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ECONOMIC IMPACTS BROUGHT ABOUT BY ALTERATIONS TO FRESHWATER FLOW

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In order to formulate quantitative guidelines and policy for the management of water, a measure of environmental and human services on a common basis (the *emdollar*) is used to select alternatives that maximize the combined and symbiotic economy of humanity and nature. In this paper, water and some alternative systems of use and management are evaluated as assigned by conference organizers.¹ For definitions and methods, see the Appendix to this paper.

In this procedure, we accept the concept (defended elsewhere) that all aspects of a system of many scales, with and without people, self-organize to sustain the highest EMERGY production and use (highest emdollars). Therefore, selecting the highest emdollar value provides a scientific basis for sustainable public policy decisions (sustainable because they compete). Based on previous emdollar evaluations of the Mississippi River,² economic values are assembled for water management alternatives.

Gibbons (1986) provided a convenient review of economic (microeconomic, market) values of water; Appendix Table A2 compares economic market values of water with emdollars, which are usually much higher. (Market dollars represent what is paid for the human service part of processing water; emdollars represent both the environmental and the human service part).

Water is a main way in which the geobiosphere self-organizes the whole landscape for maximum function. For example, the geopotential of elevated rainwaters after contouring the land is used to distribute the chemical potential energy of fresh water to interact with sunlight, soils, and nutrients in the biological production of the land, wetlands, and estuaries. We should not make the error of managing water to maximize water value alone, when the correct principle is to manage water to maximize the landscape's total contribution. (Recall the error of destroying social organization of cities by maximizing the traffic for its own sake).

Public policy is made with a large-scale view of rivers, estuaries, human settlements, agriculture, forestry, and other elements of the environment. Evaluating alternatives on this scale with a scientific procedure requires that the main components and alternative uses be defined first. One way is to make an energy system diagram of components and their relationships. Such a diagram has symbols arranged from left to right according to their unit value (see *transformity* in Appendix). Then, an emdollar evaluation table is prepared for that diagram and for the different arrangements for alternative water management. Table 1 summarizes evaluation tables for the Mississippi River showing the contributions of different aspects of the system. Unfortunately, in the rush to add navigation values, other values such as the wetlands and their role in the use of sediment, productivity, and filtration were reduced.

Maximum value comes from retaining as much as possible of the original values of the undeveloped system while using economic or public investment to bring in additional resources on a matching basis. In the United States, on the average, each emdollar of natural contribution attracts 7 emdollars (Em\$) of matching value. The ratio of attracted value (emdollars purchased outside) to environmental free emdollars is the *EMERGY investment ratio* (see Appendix). Notice that in the evaluation process there are two values for the water and the resources with which it interacts: (1) contribution alone and (2) attracted matching contribution. Table 1 shows both values as observed several years ago.

Figure 1 summarizes the predevelopment values, the developed situation, and two measures of potential development. In one, the observed emdollar investment was matched with environmental use on a 1:7 basis. In the second, the original environmental values were matched on a 7:1 basis, showing the much greater economic development that is possible in the Mississippi River if the multiple uses can be made compatible, especially restoring wetland contributions and retaining more of the river within the economy (instead of jetting into the Gulf of Mexico).

The water and sediments going into the Gulf do contribute emdollars to that system, but there they apparently do not get the manifold matching that generates high economic value. Those with estuaries and wetlands accustomed to receiving fresh water and freshwater pulses (high EMERGY) lose value if they are stopped upstream. Elsewhere, estuaries adapted to little freshwater inflow are stressed at first when more is added, but eventually

reorganize to generate useful contributions. In general, the use on land or in well-used estuaries is a higher emdollar generator than release to the open sea. If unnecessary storage of water in open reservoirs causes water evaporative losses, economic values may be less. Diverting geopotential from its role in spreading chemical potential may reduce other economic potentials.

There are special values of pulses that have high unit value (high transformity). Annual pulses contribute to adapted systems such as estuarine oyster reefs by focusing resources into emdollars. Infrequent, intensive pulses such as floods and hurricanes are catastrophic to the smaller-scale parts of a system, while contributing large emdollars to the larger-scale Earth systems to which the human economy is still learning how to adapt (to use for economic value).

In Table 2, emdollar values of various alternatives for water use are compared on a cubic meter and hectare basis as guidelines for public policy thinking about water management and the coastal zone. Figure 2 shows the main water interactions and uses in a coastal zone.

TABLE 1 EMERGY Values in the Mississippi River System^a

Item	Solar Empower (E22 sej/yr)	Em\$/yr (E9 1991\$) ^b
Original rivers		
Chemical potential of fresh water	11.5	81.5
Geopotential of river	10.0	70.9
Water used by the original floodplain	7.9	56.0
Modified river in 1986		
Water used by developed and drained floodplain	3.0	21.2
Sediments carried	230.	1,631.
Sediments discharged to Gulf of Mexico	127.	900.
Fisheries production	0.99	7.0
Loss of coastal land	1.4	9.9
River energy used by barges ^c	0.43	3.
Purchased inputs for economic use		
In agriculture, forestry, crayfish culture	0.86	6.1
In river transportation ^d	0.96	6.8
(If railroad substituted for river transport)	(4.61)	(32.7)
In oil and gas production	5.2	36.8
In urban economy	8.2	58.2
Oil and gas production for use elsewhere	55.2	391.5

NOTE: sej = solar emjoules; Em\$ = emdollars

^aOdum et al (1987a) represent an update and elaboration of earlier studies (Young et al., 1974; Bayley et al., 1977; and Zuchetto et al., 1980).

^bSolar empower divided by 1.41 E12 sej/1991 U.S. em\$.

^cIf fraction of river required per vessel considering turbulent eddies is 100 times vessel displacement.

^dIncludes fuel use, shipping goods and services, operation of locks.

SOURCES: Condensed from Diamond (1984) and Odum et al. (1987a)

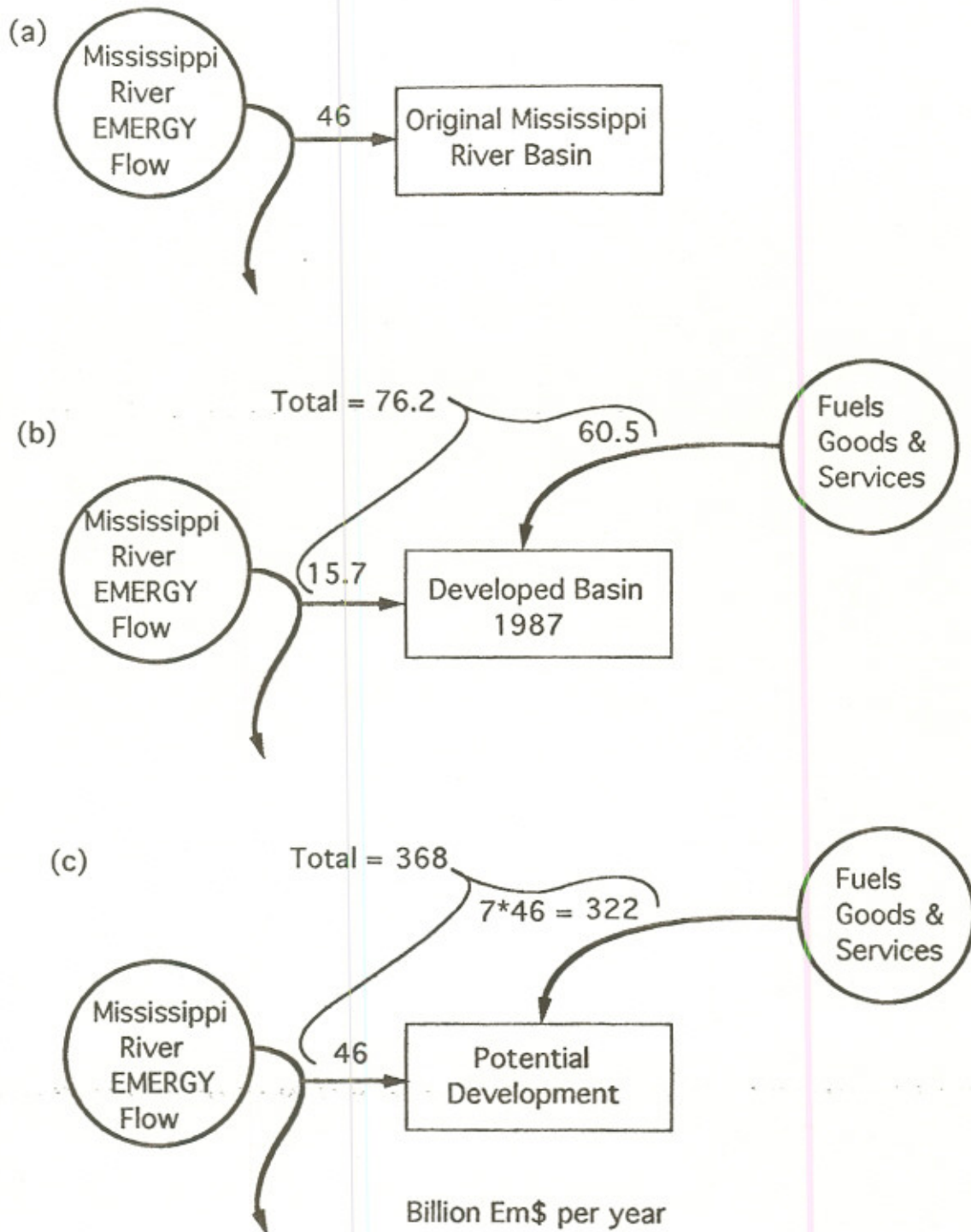
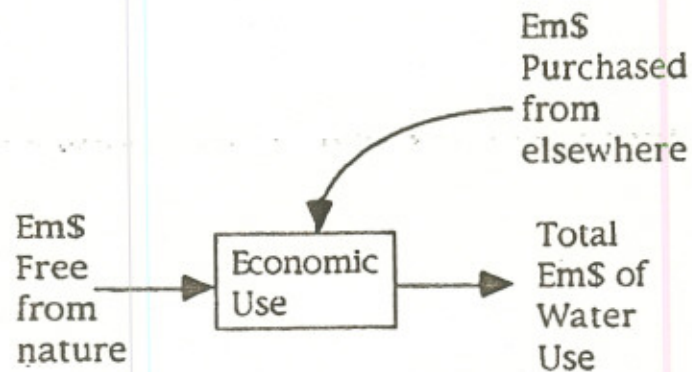


FIGURE 1 EMERGY flows for alternative development of the Mississippi River Basin (Odum et al., 1987a). (a) Pre-development; (b) developed basin; (c) potential development.

TABLE 2 Typical Emdollar Values of Freshwater Use

Item	Em\$/m ³	EM\$/ha/yr
1 Rain, 1.5 m/yr	0.04	675
2 Rain plus 7:1 economic matching in the United States	0.28	5,400
3 Irrigation with 1-m/yr river water	0.12	1,200
4 Irrigation plus 7:1 economic matching	0.84	9,600
5 Florida tidal salt march	0.08	590
6 Salt marsh plus 7:1 economic matching	0.56	4,720
7 Urban use, San Juan, Puerto Rico, 2E4 ha	0.12	3,250
8 Urban use plus 45:1 economic matching, Puerto Rico	5.4	146,240

NOTE: ha = hectare; for each pair of items above, the first lists emdollar values of the water as contributed from nature (chemical potential energy of fresh water) before use. The second item in each pair includes the water value plus the emdollar value of purchased products and services that interact in that process, as shown in the following diagram:



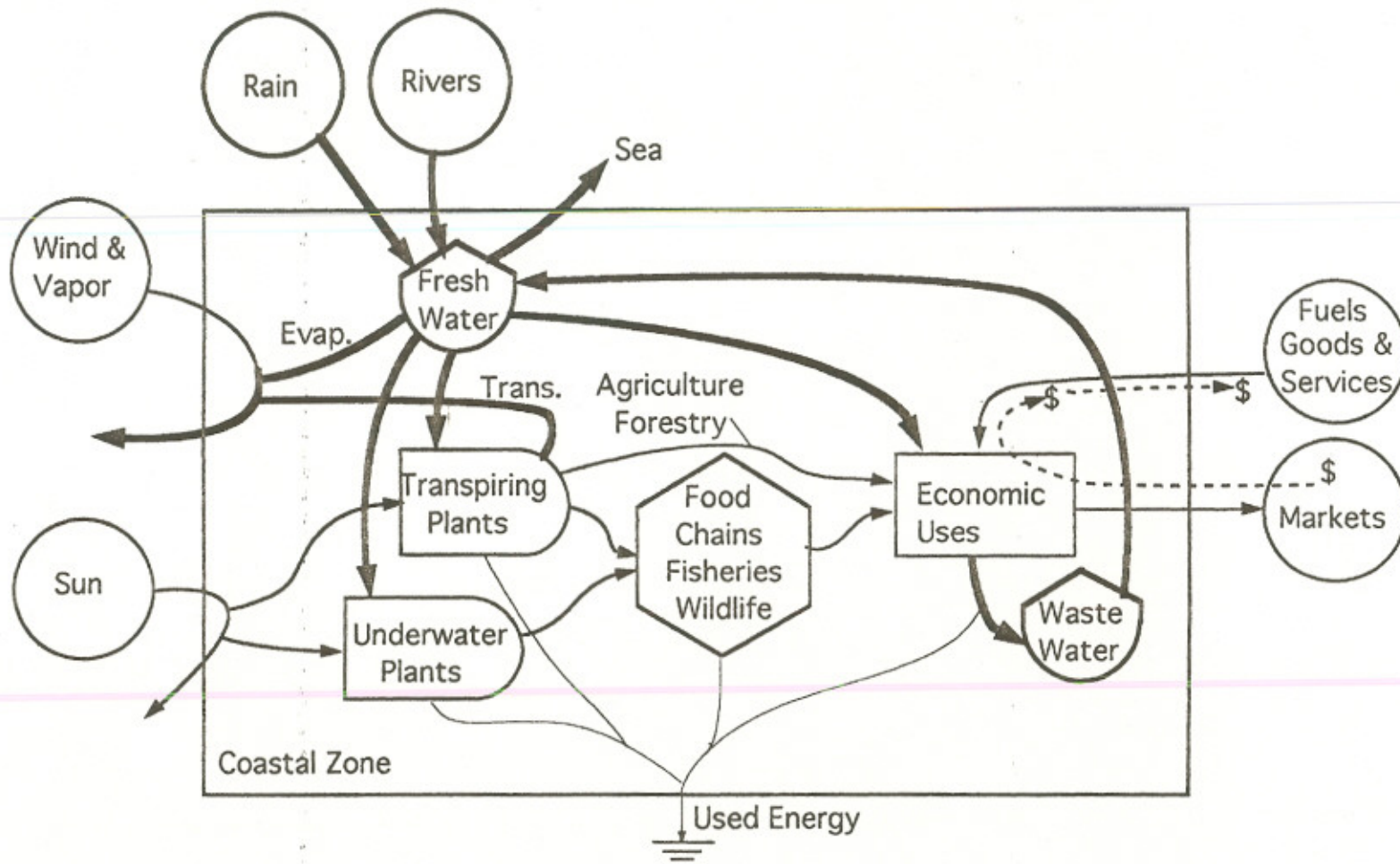


FIGURE 2 Freshwater use in a coastal system. Flows of water are emphasized as wide, black pathways.

References

- Bayley, S., and R. Walker. 1976. *Energy Methodologies for Assessing the Regional Role of Transportation Systems and for Evaluating Environmental Economic Tradeoffs*. CFW-76-40. Final Report to the Florida Department of Transportation Research. Department of Environmental Engineering and Science, University of Florida, Gainesville.
- Bayley, S., J. Zuchetto, L. Shapiro, D. Mau, and J. Nessel. 1977. *Energetics and Systems Modeling: A Framework Study for Energy Evaluation of Alternative Transportation Modes*. Final Report to U.S. Army Engineer Institute for Water Resources, Fort Belvoir, Virginia. IWR Contract Report 77-6 and 77-10.
- Diamond, C. 1984. Energy basis for the regional organization of the Mississippi River Basin. M.S. thesis, Environmental Engineering Sciences, University of Florida, Gainesville.
- Ewel, K.C., and H.T. Odum (eds.). 1985. *Cypress Swamps*. University of Florida Press, Gainesville.
- Gibbons, D.C. 1986. *The Economic Value of Water*. Resources for the Future, Washington, D.C.
- Odum, H.T. 1985. Water conservation and wetland values. Pp. 98-111 in P.J. Godfrey, E.R. Kaynor, S. Pelezrski, and J. Benforado (eds.), *Ecological Considerations in Wetlands Treatment of Municipal Wastewaters*. Van Nostrand Reinhold, New York.
- Odum, H.T. 1995. *Environmental Accounting, Energy and Decision Making*. John Wiley, New York. In press.
- Odum, H.T., M.T. Brown, and R.A. Christianson. 1986. *Energy Systems Overview of the Amazon Basin*. Center for Wetlands Publication 86-1, University of Florida, Gainesville.
- Odum, H.T., C. Diamond, and M.T. Brown. 1987a. *Energy Analysis Overview of the Mississippi River System*. Report to the Cousteau Foundation, Center for Wetlands Publication #87-1, University of Florida, Gainesville.
- Odum, H.T., E.C. Odum, and M. Blissett (eds.). 1987b. *Ecology and Economy: EMERGY Analysis and Public Policy in Texas*. LBJ School of Public Affairs and Texas Department of Agriculture, Policy Research Publication #78, University of Texas, Austin.

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- Young, D., H.T. Odum, J. Day, and T. Butler. 1974. *Evaluation of Regional Models for Alternatives in Management of the Atchafalaya Basin*. Report to U.S. Department of the Interior, Bureau of Sport Fisheries and Wildlife, Washington, D.C.
- Zuchetto, J., S. Bayley, L. Shapiro, D. Mau, and J. Nessel. 1980. The direct and indirect energy costs of coal transport by alternative bulk commodity modes. *Resource Recovery and Conservation* 5:161-177.

Appendix - Definitions, Methods, and Emdollar Evaluation

In this Appendix, EMERGY, transformity, and emdollars are defined and the methods for evaluating environmental alternatives are introduced using fresh water as an example. Although water and the systems in which it is used constitute the subject here, the methodology is general for all resources and environmental alternatives. The circulation of water in the geobiosphere, including human urban society, involves a series of steps that start with the sunlight and geological inputs to the ocean, simplified in Figure A1. For each step in the diagram from left to right, water is more concentrated. At each step, some of the water circulates back to the right. Thus, there is less water but at higher quality in the sense of having more unit effect. Notice that money circulates to purchase water only in the upper levels to the right. These stages in the processing of water go through several scales of Figure A1.

Figure A2 shows the interface between free environmental contributed work and the economy, where money circulates only among people. The money paid for humans to process the water is only a small part of the work of Figure A2 in generating fresh water to the land. Neither monetary cost nor price is a measure of environmental contribution. The two are often inversely related: when water is abundant, costs and prices are low, but everyone has a high standard of living with respect to water. When water is scarce, procurement costs and prices are high and scarce water contributes less to producing real wealth and thus economic prosperity.

- Market values cannot be used to evaluate the contribution of water (or any other environmental product) to the economy.

However, the contribution of water to the economy can be expressed as the *proportion* of the real wealth that water contributes in the process of being used. For example, 9 percent of the total annual EMERGY use by the state of Florida is from freshwater inflows.

Thus, it is inferred that 9 percent of the buying power of the gross economic product of Florida is due to the real wealth of water contributing directly and indirectly. The contributions of real wealth to the gross economic product may be expressed as emdollars. These are calculated from the EMERGY values:

- The emdollar (Em\$) value of something is the proportion of the gross economic product according to its proportion of the economy's total EMERGY budget.
- EMERGY is the sum of all the inputs of energy of various kinds, each expressed in units of one kind of available energy required.

Available energy of one form consumed to produce another is defined as the EMERGY (spelled with an "m") of the product. Its unit is the emjoule. (Energy of different kinds cannot be used without transformation to evaluate economic contributions.³) The annual solar EMERGY budget of Earth is 9.44 E24 solar emjoules per year including the direct sunlight, the concentrated heat from the interior of Earth driving geologic aspects, and the tides.

Transformity a Measure of Unit Value. Energy of some kind is found in everything, including information. Each kind of energy can be arranged in a series according to the amounts of one kind of energy required for another, thus forming a universal energy hierarchy. Position in this series is indicated by the transformity. The realms of water circulating in the geobiosphere and the human economy involve several scales of size and time (Figure A1). Transformities increase with scale because larger realms include more of Earth's EMERGY flows.

- *Transformity* is the available energy of one kind that has to be transformed to make one energy unit of the next higher form. See for example, the transformity of rain over land (Figure A1b).

For other examples, there are about 40,000 solar emjoules per joule of coal and about 174,000 solar emjoules per joule of electric power. Salmon, electric power, and hydrogen gas have similar transformities.

Water in its geobiospheric cycle increases its transformity (to the right in Figure A1) as successive processes bring vapor out of the ocean—by wind to continents, through rain to the land, through stream convergence to larger rivers, and into snow storage and/or glacial flows. Appropriate water uses depend on the transformity of the water and its uses. Examples of transformity of water are given in Table A1.

EMERGY Investment Matching. In any region, an economic proposition should be competitive that has as much free environmental resource contribution (such as water) as the regional average. In the United States as a whole, this is 7:1 in EMERGY units. In one sense the dollars attracted are seven times the free emdollars. In Table A2, there are three dollar values, first the market value (to the left), next the emdollar value contributed by nature, and third (to the right) the market values that can be attracted if the economic development is of average intensity for the region. To be competitive with less developed overseas economies (lower EMERGY investment ratio), less intensive EMERGY investment matching may be required.

Exergy. Sum of available energy, not a correct way to relate energies of different kinds.

Notes

1. Assigned content: "Discuss the dollar amounts generated or lost shielding certain areas from the regular flooding versus the more severe but more irregular floods such as experienced by the Upper Mississippi River Watershed in 1993. Types and estimates of losses due to impoundments should be discussed. Estimates of gains due to new or expanded opportunities such as river transportation, shipping, and environmental quality should also be included."
2. Previous water evaluations. Economic market values of water were summarized by Gibbons (1986). Research embodying evaluations of water's contribution to the economy in emdollars developed over a period of 25 years with the definition of EMERGY spelled with an "m" and emdollars after 1983 (examples: Odum, 1985; Odum et al., 1986, 1987b). Several emdollar evaluations using what is now called EMERGY were made of Mississippi River alternatives starting in 1974 (Young et al., 1974; Bayley and Walker, 1976; Diamond, 1984; Odum et al., 1987a). The author's book summarizing two decades of environmental accounting with EMERGY and emdollar values is in press.
3. Incorrect use of available energy alone. Energy, without converting each kind to one kind, cannot be used to evaluate all the different kinds of inputs because energies of different types contribute differently to the work of producing real wealth. For example, sunlight is abundant, but with little work per calorie. Human energies in calories are low, but contribute high-quality work. Fuels are intermediate. Degraded heat (no availability because there are no temperature differences) contributes none. However, energy of different kinds can be arranged in order of the amounts of one kind required to produce the next. Table A2 has the energy of one kind of water required for waters as they are successively transformed.

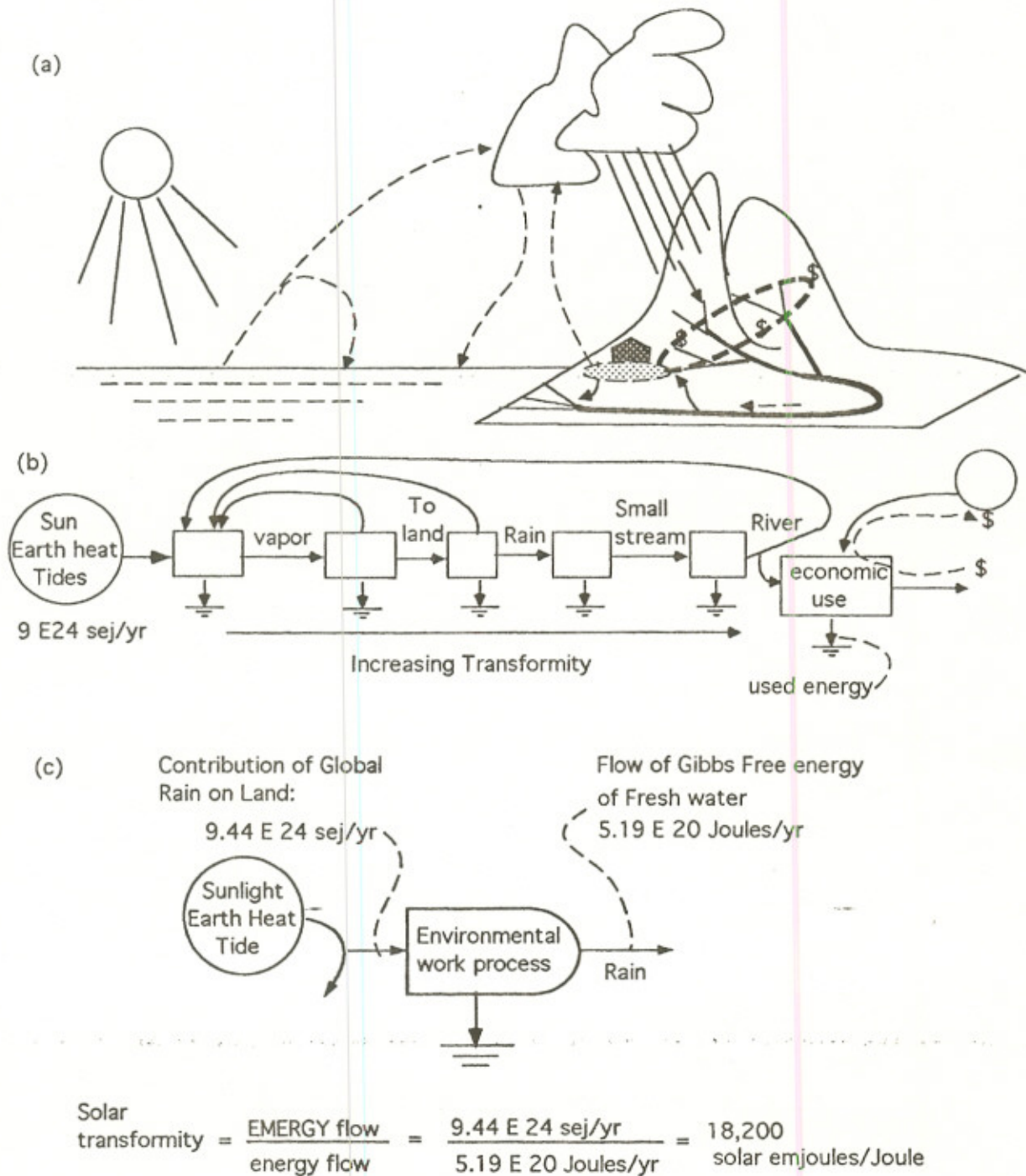


FIGURE A1. Hydrologic cycle and the energy transformation hierarchy (a) sketch; (b) energy systems diagram; (c) sample calculation of transformity.

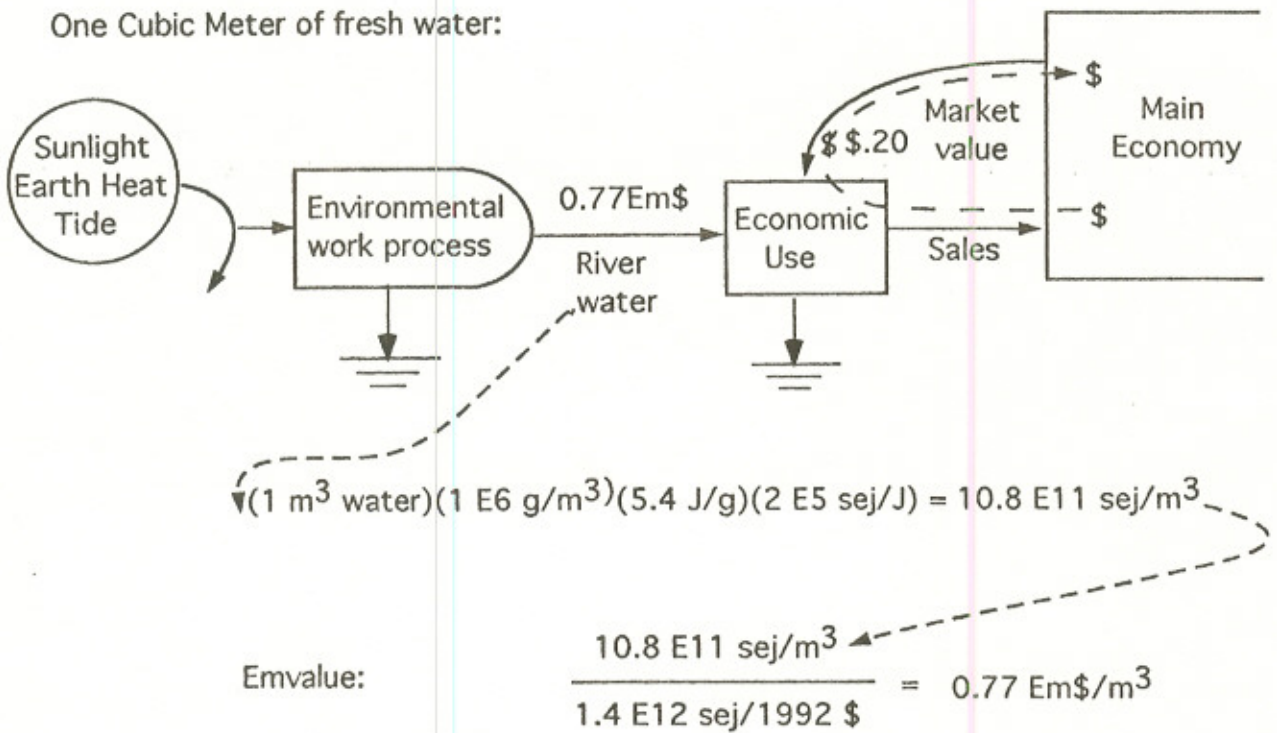


FIGURE A2 Energy diagram of the environmental-economic interface comparing market value and emvalue.

TABLE A1 Transformities of Waters

Items	Transformity (E4 sej/joule)	Emdollars (1985 Em\$/m ³)
Chemical potential energy in world cycle ^a		
Rain over the land	1.81	0.045
River waters, 150 ppm salts	4.84	0.12
Chemical energy of water processing in Texas (Odum et al., 1987) ^a		
Rain on plains	1.8	0.045
Runoff	4.7	0.118
Recharge of groundwater	12.7	0.32
Irrigation pumping (\$0.04 cost)	27.0	0.68
Urban distribution (\$0.79 cost)	76.6	1.92
Chemical energy in water flow through Florida wetlands (Ewel and Odum, 1984) ^a		
Rain over the land	1.81	0.045
Upland runoff	7.11	0.17
Headwater bayhead	9.4	0.22
Dwarf cypress	11.6	0.29
Cypress pond	13.4	0.33
Cypress strand	13.5	0.34
Floodplain	13.7	0.34
Geopotential energy in world cycle ^b		
Rain, mean elevation 875 m	1.05	0.09
Rivers, 875 m	2.78	0.12
Geopotential Energy in Mississippi River (Diamond, 1984)		
Rain over land	1.0	0.050
1st order streams	2.0	0.070
2nd order streams	2.5	0.076
3rd order streams	3.0	0.094
4th order streams	5.0	0.060
5th order streams	19.0	0.058
6th order streams	80.0	0.049

^a(1 m³ water)(1 E6 g/m³)(5 J Gibbs free energy/g) = 5 E6 J/m³; (5 E6 J/m³) times (solar transformity in column 2) divided by EMERGY-money ratio for United States in 1985, 2.0 E12 solar emjoules per dollar of Gross National Product (GNP).

^b(1 m³ water)(1,000 kg/m³)(9.8 m/s²)(875 m) = 8.6 E6 J/m³; (8.6 E6 J/m³) times (solar transformity in column 2) divided by EMERGY/money ratio for the United States in 1985, 2.0 E12 solar emjoules per dollar GNP.

TABLE A2 Economic and Emdollar Values of Water Per Cubic Meter

Note	Category	Economic ^a	Emdollars ^b	Attracted ^c
1	Irrigation	1 to 0.31	0.44	3.0
2	Municipalities	0.1 to 0.46	1.48	4.4
3	Industry	0.005 to 0.031	0.34	2.4
4	Waste assimilation	0.0001 to 0.005	0.19	1.3
5	Recreation, aesthetics	0.004 to 0.013	0.28	2.0
6	Navigation	0.0008 to 0.22	0.077	0.54
7	Hydropower	0.0016 to 0.026	0.007	0.05

^aFrom Gibbons (1986)

^b1983 U.S. dollars evaluated by dividing EMERGY value by EMERGY-money ratio for 1983. Examples from Odum (1995).

^cEmdollar value times 7, representing the matching of water input with fuel-based input from the main economy.