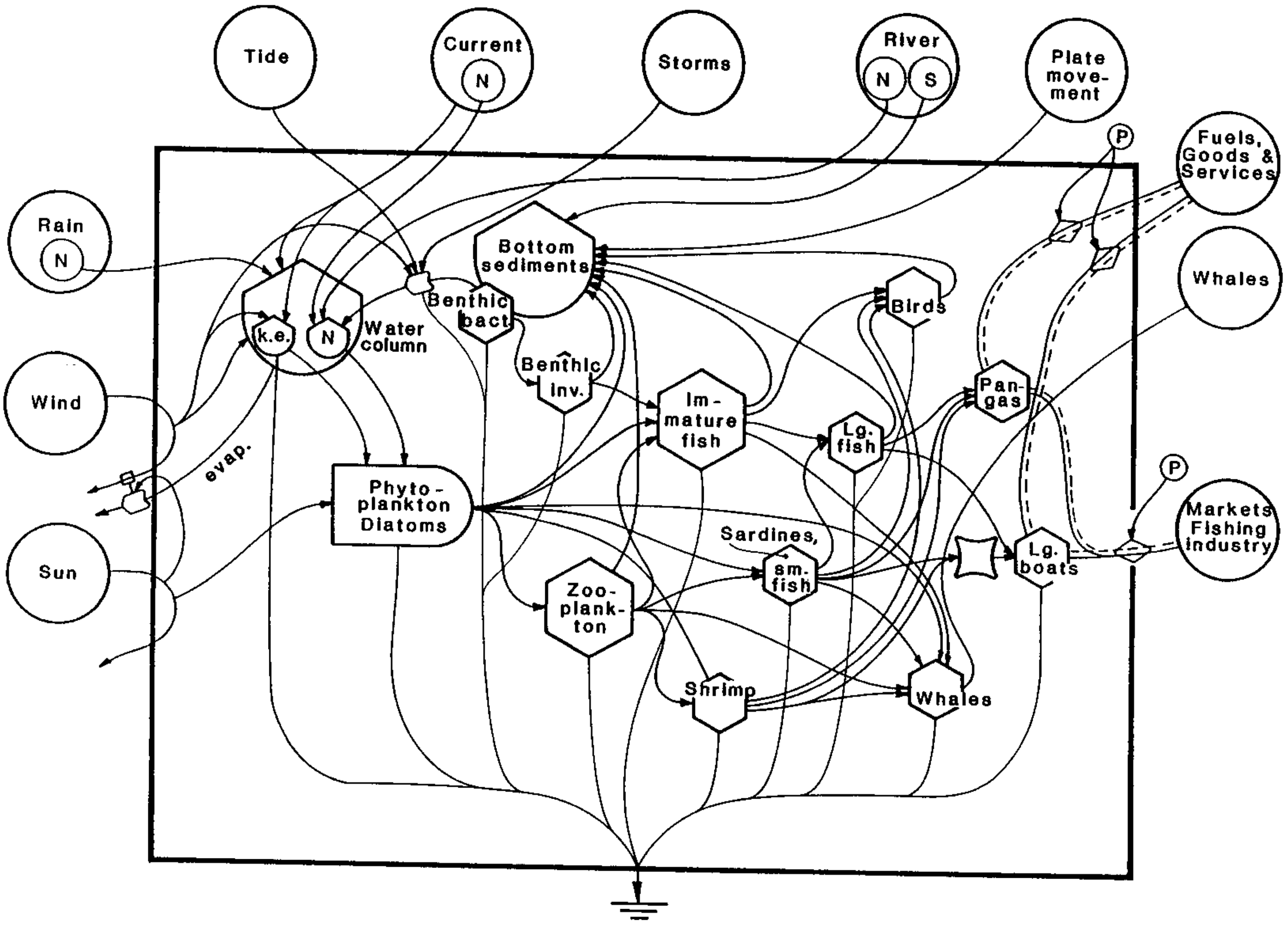


Figure 6. Energy systems diagram of the Sea of Cortez. Items are arranged from right in order of their solar transformity. K.e. = Kinetic energy, N = nutrients, S = sediments, P = price, EVAP. = evaporation.

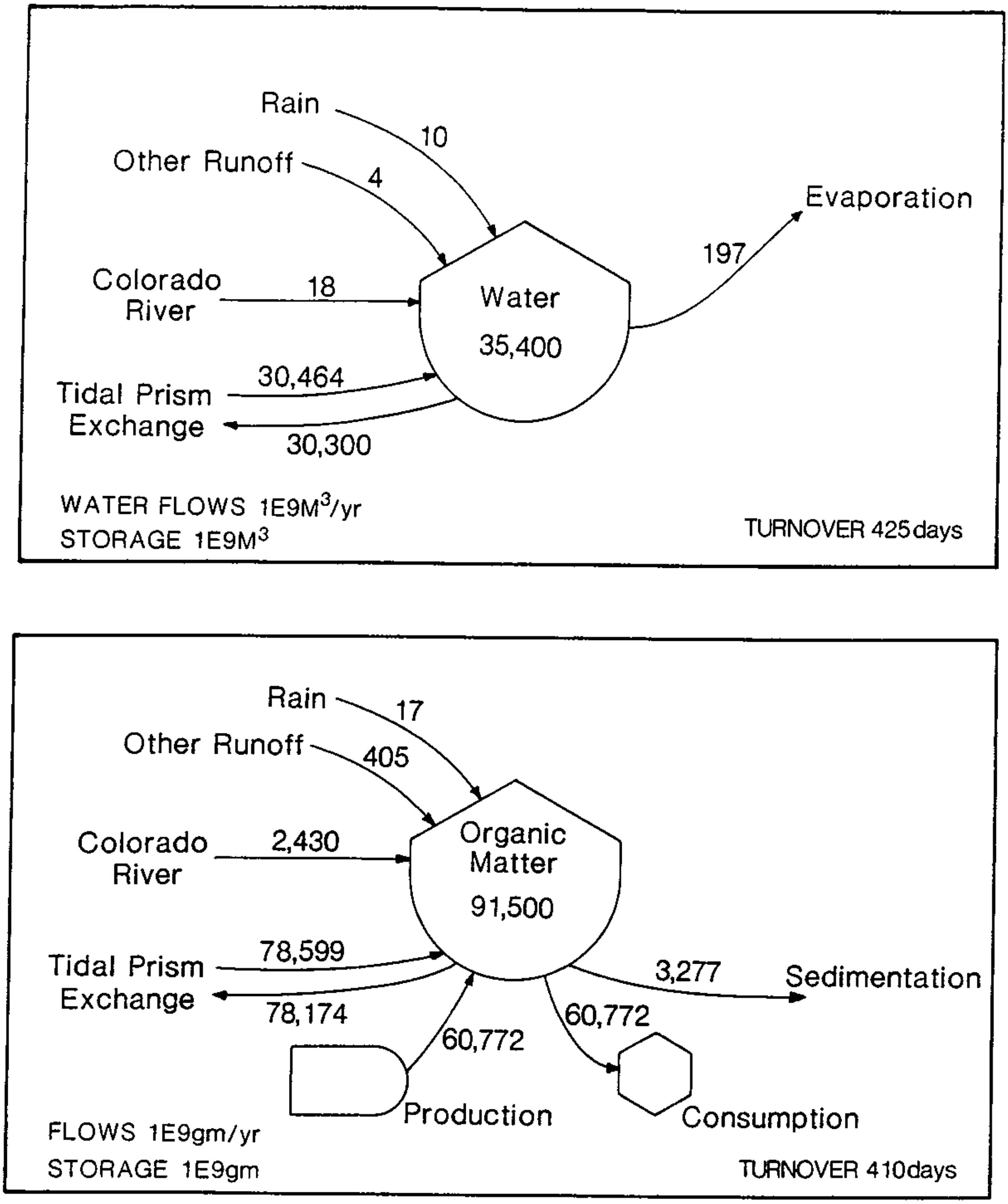
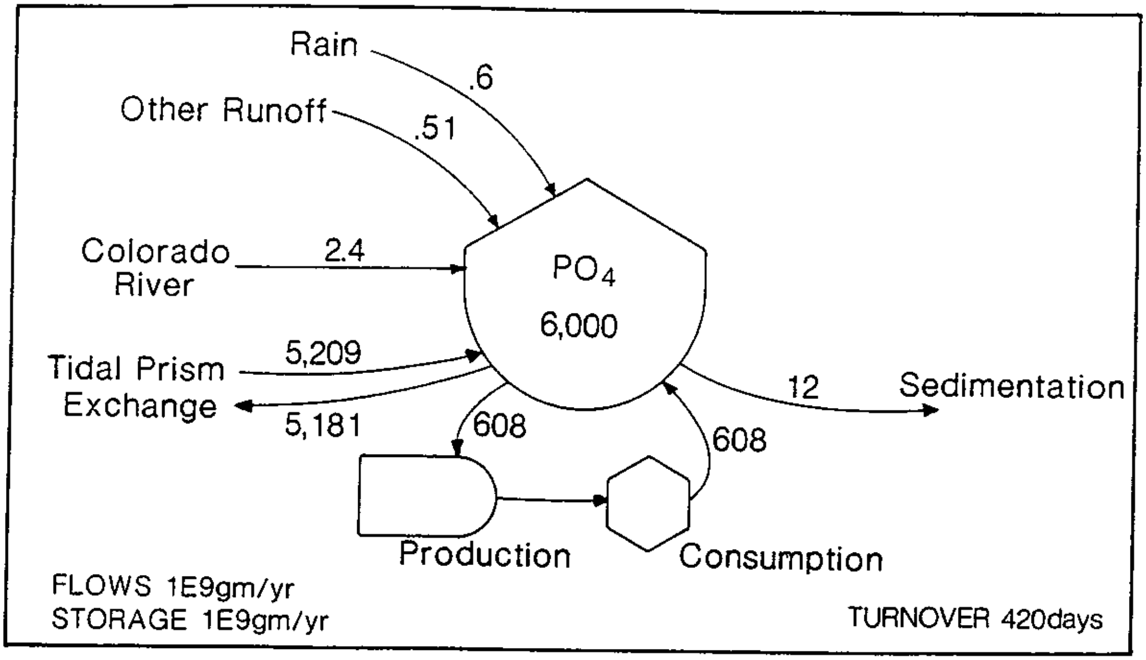


Figure 7. Total storages and annual flows of water (top) and organic matter (bottom) in the Sea of Cortez in the 1980s. Data and calculations are given in the appendix.



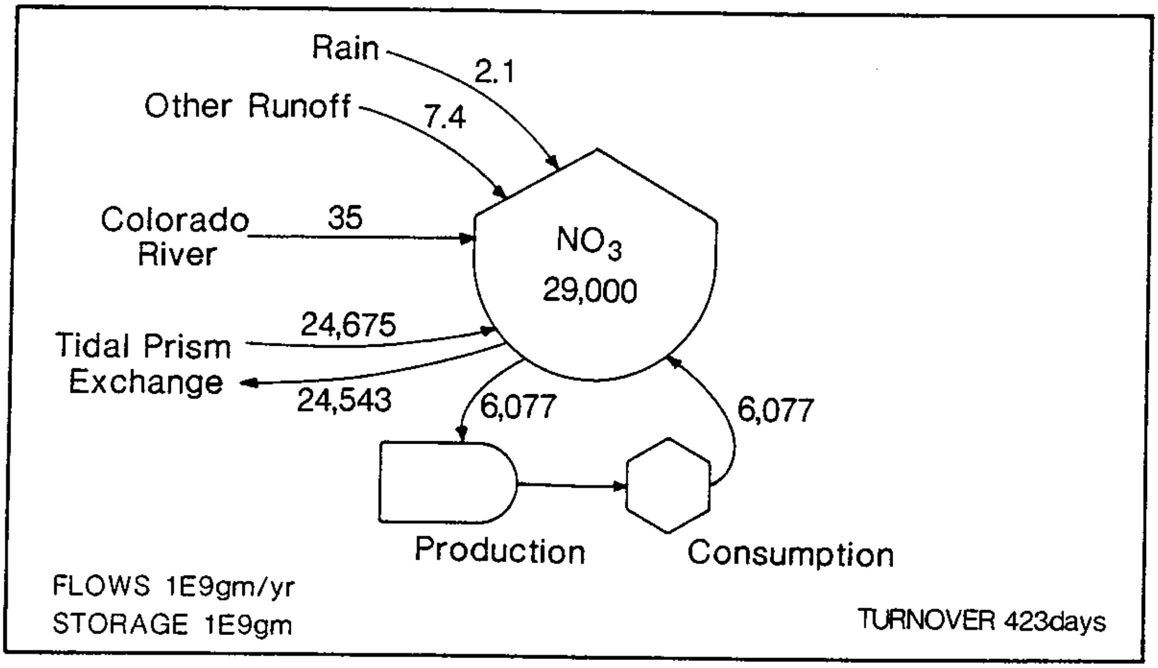


Figure 8. Total storages and annual flows of phosphorus as PO_4 (top) and nitrogen as NO_3 (bottom) in the Sea of Cortez in the 1980s. Data and calculations are given in the appendix.

included in Figures 9 and 10, but most of the water sliding in and out is the same water little changed in the course of one tidal cycle. The Colorado River brings substantial emergy to the Sea which was much reduced when the Colorado River was diverted (Figure 9).

EMERGY Tables for the Sea of Cortez. The overview diagram (Figure 6) was used to set up three emergy analysis tables for the Sea of Cortez for three time periods: Table 2 for the 1920s, Table 3 for the mid 1960s, and Table 4 for the early 1980s. For the calculations, the system was defined by the shaded area in Figures 1 and 2 and included the entire water column and the part of the bottom sediments involved in regular biological and chemical processes within the sea. Also included in the tables are economic inputs and outputs. The tables show which inputs to the sea were large and important. Notice the high values for freshwater inflows, tidal energy, and goods and services involved in fishing.

Primary Production by Photoplankton and its EMERGY Evaluation. Because of its importance to the food chains of shrimp and fish, primary production data were assembled and the emergy contribution evaluated as given in Table 5 and Figure 10. Note the importance of tidal energy and nutrients. The primary production process is shown in Figure 6 within the system that controls it and supplies its inputs. Figure 10 shows substantial differences on an emergy basis among the different periods of Colorado River management.

Fishing and EMERGY Evaluation. Data were assembled on fishing efforts for shrimp in the Sea of Cortez and evaluated for the emergy inflows and yields. The number of boats involved is shown in Figure 11, which shows a large expansion of the fleet in the 1970s. Figure 12 shows details of the way the food chain of the Sea is driven and coupled to the fishery harvests.

A comparison was made between the older pattern of small boats and local markets and some newer shrimp trawlers and international markets. Table 6 has the emergy evaluation based on the inflows and yield of the larger shrimp trawlers. Table 7 has the emergy analysis of the smaller boats. Figure 13 compares the small and larger boat systems.

Table 2. Emergy flows of the Sea of Cortez (1920s).

Note[a]	Name	Raw Units (units/yr)	Trans- formity (sej/unit)	Emergy E18 sej/yr
1	SUN	5.60 E20 J	1.00	560.2
2	RAIN			
2	Chemical Potential	4.90 E16 J	1.54 E4	756.5
2	Kinetic Energy	2.88 E14 J	8.89 E3	2.6
12	Organic Matter	3.80 E14 J	1.90 E4	7.2
12	Phosphate	5.95 E8 gm	1.40 E10	8.3
12	Nitrate	2.08 E9 gm	4.19 E9	8.7
3	TIDE	6.90 E16 J	2.36 E4	1625.9
4	WIND	4.74 E17 J	6.23 E2	295.4
5	HURRICANES	3.40 E13 J	4.10 E4	1.4
6	OCEAN CURRENT			
6	Geopotential	2.07 E15 J	2.36 E4	48.8
10	Organic Matter	6.27 E16 J	1.90 E4	1191.1
10	Phosphate	4.05 E10 gm	1.40 E10	567.0
10	Nitrate	2.63 E11 gm	4.19 E9	1102.0
7	RIVER			
7	Chemical Potential	8.99 E16 J	4.11 E4	3692.0
8	Organic Matter	5.49 E16 J	1.90 E4	1043.1
11	Phosphate	2.39 E9 gm	1.40 E10	33.5
11	Nitrate	3.49 E10 gm	4.19 E9	146.2
7	OTHER RUNOFF			
7	Chemical Potential	1.91 E16 J	4.11 E4	784.4
8	Organic Matter	9.15 E15 J	1.90 E4	173.9
11	Phosphate	5.07 E8 J	1.40 E10	7.1
11	Nitrate	7.14 E9 J	4.19 E9	29.9
13	SEISMIC ACTIVITY	4.24 E13 J	4.70 E6	199.1

sej = Solar equivalent joules

[a] Refer to numbered notes and calculations given in the appendix.

Table 3. Emergy flows of the Sea of Cortez (1960s).

Note[a]	Name	Raw Units (units/yr)	Trans-formity (sej/unit)	Emergy E18 sej/yr
1	SUN	5.60 E20 J	1.00	560.2
2	RAIN			
2	Chemical Potential	4.90 E16 J	1.54 E4	756.5
2	Kinetic Energy	2.88 E14 J	8.89 E3	2.6
12	Organic Matter	3.80 E14 J	1.90 E4	7.2
12	Phosphate	5.95 E8 gm	1.40 E10	8.3
12	Nitrate	2.08 E9 gm	4.19 E9	8.7
3	TIDE	6.90 E16 J	2.36 E4	1625.9
4	WIND	4.74 E17 J	6.23 E2	295.4
5	HURRICANES	3.40 E13 J	4.10 E4	1.4
6	OCEAN CURRENT			
6	Geopotential	2.29 E15 J	2.36 E4	54.0
10	Organic Matter	6.96 E16 J	1.90 E4	1322.4
10	Phosphate	4.50 E10 gm	1.40 E10	630.0
10	Nitrate	2.93 E11 gm	4.19 E9	1227.7
7	RIVER			
7	Chemical Potential	5.50 E14 J	4.11 E4	22.6
8	Organic Matter	2.14 E12 J	1.90 E4	.0
11	Phosphate	1.50 E7 gm	1.40 E10	0.2
11	Nitrate	2.19 E8 gm	4.19 E9	0.9
7	OTHER RUNOFF			
7	Chemical Potential	1.91 E16 J	4.11 E4	784.4
8	Organic Matter	9.15 E15 J	1.90 E4	173.9
11	Phosphate	5.07 E8 J	1.40 E10	7.1
11	Nitrate	7.14 E9 J	4.19 E9	29.9
13	SEISMIC ACTIVITY	4.24 E13 J	4.70 E6	199.1

sej = Solar equivalent joules

[a] Refer to numbered notes and calculations given in the appendix.

Table 4. Emergy flows of the Sea of Cortez (1980s).

Note[a]	Name	Raw Units (units/yr)	Trans-formity (sej/unit)	Emergy E18 sej/yr
1	SUN	5.60 E20 J	1.00	560.2
2	RAIN			
2	Chemical Potential	4.90 E16 J	1.54 E4	756.5
2	Kinetic Energy	2.88 E14 J	8.89 E3	2.6
12	Organic Matter	3.80 E14 J	1.90 E4	7.2
12	Phosphate	5.95 E8 gm	1.40 E10	8.3
12	Nitrate	2.08 E9 gm	4.19 E9	8.7
3	TIDE	6.90 E16 J	2.36 E4	1625.9
4	WIND	4.74 E17 J	6.23 E2	295.4
5	HURRICANES	3.40 E13 J	4.10 E4	1.4
6	OCEAN CURRENT			
6	Geopotential	2.22 E15 J	2.36 E4	52.3
10	Organic Matter	6.58 E16 J	1.90 E4	1250.2
10	Phosphate	4.25 E10 gm	1.40 E10	595.0
10	Nitrate	2.77 E11 gm	4.19 E9	1160.6
7	RIVER			
7	Chemical Potential	3.01 E16 J	4.11 E4	1236.1
8	Organic Matter	1.67 E14 J	1.90 E4	3.2
11	Phosphate	8.10 E8 gm	1.40 E10	11.3
11	Nitrate	1.18 E10 gm	4.19 E9	49.4
7	OTHER RUNOFF			
7	Chemical Potential	1.91 E16 J	4.11 E4	784.4
8	Organic Matter	9.15 E15 J	1.90 E4	173.9
11	Phosphate	5.07 E8 J	1.40 E10	7.1
11	Nitrate	7.14 E9 J	4.19 E9	29.9
13	SEISMIC ACTIVITY	4.24 E13 J	4.70 E6	199.1
14	FOSSIL FUELS (1983)			
	Coal	2.02 E14 J	3.98 E4	8.0
	Oil	5.33 E15 J	5.30 E4	282.5
	Gas	1.99 E15 J	4.80 E4	95.5
	Wood	1.53 E14 J	3.50 E4	5.4

Table 4. continued.

Note[a]	Name	Raw Units (units/yr)	Trans-formity (sej/unit)	Emergy E18 sej/yr
15	ELECTRICITY (1983)	4.58 E14 J	1.59 E5	72.8
16	GOODS & SERVICES (1983)			
	Direct	2.10 E8 $	3.00 E12	630.0
	Imports	4.80 E7 $	3.80 E12	182.4
	Taxes	2.96 E16	3.00 E12	8.9
17	TOTAL INPUT			7539.5

sej = Solar equivalent joules

[a] Refer to numbered notes and calculations given in the appendix.

Table 5. Emergy flows of primary productivity (1960s).

Note[a]	Name	Raw Units (units/yr)	Trans-formity (sej/unit)	Emergy E18 sej/yr
3	TIDE	6.90 E16 J	2.36 E4	1625.9
2	RAIN			
2	Chemical Potential	4.90 E16 J	1.54 E4	756.5
2	Kinetic Energy	2.88 E14 J	8.89 E3	2.6
12	Phosphate	5.95 E8 gm	1.40 E10	8.3
12	Nitrate	2.08 E9 gm	4.19 E9	8.7
6	OCEAN CURRENT			
6	Geopotential	2.29 E15 J	2.36 E4	54.0
10	Phosphate	3.77 E10 gm	1.40 E10	630.0
10	Nitrate	2.11 E11 gm	4.19 E9	1227.7
7	OTHER RUNOFF			
7	Chemical Potential	1.91 E16 J	4.11 E4	784.4
11	Phosphate	5.07 E8 J	1.40 E10	7.1
11	Nitrate	7.14 E9 J	4.19 E9	29.9
7	RIVER			
7	Chemical Potential	5.50 E14 J	4.11 E4	22.6
11	Phosphate	1.50 E7 gm	1.40 E10	0.2
11	Nitrate	2.19 E8 gm	4.19 E9	0.9
9	PRIMARY PRODUCTION	4.75 E17 J	1.09 E4	5158.8

sej = Solar equivalent joules

[a] Refer to numbered notes and calculations given in the appendix.

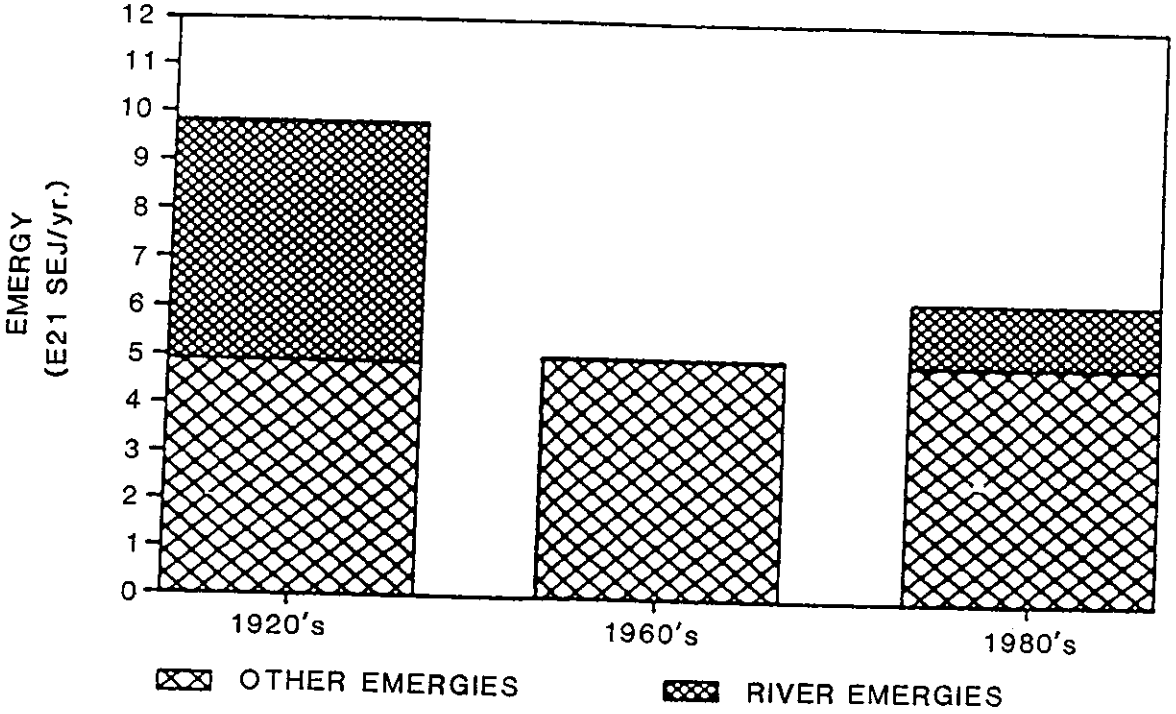


Figure 9. Average annual EMERGY inflowing to the Sea of Cortez for temporal periods 1920s, 1960s, and 1980s. Data are from Tables 2-5.

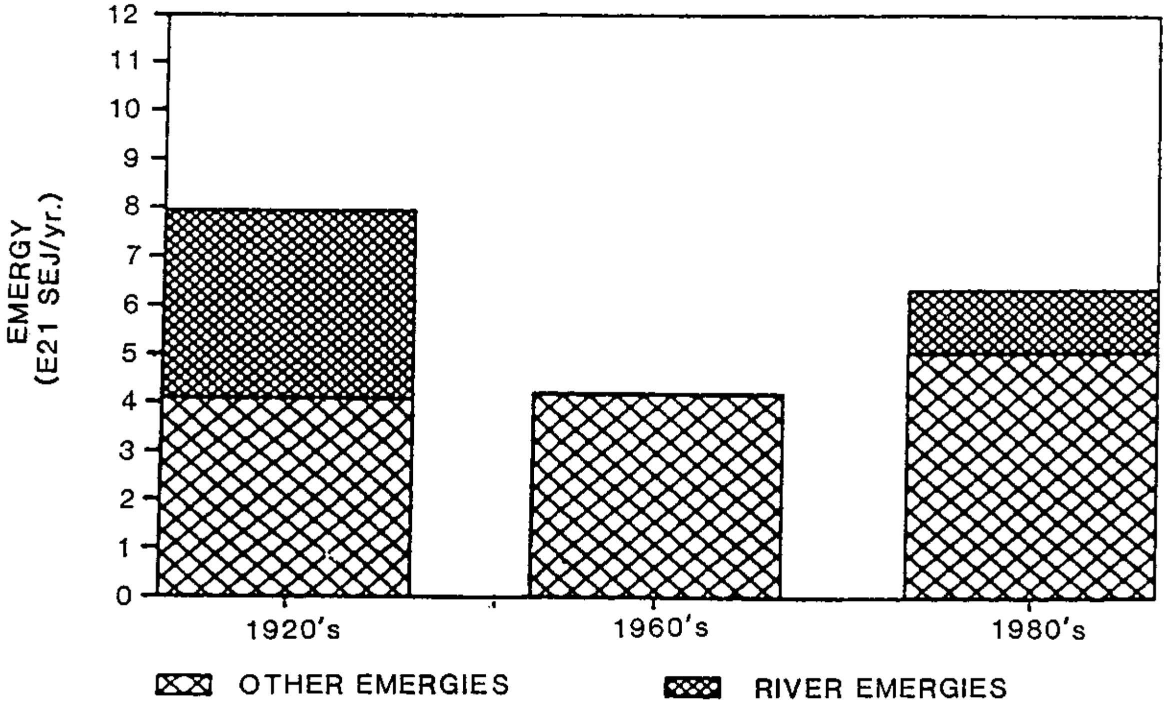


Figure 10. Average annual EMERGY inflowing to primary production in the Sea of Cortez for the temporal periods 1920s, 1960s, and 1980s. Data are from Tables 2-5.

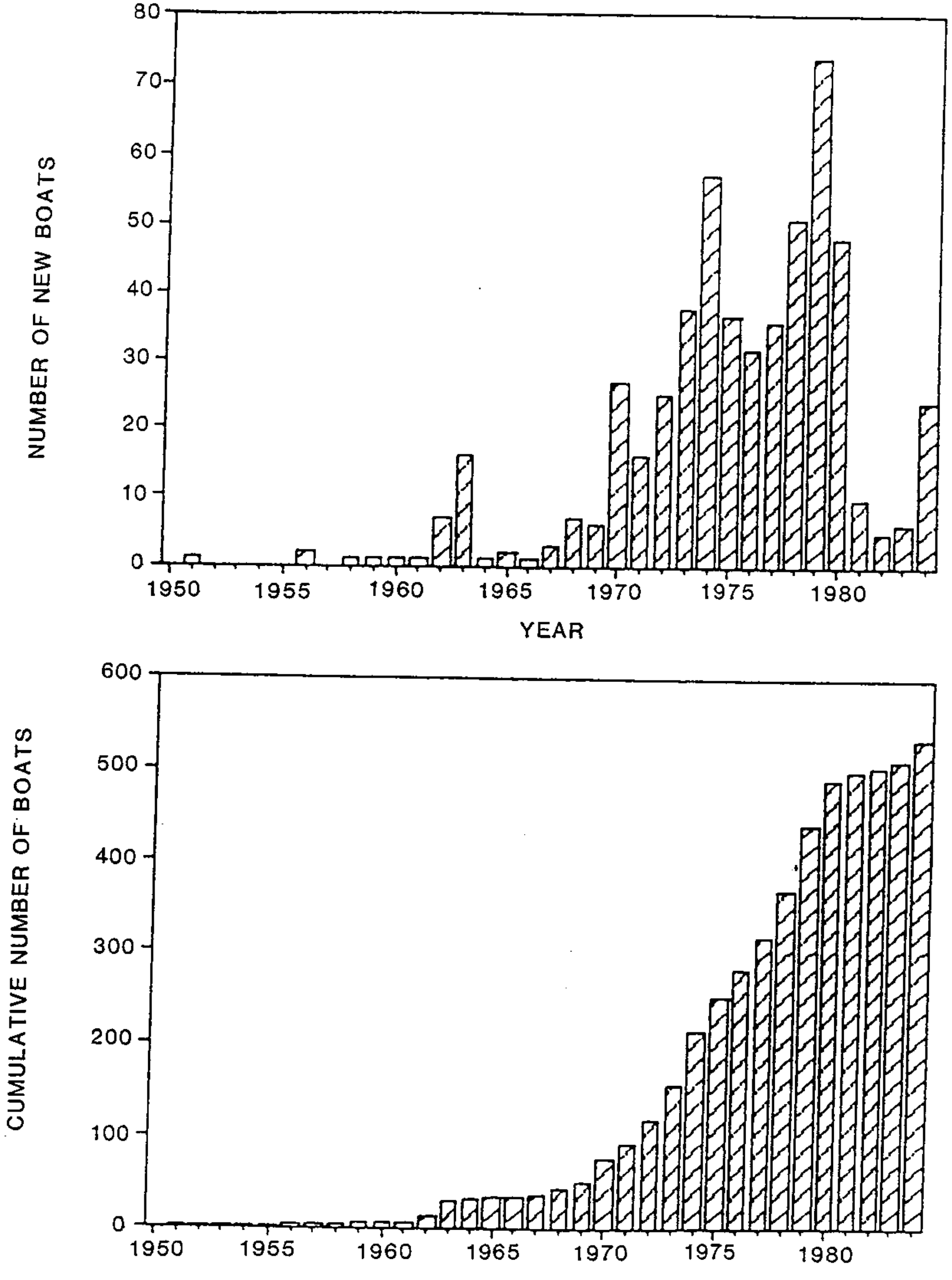


Figure 11. The number of new fishing boats commissioned each year that are still fishing (top) and cumulative number of boats (bottom). Data are from records of Delegacion Federal de Pesca en Sonora.

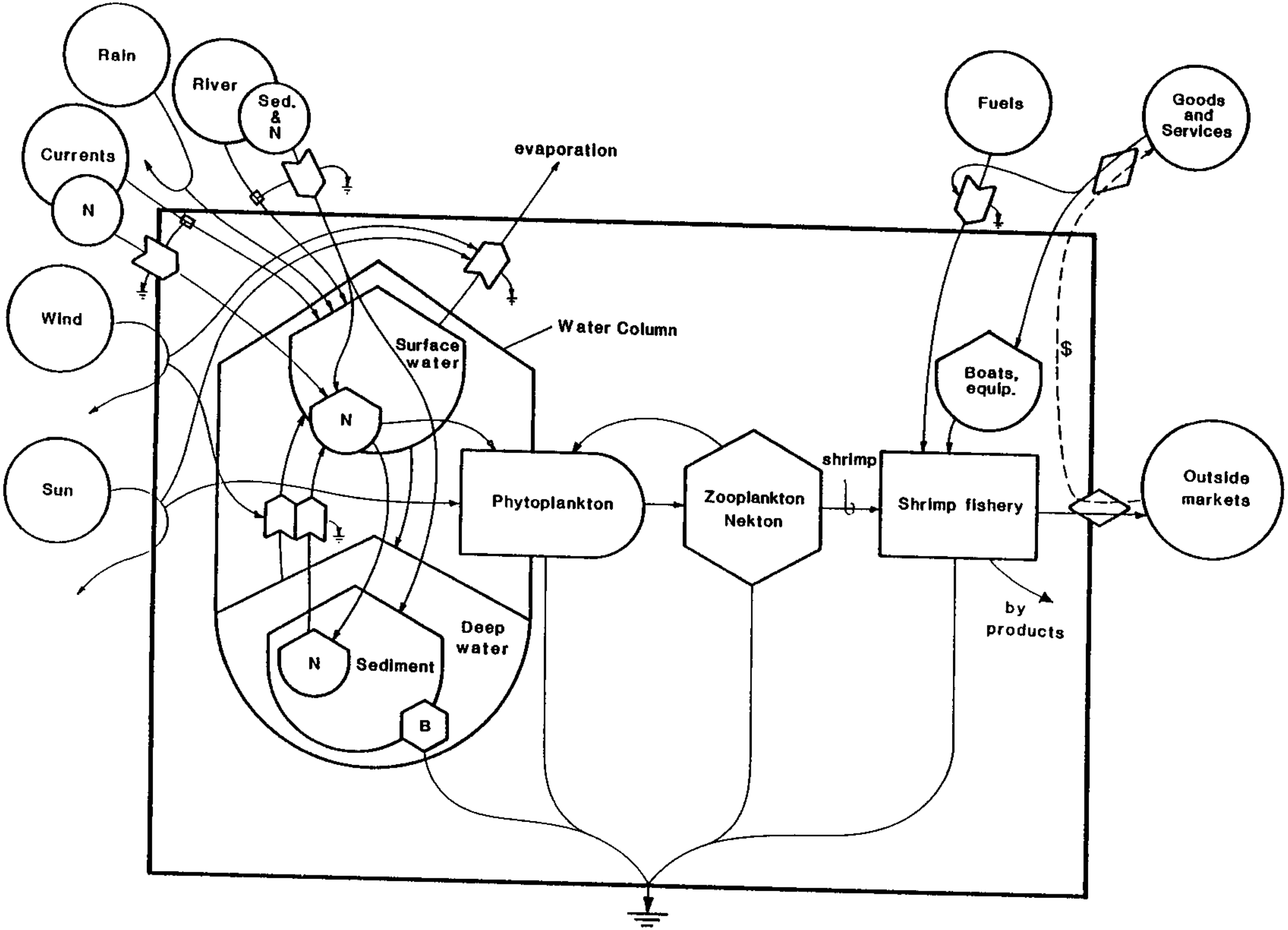


Figure 12. Summary diagram of the Sea of Cortez shrimp fishery showing driving energies inflowing from left and bought goods and services and the economic sector to the right. N = nutirents, Sed. = sediments, B = benthic organisms

Table 6. Emergy costs and shrimp yield per year: Shrimp Trawlers.

Footnote[a]	Name	Actual Units	Trans-formity* (sej/unit)	Emergy E15 sej/yr
1	Fuel	7.2 E12 J	53000 sej/J	380
2	Misc. Goods & Svcs	\$6.6 E4	2.9 E12 sej/\$	200
3	Salary	\$1.7 E4	2.9 E12 sej/\$	50
4	Boat	\$4.1 E3	2.9 E12 sej/\$	10
5	Engine	\$4.1 E3	2.9 E12 sej/\$	10
	TOTAL EMERGY			650
6	Shrimp	3.8 E10 J	8 E6 sej/J	300

Catch/effort ratio: $\frac{300 \text{ E15 sej/yr}}{650 \text{ E15 sej/yr}}$ = 0.46/1 (Net Emergy yield ratio)

*Transformities for fuel, dollars, and shrimp are from Odum et al. (1986). The transformity for dollars is the total Solar Emergy driving the Mexican economy divided by the GNP in U.S. dollars.

[a] Refer to numbered notes and calculations given in the appendix.

Table 7. Emergy costs and shrimp yield per year: Small boats (Pangas).

Footnote[a]	Name	Actual Units	Trans-formity*	Emergy E15 sej/yr (sej/unit)
1	Fuel	1.35 E11 J	53000 sej/J	7.2
2	Misc. Goods & Svcs	$ 879	2.9 E12 sej/$	2.6
3	Salary	$2400	2.9 E12 sej/$	6.7
4	Boat	$ 50	2.9 E12 sej/$	0.1
5	Engine	$ 271	2.9 E12 sej/$	0.8
	TOTAL EMERGY			17.4
6	Shrimp	1.1 E10 J	8 E6 sej/J	88.0

Catch/effort ratio: $\frac{88.0 \text{ E15 sej/yr}}{17.4 \text{ E15 sej/yr}} = 5.1/1$ (Net Emergy yield ratio)

*Transformities for fuel, dollars, and shrimp are from Odum et al. (1986). The transformity for dollars is the total Solar Emergy driving the Mexican economy divided by the GNP in U.S. dollars.

[a] Refer to numbered notes and calculations given in the appendix.

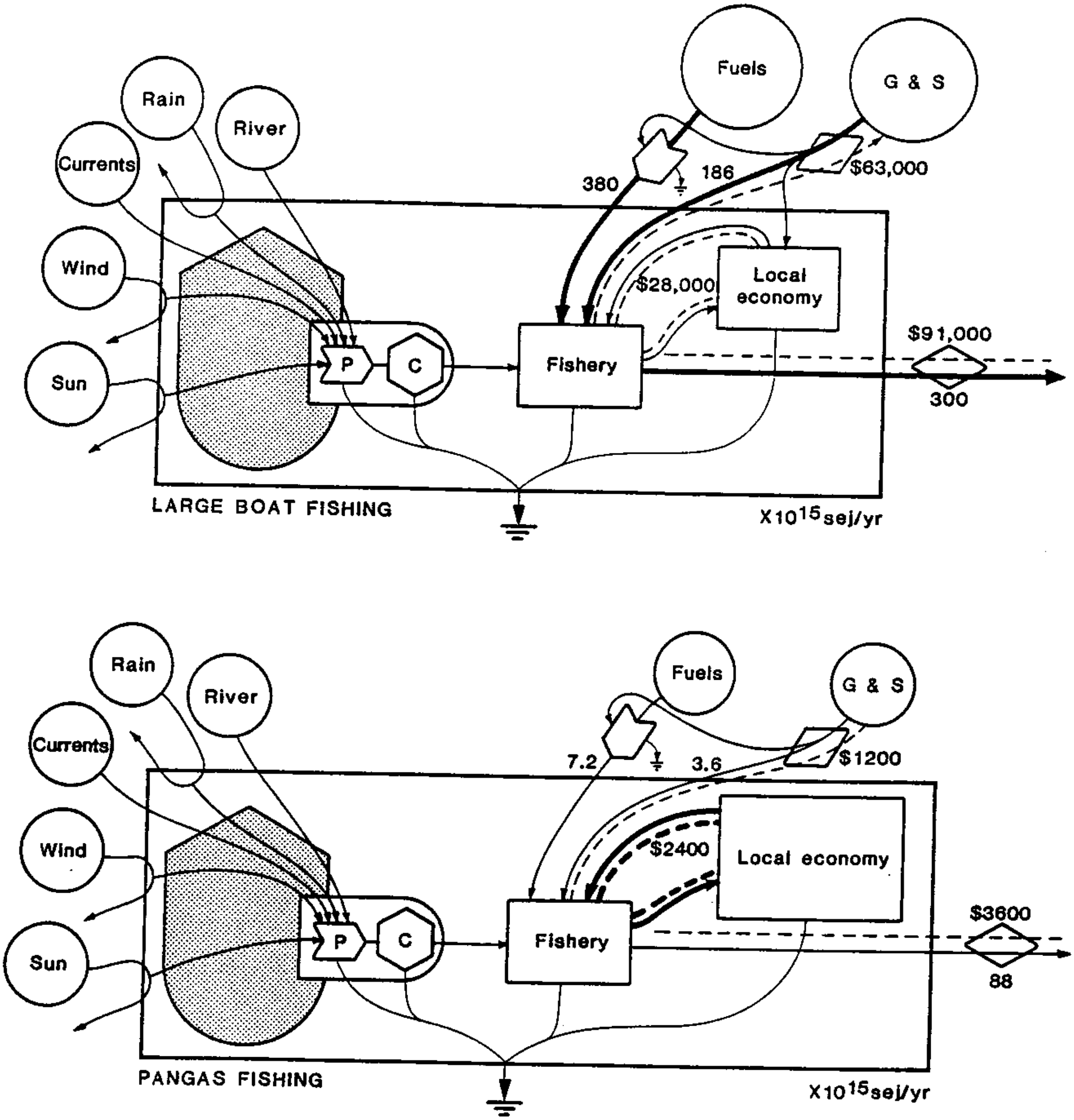


Figure 13. Summary diagrams of EMERGY and dollar flows for the large boat shrimp fishery (top) and pangas shrimp fishery (bottom) in the Sea of Cortez. Data are from Tables 6 and 7. P = production, C = consumer organisms

DISCUSSION

In this section we develop a synthesis overview of the Sea of Cortez, its driving energies, its storages and processes, and its place in the Mexican economy. We examine public policy implications of present and past resource management and suggest alternatives that may maximize long-term economic vitality. Of greatest concern is the issue of sustainable economic development. Throughout the development world, the single most important issue facing public officials is related to the long-term consequences of selling raw resources abroad and thus in essence supporting the economy of other nations at the expense of the local economy. The methods and results of emergy analysis highlight this issue and may make policy decisions more easily understood.

Consider first the way the Colorado River and tidal inputs to the Sea of Cortez support primary production and food chains leading to fisheries that have immense value to the economy.

The Effect of the Colorado River Diversion

The discharge rates of the Colorado River during the 1920s were taken as a baseline for the era preceding heavy influences by humanity. Since 1935, discharge of the Colorado has been significantly altered (Figure 2). Both low flows and annual peak discharges have been reduced. The average flows during the 1980s represent current flow rates and are about 33% of those recorded during the 1920s.

EMERGY Budget

The effects of diversion and decreased discharges of the Colorado River on the Sea of Cortez have been a source of speculation for a number of years. With such a large discharge, it has been speculated that the diversion and losses of river water as agriculture and damming increased should have had a deleterious impact on the Gulf. Indeed, when comparisons among Tables 2, 3, and 4 are made, the magnitude of river diversion is significant. The contribution of river-derived phosphorus, nitrogen and organic matter, as well as chemical potential of freshwater, were a significant portion of the northern Gulf's yearly net emergy inflow (40%) during the 1920s. The emergies given in the last column of the tables are calculated by determining net inflows from all outside driving energies. The loss of discharge during the 1960s resulted in a loss of almost 40% of the net yearly emergy flux, and present day discharges still contribute only about 70% of the original net emergy to the Gulf.

The single greatest emergy input to the northern Gulf during the 1920s (Table 2) is the emergy of the chemical potential of the freshwater input from the Colorado discharge. Indeed, Alvarez-Borrego (1983) felt that "the greatest changes in the upper Gulf...[are due to] the decrease of Colorado River fresh-water input [that] has drastically changed the ecological conditions of what used to be an estuarine system, and is now an area of the highest salinities of the whole Gulf." Copeland (1966) suggests that the most important hydrobiological parameter in estuaries is salinity, and if river flow is diminished by activities in the upper watershed, salinity in the receiving estuary may increase to levels that are detrimental to biological communities. However, he also questions whether the loss of freshwater input actually results in lessened productivity in the estuary or only in changes in the channels of productivity.

Budgets of Water, Organic Matter, and Nutrients

While the emergy analysis suggests that significant changes in the total emergy of the upper Gulf resulted from the diversion of the Colorado River, comparison of the year fluxes and storage of water, organic matter, PO -phosphorus and N -nitrogen lend additional insight. The magnitudes of inputs resulting from the Colorado and those from net tidal flux and overall storages within the upper Gulf are shown in Figures 7 and 8. In general, they suggest that internal cycling and tidal flux may account for more importance than the inflows resulting from the Colorado.

***Fresh Water*:** Figure 7a gives the water balance in the upper Gulf during the 1920s. Comparison of the magnitudes of inflowing water from the river and net tidal inflow indicates how small the river input actually is. Calculated evaporation is more than 10 times the inflow of the river. Yearly rainfall over the Gulf is half of the inflow from the Colorado. Just in terms of volume of the exchange of the tidal prism, the yearly exchange of water is three orders of magnitude greater than the yearly input from the river. Yet the influence of the Colorado's fresh water, when considered relative to its emergy input as chemical potential energy (Table 2) was the greatest single input during the 1920s era.

***Organic Matter*:** The yearly fluxes and storage of organic matter in the northern Gulf as shown in Figure 7b indicate that the Colorado River's contribution is nearly 3% of the total storage. Tidal flux of organic matter is difficult, at best, to calculate, since it depends in part on the effects of mixing resulting from currents around the mid-riff. So comparisons between river input and net tidal flux may be inappropriate. Yet if the net tidal flux shown in Figure 7b is an indication of the relative magnitudes, river inputs of organic matter were six times greater than the net tidal flux. Comparison between river inflow and total tidal exchange, on the other hand suggests that the river represents approximately 3% of the overall balance of inflows and outflows. In terms of the total flux of organic matter, the Colorado contribution seems small, but may have been extremely important in the yearly budget of organic matter.

Nutrients: The determination of net tidal flux of nutrients between the upper and lower Gulf depends on how well mixed the zone between these two water masses is, since the exchange occurs over this relatively small interface. The currents in the mid-riff area of the Gulf are exceptionally complex, thus determination of actual exchange of nutrients is further compounded in complexity. Nevertheless, if a simplifying assumption (complete mixing at the interface) is made, relative comparisons between magnitudes of river inputs of phosphorus and nitrogen and those resulting from tidal exchange can be made. Figures 8a and 8b suggest that river inputs of PO_4-P and NO_3-N are quite small when compared to internal cycling. The effects of river diversion on nutrient budgets of the upper Gulf would seem to be of lesser importance than those of organic matter and the chemical potential energy of its fresh water, since the volume of these materials and internal cycling seem to be at least three orders of magnitude greater than river inputs.

Summary: Impacts of the Colorado Diversion

It is somewhat surprising that apparently there was not a decline in the fishery recorded in the northern Gulf after the diversion in the 1960s as a result of the loss of emergy of this magnitude. The reason for a lack of measurable decline in productivity over large areas of the Gulf (Zeitzschel 1969 concluded, after measurements in 1968, that productivity in the northern Gulf was approximately 0.6 g C/m^2 day) may be related to the nature of the emergy inputs. The major components of the emergy inflowing to the Gulf as a result of the Colorado River discharge were the chemical potential energy of freshwater and organic silts, both of which would have their strongest impact at the delta and immediate surrounding areas. The loss of emergy of estuarine upwelling that was generated by the chemical potential (of the order of ten times the river water input [Gross, 1982]) would probably have a direct impact on the primary production in areas relatively close to the river discharge. Direct impacts on the benefits and protection derived by benthic filter feeders and a few notable species of fish such as totoaba (*Cynoscion macdonaldi* [Flanagan and Hendrickson, 1976]), from the organic silts and salinity fluctuations would be local as well.

Aside from these local effects, the lack of a more pervasive impact on the productivity of the northern Sea of Cortez may be related to the buffering capacity of the large storage of nutrients and organic matter within deep waters and sediments of the Gulf and their availability via upwelling and tidal resuspension. When the river inflows during the 1920s are compared to the storages of each material within the northern Gulf and the yearly flux of each as a result of tidal exchange and ocean currents, the amounts of river-derived organic matter and nutrients are minor (Figures 7 and 8). Yearly fluxes shown in Figures 7 and 8 are for the "unaltered condition," prior to intervention by humanity, that is represented by the 1920s data. During this time, discharge of the river represented only about 0.01% of the total volume of water in the northern Gulf, and yearly organic matter contribution was about 0.4% of the total volume of organic matter. The contributions of phosphorus and nitrogen in river water were small when compared to their volumes (about 0.01% and 0.02%, respectively).

Thus, when the river was diverted during the 1960s, the loss of these constituents was buffered by the enormous storages within the northern Gulf and exchanges with the Pacific.

Primary Production

A major part of the ecosystem is primary production of the phytoplankton which supports food chains. Figure 6 shows the way the rest of the system interacts. A separate analysis was performed for the euphotic zone subsystem. Given in Table 5 is an emergy analysis of primary production for the Sea of Cortez during the 1960s. Data on primary production were available for the 1960s (Zeitzschel, 1969), thus the 1960s emergy data (Table 5) were used to calculate emergy input to primary production. The area for which primary production calculations were made is comprised of the surface of the northern Gulf to a depth of roughly 40 meters (the photic zone). Therefore, not all the emergy inputs to the northern Gulf are used in the calculations of emergy for primary production. Those like sunlight, wind, and hurricanes that are already embodied in rainfall are not double counted. Organic matter that must sink below the photic zone and decompose before upwelling as nutrients is not included since the upwelled nutrients are included, and seismic activity, which is much below the photic zone, is not included.

The emergy column in Table 5 expresses the various energy inputs to primary production in the northern Gulf in common units of Solar Emergy. The single largest input is the physical energy in tides, followed in order of importance by nitrate in sea water, chemical energy in runoff from the surrounding lands, and the chemical potential energy in rainfall. During the 1960s, the relative contributions from the Colorado are quite small. Figure 9 illustrates the relative importance of the inputs derived from the Colorado. Emergy inflows derived from the Colorado during the 1920s were nearly half of the total emergy budget, were nearly absent during the 1960s, and represent about 20% of the total emergy budget during the 1980s.

Theory suggests that with the loss of emergy contribution from he river discharge after the 1920s, there could have been a corresponding decline in primary production. The change in primary production over time and how it has been affected by the decline in river flow and consequent decline in emergy input is still open to speculation, since there are no data during the earlier years when the Colorado discharges were greater. However, if we assume that there is a direct relationship between the total emergy input and primary production in the northern Gulf, then the annual emergy inputs for the three time periods that are illustrated in Figure 9 might be used to suggest changing primary production from the 1920s through the 1980s. From emergy contributions in Figure 9, we might speculate that current primary production in the northern Gulf is about 75% of that which was characteristic of the area when the Colorado River discharged unimpeded by the works and uses of humanity.

Fisheries in the Sea of Cortez

The shrimp fishery of the northern Sea of Cortez is the single largest fishery of the entire Mexican economy, contributing more than $350 million. In the same year, the total commercial fishery catch for all species from the Sea of Cortez contributed over 55% of the total value of the Mexican commercial fishery.

In recent years the Mexican government has been monitoring the shrimp fishery and, as a result, much data on total catch have been collected. However, it still remains to be seen if these data can be used to relate catch to population size and then to outside influences like changes in the discharge rates of the Colorado. The response of the fishery to changes in the Colorado may be overridden by changes in the intensity of fishing by the Mexican fleet (Flanagan and Hendrickson, 1976).

To better understand these trends in the shrimp fishery of the northern Gulf, we examine the emergy analysis of the costs and yield of shrimp trawlers (i.e., more energy intensive equipment) and the costs and yields of small boats. Figure 12 is a summary diagram of the shrimp fishery showing the driving energies, gross production, the simplified estuarine food chain, and harvesting efforts using boats and equipment purchased from outside. Tables 6 and 7 summarize the emergy analysis for large and small boats. The shrimp trawler is typically of a size class of about 100 tonnes, driven by a 400 hp diesel engine. The small boat is a fiberglass boat called a "panga" typically about 5 meters in length with a 42 hp outboard motor. Currently the shrimping fleet of the northern Gulf is comprised of about 587 shrimp trawlers and about 1600 to 1800 pangas.

An important index calculated in the emergy analysis is the ratio of catch to effort. By comparing the emergy of the shrimp caught per year with the sum of the total emergy costs of operation, maintenance, labor, and boat replacement for each of the two types of boats, a catch to effort ratio is calculated and shown at the bottom of Tables 6 and 7. The ratio relates the total emergy of the shrimp catch with the total emergy cost of the effort. For the shrimp trawlers, the ratio is 0.46/1, indicating that for one joule of emergy in shrimp caught roughly 2 joules are utilized in fishing effort. The ratio for the pangas fishermen is about 5/1, indicating that for each joule of emergy used in fishing effort, 5 joules of shrimp emergy are caught. While there may be some question concerning the reliability of the data for the pangas fishing system because the data are based on dockside interviews of fishermen, the analysis suggests, unless our estimates from interviews are off by two orders of magnitude, that the smaller boats are more efficient.

From a larger scale perspective, if the differences between these two methods of fishing are as dramatic as indicated by these data, policy that encourages larger boats may in the long run be counterproductive, as the large boats require nearly 12 times the energy to harvest the same shrimp as the smaller boats. Other factors affect these decisions, however. First, the larger boats can fish for shrimp in areas where it would be difficult or impossible with the smaller boats that are confined to the relatively calm coastal waters. Second, the large boats can fish a more dilute fishery; the smaller boats require a more concentrated fishery, since their methods are not those of dragging nets for hours at a time in deep waters. Third, the larger boats are better able to preserve their catch, thus ensuring a high quality product for the export market.

Policy also needs to consider the effects of the shrimp fishery on the economy. As we have shown, the shrimp fishery of the northern Gulf is important to the economy of Mexico, contributing over a 55% share of the total income derived from fishing nationally. Figure 13 summarizes the two methods of shrimp fishing and relates each to the economy. The top diagram summarizes the flows of emergy and money for the shrimp trawlers, and the bottom diagram summarizes the flows for the pangas. The striking difference between the two diagrams is the relative proportions of the dollar budgets that are spent on fuels, goods and services compared to labor. Almost 70% of the total income derived from the export of 100% of the catch from the shrimp trawlers (top diagram) is used to purchase fuels, goods, and services, while about 33% of the pangas' income is used to purchase those inputs. The remaining income for each type of boat is spent in salary and considered as direct inputs to the local economy. In other words about 66% of the pangas' income is spent as salary, while only 30% of the shrimp trawler income is salary, an interesting consequence since recent government policy has been to encourage the larger boats because of the number of individuals they employ.

A second difference is related to income generated from the sale of shrimp. The emergy per dollar of catch from shrimp trawlers is about 3.3 E12 sej/\$, while the emergy per dollar of the catch from the pangas is about 24.4 E12 sej/\$. This is a reflection of the difference in price obtained by the pangas fisherman as a result of lower quality catch and local market conditions. Interestingly, though, the local economy benefits more from the sale than does the external buyer.

When goods are purchased from the U.S. economy with the income earned from the sale of shrimp, the net trade balance favors the U.S. economy since the emergy per dollar ratio for the U.S. economy is 2.4 E12 sej/\$, while that for shrimp caught by shrimp trawler is 3.3 E12 sej/\$.

Other aspects of the shrimp fishery that may have implications and affect policy decisions are related to the environmental impacts of the two methods of fishing. It was estimated by Delegacion Federal de Pesca En Sonora personnel that the by-catch (the other fish caught in nets during shrimping) is at times twice the weight of shrimp caught. Our observations were that as much as 90% of a haul was by-catch at the end of the 1986 fishing season. Most of the by-catch dies on the decks of the shrimp boats before being returned to the Gulf waters. If the average weight of the 50% by-catch is that of the shrimp caught over the entire shrimping season, adding the by-catch to the emergy costs in Table 6, decreases the catch to effort ratio from 0.46/1 to 0.32/1. The by-catch of the pangas fishermen is minor, and any commercial fish in the by-catch may get into the local economy at day's end. In essence, the smaller boats have a smaller environmental impact. Pauly and Neal (1985) have found the same is true in Southeast Asian fisheries.

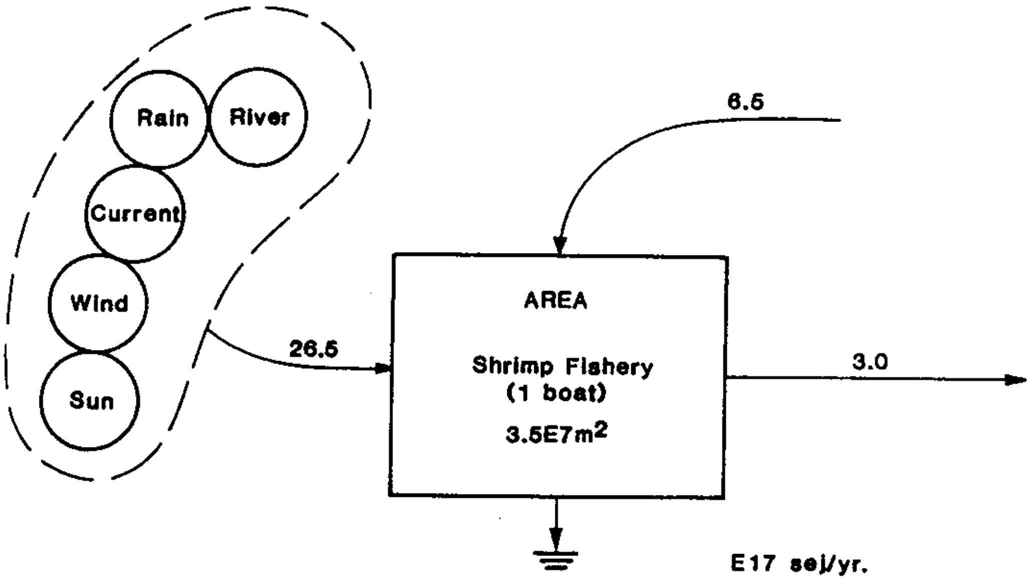
Mathews (1974) estimated that every square meter of the shrimp grounds in the Gulf are passed over 7 times each year by the nets of the shrimping fleet. In August 1986, we used data gathered from the Delegacion

Federal de Pesca En Sonora and determined that the total area dragged for the entire fleet was 1.2 E11 m^2 for the previous fishing season. And, if we assume that 1/4 the area of the northern Gulf (1.97 E10 m^2) is dragged for shrimp, this would mean that, on the average, each square meter would be dragged 6.1 times. In reality, the area of shrimp harvesting is probably smaller than 1/4 of the northern Gulf, and some areas are dragged more frequently than others, so that the number of times the shrimp nets pass over these areas may be much higher.

The summary diagram of large boat shrimp fishing in the northern Gulf, given in Figure 14, shows the relationship of emergy flows driving productivity (flow from the left) of the fishing area for an average large boat, and the emergy associated with fishing effort (flow from the right). Combining these two flows of emergy as a ratio, where the renewable emergy from nature is the denominator and the emergy in human effort is the numerator, yields the investment ratio, which relates the emergy "invested" to the renewable emergy driving a system. Put another way, it is a measure of environmental loading, the "load" of input stresses that the environment must handle during the course of a particular human activity. A high ratio suggests high environmental loading, while a low ratio suggests low environmental loading. The investment ratio for shrimp fishing using large boats is about 0.25/1. Investment ratios for other food systems are also given in Figure 14 for comparison.

The investment ratio for shrimp fishing when compared to other food systems suggests that the environmental loading is significantly less than that of other food technologies. Data on the area of shrimping grounds for the smaller boats were not available and comparisons between these technologies were therefore not possible (although using an estimate of area per small boat of 1/100th that of the large boat would yield an investment ratio of almost 0.07/1).

When viewed in the context of the maximum emergy principle, these data suggest efficiency is not the primary principle by which selective processes operate to allocate resources, but rather they operate so as to maximize the rate of resource use. In so doing, the larger system (in this case, the economy) maximizes emergy flow. Clearly, the data suggest that the panga is the more efficient fishing boat, but much less "productive" than the shrimp trawler, since a trawler can catch a larger amount of shrimp in a shorter period of time. All other things being equal, and as long as the costs of energy and machinery remain low, trawlers make "good economic sense." On the other hand, good economic sense does not address sustainability or the future availability of energy and machinery. Overfishing, in the long run, may undermine the capacity of the population to regenerate. Without a productive, balanced population, the fishery cannot sustain high catch rates nor support the high economic investments in trawlers that are currently being made. Current costs of energy and machinery and the present abundance of shrimp in the northern Gulf favor energy intensive processes for harvest.



Shrimp Investment - Ratio + $\frac{6.5}{26.5} = 0.25/_1$

Other Investment Ratios

Brazilian Cacao	$17/_1$
USA Ind. Corn	$11/_1$
Texas Agriculture	$5.7/_1$
New Zealand Sheep	$3.7/_1$
Rainforest Pulp Plantation	$0.46/_1$
Rainforest Wood Power Plant	$0.38/_1$
Subsistance Corn	$1.3E-7/_1$

Figure 14. Diagram summarizing the investment ratio for the large boat shrimp fishery in the Sea of Cortez. Data are from Table 7. Investment ratios for other resource extraction and food systems are given for comparison.

Yet, if either of these two factors change (i.e., if energy costs rise or populations decline), the ability of the fishery to sustain high economic investment is diminished. Conditions may then favor the smaller, more efficient pangas; however, in spite of the higher total investment costs for shrimp trawlers, as compared to pangas, the investment ratio (0.25/1) is low compared to other land based food systems (Figure 14). This should not be surprising since land based agriculture requires purchased energy input for cultivation, protection, and harvest while fishing relies on free services and emergy for most population support functions and only requires purchased energy for harvest.

The Sea of Cortez and the Economy of Mexico

The total emergy flow of the present Sea of Cortez from Table 4 is about 7540 E18 sej/year, which is 2% of the Mexican National emergy from Table 1. The total emergy driving primary production in the northern Sea of Cortez during the 1980s is about 6.4 E21 sej, while the total emergy budget for the Mexican economy as a whole was about 34.6 E22 sej (Table 1). Thus primary production in the northern Sea of Cortez represents approximately 1.5% of the national economy. The importance of the Colorado discharge in terms of its values to the overall economy, then, represents about 0.4% of the national economy (20% of 2%). The gross effect of the loss of Colorado River water between the 1920s and 1980s (where the contribution of the discharge in the 1920s would have been approximately 0.8% of today's economy) is a loss of 0.4% of the emergy driving the economy, or a reduction in economic activity of 0.4%. The magnitude of loss when related to the national economy suggests, its importance can (and did) go unnoticed in light of other more significant factors perceived to affect the national economy in a more direct manner.

The importance of primary production in the northern Gulf to the economy of coastal regions of Sonora and the Baja Peninsula is more significant. Comparison among the emergy inflows to the region given in Table 4 shows that of the total emergy inflowing more than 80% is from sources directly related to the northern Gulf. In other words, the emergies associated with the northern Gulf account for more than 80% of the local economy, and, as a result, they are by far the most important constituent of the local economy. While seemingly unimportant to the national economy of Mexico, primary production in the northern Sea of Cortez represents 80% of the resource base of the coastal region of Sonora and the Baja peninsula. Policy decisions and management alternatives that affect the northern Gulf should be concerned with and reflect regional implications first and national concerns only secondarily.

To effectively manage the Sea of Cortez fishery, the trends of primary production are especially important. With increasing pressure to use the Colorado for irrigation, thus lowering discharges and increasing salinities in the Northern Gulf, the impacts on the fishery and consequently on the economy of the Gulf States and, for that matter, the whole of Mexico, are unknown, yet they may be significant.

Local Use of Fisheries Versus Export Sales

The shrimp fishery of the northern Sea of Cortez has been increasingly exploited by a larger and more energy intensive fishing fleet within the last decade, and the local and national economy have been increasingly affected. In the old pattern of resource use, small boats with small nets harvested shrimp for local consumption, while in the modern pattern, large boats and large nets harvest the resource primarily for export. Recently there have been expressions of concern that the growing shrimping fleet of the northern Gulf (see Figure 11) may be overexploiting the resource. Combined with unknown impacts of decreased Colorado River flow, the increasing fleet size may increase the likelihood of a collapse of the fishery.

Generally, as a resource, like the shrimp population in the northern Gulf, is increasingly exploited, local markets are not large enough or developed enough to accommodate the increasing supplies, and thus the price falls. If sales were limited to the local markets, the size of the fleet would rapidly adjust and exploitation would track the ability of the local market to demand (or consume) the resource. However, where large outside markets can be found, demand, can remain high, external prices will be higher than local markets can sustain, and as production is increased to meet the demand a cycle of increasing dependence on external markets is initiated.

Once the external dependence cycle begins, it is difficult if not impossible to break because the local demand of the resource is kept low by the high price buoyed up by the outside markets. The costs associated with exploiting the resource increase as the technology increases and eventually, one can no longer "afford" to sell the resource locally since the local economy cannot support the price that must be demanded.

On the other hand, the local economy is expanded as local people are involved in exploiting, processing, and transporting the product, leading most policy makers to believe that the net effect is positive even though external markets become increasingly influential. The money derived from exports of the resource is used to purchase external goods, services and energy that in turn increase the ability to exploit the resource even further. In the rush to increase the economic cycles of exports and imports, often the local economy suffers as the emergy of the harvested resource contributes less to the home economy than to the economy that imports it.

The increasing externalization of economies throughout the developing world can lead to serious instability in local production and economies, as well as short-run problems for national economies. Throughout Central and South America there is a trend of changing local agricultural production from crops with food value grown for local consumption to "specialty" crops grown exclusively for export to the United States and Europe. The best agricultural lands are given over to these crops, sometimes greatly encouraged by well-intentioned governments, and marginal lands are used for local food production. Monies earned from the sale of exported crops are used to purchase consumer goods and food that are usually not locally produced. Increasingly, fisheries are developed with external investments for the sole purpose of exporting them to help with international balance of payments. The net effect is to drive the price so high that the local population can no longer afford to eat the fish themselves. In many cases, they turn to lower quality sources of protein, or do without altogether.

It is difficult to fully measure the consequences of these trends; however, in recent analysis (Odum, 1984; Odum et al., 1986; Odum et al., 1987) we have suggested that the trading partner receiving raw materials benefits far more than the partner who receives highly refined or manufactured goods. The emergy per dollar spent is much higher for raw materials and resources than for finished goods. Given in Figure 15 is a summary of the benefits to the Mexican economy versus the United States economy that are derived from the sale of shrimp. The top diagram illustrates shrimp caught by small boats and sold in the local economy, while the bottom diagram shows the benefits from shrimp caught using the larger shrimp trawlers and exported to the United States. In both diagrams the amount of money that circulates is $1 and the emergy is taken from Figure 13. The net benefit to the Mexican economy is derived by dividing the emergy received (the flow to the right) in the economy by the emergy invested (the flow to the left).

The greatest net benefit is derived from the sale of shrimp caught by traditional pangas and sold within the Mexican economy. In this case the net benefit to the Mexican economy is about 8.6 to 1. In contrast to this relatively large net benefit, the benefit to the Mexican economy through export of shrimp caught using shrimp trawlers is negative (in other words, more emergy is exported to the United States than is received). This is illustrated in the lower diagram where the trading advantage favors the United States and net benefit to the United States is 1.4 to 1. These net benefits are based on fishing boats and trawlers that are of Mexican origin, so that the benefits derived from sales of shrimp accrued to the Mexican economy. If the fishing trawlers are foreign owned and only pay taxes on tonnage of shrimp or fish caught, the net benefit to the economy is much less. While we did not evaluate this condition, it is relatively easy to visualize that the only benefit to the Mexican economy comes from what emergy might be purchased with the taxes received.

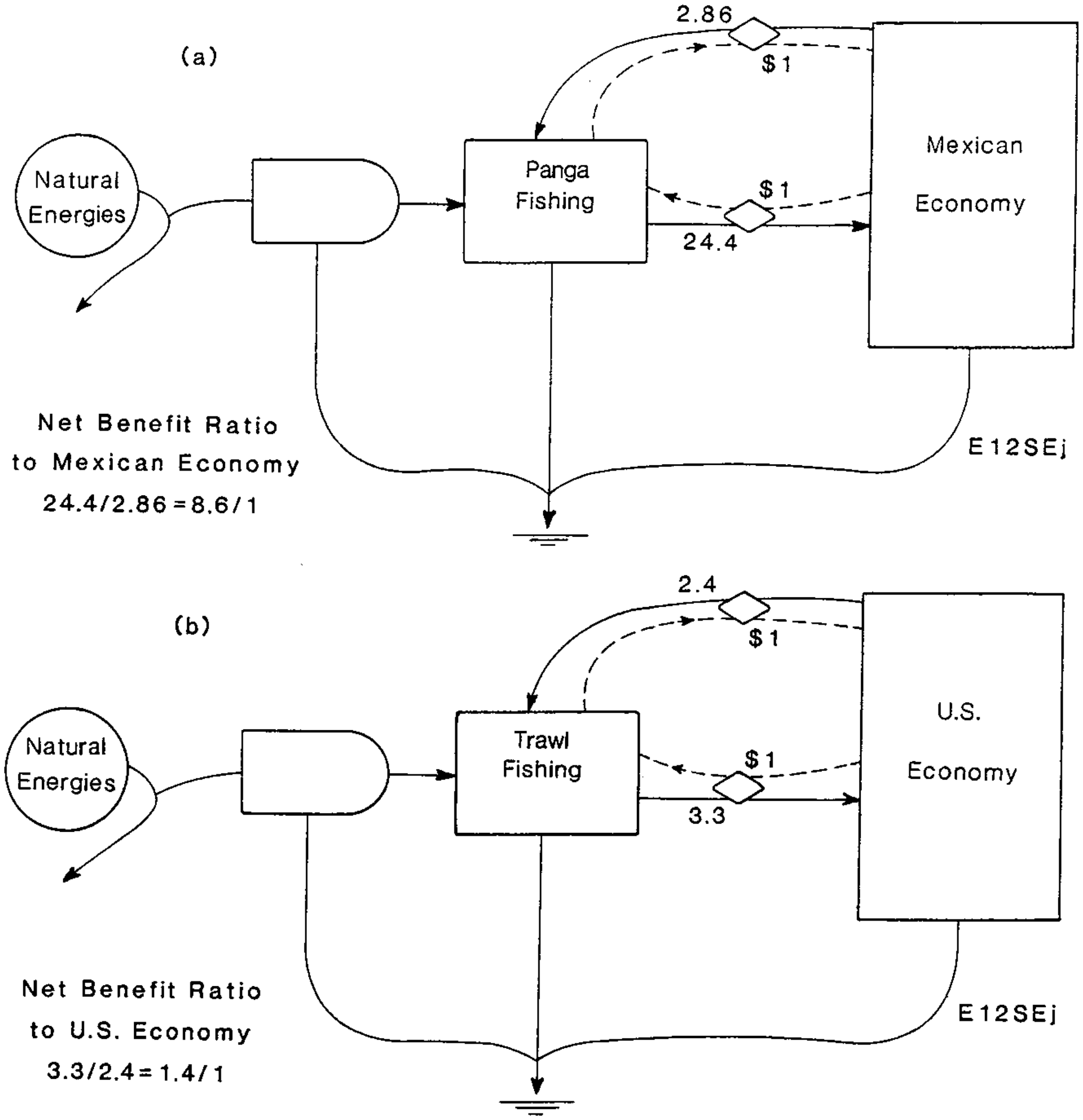


Figure 15. Net benefits resulting from the sale of shrimp, within the Mexican economy (top diagram) and exported sale to the U.S. economy (bottom diagram). The upper diagram (a) illustrates the pangas shrimp fishery and sale within the local economy where feedback is calculated using the Mexican EMERGY/dollar ratio (from Table 1). Export sales of shrimp caught using Mexican shrimp trawlers is illustrated in the lower diagram (b) where feedback is calculated using the EMERGY/dollar ratio of the U.S. economy. Shrimp exported represent a net EMERGY loss to the Mexican economy.

SUMMARY AND RECOMMENDATIONS

Analysis of the resource base of the economy of Mexico (Table 1) suggests that its largest, single, driving energy is fossil fuels, contributing more than 80% of the total emergy driving the economy. Comparison with the evaluation of the resource base of the Sea of Cortez reveals its importance to the economy of Mexico. The driving emergies of the Sea of Cortez represent almost 3% of the total resource base of the economy and more than 14% of the natural resource base. Its importance is reflected in the fact that the upper Sea of Cortez is Mexico's most productive fishery.

During the 1920s the Colorado River discharge alone represented over 8% of the natural resource base of the Mexican economy. Today, since its emergy has been reduced by almost 66%, its contribution to the natural resource base of the economy has diminished to less than 4%. Concern at the national level is certainly warranted in light of the overall contribution the Colorado River makes to the Mexican economy.

Energy analysis overview of the Sea of Cortez suggests that the northern Gulf, while having great buffering capacity against the loss of the Colorado River discharge (because of its large volume and because of the large volume of water exchanged with the lower Gulf and the Pacific), has still lost about 30% of the total emergy driving the system when compared to the total emergy that may have been characteristic during earlier periods of high discharge. The decreased emergy flow is caused more by the loss of chemical potential energy of the freshwater in Colorado River discharge than by the losses of organic matter or nutrients. The single largest emergy inflow to the northern Gulf during the 1920s era of high river discharge was its chemical potential energy. Today, while the chemical potential energy of the river is high, it is exceeded by tidal energy.

Much research is needed to better understand the relationship of the Colorado discharge and continued primary production and fishery production within the northern Gulf. While past measurements have shown very high productivity, little is understood of this relationship. The maintenance of a viable fishery may well depend on how well these relationships are understood so that catches might be limited during times of low flow to ensure that overfishing is minimized.

To determine public policy relative to the Colorado River, detailed emergy analysis of the alternative uses of freshwater for irrigation and for urban uses needs to be related to northern Gulf productivity. Optimum configurations of agricultural, urban, and estuarine uses might be defined to ensure long-term maximum benefits to the economy as a whole. Without question, a better understanding of the relationship of the Colorado River to northern Gulf productivity and the value of river water to such competing uses as agricultural irrigation and urban uses should guide policy in determining its optimum use.

Current governmental policy favors a large mechanized shrimp fishing fleet, which may be the proper posture in light of the relatively low investment ratio compared to other food technologies. Recently there has been much concern over other nations using highly mechanized fishing techniques and competing with the local Mexican fleet. When a fishery is underused, as it might be if only small boats worked the shallow coastal areas, the resource draws investment from outside sources. The best way to protect the fishery is to competitively exclude foreign competition by "intensifying" one's own methods of fishing. Of course, this must be managed so that the more intensive rate of exploitation is sustainable. This rate can only be determined by thorough research on the target species and its supporting ecosystem. In the case of the Sea of Cortez, overdevelopment may drive shrimp populations too low, and combined with an unknown relationship to the discharge of the Colorado River, overexploitation could result. Much caution is warranted.

As we have seen in the economies of other developing nations, as they exploit their resources, their economies become more and more externalized, relying to a larger extent on outside sources of goods and services. This is another way of saying that the world economy is becoming more and more integrated. However, in the rush to develop these resources, their emergy is sold for a nominal price and goods and services bought with the proceeds have a relatively high price. The raw resources that are sold contribute much more to the economy that purchases them than the "home" economy receives with the purchase of finished and highly refined goods. Once the system for exploitation is in place, the overall issue that must be considered is acknowledging the high emergy value of one's resources so as to develop a sustainable balance between export and supporting the growth or sustainability of economies. We believe that the emergy analysis approach presented here may help in achieving such a balance.

APPENDIX

NOTES AND CALCULATIONS FOR TABLES AND FIGURES

FOOTNOTES AND CALCULATIONS TO TABLE 1

1. Rainfall: (0.81 m/y)(1.97 E12 m^2)(1 E6 g/m^3)(5 J/g) = 7.97 E18 J/yr.
2. Tides (Miller, 1980).
3. Waves (Miller, 1980).
4. Oil use, production minus exports:
   [(2.7 - 1.5) E6 bbl/day](365 d/yr)(6.28 E9 J/bbl) = 2.75 E18 J/yr.
5. Natural gas use: production minus export.
6. Imports for 1981 (Brown, 1985). Expressed in U.S. dollars.
7. Exports for 1981 (Brown, 1985). Expressed in U.S. dollars.
8. Export of oil and gas from Mexico (273 E6 cu ft/day)(1.1E6 J/cu ft)(4.8 E4 sej/J)(365 d/y) = 0.53 E22
   (250 E6 bbl/y)(6.3 E9 J/bbl)(5.3 E4 sej/J) = 8.3 E22
   Total oil and gas export: 8.8 E22 sej/y
9. Electric power, coal equivalents: (239 E12 Btu/yr)(1013 J/Btu) = 2.4 E17 J/yr.
10. Total of independent import items 1,2,4,5, and 6.
11. 1982 GDP, $98.6 E9 + $23.1 E9 imports = 121.7 E9 $/yr.

FOOTNOTES TO TABLES 2 THROUGH 5

1. **Sunlight.** Average sunlight over Gulf taken as 170 Kcal/m^2 · yr (Woldt and Jusatz, 1965). Area = 78700 km^2 (Roden 1958).

   Sun energy = 170 Kcal/m^2 . yr * 4.187 E3 J/Kcal * 10 E9 cm^2/km^2
   * 78700 km^2 = 560.14 E18 J/yr.

2. **Rainfall.** Average rainfall over northern Gulf taken as 126 mm/yr (Roden, 1958).

   Velocity = 762 cm/sec (Odum et al. 1983).
   Chemical potential energy: 126 mm/yr * .1 cm/mm * .5 * 1 gm/cm^3
   * $(762\ cm/sec)^2$ * 2.38 E-11 Cal/erg = 87.062 E-6 Kcal/cm^2
   * 4.1867 E3 J/kCal * 78700 km^2 * 1 E9 cm^2/km^2 = 786.86 E12 J/yr.

3. **Tide.** Average tidal height taken as 109 cm over 200 m depth limit (Alvarez-Borrago, 1983).
   Assumed 3/8 of energy absorbed over area of 200 m depth (43700 km^2).

   Tidal energy: 3/8 * 43700 km^2 * .5 x 706 tides/yr * $(109\ cm)^2$
   * $(0.01\ m/cm)^2$ * 1.0253 E3 kg/m^3 * 9.8 m/sec^2
   * $(1000\ m/km)^2$ = 6.9 E16 J/yr.

4. **Wind.** Eddy diffusion coefficient = 8.4 m^2/sec.

   Vertical wind velocity gradient: 4.29 E-3 (m/sec)/m (Odum et al., 1983).
   Wind energy = 1000 m * 1.23 kg/m^3 * 8.4 m^2/sec * 3.154 E7 sec/yr
   * $[4.29\ E\text{-}3\ (m/sec)/m]^2$ * 78700 km^2
   * $(1000\ m/km)^2$ = 4.72 E17 J/yr.

5. **Hurricanes.** Average energy per storm 5 E5 Kcal/m^2 • day (Odum et al., 1983); 3% kinetic energy; 10% dispersed to surface (Odum et al. 1986); residence time/day, 1 in 10 yrs reached 20 N Lat. (Roden 1964); average area of a hurricane = 20,000 km^2 (Odum et al., 1983). Assumed area affected in Sea of Cortez is that of one hurricane diameter.

   Hurricane energy = .1/yr * 1 yr/365 days * 5 E5 Kcal/m^2 • day * .003
   * 20,000 km^2 * 1 E6 m^2/km^2 * 4186.7 J/Kcal = 3.44 E14 J/yr.

6. **Ocean Current.** Net current inflow assumed equal to difference between inflows and volume of water evaporated (2500 mm/yr) (Alvarez-Borrego, 1983).

Footnotes to Tables 2 through 5 (continued).

Colorado River inflow:

(1920s)	18.379 E9 m^3/yr (USGS, 1954);
(1965-1970)	0.115 E9 m^3/yr (USGS, 1976);
(1980-1984)	6.229 E9 m^3/yr (McCleary, 1986).

Runoff excluding Colorado River: 3.9 E9 m^3 yr (Byrne and Emery, 1960);
Rainfall: 9.92 E9 m^3/yr (Roden, 1958);
Evaporation: 2500 mm/yr * 7.87 E10 km^2 * 1 E-3 m/mm
= 196.75 E9 m^3/yr.

Net ocean current inflow:
(1921-1930): 196.75 E9 m^3 - 18.38 E9 m^3 - 3.9 $E9^3$ - 9.9 E9 m^3 = 164 E9 m^3.
(1965-1970): 196.75 E9 m^3 - .115 E9 m^3 - 3.9 E9 m^3 - 9.9 E9 m^3 = 182 E9 m^3.
(1980-1984): 196.75 E9 m^3 - 6.23 E9 m^3 - 3.9 E9 m^3 - 9.9 E9 m^3 = 176 E9 m^3.

Geopotential energy integrated over one year:
(1921-1930): 164 E9 m^3 * 2500 mm * 1 E-3 m/mm * 1/2 * 1027 kg/m^3 * 9.8 m/s^2 = 2.07 E15 J.
(1965-1970): 182 E9 m^3 * 2500 mm * 1 E-3 m/mm * 1/2 * 1027 kg/m^3 * 9.8 m/s^2 = 2.29 E15 J.
(1980-1984): 176 E9 m^3 * 2500 mm * 1 E-3 m/mm * 1/2 * 1027 kg/m^3 * 9.8 m/s^2 = 2.22 E15 J.

7. **River (Chemical Potential.)** Salinity in 1920s taken as approximately 400 mg/L (Applegate, 1986); in 1960s approximately 1000 mg/L (USGS, 1976); in 1980s approximately 800 mg/L (Applegate 1986).

Other runoff: 3.9 E9 m^3 -- assume salinity of 400 mg/L (Byrne and Emery, 1960).

Chemical Potential:
1920s: 18.379 E9 m^3/yr * 8.33 J/mole • 300 K * 1 mole/18 gm
* 1 E6 gm/m^3 * Ln [(1 E6 - 400)/9.65 E5] = 89.89 E15 J/yr.
1960s: .115 E9 m^3/yr * 8.33 J/mole • 300 K * 1 mole/18 gm
* 1 E6 gm/m^3 * Ln [(1 E6 - 1000)/9.65 E5] = .55 E15 J/yr.
1980s: 6.229 E9 m^3/yr * 8.33 J/mole • 300 K * 1 mole/18 gm
* 1 E6 gm/m^3 * Ln [(1 E6 - 800)/9.65 E5] = 30.12 E15 J/yr.

Other Runoff:
3.9 E9 m^3 * 138.83 E6 J/m^3 * Ln [(1 E6 - 400)/9.65 E6] = 19.07 E15 J/yr.

8. **River (Organic Matter).** Sediments are 27% silt and 5% of that is organic (Byrne and Emery, 1960).

Sediment Load (Byrne and Emery, 1960; Fortier, 1928; McCleary, 1986):
1920s: 180 E6 T/yr;
1960s: .007 E6 T/yr;
1980s: .55 E6 T/yr;

Using data from McCleary (1986) for sediment load during 1970-1979, the following relatinship between sediments and discharge was regressed.
Sediments (T/y) = 1.778 E-9 * discharge $(m^3/yr)^{1.54}$.
Sediments from other runoff sources approximately 30 E6 T/yr (Byrne and Emery 1960).

Colorado River Organic Matter:
1920s: 180 E6 T/y * .27 * .05 * 1 E6 gm/T * 5.4 Kcal/gm * 4186.7 J/Kcal = 54.94 E15 J/yr.
1960s: .007 E6 T/y * .27 * .05 * 1 E6 gm/T * 5.4 Kcal/gm * 4186.7 J/Kcal = 2.14 E12 J/yr.
1980s: .55 E6 T/y * .27 * .05 * 1 E6 gm/T * 5.4 Kcal/gm * 4186.7 J/Kcal = 1.67 E14 J/yr.

Other Runoff Organic Matter:
30 E6 T/y * .27 * .05 * 1 E6 gm/T * 5.4 Kcal/gm * 4186.7 J/Kcal = 9.15 E15 J/yr.

9. Primary Productivity (1968).

North Gulf (average December) .572 gm C/m^2 • d (C^{14} method by Zeitzschel, 1969).
South Gulf (average December) .737 gm C/m^2 • d (C^{14} method by Zeitzchel, 1969).
South Gulf (average May) .308 gm C/m^2 • d (C^{14} method by Zeitzchel, 1969).
For southern Gulf, spring productivity is 42% of winter. If same drop is assumed for the northern Gulf, then May productivity is approximately
.42 * .572 gm C/m^2 • d = .24 gm C/m^2 • d.
Average for year = (.572 + .24)/2 gm C/m^2 • d = .41 gm C/m^2 • d.

C^{14} method underestimates gross production (Mann, 1982; Valiela, 1984). Estimates range from 1/5 to 1/15 actual productivity, however, we will be conservative and assume 3 times this productivity:
3 x .41 gm C/m2•d = 1.23 gm C/m^2 • d.
(7.87E 10 m^2)(1.23 gc/m^2/d)(365 d) = 3.53 E13g C/yr.

10. Nutrients Carried by Current.

Phosphate:
Pacific equitorial current: 2.6 μM PO$_4$ (Warsh et al., 1972).
Average Gulf concentration: 1.8 μM PO$_4$ (see Footnotes to Figs. 7-8, No. 3).
2.6 uM * 1 E3 L/m^3 * 1 E-6 mole/umole * 95 gm/mole = 0.25 gm/m^3.
1920s: 0.25 gm/m^3 * 164 E9 m^3/yr = 40.5 E9 gm/yr.
1960s: 0.21 gm/m^3 * 182 E9 m^3/yr = 45.0 E9 gm/yr.
1980s: 0.21 gm/m^3 * 172 E9 m^3/yr = 42.5 E9 gm/yr.

Nitrate: Regression for nitrate μM NO$_3$ = 16.2 μM PO$_4$ - 16.2 μM (Alvarez-Borrego, 1983).
Therefore, 2.6 μM PO$_4$ predicts have 25.9 μM NO$_3$.
Average Gulf concentration: 13 μM NO$_3$ (see Footnotes to Figs. 7-8, No. 4).
25.9 μM * 1 E3 L/m^3 * 1 E-6 mole/mole * 62 gm/mole = 1.61 gm/m^3.
1920s: 1.61 gm/m^3 * 164 E9 m^3/yr = 263.4 E9 gm/yr.
1960s: 1.61 gm/m^3 * 182 E9 m^3/yr = 293.0 E9 gm/yr.
1980s: 1.61 gm/m^3 * 172 E9 m^3/yr = 276.9 E9 gm/yr.

Organic Matter: Approximately 7.1 mg C/L assumed for incoming current. This number is from Mississippi coastal waters where PO$_4$ and NO$_3$ concentrations were comparable to those above (Costanza 1983).
Average Gulf concentration: 1.5 mg C/L (see Footnotes to Figs. 7-8, No. 2).
7.1 gm C/m^2 * 1.72 gm OM/gm C * 6.5 Kcal/gm * 4816.7 J/Kcal = 3.8 E5 J/m^3.
1920s: 1.4 E5 J/m^3 * 164 E9 m^3/yr = 62.7 E15 J/yr.
1960s: 1.4 E5 J/m^3 * 182 E9 m^3/yr = 69.6 E15 J/yr.
1980s: 1.4 E5 J/m^3 * 172 E9 m^3/yr = 65.8 E15 J/yr.

11. Nutrients in Colorado River and Other Runoff.

Colorado River: PO_4 is about .13 mg/L = .13 gm/m^3 (USGS, 1970).
NO_3 is about 1.9 mg/L = 1.9 gm/m^3 (USGS, 1970).

Other Runoff is assumed to be close to these values.

Phosphate:
1920s: .13 gm/m^3 * 18.38 E9 m^3/yr = 2.39 E9 gm/yr.
1960s: .13 gm/m^3 * .115 E9 m^3/yr = 1.5 E7 gm/yr.
1980s: .13 gm/m^3 * 6.23 E9 m^3/yr = 8.1 E8 gm/yr.

Other Runoff: .13 gm/m^3 * 3.9 E9 m^3/yr = 5.1 E8 gm/yr.

Nitrate:
1920s: 1.9 gm/m^3 * 18.38 E9 m^3/yr = 34.9 E9 gm/yr.
1960s: 1.9 gm/m^3 * .115 E9 m^3/yr = 2.19 E8 gm/yr.
1980s: 1.9 gm/m^3 * 6.23 E9 m^3/yr = 11.84 E9 gm/yr.

Other Runoff: 1.9 gm/m^3 * 3.9 E9 m^3/yr = 7.41 E9 gm/yr.

12. Nutrients in Rain.

PO_4 = .06 mg/L (Hendry and Brezonik, 1980; Graham, et al., 1979);
NO_X = .21 mg/L (Hendry and Brezonik, 1980); Chapin and Uttormarsh, 1973);
Org C assumed to be 1 ppm (1 mg/L).

Phosphate: .06 gm/m^3 * 9.92 E9 m^3/yr = 5.95 E8 gm/yr.

Nitrate and Nitrite: .21 gm/m^3 * 9.92 E9 m^3/yr = 2.08 E9 gm/yr.

Organic Matter: 1 gm/m^3 Org C * 1.72 gm OM/gm C * 5.4 Kcal/gm * 4186.7 J/Kcal
* 9.92 E9 m^3/yr = 3.8 E14 J/yr.

13. Seismic Activity (Earthquakes).

Effective Peak Acceleration = .5 * X (force of gravity) (Odum et al., 1983).
Frequency 613.8/100 yrs (Odum et al., 1983).
Fault Length approximatly 530 km (Alvarez-Borrego, 1983).
Fault Width approximately 3 m (Alexander, 1978).
Energy = $k_e A^2 \bullet f$ (k_e = 4168) (Odum et al., 1983).

E_S = 4168 * (.5)^2 * 6.138 * 4186.7 J/Kcal = 2.68 J/m^2 •yr.
2.68 E7 J/m^2•yr * 3 m * 530 km * 1 E3 m/km = 4.26 E13 J/yr.

14. Fuel Use in Coastal Region (based on percent of Mexico's population).

Total population (1983) 75,103,000 (UN, 1985).
Coastal population: Guamos (1969) 60,981; Puerto Penasco (1970) 10,245; estimate for the rest of the northern gulf coastal area 29,000. Total approximately 100,000 (*Webster's Geographical Dictionary,* 1980).

Population increased at a rate of 2.6% per year (UN 1985). This yields an increase of 40% from 1970 to 1983.

100,000 + (.4 * 100,000) = 140,000.
(140,000/75,103,000) * 100% = 0.19% of total population.

<u>Fossil Fuel Use</u> (1983) (UN, 1985);
Coal: 3.346 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 2.02 E14 J/yr.
Oil: 88.270 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 5.33 E15 J/yr.
Gas: 32.914 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 1.99 E15 J/yr.
Wood: 2.525 E6 T coal eq/yr * 3.18 E10 J/T coal eq * 0.0019 = 1.53 E14 J/yr.

15. **Electricity Use** (based on percent of population).
66.954 E9 kWh/yr * 3.6 E6 J/kWh * 0.0019 = 4.58 E14 J/yr.

16. **Goods and Services** (assume fisheries are the major industries).

Mexico's GDP: 1.4274 E11 $US/yr (UN, 1985);
Mexico's fish production: 1.07 E6 T/yr (UN, 1985);
Emergy Dollar Ratio for Mexico: 2.86 E12 sej/$US (Odum 1984);
Transformity for fish: 8 E6 sej/J (Odum 1984);
Fish are .2 dry/wet weight and 5 Kcal/gm (dry) (Parsons et al., 1977; Kemp et al., 1975).
1.4274 E11 $US/yr * 3 E12 sej/$US = 4.28 E23 sej/yr.
1.07 E12 gm/yr * .2 dry/wet * 5 Kcal/gm (dry) * 4186.7 J/Kcal
* 8 E6 sej/J = 3.58 E22 sej/yr.

Fishing is (3.58 E22/4.14 E23) * 100% = 8.7% of Mexico's economy.
Assume 1/4 of this is from Sea of Cortez.

17. **Total Emergy Imput** is sum of emergy of rain, tide, ocean currents, river inflow, other runoff: seismic activity, fossil fuels, and goods and services. Other emergies shown in the table are not added to minimize double counting.

FOOTNOTES TO TABLE 6

General Note: All data were provided by Delegacion Federal de Pesca En Sonora, Departamento de Flota E Industria, Guaymas Sonora, Mexico. From data collected during the month of July, 1986, and for the 1984-1985 shrimping year.

1. Fuel use = 1,200 l/day. Total days calculated as 160 days/yr by dividing total working days (55006) by number of boats (343) in the shrimping fleet.
   Energy in Fuel = 1200 l/day * 160 days * 3.75 E7 J/l = 7.2 E12 Joules.

2. Miscellaneous Goods and Services = 7.4 E6 pesos/boat/month of operation, about 83% of which is fuel costs.
   Misc. costs = 7.4 E6 peso * 5.33 mo = (3.95 E7 peso)/(600 peso/$) = $6.6 E4/yr.

3. Salary = 1.12 E6 peso/ton of catch. Average catch per boat is 8.95 tons per season (see footnote 6).
   Total Salary = 1.12 E6 peso/ton * 8.95 tons/yr = (1.0 E7 peso)/(600 peso/$) = $1.7 E4.

4. Boat Replacement. Boat costs 98 E6 peso (1985) and has an expected life of 20 years, and is used 1/2 of the fishing year for shrimp.
   Boat Replacement = (98 E6 peso * 0.5)/20 yrs = (2.5 E6 peso)/(600 peso/$) = $4.1 E3/yr.

5. Engine Replacement. Engine costs 20 E6 peso (1985) and has an expected life of 4 years and is used 1/2 of the fishing year for shrimp.
   Eng. Replacement = (20 E6 peso * 0.5)/4 yrs = (2.5 E6 peso/yr)/(600 peso/$) = $4.1 E3/yr.

6. Shrimp harvest. From data collected by Delegacion Federal de Pesca En Sonora, Departamento de Flota E Industria, Guaymas Sonora, Mexico, for the year 1984-1985. Total shrimp catch = 3.07 E6 Kg. Total number of boats = 343. (Dry weight is 20% of wet weight.)
   *Average catch/boat = (3.07 E6 Kg)/343 = 9.0 E3 kg wet wt/boat.
   Energy in shrimp = 9.0 E6 g * 0.2 * 5 cal/g * 4186 J/Cal = 3.8 E10 J/yr.

FOOTNOTES TO TABLE 7

General Note: Data from interview of Pangas Fishermen, July 1986. Generally the shrimp season is 3 months (Sept., Oct., & Nov.). During this time they fish approximately 70 days, harvesting an average of 60 Kg/day of shrimp.

1. Fuel use estimated as 25 l/day on a slow day, and 90 l/day on a good day. Assume average of 40 l/day.
   90 days * 40 l/day * 3.75 E7 J/l = 1.35 E11 J/season.

2. Miscellaneous Goods and Services is the dollar costs of fuel, net, and incidental expenses. Incidental expenses were calculated as difference between boat and motor replacement costs and money allocated to boat (see footnotes 3, 4, and 5). Dollar costs of fuel were as follows:
   Fuel = 3600 l/yr * $0.155/l = $558.

   Dollar costs of net were calculated using cost of net and useful life as follows:
   Net = 250,000 peso/2 yrs = (125,000 peso)/(600 peso/$) = $208.

   Incidental expenses are difference between boat allocation (.33 of $4.2 E3 = $1400) and fuel and net costs, and boat and engine costs as follows:
   Incidental expenses = $1200 - (698 + 208) - (50 + 271) = $113.

3. Salary is equal to 2/3 of total value of catch. Total value is distributed as follows: 1/3 to boat, 1/3 to Owner, and 1/3 to helper(s).
   Total catch value = 3.6 E3 Kg * 600 peso/Kg
   = (2.16 E6 peso)/(600 peso/$) = $3.6 E3/season.
   Salary = $3.6 E3 * 0.667 = $2,400.00.

4. Boat replacement costs were estimated using a new boat cost of 600,000 pesos, an average life span of 5 years and 25% of use per year for shrimp season.
   Boat replacement = 600,000 peso/5 yrs * 0.25 = (3 E4 peso/yr)/(600 peso/$) = $50/season.

5. Engine replacement costs were estimated using new engine costs of 1.3 E6 peso, 2 year life span and 25% of use per year for the shrimp season.
   Engine replacement = 1.3 E6 peso/2 yrs * 0.25 = (1.625 E5 peso)/(600 peso/$) = $271.

6. Average catch is 30 Kg/day wet weight during season, assume dry weight is 20% of wet weight.
   Energy in shrimp = 30 Kg/day * 0.2 * 90 days * 5 Cal/g * 4186 J/Cal * 1 E3 g/Kg = 1.1 E10 J.

FOOTNOTES FOR FIGURES 7 AND 8

Storages and Gross Flows:

1. **Volume of Sea of Cortez** (average depth approximately 450 m [Roden, 1958]).
78700 km^2 * .45 km * (1 E9 m^3)/km^3 = 3.54 E13 m^3.

Tidal prism exchange: 109 cm * 78700 km^2 * 1 E-2 m/cm * 1 E6 m^2/km^2
* .5 * 706 tides/yr = 30.300 E9 m^3/yr.

Evaporation: 2.5 m/yr * 7.87 E10 m^2 = 196.75 E9 m^3/yr

Net tidal prism exchange is excess of evaporation, 197 E9 m^3/yr minus inflows (river, 18.4 E9; rain 10 E9; other inflow, 3.9 E9) m^3/yr = 164.7E 9 m^3/yr.

2. **Organic Matter** (average concentration 1.5 gm C/m^3 [Mann, 1982]).

Storage: 1.5 gm C/m^2 * 1.724 gm OM/gm C * 3.54 E13 m^3 = 9.15 E13.

River (1920s; see Footnotes to Tables 2-5, No. 8):
180 E6 T/yr * .27 * .05 * 1 E6 gm/T = 2430 E9 gm/yr.

Other runoff (1920s; see Footnotes to Tables 2-5, No. 8):
30 E6 T/yr * .27 * .05 * 1 E6 gm/T = 405 E9 gm/yr.

Rain (1920s; see Footnotes to Tables 2-5, No. 12):
1.0 gm/m^3 * 1.72 g OM/gm C * 9.92 E9 m^3/yr = 17 E9 gm/yr.

Net tidal inflow (1920s; see Footnotes to Tables 2-5, No. 10):
1.5 gm C/m^3 * 1.72 g OM/gm C * 164.7 E9 m^3/yr = 425 E9 g/yr.

Tidal exchange: (30,300 E9 m^3/yr * 1.5 gC/m^3 * 1.72 gO.M./gC = 78,174 E9 g/yr.

Inflow = 425 E9 g/yr + 78,174 g/y = 78,599 g/yr

Outflow = concentration * volume of water
1.5 gC/m^3 * 1.72 gO.M./gC * 30,300 E9 m^3/y = 78,174

Production: (see footnotes to Tables 2-5, No.9).
7.87 E10 m2 * 1.23 gC/m2/d. * 365 d. * 1.72g O.M./gC = 60,772 E9 gO.M./yr.

Consumption: assume equal to production.

3. **Phosphorus** (average concentration approximately 1.8 μM [Alvarez-Borrego, 1983]).
1.8 μM * (1 E3 L)/m^3 * (1 E-6 mole)/μMole * 95 gm/mole = .17 gm/m^3.

Storage: .17 gm/m^3 * 3.54 E13 m^3 = 6.0 E12 gm.

River (1920s; see Footnotes to Tables 2-5, No. 11): 2.4 E9 gm/yr.

3. **Phosphorus** continued.

Other Runoff (1920s; see Footnotes to Tables 2-5, No. 11): 5.1 E8 gm/yr.

Rain (1920s; see Footnotes to Tables 2-5, No. 12): 5.95 E8 gm/yr.

Tidal prism exchange:

Inflow = volume of water * integrated concentration of PO_4 in flowing water (1.8 μM)
30,464 E9 m^3/yr. * 1.8 μM * 1E3 L/m^3 * 1E-6 Mole/μMole * 95 gm/Mole
= 5209 E9 gm/yr.

Outflow = volume of water * concentration of PO_4
30,300 E9 m^3/y * 1.8 μM * 1E3 L/m^3 * 1E-6 Mole/μMole * 95 gm/Mole
= 5181 E9 gm/yr.

Sedimentation: assume 1% of $CaCO_3$ deposition rate (1.5 gm/cm^2 per 10^3 years; Broecker and Peng, 1987).
1.5 gm/cm^2 * 1E4 cm^2/m^2 * 7.87 E10 m^2 * 1E-3 yrs. * 0.01
= 11.8 E9 gmP./yr.

Production: assume 1% of organic matter production
60,772 E9 gm O.M./yr * 0.01 = 608 gm P/yr.

Consumption: assume equal production

4. **Nitrate** (Alvarez-Borrego, 1983).

13 μM NO_3 * (1 E3 L)/m^3 * (1 E-6 mole)/μmole * 62 gm/mole = .81 gm/m^3.

Storage: 0.81 gm/m^3 * 3.54 E13 m^3 = 2.87 E13 gm.

River (1920s; see Footnotes to Tables 2-5, No. 11): 34.9 E9 gm/yr.

Other Runoff (1920s; see Footnotes to Tables 2-5, No. 11): 7.41 E9 gm/yr.

Rain (1920s; see Footnotes to Tables 2-5, No. 12): 2.08 E9 gm/yr.

Tidal prism exchange:

Inflow = volume of water * concentration of NO_3 in inflowing water (13 μM).
30,464 E9 m^3/yr * 0.81 gm/m^3 = 24,675 E9 gm/yr.

Outflow = volume of water * concentration.
30,300 E9 m^3/yr * 0.81 gm/m^3 = 24,543 E9 gm/yr.

Production: assume 10% of organic matter production
60,772 E9 gm O.M./y * 0.10 = 6077 gm NO_3/yr.

Consumption: assume equal to production.

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