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Energy flow in the Ebro basin

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Models of Energy Flow for Rural Planning in the Ebro River Watershed

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INTRODUCTION

The rate of human population dispersal into rural areas should increase as world energy resources become scarcer and as the energy scarcity inflates the high cost of maintaining large urban agglomerations. Without fossil fuels, human settlements in the rural environment must and can quickly adjust to locally available energy resources and reach viable steady states. Adjustments will be required in the density of human populations and in the intensity of human activity to assure the development of steady state conditions in rural areas. However, during the period of transition there is the danger that the availability of residual fossil fuels and energy intensive technology plus unrealistic human aspirations may misdirect rural development. Many will try to apply the same concepts of development that failed in the large, growth-oriented cities to the rural environment without realizing that in energy-limited environments an efficient steady state system should always prevail over wasteful transient systems.

The task that faces rural planners is the planning of the future rural steady state without causing irreversible imbalances during the period of transition. This will require rational use of residual fossil fuel energies and judicious application of intermediate level technologies. The potential penalty of a failure in this task will be the irreversible alteration of the rural environment. If land and resource use during the transition period leads to such an alteration, the rural steady state will have a lower carrying capacity.

The danger of resource overexploitation and consequent reduction of carrying capacity is specially critical for Mediterranean countries where water shortages are a major factor in reducting the natural carrying capacity of the environment. For example, an effort to exploit rural environments during the transition period could lead to excessive land reclamation schemes, salinization of the land, and deterioration of water quality. Later, without the support of fossil fuels, or if alternative energy resources provide less power to humans, the original quality of these lands and water cannot be adequately restored. Their value and usefulness will be lost for a long time because natural recovery processes are inherently slow and the recovery capacity of these resources may be adversely affected by the excessive use of technology.

Tools are needed to plan and execute the rational use of land and natural resources while the fossil fuels are still available to implement them because we do not know if future energy sources will be as net energy yielding or as abundant as were fossil fuels. Proper actions will assure a healthier and longer-lasting steady state society in the absence of those fuels. The objective of this paper is to begin the discussion of a systems approach to rural planning in the Mediterranean. This work evolved from the «Water Component» of an international and interdisciplinary course of Rural Planning and the Environment in the Mediterranean Region given in Zaragoza at the Mediterranean Agronomic Institute in 1978.

Planning from a systems point of view requires the formulation of a regional model, quantification of the model in equivalent units, computer simulation, validation of the model, and making decisions using the model as a principal tool for evaluating the regional impacts of resource allocation policies and for the solution of management problems.

In this work we only cover the first two steps with data for the Ebro River Watershed in Spain. Admittedly, this is an imperfect first step hampered by the lack of information and conflicting data for this region. Our hope is to begin the task of unifying research efforts that to date have been uncoordinated. The simple act of formulating a regional model acts as a planning tool in the sense that it forces one to identify the sectors that comprise a region, the forces that are responsible for their function, and their interrelationships. In addition, the model identifies data needs and therefore it also serves as a research planning tool.

During our effort to evaluate the Ebro River Watershed model we identified data gaps, and found conflicting values for the same process or state variable. For these reasons, we had to make numerous assumptions in order to complete model evaluations. In spite of these obvious deficiencies, the values that are reported should be fairly close to real values or at least within the correct order of magnitude. They are the best numbers available to us, within the time constraints of the course.

Regional models of the type discussed here obey the basic laws of energy and matter and data gaps can thus be approximated within a certain degree of accuracy. This is especially significant to rural planning where data banks are not as complete as those available for urban sectors in developed countries. The technique and energy principles embodied in the models are described in detail in Odum (1971 and 1978) and Odum and Odum (1976). For this reason, only a short summary of the most important principles is given below. All the symbols are explained in Fig. 1.

CONCEPTUAL BACKGROUND

The following is a list of natural laws, concepts, indices, or points of theoretical importance that are used in this paper. Many statements are direct quotations from Odum (1973 and 1978).

1. Principle of conservation of matter and energy. This is the first law of thermodynamics and it states that in all energy or matter transformations inputs must equal the changes in storage plus outputs (Fig. 2-a).

2. The principle of entropy generation. This is known as the second law of thermodynamics and it requires that every energy transformation be accompanied by a conversion of part of the potential energy into a form (heat or entropy) that can no longer perform useful work in the system (Fig. 2-a).

3. Energy is measured by calories, BTU's, kilowatt hours, and other intraconvertible units, but energy has a scale of quality which is not indicated by these measures. The ability to do work depends on the energy quality and quantity. As energy flows through biotic and abiotic compartments in the biosphere its *quantity* decreases as expected from the second law of thermodynamics. However, its *quality* may be upgraded if the energy concentration in the downstream compartments increases relative to its concentration in the upstream compartments. For example, along a food chain, solar energy is transformed from diluted electromagnetic radiation to a more concentrated chemical energy in the form of sugars. Eventually, the energy embodied in the sugars may be concentrated into wood which may eventually form coal or be transformed into electricity when concentrated further. Coal and electricity are higher quality energy forms relative to wood, sugars or solar energy. One can thus calculate how many calories of solar energy are embodied in one calorie of sugar, how many calories of sugar are needed to form one calorie of wood, or how many are required to form one calorie of any kind. Table 1 shows some of these ratios and Figure 2-b illustrates the calculation of the energy quality ratios based on the data presented in Figure 2-a.

4. The maximum power principle. This principle states that systems that maximize useful energy flow per unit area outcompete those that do not.

5. The concept of natural selection. Natural selection is the process that determines the survival of a system. Natural selection permits systems with high-

Figure 1. Energy analysis symbols (Odum, 1978).

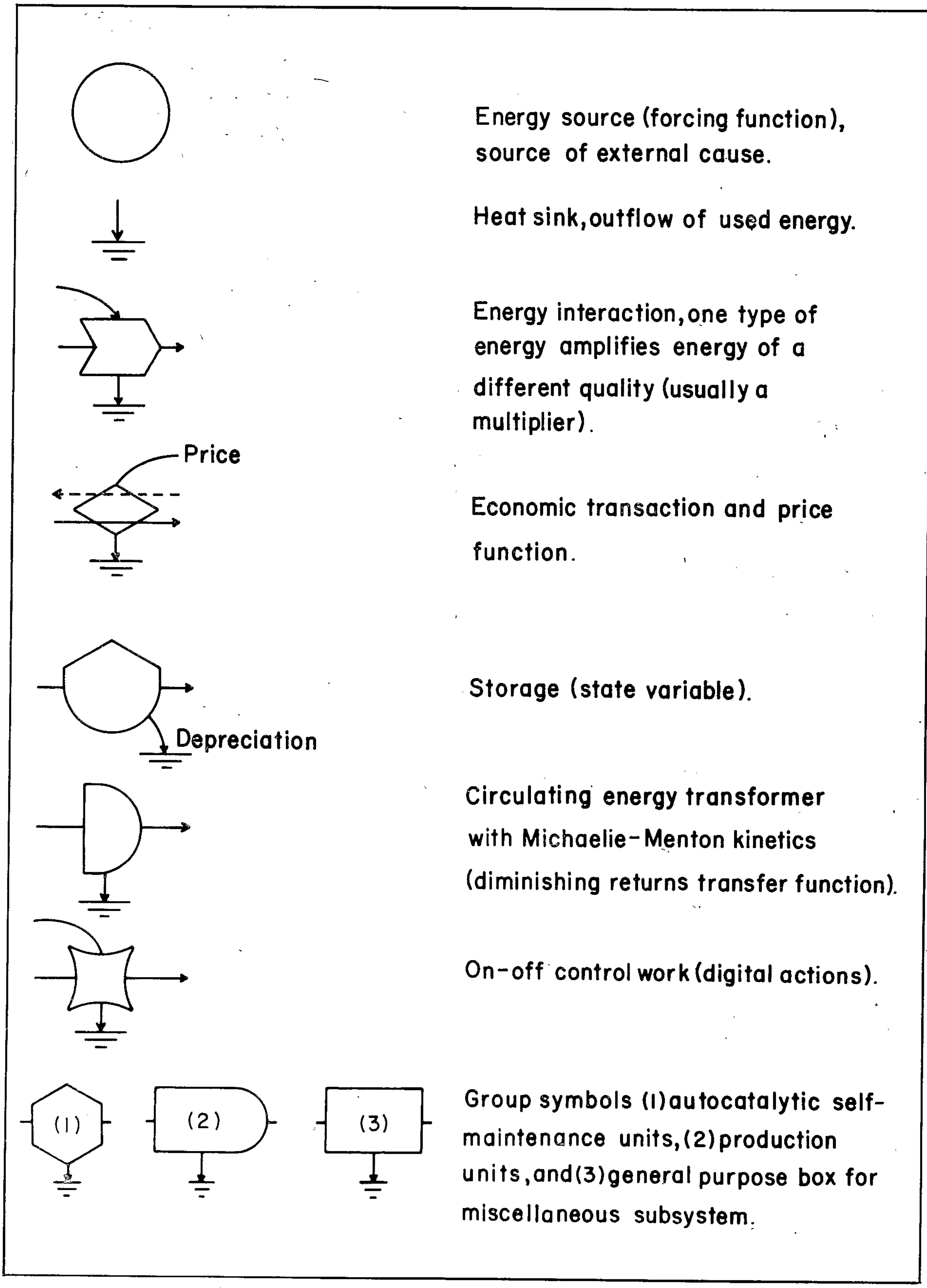
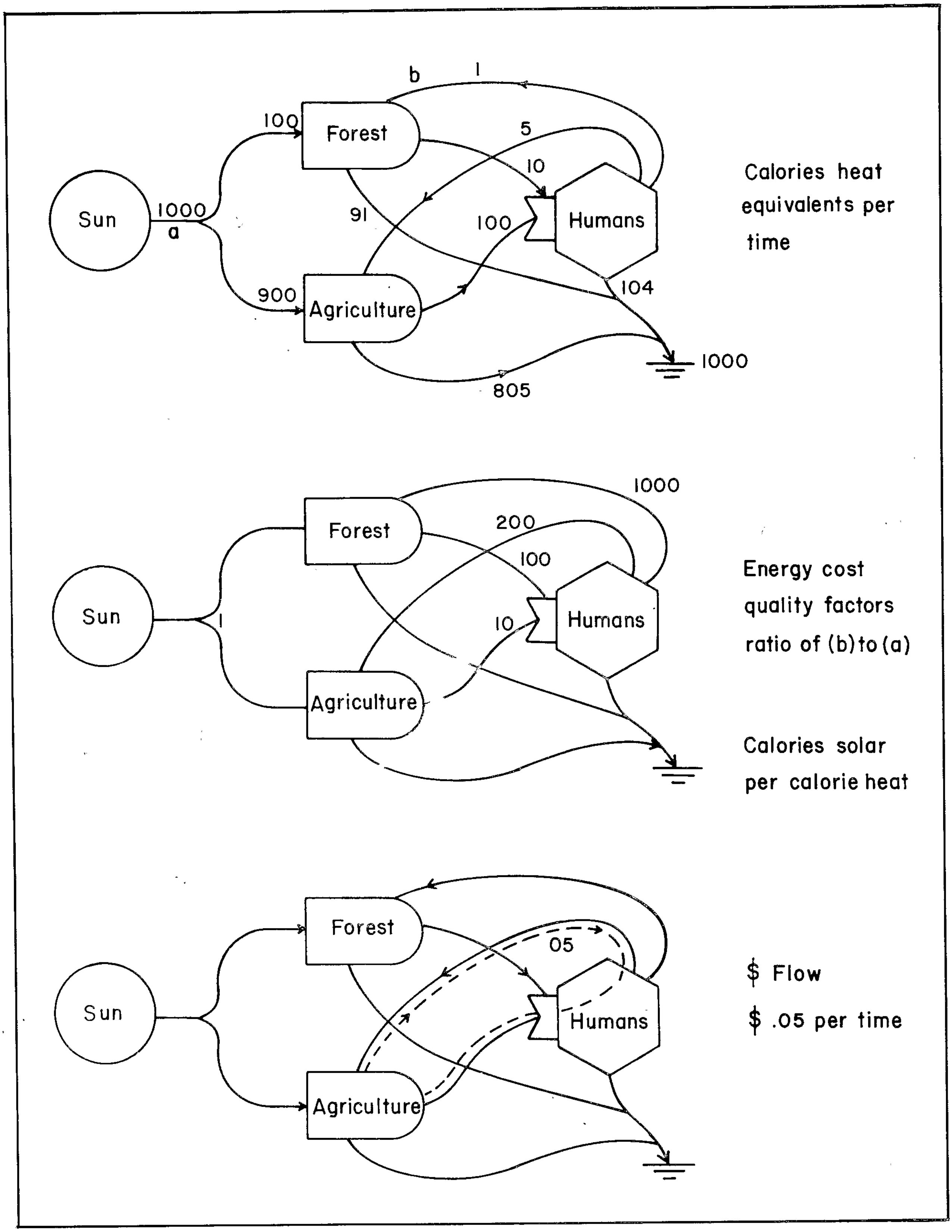


Figure 2. Typical form of an energy web observed in landscapes. (a) The upper figure contains heat equivalent numbers included to form a diagram that illustrates the first law of thermodynamics. (b) The middle figure is the same diagram illustrating solar energy quality factors written on pathways; these numbers were obtained by dividing those in Fig. 2a by the solar energy input required to maintain the system. The figure in the bottom is the same diagram showing the flow of dollars with a dotted line. Notice that dollars do not flow through sectors where natural ecosystems do not have direct interaction with humans (Odum, 1978).



er useful energy flow per unit area to outcompete those with lower energy flows.

6. Energy flows are constrained by the second law of thermodynamics which sets limits on the efficiency of energy transformations. After millions of years of evolution steady state ecosystems are presumed to have evolved to a point where maximum useful energy flow is achieved at the optimal efficiency of transformation. A corollary of this statement is that since solar energy is very dilute, the inherent energy cost of concentrating solar energy into a form useful for humans has already been maximized by forests and food producing plants. Without energy subsidy there is no yield from the sun possible beyond the familiar yields from forestry and agriculture. It is hypothesized that there is a minimum energy cost for a transformation at maximum power. That cost represents an inherent thermodynamic limit below which no improvement can be made. It is further reasoned that systems that have had a long period of evolution and survival under competition have approached thermodynamic limits.

7. The energy principles apply to all systems of nature including human cultures, cities, and civilizations. All these systems have common characteristics that include energy procurement, transformation, storage, depreciation, and so on (Fig. 3).

8. The true value of energy to society is the net energy, which is that amount remaining after the energy costs of getting and concentrating that energy are subtracted (Fig. 4). Many forms of energy are low grade because they have to be concentrated, transported, dug from deep in the earth or pumped from far at sea. Much energy has to be used directly and indirectly to support the machinery, people, supply systems, etc., to deliver the energy. If it takes 10 units of energy to bring 10 units of energy to the point of use, then there is no net energy gain. Right now we go further and further, and dig deeper and deeper for energies that are more and more dilute in the rocks. Sunlight is also a dilute energy that requires work to harness.

9. Even in urban areas more than half of the useful work on which our society is based comes from the natural flows of sun, wind, waters, waves, etc., that act through the broad areas of seas and landscapes without money payment (Fig. 2-c). An economy to compete and survive must maximize its use of these natural energies, not destroying their enormous free

Figure 3. Typical sub-unit observed in all systems. Note storage, depreciation, feedback, and production (transformation work) process.3

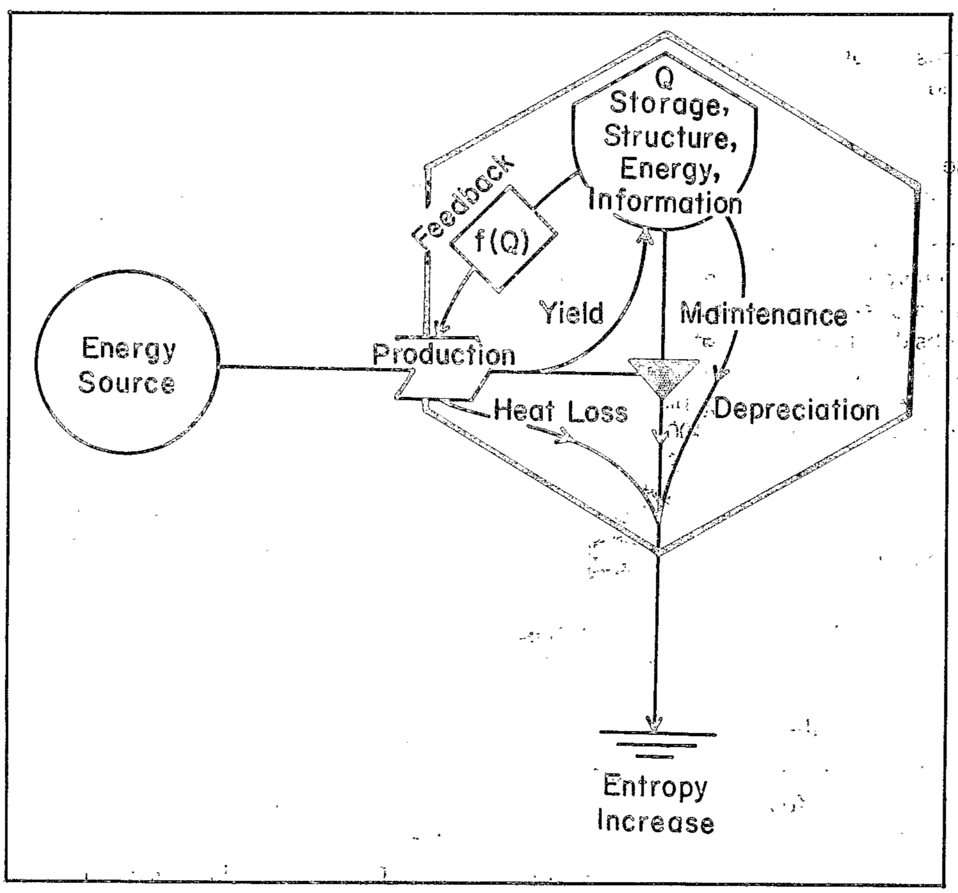
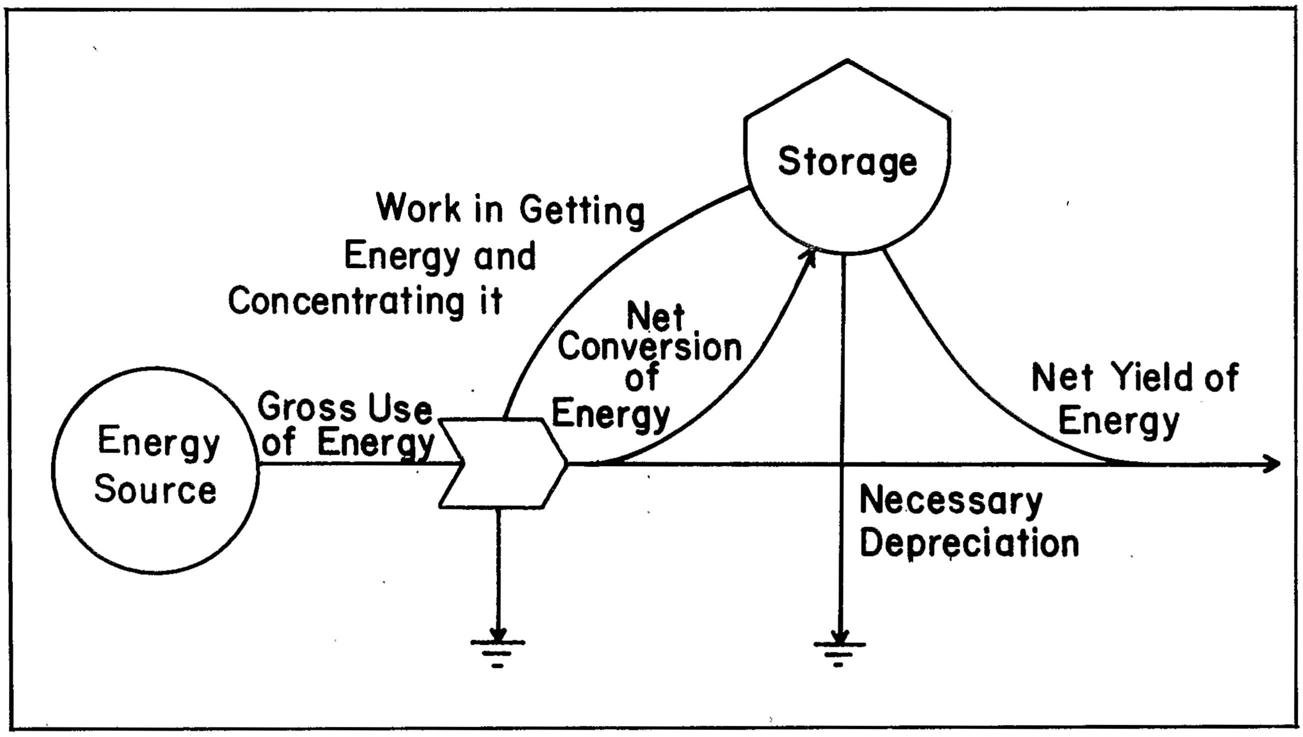


Figure 4. Energy flow diagram illustrating energy laws, and the difference between net and gross energy flows. The net energy of the transformation of the flow labeled «gross use of energy» into the flow labeled «net conversion of energy» is equal to the net conversion of energy minus the flow labeled «work of getting energy and concentrating it». (Odum, 1973).



subsidies. Necessity of environmental inputs are often not realized until they are displaced.

10. Environmental technology which duplicates the work available from the natural, sun powered environment is an economic handicap.

11. Increasing energy efficiency with new technology is not an energy solution since most technological innovations are really diversions of cheap energy into hidden subsidies in the form of energy-expensive structures. For example, Odum (1978) reported that a tertiary sewage treatment plant in Florida would represent an investment of 100 cal per cal of coastal zone productivity. Passing the sewage through a secondary treatment plant and then through a natural swamp would accomplish the same objective at a cost of 3.8 cal per cal of coastal zone productivity.

12. Energy sources which are now marginal, being supported by hidden subsidies based on fossil fuel, become less economic when the hidden subsidy is removed. This could be the case of nuclear energy.

13. World wide inflation is driven in part by the increasing fraction of our fossil fuels that have to be used in getting more fossil and other fuels.

14. The successfully competing economy must use its net output of richer quality energy flows to subsidize the poorer quality natural energy flow so that the total useful energy flow per unit area is maximized.

DISCUSSION OF CONCEPTS

Energy analysis of ecosystems begins with establishing numerical values of flows and storages using energy units in heat equivalents. These are energy units that measure the amount of heat that can be produced during an energy transformation if all the potential energy was transformed into heat. In such diagrams calories entering the system must be accounted for by outputs or storages (Fig. 2-a). The next step is to convert all heat equivalents into units of equal energy quality. This is necessary because heat equivalents do not measure the capacity of substances to do work, but only its capacity to generate heat energy. To measure and compare the capacity of many substances to do work, their quality or concentration of energy must be calculated in units of equivalent quality. Calculations of energy quality relative to sunlight are illustrated in Figure 2-b and ratios are reported in Table 1.

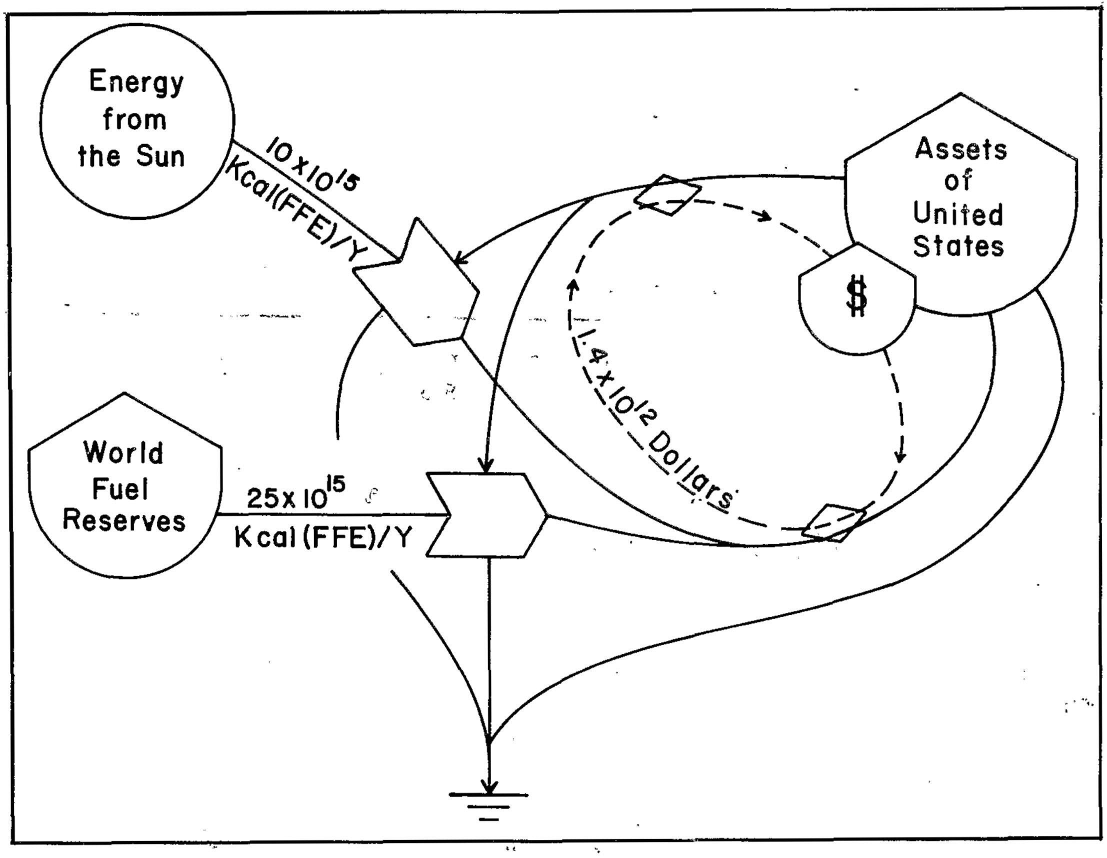
Some practical applications of energy analysis include:

1. The ratio of high quality purchased energies entering a region to the flow of low quality natural

Figure 5. Energy flow and money circulation for the United States in 1973. (Odum and Odum, 1976).

$$\frac{\text{Total energy flow}}{\text{GNP}} = \frac{35\times 10^{15}\ \text{kcal/year}}{1.4\times 10^{12}\ \text{dollars/year}} = 25{,}000\ \text{kcal/\$ (1973)}$$

$$\text{Investment ratio} = \frac{\text{Purchased Energy Sources}}{\text{Natural Energy Sources}} = \frac{25\times 10^{15}}{10\times 10^{15}} = 2.5$$



energies in the region (energy investment ratio) can be used to analyze the dependence of a region on external supplies of high quality energies. Fossil fuels are the usual high quality inputs while sunlight, tides, winds, and so on are examples of the free natural energy flows. In the United States, this ratio is in the order of 2.5 cal of fossil fuel per cal of natural energies (Fig. 5), while the ratio for the world is 0.3.

2. Calculation of energy ratios to evaluate the amplifier value of limiting factors in a system. We calculated these type of energy ratios to evaluate rates of primary productivity with and without irrigation in the Ebro River Watershed (Table 2). These ratios are useful indicators of the efficiency of resource use under different technological strategies.

3. Calculation of the energy value of money in the economy. Normally, economic analysis does not evaluate natural processes because money flows only account for human-related activities and it is difficult to show that natural processes are subsidizing the market place. Yet, natural energies do contribute to the economy in many hidden ways that only become obvious when human technology is forced to substitute for a natural process. The energy value of money is the ratio of the total energy flow (natural plus purchased) through the economy and the gross national product (GNP, Fig. 5). This ratio has remained fairly constant in the U.S. since 1880 if constant dollars are used (Fig. 6).

Other applications of energy analysis are discussed by Odum (1978) but will not be used in this paper.

Figure 6. Relationship between dollar flow and energy flow in the U.S., economy for a period of almost 100 years. When corrected for inflation the relationship appears to remain constant. This figure is from an unpublished report of the Council on Environmental Quality.

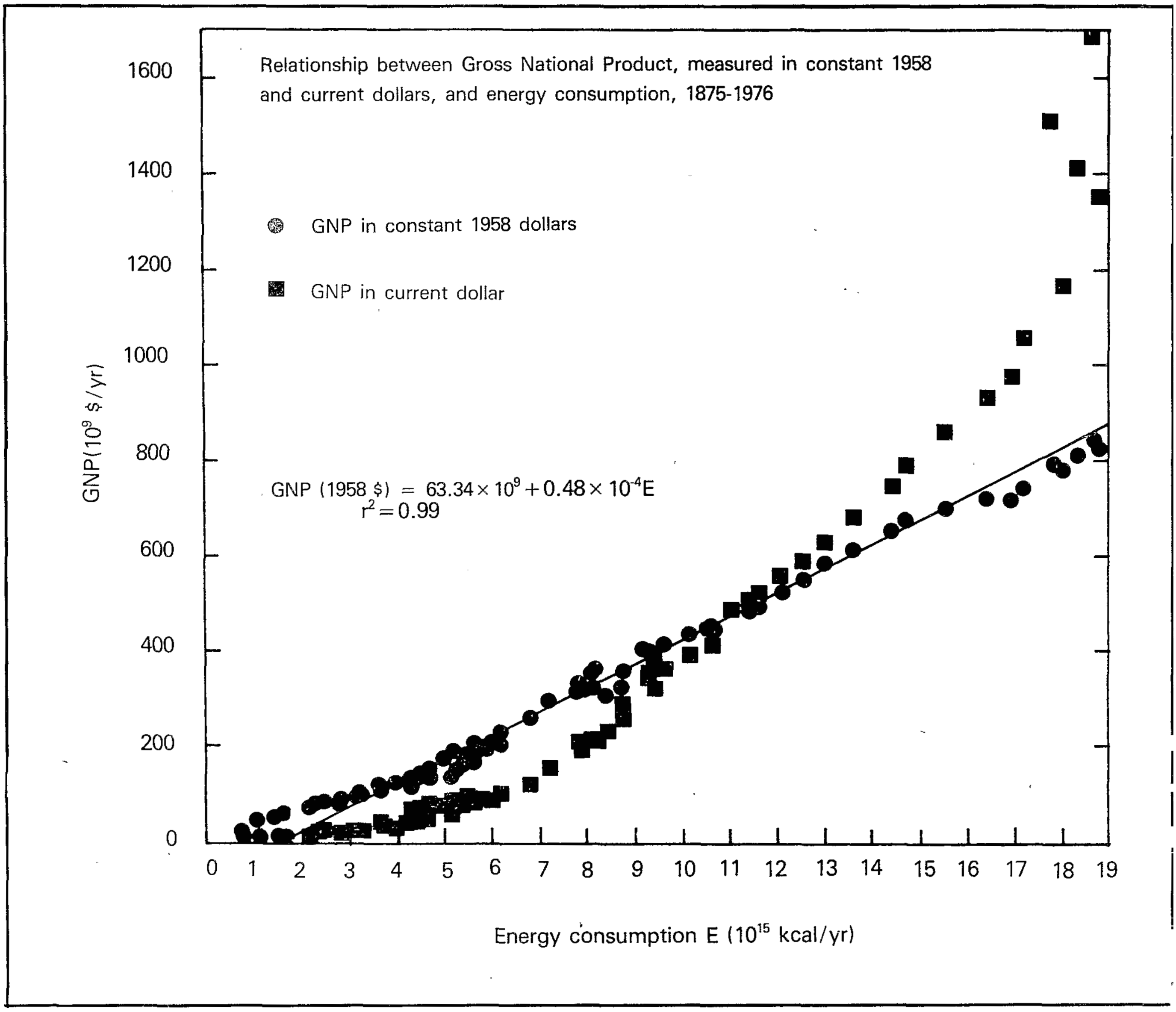
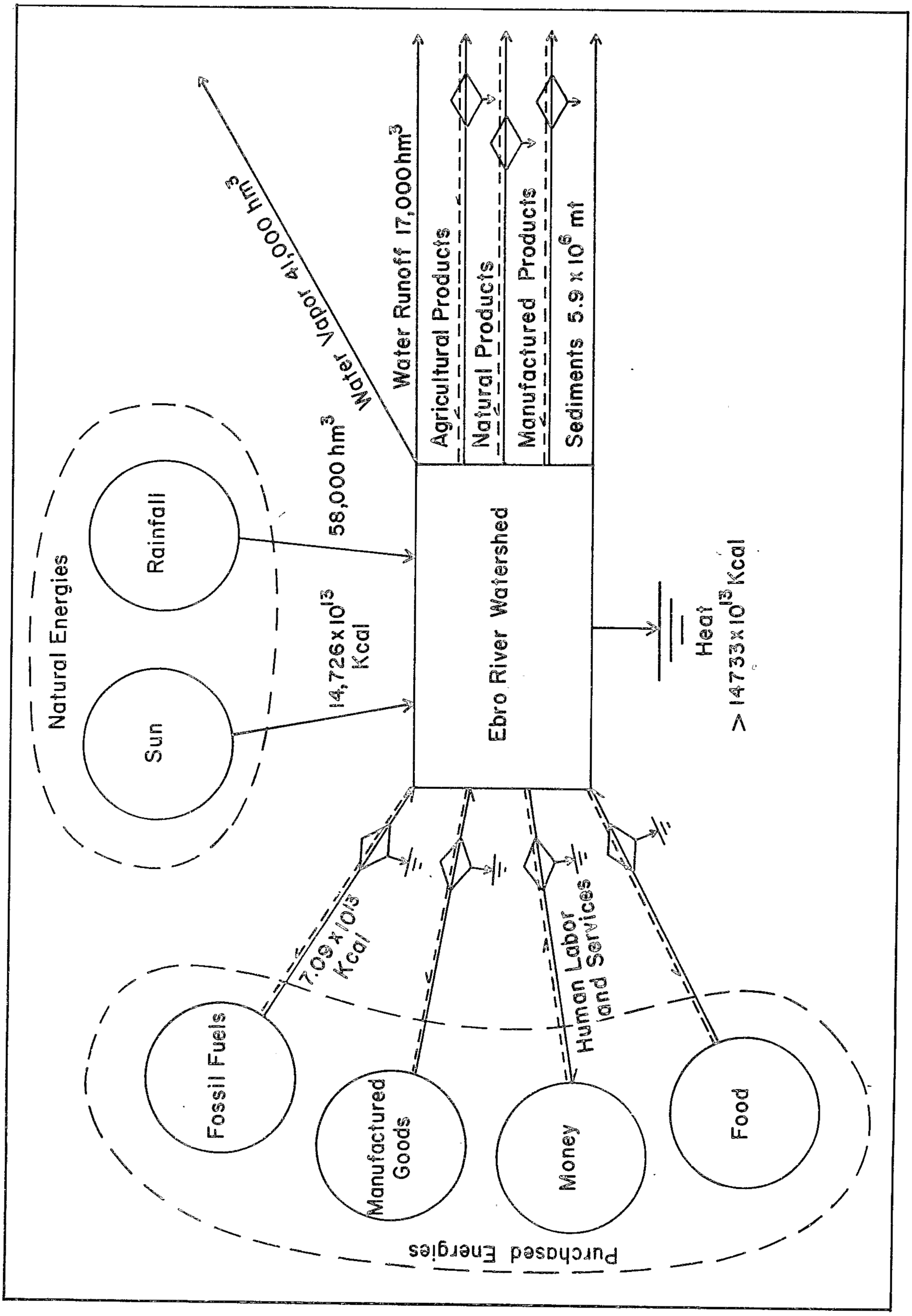


Figure 7. Macromini model of the Ebro River Watershed. Only inputs and outputs are shown. Purchased energy sources are grouped together as are the natural sources. Details of energy calculations are shown in other Tables and Figures and are discussed in the text.



MODELS OF THE EBRO RIVER WATERSHED

SIMPLIFIED MODEL

Figure 7 is a simplified model of the Ebro River Watershed. The watershed is represented by a box with inputs and outputs of energy and materials. No details are shown for the inner works of the watershed. This type of diagram is a first step in the process of conceptualizing a region. On the left we show the purchased and natural energies that enter the watershed. Notice that money flows are associated with the purchased energy flows but not with the natural energy flows. To the right we show the outputs of the region. Money and energy always flow in opposite direction (Fig. 1) and money enters the region in proportion to the output of products and services from the region. This model is the basis for the development of a more detailed model of the region where some details of the subsystems within the basin are shown. To calculate the total energy input to the Ebro River Watershed it was assumed that the pattern of fossil fuel uses in this region was similar to the energy use in the rest of Spain. Thus, the total fossil fuel input to Spain (Table 8) divided by its area (Table 3) yielded 8.288×10^{8} kcal/km^{2}. When multiplied by the area of the Ebro River Watershed (Table 3) one obtains the reported value of 7.09×10^{13} kcal (Fig. 7). Other numerical values shown in Fig. 7 were derived from the more detailed models discussed in the next section.

CONCEPTUAL MODEL SHOWING INTERACTIONS WITHIN THE EBRO RIVER BASIN

In Fig. 8, we show the more detailed conceptual model that we developed as a tool for gathering information from the region. This model is composed of a number of subsystems. These are: 1) the agricultural subsystem including cattle and other range animals, 2) natural ecosystems, 3) the urban subsystem, 4) the industrial subsystem and 5) the subsystem of water irrigation. In the process of interconnecting these subsystems, we had to add a water budget, a land use submodel, inputs and outputs of energy, materials, and goods, and the various storages where products of the activites of the various subsystems accumulate. These storages include agricultural and natural products, manufactured goods, wastes, and water. Money flows are not shown in Fig. 8 to avoid complicating the model. However, as already discussed, the flow of money is in the opposite direction of the energy flows associated with human activity (Figs. 2-c and 7). Money flows are not associated with natural processes. Table 3 contains some of the basic data collected to quantify the models of the region. As each model is introduced more data and conversion factors will be given.

LAND USE SUBMODEL

Land use data for the Ebro River Watershed are not abundant (Table 4) and were summarized in Fig. 9. There is considerable disagreement in land use data for the region. We used 85,500 km^{2} as the total watershed area for most of our calculations. Rates of change in the patterns of land use could not be calculated. This requires careful analysis of land uses using sequential aerial photography. Also we could not find data to calculate the energy cost of converting one land use to another. In this region of Spain the change of land from «secano» (non-irrigated lands) to irrigated land involves costly land levelling techniques which are fossil fuel intensive. The values for the cost of these land use changes are based on data for flatlands in Puerto Rico. There, Lugo *et al.* (1977) estimated a cost of 4.5×10^{5} kcal/ha.year to convert natural lands to agricultural lands and 2.7×10^{9} kcal/ha.year to convert agricultural lands into urban lands.

The cost of converting agricultural lands into natural lands is free since it it based on solar input and rainfall. In the Ebro River Watershed however, poor land-use practices may lead to salinization and thus the cost of recovering lands increases. The process may be accelarated if water is available to leach the salts. If not, the cost of poor land use is the longer time that is required for recovery of the land through a slower natural succession. Meanwhile, salinized soils are waste lands that contribute nothing to the regional welfare but do drain resources and opportunities away from humans.

WATER SUBMODEL

The water balance for the Ebro River Basin is shown in Fig. 10. The rainfall and discharge values are the annual mean values. Annual variations fluctuate between 8,000 and 31,300 hm^{3} for the river discharge due to similar wide fluctuations in rainfall. As water flows through the river valley, it is intercepted by numerous water dams (in the order of 100). Electricity is generated in these dams and water is used for irrigating agricultural lands.

Runoff from each sector of the model eventually reaches the Mediterranean Sea. Evapotranspiration accounts for 71 % of the rainfall in the region. This value has increased above the natural value due to the large area of open water in reservoirs which increase the residence time of water in the watershed and thus increases the opportunities for evaporation.

AGRICULTURE AND NATURAL ECOSYSTEM SUBMODEL

A combined model of agriculture and natural ecosystems is shown in Fig. 11. The diagram shows that considerable amount of work is done by cattle and wildlife in the natural and agricultural sectors of the model. Human work in this sector is not known.

Figure 8. Generalized diagram of all subsystems of the Ebro River Watershed. This model was used as a planning tool for data gathering and discussion. Details and documentation of flows and storages are shown in other Tables and Figures and discussed in the text.

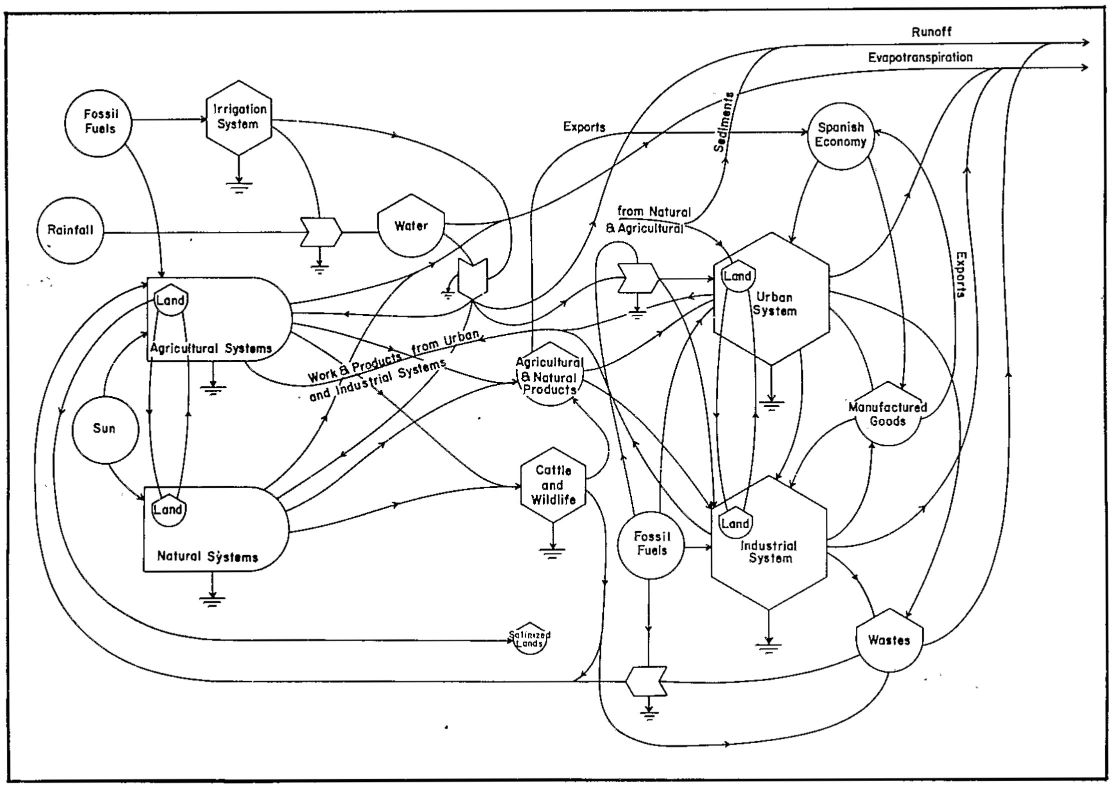


Figure 9. Land use model in the Ebro River Watershed. Fossil fuel inputs were taken from Lugo et al. (1977). Land use data were derived from Table 4 and from Jordana de Pozas (1973). Light energy input was taken from Table 6 and rainfall from Table 3.

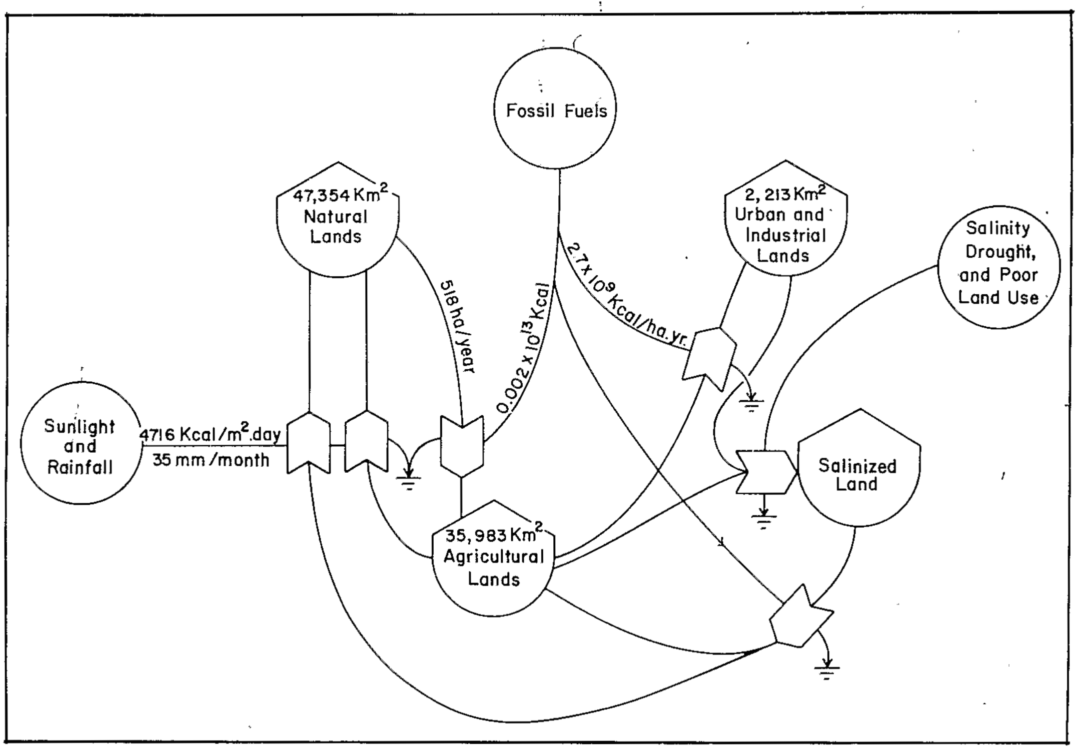
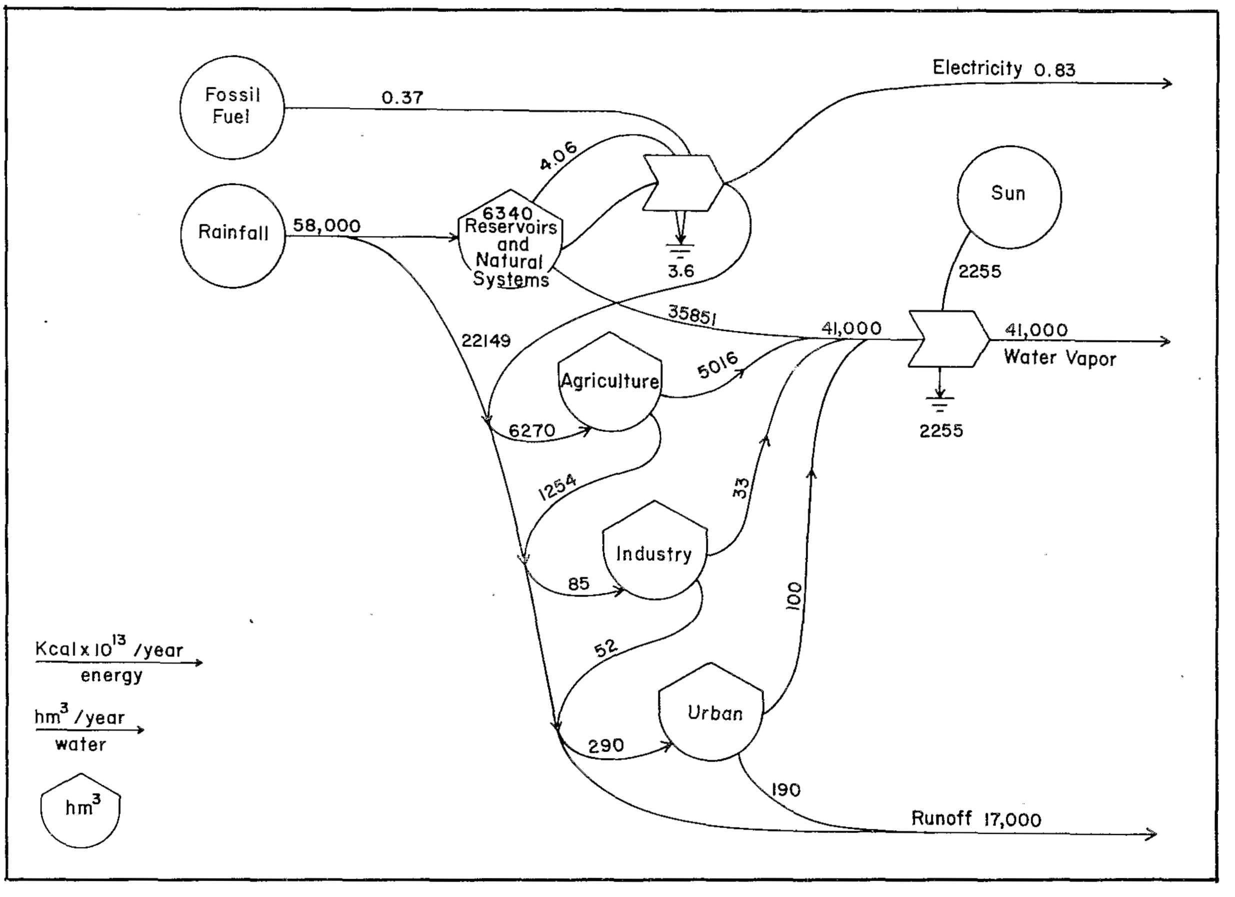


Figure 10. Water balance for the Ebro River Watershed illustrating the energy flows associated with the water flows. Water balance data was taken from CESIE (1973). The potential energy of water was calculated from Odum (1970). Fossil fuel input was back calculated from electricity production (obtained from Reguart Monreal, 1971) and a power plant efficiency of 37 percent (Table 3). Energy loss for water evaporation was taken as 550 g. cal/g.



URBAN AND INDUSTRIAL SUBMODEL

For the quantification of the urban and industrial submodel (Fig. 12) we had to depend on the input-output data from the other submodels of the region. Obtaining independent data for this sector of the watershed is another priority for future research. For example, more research is needed in water quality. In 1964 a survey of 1117 municipalities in the tourist areas of the Ebro River Watershed found that 68.8% of the areas had potable waters, 8.2% had suspicious water quality, and 22.9% had non-potable waters.

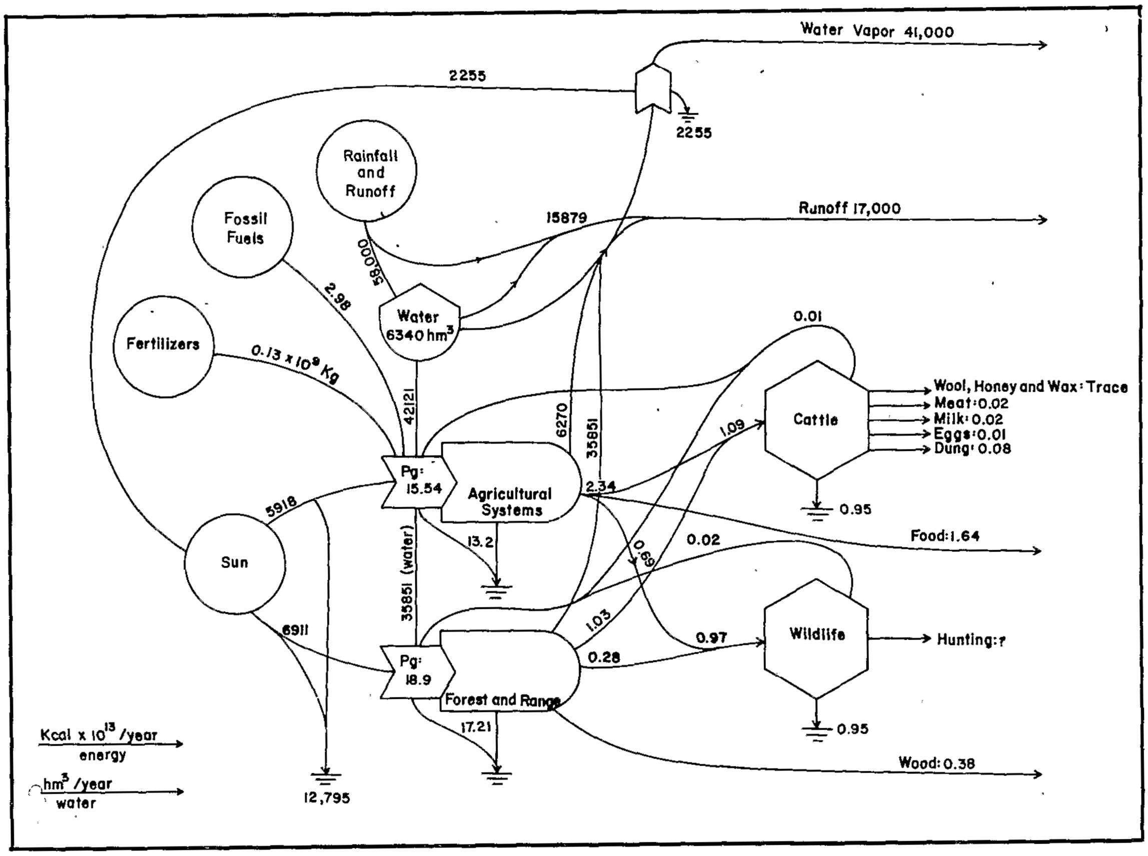
COMPOSITE MODEL

Figure 13 incorporates all the submodels into one diagram that highlights the role of water in the region. This model includes the water, land, energy, and material balance for the region. From these numbers we can aggregate data to quantify the simple model of Fig. 1. In addition, we added information on the export of sediments, salts, and BOD from the region. BOD data includes urban exports (Fig. 12) plus animal BOD (Table 3).

According to Jaime Fanlo and Aguilar (1967), the Ebro River Watershed reaches peak sediment losses of 688 m^3/km^2.year. This is equivalent to 0.7 mm. of top soil or 482 mt/km^2.year. The value reported in Fig. 13 is equivalent to 693 mt/km^2.year. In the USA the average river sediment load was estimated at 220 mt/km^2.year (Leopold *et al.,* 1964).

All these models will now be used to develop a discussion on the dynamics of the Ebro River Watershed, its potential for development, and its limits to growth. For the purpose of this paper, growth and development is defined as the intensification of energy flow per unit area by humans above values normally associated with natural energy flows.

Figure 11. Model of forest and agricultural production in the Ebro River Watershed. Table 5 summarizes some of the assumptions that were used in the quantification of this model which is discussed in the text.



DISCUSSION

In this discussion attention is given to both the Ebro River Watershed and Spain as a whole. It is necessary to discuss the whole country since the development of a watershed such as the Ebro River Watershed is dictated to a considerable degree by the behavior of the larger system to which it belongs.

Table 9 contains population statistics about Spain. While the population is growing, the rate of growth is slow (1 %/yr), 61 % of the population is urban, and only 10 % of the population is over 64 years of age. These statistics and the 72-year life expectancy reflect the youth and vigor of the human population.

The food consumption of the population of the Ebro River Watershed is about 0.26×10^{13} kcal/year (Fig. 12). Agricultural and natural systems in the watershed produce enough organic matter to satisfy this caloric intake plus an export of 1.51×10^{13} m/kcal/year. The function of these ecosystems is finely tuned to water availability. The linear equation that describes the relationship between crop yield (y in kg/ha.year) and rainfall (x in mm) is $y = 15x + 241$ ($r^2 = 0.62$). As water becomes available, yields increase proportionally. Table 2 summarizes the multiplicative value of water in a number of sectors of the region. Three points merit discussion.

1. In agricultural and natural ecosystems, higher water use efficiency is accompanied by lower yield. Thus, the price of higher primary productivity is higher water use and evaporation.

2. Higher water availability increases the efficiency of using solar energy. Thus, a high quality subsidy (water), allows the more efficient concentration of a lower quality energy source (solar energy).

3. The higher multiplier value of water in agriculture relative to natural systems is a reflection of point 2 above and should be interpreted with caution. Agricultural systems are heavily subsidized with high quality energy sources relative to natural systems which must cope with and survive without human interference. In addition, natural systems return high quality water to other sectors in the watershed and also provide other services that are not reflected in the yields.

Figure 12. Summary of inputs and outputs to the urban and industrial sectors of the Ebro River Watershed. The diagram is discussed in the text.

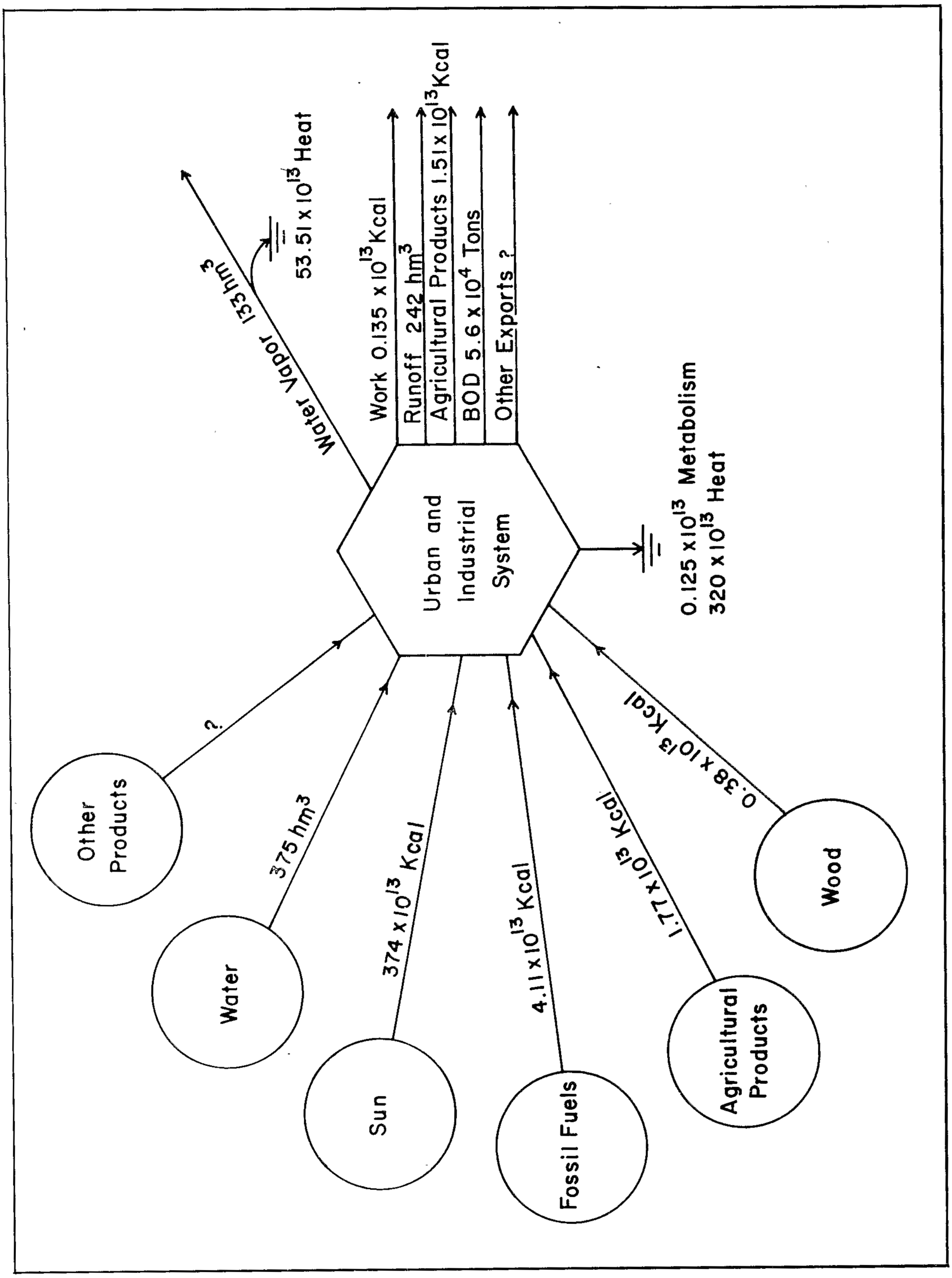
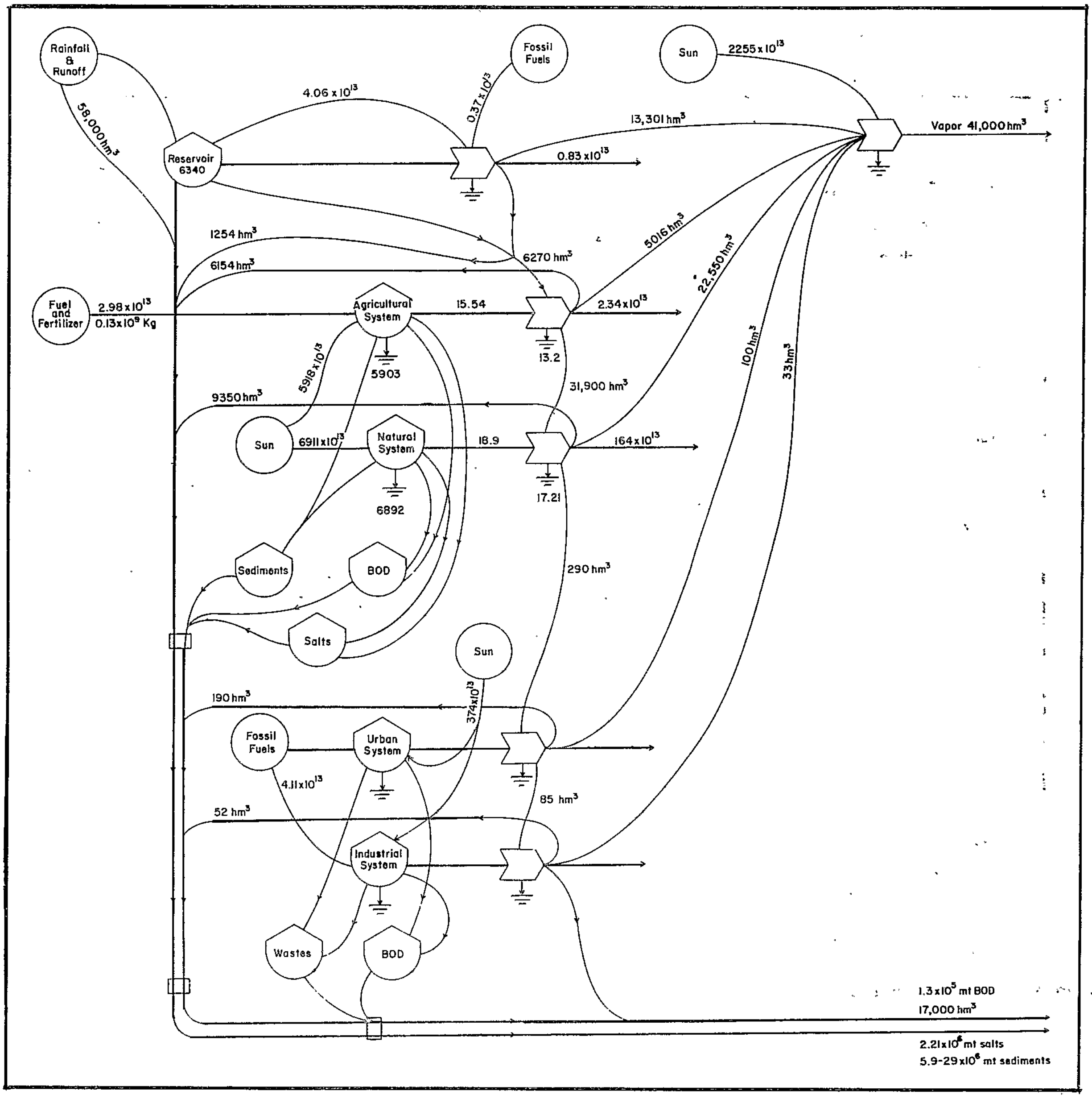
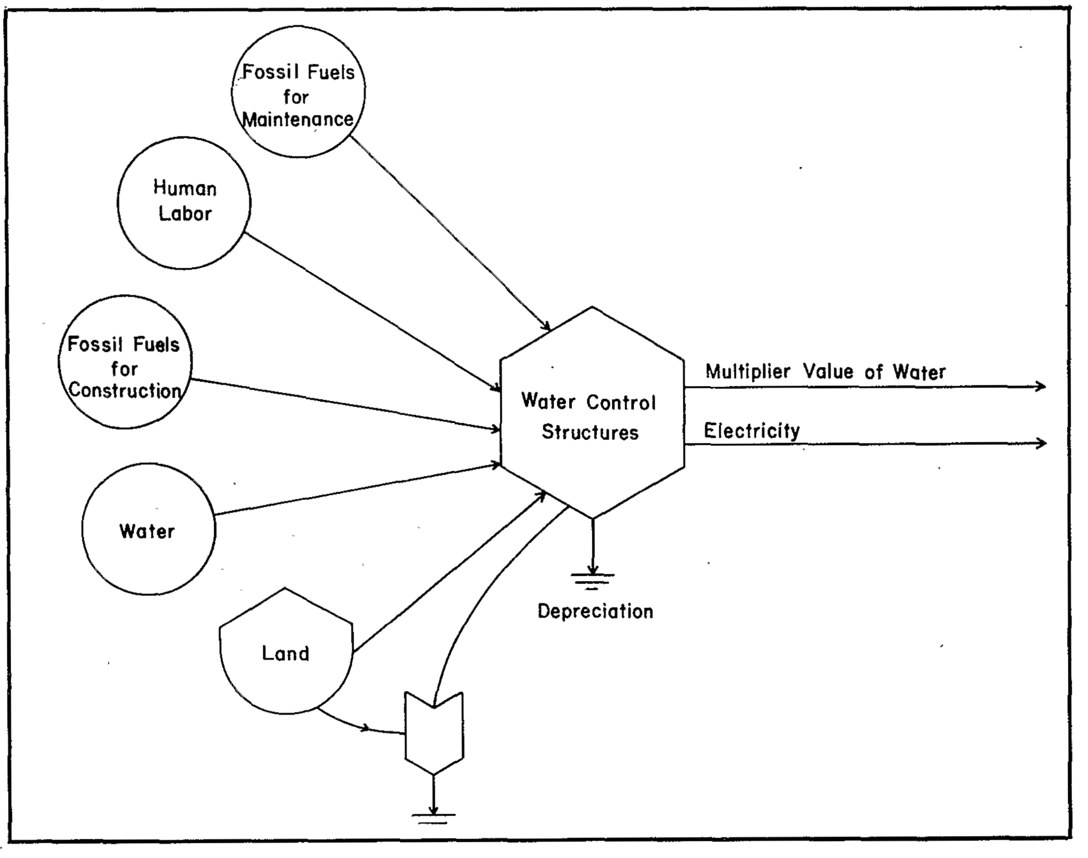


Figure 13. Model of the Ebro River Watershed illustrating the role of water in a number of sectors. The text discusses the model and sources of data.



The work of all solar systems in the Ebro River Watershed is reflected in the economic activity of the region (Table 11). The total organic production of these systems is 14.6% of Spain's agricultural production and the economic yields represent 2.6% of Spain's GNP. This high productivity has been made possible through the ingenious development of irrigation systems and the construction of water dams. These human activities subsidize natural productivity, but have a cost. Fossil fuels, human labor, and losses of environmental quality and organic productivity are some of the costs associates with them (Fig. 14). We could not quantify the cost of developing, operating, and maintaining the massive water irrigation systems of the Ebro River Watershed. This must be another priority for work in this region. Yet, judging from the return that is obtained in the form of increased agricultural production (Tables 2 and 11), it is obvious that the returns justify the investment. One must expect, however, that as the availability of flat lands become more scarce, the cost of land levelling and irrigating must increase. This will be aggravated by the fact that at the same time, fossil fuels will become more expensive and harder to obtain. At that time, continued development of water works projects may not be as desirable as they were in the past. A net energy analysis of future water development projects is needed but cannot

Figure 14. Conceptual diagram illustrating the gains and losses associated with the development of water control structures in the Ebro River Watershed. Electricity and increased agricultural productivity are the two main benefits. Costs include the fossil fuels expenditures for development and maintenance, human labor, water losses associated with the system (including losses due to water quality deterioration), irreversible commitment of land, and stresses on the environment including the reduction of natural productivity and downstream effects on the river delta and its estuaries.



be done at this time for lack of data. Some criteria that should be considered are given in Fig. 14.

The plans for future water development in the Ebro River Watershed are discussed in CESIE (1973) and by Ministerio de Obras Públicas (1974). This plan may be evaluated qualitatively by examining Fig. 15 where the proposed water balance for the year 2000 is given. The plan calls for the construction of 141 water dams in addition to the current 92 dams in the watershed. The plan also calls for almost complete control over the flow of the Ebro River. No provision is made for water quality control nor for the maintenance of the complex system which will undoubtedly be subject to intensive sedimentation and high maintenance costs.

Other environmental aspects that require careful consideration are:

1. Loss of natural productivity as more water is diverted to human uses.

2. Loss of water quality as natural ecosystems are prevented from performing their ecological role.

3. Increased sedimentation and possible eutrophication from increased agricultural activities.

4. Downstream effects, particularly in the delta where less runoff means that salinity will increase, sediments will no longer build the delta, and fisheries will certainly decline.

5. Increased probability of public health hazards due to lower water quality and higher intensity of human activity.

All these environmental hazards translate into economic losses expressed through higher costs to sustain growth and human activity plus losses in alternative economic opportunities. Yet, the most serious threat to the continued development in the Ebro River Watershed is the issue of energy availability.

To fully understand this issue as well as the function

Figure 15. Expected water balance for the Ebro River Wateshed in ther year 2000.

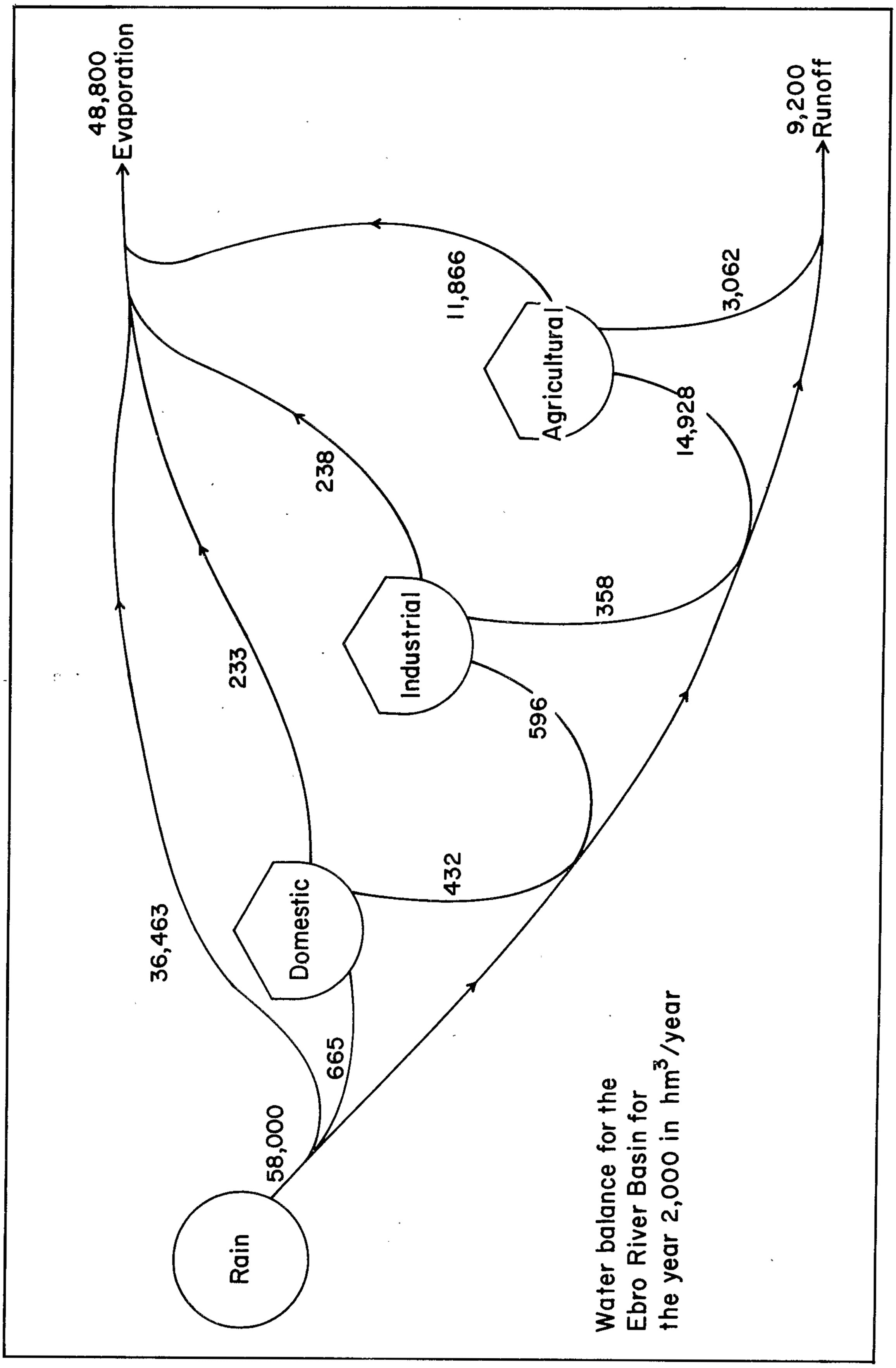
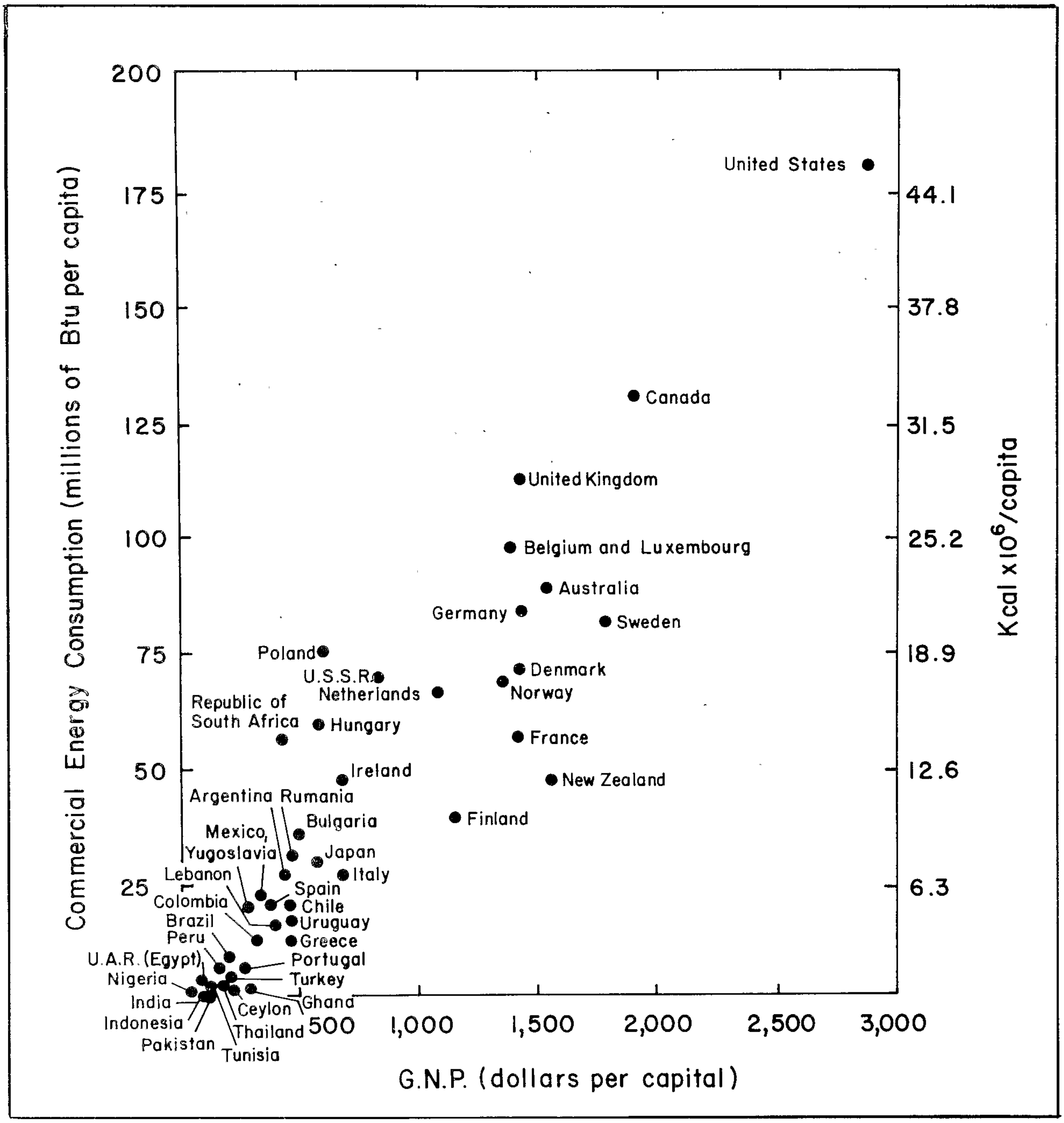


Figure 16. Relationship between Gross National Product (GNP/capita) and total energy consumption/capita for various countries (Odum, 1971).



of the Ebro River Watershed, one must study the regressions on Table 10 and Figs. 6 and 16. Table 10 shows that the economic vitality of a region (measured by the GNP corrected for inflation) is a linear function of fossil fuel input. When GNP is not corrected for inflation a poor correlation is found. Figure 16 illustrates that the relation between fossil fuels and GNP applies worldwide while Fig. 6 shows that the relationship is relatively constant over a long period of time for the United States.

The economic system is driven by two sources of energy: fossil fuel energies and natural energies (Fig. 5). In the Ebro River Watershed, the natural energies are solar energy and water. Knowing the relative contribution from both sources allowed us to calculate the investment ratio for Spain and for the Ebro River Watershed. Table 12 shows this calculation in equivalent energy units. Ratios are low compared to the value reported for the United States but higher than the world average. Normally this could be interpreted as meaning that there is ample room for economic development because the area appears to be limited by fossil fuels.

As explained in the disscusion of concepts, a country or region with a low investment ratio has enough natural energy resources to attract and match fossil fuels and thus maximize the flow of useful energy. However, in the case of Spain, the ability of its low quality natural energies to match fossil fuels is impaired by water shortages. Seventy-three percent of the low quality energy available to Spain is solar and the country does not get enough water to match this solar energy input. Without this initial matching it cannot match fossil fuels. Increasing costs of fossil fuels due to world shortages further complicate matters.

Spain may be compared with other countries to further clarify the factors that regulate the growth and development of a country (Table 13). Data in Table 13 are in heat equivalents and thus do not account for the difference in quality. The table illustrates two points. First it shows that in countries considered to be underdeveloped, there is considerable use of fossil fuels but the efficiency of energy use is low. Secondly, the percentage of fossil fuel dependence ranges from 3 to 70 %. These two points have important implications that must be examined in the context of the competition for energy and resources that exist among countries; in the context of the overall resource limitation of the world; and in the context of the eventual consequences of the actions of natural selection over alternative resource-use strategies.

Fossil fuels are no longer easily available in rich deposits. Without fossil fuels, other important minerals and resources cannot be concentrated and made available to the world economy. Furthermore, fossil fuel reserves are not expected to last more than several decades (Landsberg, 1973). It would then be unrealistic to expect that countries that are now underdeveloped will be able to raise their standard of living to levels similar to western countries (Fig. 16, Table 13). There may not be enough energy to go around. In addition, The capacity to use and process energy efficiently depends on the structure already built up to perform this role and thus developed countries will always outcompete developing countries in the competition for energy and resources. Makhijani (1976) implied the same thing when he suggested that the low energy use efficiency shown in Table 11 for underdeveloped countries was due to a lack of technology. Yet, the competitive advantage of western countries over less developed countries rests on their capacity to match fossil fuels with natural energies. In essence, the efficiency of energy utilization by the economy of any country appears to change with the intensity of development. In overdeveloped countries energy use efficiencies may depend on the energy capture by natural systems because highly sophisticated technology developments actually reduce the efficiency of energy use by wasting fossil fuels. In under-developed countries, the efficiency of energy utilization is limited by technology because the lack of technology does not permit the full utilization of fossil fuels and this forces the use of high quality energy for functions that could be performed by more efficient technologies or by natural systems. The result is a lower energy use efficiency.

The alternative left to less developed countries that possess an excess of natural energies but lack fossil fuels, is to develop these natural energy resources in ways that will allow them to gain a competitive advantage over countries that are now developed. If done properly, this advantage will become obvious when fossil fuels run out.

In the rural environment, care should be taken to balance the use of technology with the management of natural resources such that over all energy-use efficiency and useful energy flow per unit area are maximized. When this happens, the competitive position of the rural environment will reach its peak and such a strategy may be favored by natural selection over alternatives with less competitive energy uses. An example of efficient energy use in a rural setting is shown in Fig. 17.

Figure 18 summarizes the concept of the desired scheme. In this example, natural energies are coupled to the main economy through an interface economy that buffers human impact on natural ecosystems. As long as the natural ecosystems are maintained in a «healthy» state, their contribution will allow the attraction and matching of external high quality energy needed for development. In the Ebro River Watershed, the infrastructure and cultural adaptations from the pre-fossil fuel years preadapt

Figure 17. Energy flow in a hypothetical village, where natural energies are coupled to intermediate technology (Makhijani, 1976).

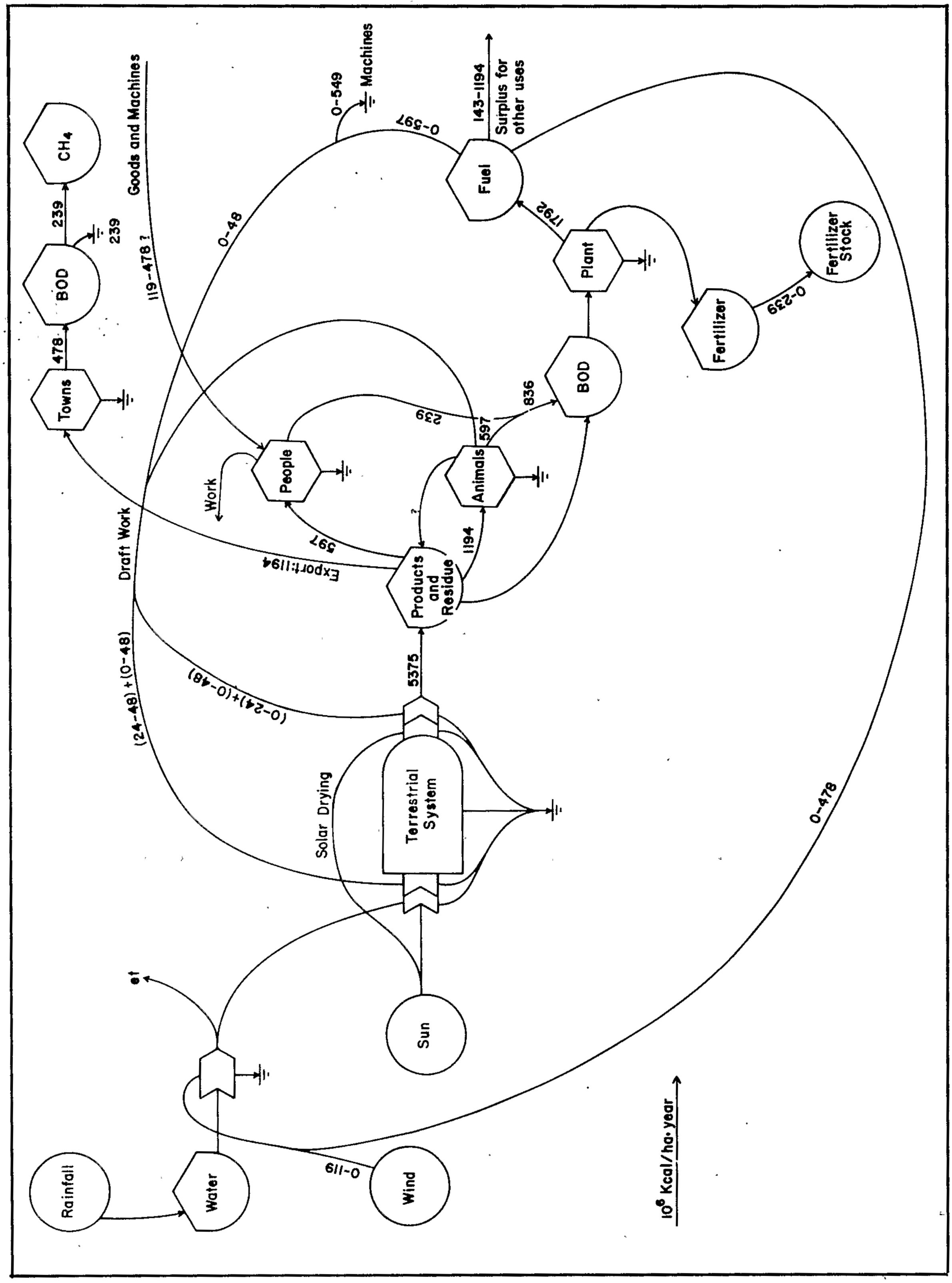
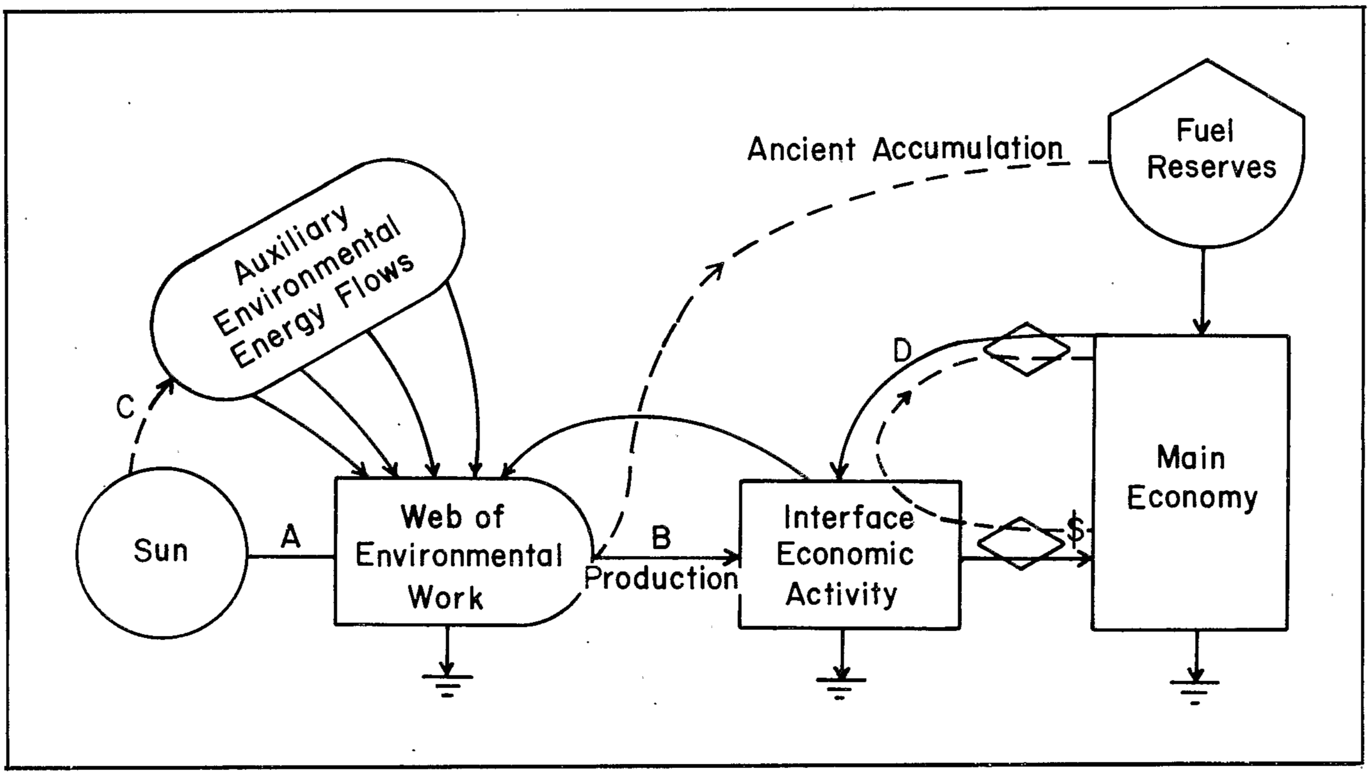


Figure 18. Summary of energy flows of the environment attracting additional energies of investment and economic development. Cost equivalents are evaluated at A or B and related to actual or potential energy flows attracted at D (Odum, 1978).



the region for a succesful transition from a high intensity fossil fuel condition to a lower energy intensity steady state. Today, in spite of the impending energy crisis, many continue to advocate the mechanization of agriculture, continued urbanization, and unrealistic water irrigation plans. Yet, the old agricultural system has left behind a network of small towns and road infrastructure that will facilitate the return of traditional, less energy intensive agriculture to the region without the necessity of incurring in excessive development costs. Irrigation systems that have survived since the time of the Moors are still intact and operational. Furthermore, the hydroelectric dams that have been constructed during periods of excess fossil fuels now yield considerable amounts of high quality energy in the form of electricity that can be used locally to supplement natural energy resources. The use of these local resources and facilities should have priority over more exotic solutions that may place the region in an irreversible course that could eventually make it totally dependent on outside subsidies.

In summary, energy analysis can be a useful tool in the planning of a steady state society for rural regions such as the rural areas in the Mediterranean. Efforts from planners to document the models here presented and to actually manipulate them with computers will certainly enhance the capacity to minimize errors that in time may cause irreversible damage to local ecosystems and thus eliminate the possibility of selfsustaining steady states.

T A B L E S

Table 1. Energy quality conversions (Odum and Odum, 1976, 1978)

Type of Energy	Fossil Fuel Equivalence (kcal/kcal)
Solar	0.0005
Products of gross productivity	0.05
Wood	0.5
Coal	1.0
Fossil Fuel	1.0
Electricity	4.0
The dollar	25,000.0
Type of Energy	**Solar Equivalence (kcal/kcal)**
Solar energy at earth surface	1.
Tropical moist air	3.3
Winds	315.
Gross photosynthesis	920.
Coal	2027.
Tide	3400.
Water: World rain chemical free energy	3215.
Rain potential over land, 875 m	3870.
Potential organized in rivers	10,950.
Chemical potential energy over land	15,320.
Electricity	7200.
Human service in world	257,000.
Human service in U.S.A.	418,000.
Work of land uplift	9.2×10^{11}

Table 2. Role of water as a multiplier of primary productivity in the Ebro River Watershed. When used to generate electricity 1 kcal of potential energy in elevated water generates 0,2 kcal of electricity (Fig. 13). All energy values are expressed in heat equivalents.

Annual Inputs		Type of Agriculture	Yields	Efficiency (Yield/Input)
Water (mm)	Solar Energy kcal/m^2		kcal/m^2	
410 (rain)	16.8 × 10^5	Secano (all crops)	556.	Water use: 1.35 kcal/mm Solar energy use: 0.03 %
1410 (rain plus irrigation)	16.8 × 10^5	Irrigated* (all crops)	1240.	Water use: 0.88 kcal/mm Solar energy use: 0.07 %
1273	16.8 × 10^5	Secano (Wheat**)	171**	Water use: 0.13 kcal/mm Solar energy use: 0.10 %
Agricultural Productivity***				
Net yield				1.86 kcal/mm
Gross yield				12.39 kcal/mm
Natural Productivity***				
Net yield				0.51 kcal/mm
Gross yield				5.92 kcal/mm

*Maestro Palo, 1971.

**Mean of 20 harvests between July 1 and June 30, 1955-1975 (Alberto and Machin, 1977).

***From Figure 11.

Table 3. List of data used to quantify the models.

Parameter	Value	Source
Area of Spain	503.478 km^2	Tamames, 1977
Area of the Ebro Watershed	85.550 km^2	Tamames, 1977
Average rainfall for the Ebro River Valley (higher in the mountains)	35 mm/month 36.4 mm/month	Tamames, 1977 Alberto and Machin, 1977
Annual discharge of the Ebro River	17,000 hm^3 (Range: 8,000-31,300 hm^3)	CESIE, 1973
Population of Spain (1970)	34,032,000	Tamames, 1977
Gasoline consumption by tractors	8 l/h	Miguel Blasco, Personal Communication
Work of tractors	1500 h	Miguel Blasco, Personal Communication
Number of tractors	25,015	Jordana de Pozas, 1973
Efficiency of power plants	37 %	C. Hall, Personal Communication
Population in the Ebro Watershed	2,360,000	Bovio Fernández, 1971
Population equivalents in the Ebro Watershed	5,360,000	Bovio Fernández, 1971
BOD load per capita per day (80 % is industrial)	65 g	Carriello Queralto, 1971
Average water consumption by agricultural irrigation	10,000 m^3/ha	CESIE, 1973
Fertilizers used in Spain (N, P, and K.)	37 kg/ha	Jordana de Pozas, 1973
Number of harvesters	2,611	Jordana de Pozas, 1973
Gasoline consumption by harvesters	12 l/hr	Miguel Blasco, Personal Communicaton
Hours worked by harvesters	750 h/year	Miguel Blasco, Personal Communication
Heat energy of diesel fuel used by harvesters and tractors	19,000 btu/lb	Shell Co. brochure
Water quality of the Ebro River downstream from Zarazaga:		
Sediments	350 mg/l	Records of Zaragoza Water Treatment Plant
$CaCo_3$	100 mg/l	Bovio Fernández, 1971
NaCl	30 mg/l	Bovio Fernández, 1971

Table 4. Land use in the Ebro River Basin in 1965. Values in parenthesis represent 1970 data (Jordana de Pozas, 1973; Zarazaga Burillo, 1971).

Category	AREA (ha × 10^3)	Portion dedicated to grazing (ha × 10^3)
Total Productive Area	8,458.3	
Under cultivation	3,326.2	
Secano*	2,710.8	(1,007.2)***
Irrigated**	615.4 (639.3)	(222.7)***
Not cultivated	5,132.1	(4,254.6)***
With pasture	4,345.5	
Without pasture	786.6	
Unproductive Area	713.9	
Total Area	9,172.2	

*Wheat represents about 75% of total.
**Wheat represents about 50% of total.
***Produces 2,832,961,800 units of nourishment or 0.71×10^{13} kcal/year.

Table 5. Some assumptions used in the evaluation of the agriculture and ecosystem model in Fig. 11.

Agriculture and Natural Ecosystem Model

1. Solar input is based on land use (Table 4) times average solar radiation (Table 6). A 732×10^{13} kcal discrepancy with the value reported in Fig. 7 is due to double accounting of water evaporation from reservoirs.

2. Productivity of Agriculture: Used net yield efficiencies of 0.3% and 0.07% for secano and irrigated fields, respectively (Table 2). Multiplied these efficiencies by solar input to these fields according to their respective areas (Table 4). Assumed that net yield was 15% of gross primary productivity. This assumption is based on subsidized american agriculture.

3. Productivity of Forests: Assumed net yield was 10% of gross primary productivity. This is based on results from other xeric environments in temperate zones. Yields were calculated from information in Jaime Fanlo and Aguilar (1967) for wood, Table 7 for cattle feed and animal work, and the balance was assigned to wildlife.

4. All activity related to cattle was computed from information on Table 7.

5. Agricultural subsidies were calculated from data in Table 3 for fertilizers and for fossil fuel consumption by tractors and harvesters.

6. The water budget is the same as the one in Fig. 10.

Table 6. Solar radiation measured at Zaragoza.

Month	Solar Energy* kcal/m^2.day
1973	
September	5227
October	3895
November	2049
December	1743
1974	
January	2108
February	3158
March	3872
April	6085
May	6925
June	7123
July	7690
August	6721
Mean	4716

*Heat equivalents.

Table 7. Inputs and yields of the range industry in the Ebro River Basin. The total cattle equivalent population of consumers is 1,17 × 10^6 animals which require an annual input of 4,14 × 10^9 units of nourishment (UN)**. All data from Zarazaga Burillo (1971). Value in parenthesis is the assumed dry weight.*

Inputs		Yields	
Source	Amount	Type	Amount (fresh weight)
Cultivated lands	2.83 × 10^9 UN	Meat (20%)	27.20 × 10^4 mt
Other lands	1.04 × 10^9 UN	Work	20.75 × 10^6 obradas***
Straw	0.47 × 10^9 UN	Milk	31.90 × 10^7 liters
Total fo.ↄd	4.37 × 10^9 UN	Eggs	10.98 × 10^7 dozen
Human labor		Dung (5%)	79.12 × 10^5 mt
Other subsidies		Wool	43.73 × 10^5 kg
		Honey	13.48 × 10^2 mt
		Wax (30%)	62 mt

*Based on the following inventory of animals: 284,479 heads of cattle; 3,996,417 lambs; 1,007,058 pigs; 26,201 horses; 79,640 mules; 25,387 asses; 180,647 goats; 7,553,866 chickens; 823,553 rabbits; and 58,102 bee hives. The standing crop of cattle, lambs, and pigs was 44,4 kg/ha. Total standing crop for consumers was 51.6 kg/ha.

*UN was calculated from ratios of UN/Qm of green tissue (ratio equal to 16). 1 UN equals 2.5 × 10^3 kcal heat equivalents.

***1 obrada equals 8 hr.

Table 8. Relationship between fossil fuel energy use in Spain and gross national product. Energy values are from the Shell Oil Co. And economic data and energy values in parenthesis are from Tamames (1977).

Year	Gross National Product		Fossil Fuel Input
	1969 Pesetas $\times 10^9$	Current Pesetas $\times 10^9$	kcal $\times 10^{13}$
1958	1043.3	581.8	4.77
1959	1037.5	603.4	4.61
1960	1052.2	620.4	4.56 (23.67)
1961	1172.5	706.6	5.16 (23.69)
1962	1279.2	816.7	6.19 (25.42)
1963	1396.2	963.9	7.28 (28.20)
1964	1475.5	1088.0	8.83 (29.45)
1965	1577.4	1287.0	10.74 (30.0)
1966	1699.5	1477.3	12.23 (32.23)
1967	1776.5	1632.1	14.68 (34.95)
1968	1874.8	1804.9	17.18 (37.50)
1969	2011.7	2011.7	18.73 (39.74)
1970	—	2258	21.86 (41.73)

Table 9. Some statistics about Spain taken from the 1977 world population data sheet of the Population Reference Bureau, Inc.

Parameter	Value
Population Estimate	36.5 million
Birth Rate	18/1,000
Death Rate	8/1,000
Rate of Natural Increase	1 %
Number of years to Double the Population	69
Population Under 15 Years	28 %
Population Over 64 Years	10 %
Life Expectancy at Birth	72
Urban Population	61 %
Per Capita Gross National Product	$2,700

Table 10. Linear regressions (y = m x + b) of energy in fossil fuel equivalents and gross national product and of rainfall and agricultural production in Spain and the Ebro River Watershed (respectively).

X	y	m	b	r
Fossil fuel enegy used in Spain (kcal $\times 10^{13}$ from Shell (Co. in Table 8)	Pesetas $\times 10^{9}$ (not corrected for inflation)	0.52	1126	0.55
Fossil fuel energy used in Spain (kcal $\times 10^{13}$ from Shell Co. in Table 8)	1969 Pesetas $\times 10^{9}$ (corrected for inflation)	65.97	815	0.98
Fossil fuel energy used in Spain (kcal $\times 10^{9}$ from Tamames, 1977 in Table 8)	1969 Pesetas $\times 10^{9}$ (corrected for inflation)	57.83	−224.6	0.99
Rainfall (mm) in the Ebro River Watershed	Yield (kg/ha) from Alberto and Machin, 1977	0.148	241	0.82

Table 11. Economic activity associated with primary productivity in the Ebro River Watershed during 1967 (Zarazaga Burillo, 1971 and Maestro Palo, 1971).

Productive Sector	Economic Value (10^{9} pesetas)
Agriculture	27.25
Range	14.29
Forestry	1.47
Total	43.01*

*14.6% of Spain's production and 2.6% Spain's gross national product in 1967.

Table 12. Calculation of the investment ratio for Spain (1970) and reports for other parts of the world (Maltby, 1977).

Purchased Energy (I)		Natural Energies (II)			Investment Ratio
Energy Quality	Fossil Fuel Input	Solar Input	Hydroelectric Power	Chemical potential of Water	I/II
Fossil Fuel Equivalents	41.73×10^{13}	43.33×10^{13}	12.04×10^{13}	3.60×10^{13}	$\frac{42 \times 10^{13}}{59 \times 10^{13}} = 0.7$
Heat Equivalents	41.73×10^{13}	$86{,}665.6 \times 10^{13}$	—	7.21×10^{14}	—

Country or Economic Sector	Investment Ratio
North Florida	1.8
Oyster Processing in Florida	2.2
Jacksonville, Florida	1.3-2.8
Cypress Wood Processing in Lee County, Florida	1.9
France	1.9
World Average	0.3
South Florida	2.4
Miami, Florida	4-10
United States (1973)	2.5

Table 13. Energy uses in various countries (kcal/person.year)

Country	Free Energy	Purchased Energy	% of Total that is Purchased	Efficiency of Energy Use Based on Total Input
India (East Gangetic Plain)[a]	3.6×10^6	0.6×10^6	14.3	7.6
China (Human)[a]	7.5×10^6	1.9×10^6	20.2	10.4
Tanzania[a]	6.0×10^6	0.2×10^6	3.2	5.4
Nigeria[a]	4.4×10^6	0.2×10^6	4.3	5.9
México (North)[a]	14.7×10^6	3.6×10^6	19.7	24.1
Ebro River Watershed (1970)[b]	90.8×10^6	30.0×10^6	24.8	—
Spain (1970)[c]	23.0×10^6	11.4×10^6	33.1	—
Puerto Rico (Northeast Coast, 1970)[d]	98.0×10^6	228.6×10^6	70.0	—
United States (1973)[e]	—	125×10^6	—	—
Jacksonville, Florida (1974)[f]	240.5×10^6	309.5×10^6	56.3	—

[a] From Makhijani (1976) in heat equivalents.

[b] From Fig. 7; using a population of 2.36×10^6 (Table 3); and assuming a productive area of 97 % of the watershed operating for 6 months at 0.03 % efficiency.

[c] From Table 10; using a population of 36.5×10^6 (Table 3) and assuming a productive area of 90 % of the country operating for 6 months at 0.03 % efficiency.

[d] From Lugo *et al.* (1977).

[e] From Fig. 5 and a population of 200×10^6.

[f] From Maltby (1977); in fossil fuel equivalents; and a population of 570,000.