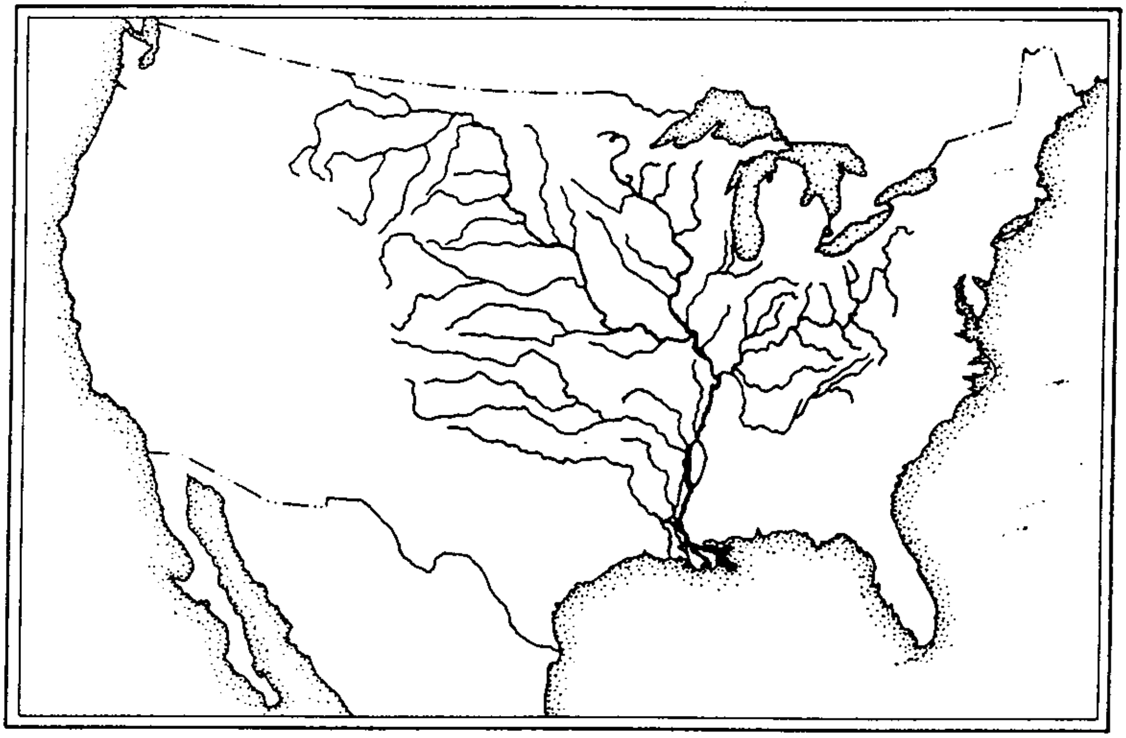
Energy Systems Overview of the

MISSISSIPPI RIVER BASIN

Howard T. Odum, Craig Diamond and Mark T. Brown



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Report to

THE COUSTEAU SOCIETY

ENERGY SYSTEMS OVERVIEW OF THE MISSISSIPPI RIVER BASIN

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Environmental Engineering Sciences

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The Cousteau Society

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 natural resources 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.

Regarding the Mississippi River, we believe no river in the world has been more used in so many varied activities. For Americans, this mighty river has been a vital artery for the transfer of food, natural resources, and industrial products to and from the American heartland. Great demands have been imposed on the Mississippi. Some say the river has been controlled and that, as a consequence, great benefit has been derived. Others maintain that attempts to control the Mississippi are futile and that the cost, both in dollars and in the health of the river's many ecosystems, will be paid by many generations yet to come.

In view of these differences of perspective and opinion, we have invited Dr. H. T. Odum and his team to employ their energy analysis techniques to evaluate river resources and their uses. We hope this approach, and the contents of this document, will contribute to better river management for the future.

The objective of The Cousteau Society is to educate and to communicate on a global scale, to document what Americans have learned from their great Mississippi "experiment", and to determine how this information can help our fellow voyagers on this water planet to manage more wisely our vital water resources.

SUMMARY

An energy systems overview was developed for the Mississippi Basin of the United States. New methods of analysis were used to evaluate environmental bases of the economy and consider alternatives, trends, and policies. Solar EMERGY, a natural measure of value, was used to determine contributions of environmental work and human work to the economy on the same basis, namely the equivalent solar energy required. Contributions of each item to the economy were estimated using the percentage its solar EMERGY was of the total solar EMERGY of the system. This proportion of the economy was expressed in dollars and was called MACROECONOMIC VALUE to distinguish it from usual economic value, which is what people are willing to pay in a market. This report includes the following sections:

1. The Introduction gives definitions, policy questions, methods, and symbols for energy systems diagrams.

2. Energy symbol diagrams compare pioneer and modern systems for interfacing the resources, the river and the economy.

3. A complex network diagram and a simpler aggregated model were drawn and the main sources evaluated in units of solar EMERGY and macroeconomic value. The main bases for the economy are flows of oil and gas, rain and the rivers, and outside goods and services. A large value is in the sediments eroded from farmlands and washed to the sea unused.

4. The physical and network characteristics of the hierarchy of stream branching was analyzed, determining energy transformed according to the order of stream. The solar EMERGY transformed per unit of water energy (transformity) measures the value of concentrating water into larger streams. Transformities increase by a factor of 60 times from small streams to the main river at New Orleans. As a measure of complexity, information contents of the network were found and related to the system of energy flow which maintains the system.

5. Tables of EMERGY flow were developed to consider public policy alternatives for the Basin. Very large values in wetland service, in sediment deposition, and in water control were diverted into the sea by diking and channelizing. Although large savings were obtained for transportation, especially for fuel transport, they were less than previous river values unnecessarily diverted. General economic development produced higher macrovalues, but they were much lower than those possible with a better use of the river. Macrovalues obtained for waters, fisheries, agriculture, and wetlands were much larger than the market values. High values justify measures for restoring wetlands and their contributions.

6. A microcomputer simulation model was developed using the data for the aggregated overview of the Basin economy. Declining fuel reserves caused a maximum in the economy, followed by gradual decline. The time of maximum assets was sensitive to the prices of foreign fuels, increasingly important with the decline of sources within the Basin.

7. With an understanding of the economy and the values of alternatives, come suggestions for the future. A challenge lies in making the transition

from a fuel-based economy to one that reorganizes the Mississippi River, its wetlands, and its economy in order to generate more services in the form of land rotation, forest production, fishery production, agricultural renewal, flood absorption, and water reconditioning, as well as transportation, trade, and human settlements.

I. INTRODUCTION

Increasingly, with new technologies, new concepts, and new attitudes, humanity is learning to take an overview of the larger systems of environment and humanity. Through television documentaries everyone is learning to think on the large scale of weather fronts, economic trends, and patterns of human development of nature. Because the water cycles of the earth are so important in the organization of the landscape, river basins form a natural unit for understanding, predicting, and planning for the future. The Mississippi River Basin System is one of the greatest, important not only to the states and the nation, but, through trade, to the world (Figure 1).

Along with the production of films that vividly represent systems at close view and with an overview, some new scientific techniques help the mind comprehend and facilitate quantitative measurements of the forces and factors at work in growth and change. This study uses energy systems models to improve our overview of the Mississippi River Basin System. Such understanding can assist humans in their new role as stewards of their own future. As with a zoom lens, we have to look at the small processes of the great watershed system up close and the large mechanisms at a distance. First, we model the geologic, meteorologic, biotic, and economic factors of the Basin as a whole and evaluate the importance of the pathways with energy analysis.

From the overview we look to see how world economic trends operating through the national economy are controlling important inputs to the Basin. Then we look more closely to see how river network energy works under natural and economic management. Energy analysis results are used to consider the role of component processes, problems, and alternatives. An overview simulation model is used to consider alternative trends for the future. Finally, perspectives are given for the future.

Because many of the earth's processes of work converge on the Mississippi River Basin and subsequently are converged by waters to the wetlands and delta, much of the economic value of the Mississippi River Basin is based on Nature's work. Often the work of the economy inadvertently eliminates some of this value. Long-range economic vitality requires management of the basin so that the work of nature and that of the economic system are symbiotic, facilitating the maximum combined work of the whole area. In the past, calculations of economic values of a single function such as navigation, flood control, or short-term yields of farm products have led to the work of humans being directed in opposition to that of nature. A larger systems view suggests alternatives in which the concentrated work of humans and their technology works as a controlling agent matching the work of water, vegetation, variations in sea level, etc.

Many questions are raised concerning development and the economic carrying capacity of the Mississippi River Basin? How is development accommodated with destruction of resources? How is a balance maintained between humanity and sustainable land uses? How will international economic trends and decreasing availability of world resources affect the Mississippi? What is the meaning of the depressed economy of agriculture and manufacturing of the early 1980's, in view of the longer range trends? What will be the

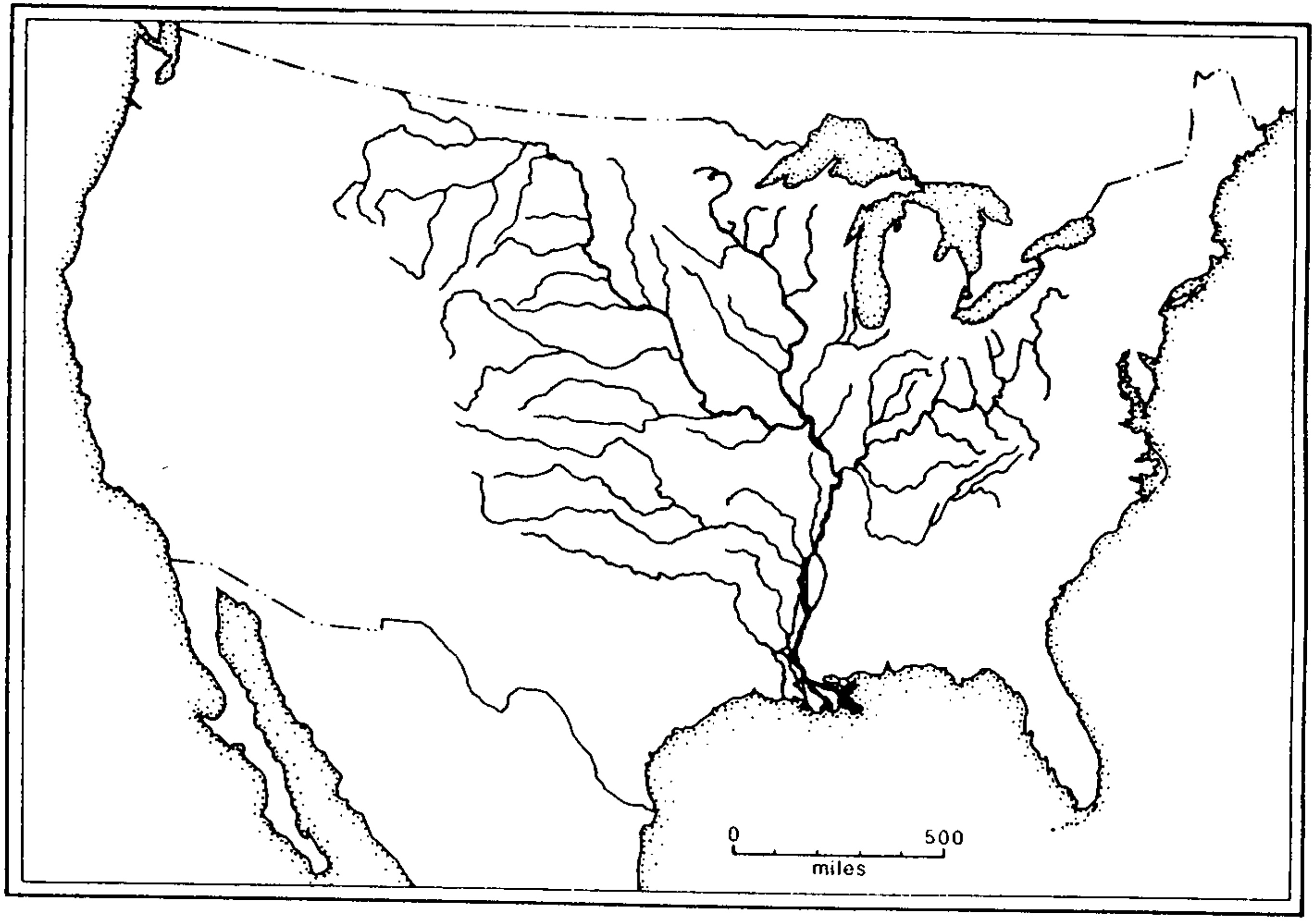


Figure 1. Map of the Mississippi River Basin showing principal features important to overview models.

sources of fuels? What is the future of soils and wetlands? How will river energies be used? What patterns of spatial development will occur? What infrastructure develops the best economy of nature and of humanity? What trends follow a decline in gas and oil resources of the region? What limits the use of waters of the river? What economic policies in world trade and within the U.S. economy will foster a sustained economy that uses environmental resource systems as a contributing partner rather than a temporary consumable to be eliminated? To obtain some answers, energy analysis tables, indices of economic contribution, and a simulation model were developed.

Perspectives

The Mississippi River Basin comprises 3.22 E6 square km (equivalent to 41% of the area of the 48 contiguous states and touching 31 of them), making it the world's second largest drainage area. Its combined length, including the Missouri River tributary, is 6020 km, the third longest river system. It receives .80 m of rainfall per year and focuses an estimated 18,100 m3/sec (sixth highest world volume) through its delta.

The Basin (Figure 1) is bounded by the Rocky Mountains on the west and the Appalachian Mountains on the east. It extends just over the Canadian border into southern Alberta and Saskatchewan and is separated from the watershed containing the Great Lakes by a narrow sandy ridge. On the south it is delimited by the Texas plains which drain directly into the Gulf of Mexico. The average elevation of the Basin is 777 m and the average slope is about 4 ft/mi (.76 m/km). The overall low relief of the Basin has contributed greatly to its use for agriculture, while the low gradient of the river and its extent have been significant for transportation use.

Since the Basin covers such an extensive area, one finds a variety of attributes in terms of precipitation, soil types, natural vegetation communities, geological substrata, etc. It is subject to a variety of weather conditions including high probabilities of tornadoes in the center of the Basin as well as hurricanes along the Gulf Coast. One important consequence of the combination of low relief and high rainfall, particularly in the south, is the occurrence of major annual flooding. Significant flooding, and damage, occur in the Ohio River tributary system primarily as a result of seasonal spring storms and melting winter snowpacks. The alluvial floodplain of the Mississippi extends as far north as southern Missouri. Development of the river's edge and fertile floodplains has necessitated extensive flood control measures which have had complicated effects on riverine ecosystems, the river's hydrology, and the growth of urban areas throughout the lower basin.

The Delta (actually the culmination of eight separate deltas in a period of less than 10,000 years) occupies only 2.04 E10 square meters, about .63% of the entire Basin, but represents the convergence of many of the Basin's energies. Each year over 2.43 E11 kg of sediments, primarily clays, are discharged through the delta into the Gulf of Mexico. An amount nearly equal to that in sand and silt is dredged by the Corps of Engineers in maintaining the harbors and navigation channels of the Basin transportation system. Preserving the current pattern of distributaries and channel cross sections is proving to be an expensive task for the Corps as the river attempts to find the shortest path to the Gulf and adjusts itself according to variance in its flow and load throughout the year. Presumably, the great concentrations of gas and oil under the Delta are attributable to the pressure and heat generated by the volume of sediment depostied by the river over the centuries on top of old layers of vegetation and marine detritus. Currently the Louisiana coast, which is dominated by the Mississippi-Atchafalaya distributary complex, is the single most productive fishing ground in North America in terms of poundage with the Mississippi River adding a small but significant percentage of catch.

The Basin is relatively rich in important resources, particularly fossil fuels. Most of the U.S.'s major coal deposits lie within the Basin borders and, as previously noted, important reserves of oil and natural gas are to be found in the vicinity of the Delta. Extensive, but low quality, reserves of uranium exist throughout the western plateaus of the Appalachians. Production of iron ore, lead, zinc, bauxite, and sulfur occurs within the Basin. Large reserves of groundwater (e.g. the Ogallala aquifer) are also mined for agricultural purposes.

Many major U.S. cities (St. Louis, New orleans, Baton Rouge, Pittsburgh, Cincinnati, Minneapolis and others) depend on the river system for substantial portions of their commodity transportation needs. In the past 15 years the Mississippi River system has come to account for more than 50% of all ton-miles of freight traffic among the coastal and inland waterways. The bulk of the nation's grain exports are transported via the Mississippi and leave through New Orleans. The river is additionally used as a source of municipal water and as a sink for industrial wastes.

In the western portion of the Basin much river water is diverted from already shallow tributaries to irrigate farmlands. Approximately 70% of the Basin's area is in cropland or range, a use which is responsible in part for increased erosion and consequently high sediment loads of the river. Runoff from farms includes relatively high concentrations of nutrients, herbicides, and pesticides which have been shown to accumulate in the Delta area. Heavy metals and other industrial byproducts have been shown to occur at the river outfall also, concentrating in body tissue of fish and birds.

Methods

Overviews and understanding of the Mississippi Basin were sought with energy systems methods that used models to analyze and synthesize knowledge about the systems of humanity and nature on three scales of size: (a) the larger national and international economies to which the river basin contributes, (b) the river basin itself, and (c) component land use systems, the wetlands, estuaries, and agroecosystems. Model diagrams were used to organize and express structure and processes. An aggregated version of these models was computer-simulated to learn the temporal consequences of resources, relationships, and policies built into the models. After aggregated diagrams were developed, EMERGY analysis was used to measure the economic importance of various inputs, processes, and accumulations. From the EMERGY tables, various ratios and indices were calculated to provide perspectives on trends and preferred policies.

Energy Diagrams of Models

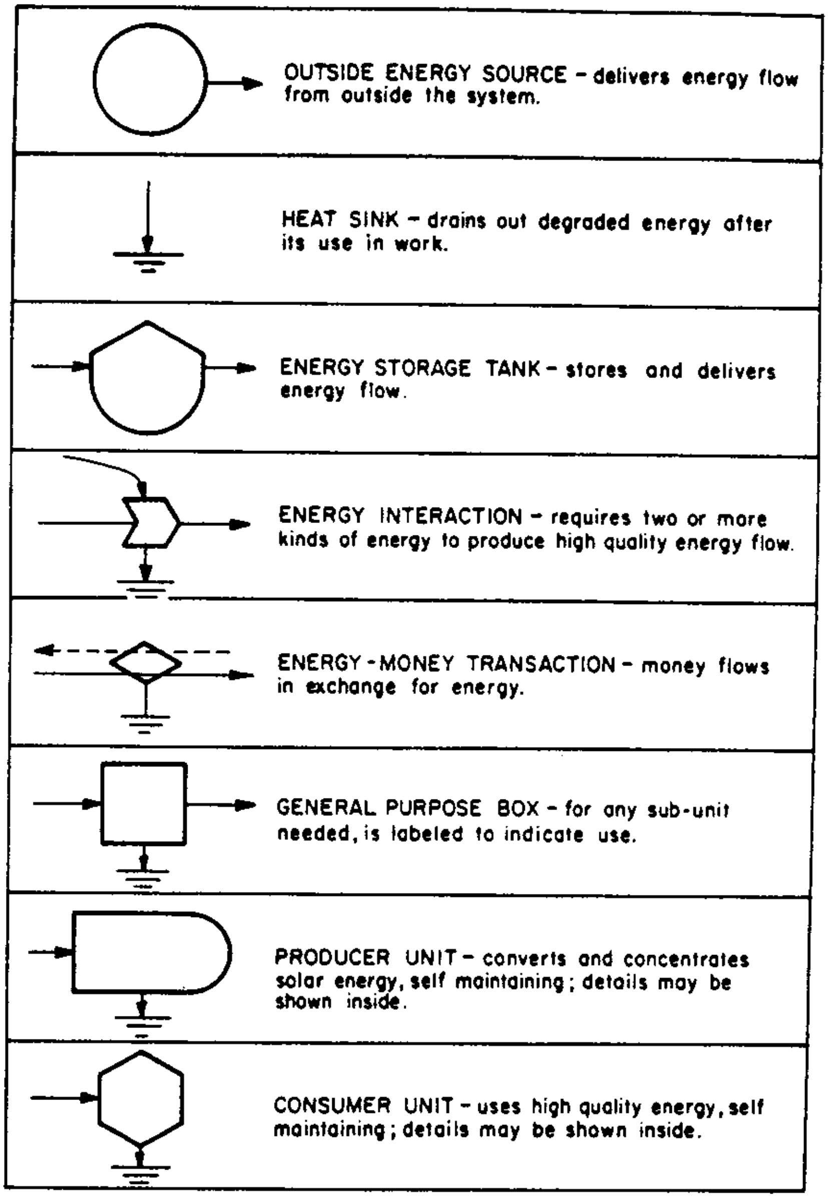
Energy systems diagrams were drawn using symbols and language conventions provided in a number of texts (Odum, 1971, 1983). Explanations of the main symbols are given in Figure 2. After a boundary of the system is indicated with a rectangular frame, outside influences are shown with source symbols (circles) arranged from left to right in order of increasing transformity (see definitions in Table 1). Within the frame, main components such as producers, consumers, storages, and interactions are shown again, arranging symbols from left to right according to energy intensity. Pathways are then connected between symbols. The way the pathways are joined to the symbols indicates mathematical relationships such as adding, multiplying, integrating, etc. The energy diagram provides a visual overview of the system. The diagrams are structured to represent hierarchy from numerous smaller items on the left converging to fewer larger-territoried items on the right. Flows of money are included as dashed lines and are related to other flows by prices. After a diagram is produced, a simpler version may be developed by aggregating (combining) some units that were shown separately in the first inventory.

Computer Simulation

Mathematical relationships are readily inferred from the energy diagram since each pathway has a characteristic term that goes with each kind of symbol-pathway pattern. Thus a set of differential equations may be written by inspection, one equation for each unit in the diagram that has storage properties. From the equations, microcomputer simulation programs may be written in a computer language such as BASIC. To calibrate the coefficients of the model's equations, values of storages and flows are written on the energy diagram pathways where it is easy to compare and check numbers. For example, flow of money in and out of a system could be set equal, thus calibrating at steady state to simplify calculations of coefficients. After substituting values for each storage term in an equation, it is solved for the coefficient value. Coefficients are then entered in the computer program. Graphs may be generated by the computer showing the nature of growth, leveling, oscillation, etc. over time that derive from the set of assumed relationships and values.

EMERGY Analysis

After the initial energy diagram was simplified by aggregation to show the main inputs and flows, solar EMERGY and macroeconomic values were calculated for the main flows and storages of interest and expressed in an EMERGY analysis table. Emergy analysis is a form of energy analysis for determining values of resources and other inputs on a similar basis. Solar EMERGY, a natural measure of value, was used to determine contributions of environmental work and human work to the economy on the same basis, namely the equivalent solar energy required. Contributions of each item to the economy was estimated using the percentage its solar EMERGY was of the total solar



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 2. Explanation of symbols of the diagrammatic energy language.

Table 1. Definitions.

EMERGY (Embodied energy)	Energy of one type required to generate a flow or storage of matter, another type of energy, or information. Embodied energy is an older name which has been used with more than one meaning. The units of EMERGY are emjoules or emcalories.
Theoretical transformity	Energy of one type required to generate a unit of energy of another type in a system adapted for optimum efficiency and maximum power.
Practical transformity	Ratio of EMERGY to energy observed in a surviving real system.
Solar transformity	Solar EMERGY per unit of energy of a particular type. Its units are solar emjoules per joule.
Net EMERGY yield ratio	Ratio of EMERGY yielded per EMERGY of the same type of energy fed back from the economy
EMERGY investment ratio (Econoic-environment ratio)	Ratio of EMERGY purchased from the economy to the input of EMERGY of the same type from the environmental resources.
Exchange ratio	Ratio of EMERGY in the currency received to the EMERGY of the same type in a product sold.
Macroeconomic value	Part of gross economic product contributed by an EMERGY input and expressed in $.
Net benefit	Difference in EMERGY or macroeconomic value in changing one alternative to another

EMERGY of the system. This proportion of the economy was expressed in dollars and was called MACROECONOMIC VALUE to distinguish it from usual economic value, which is what people are willing to pay in a market. See definitions in Table 1.

Raw data are given in Table 1. Transformities from other studies are given in the next column. Solar transformity of an item is the solar EMERGY required for one unit of energy of the type in that item. For example, about 40,000 Joules of solar energy are estimated as the necessary amount to generate a joule of coal (Odum and Odum, 1983). Therefore, the solar transformity of coal is 40,000 solar emjoules per joule.

The raw data values in the first column are multiplied by the transformities in the second column to obtain the solar EMERGY in the third column. Using the diagram to avoid double counting, sums and ratios can be calculated. By expressing inputs or production in units of solar EMERGY, flows of entirely different types may be expressed in units that can be added to determine the total contribution that has gone into a product. The solar EMERGY is a common denominator that is believed to evaluate the amount of one commoditiy that is substitutable for another.

Finally, the solar EMERGY was divided by the solar EMERGY/$ ratio for a particular year to obtain the macroeconomic value in $ for that year. The ratio of solar EMERGY per $ was obtained from national analyses which evaluated the total solar EMERGY of the main resources and services supporting an economy in a particular year and divided by the gross economic product for that year.

EMERGY Criteria for Economic Evaluation

Useful indices that use EMERGY for inference are included in Table 1. The EMERGY measures the contribution to an economy by nature or by humans. By proportion, a dollar equivalent (macroeconomic value) may be estimated. The percentage that the EMERGY of a process is of the total economy's budget of EMERGY is the percentage that that process is of the gross national product.

Fuels may be evaluated with a net EMERGY yield ratio which is the ratio of EMERGY yield to the EMERGY inputs supplied by the monied economy. Ignoring the use of subsidies, fuel sources with the highest net energy yield ratios will be the most competitive, economically. Sources with lower ratios require relatively high levels of inputs from the monied economy.

The EMERGY investment ratio is the ratio of the inputs from the economy to the free inputs from the environmental resources. The ratio is useful for determining the relative contribution of free inputs. For a process to be competitive it must have as much free input as its competitors. The ratio also measures environmental loading. A high ratio means that the environment is loaded with economic inputs.

By analyzing the main EMERGY inputs of a whole country and dividing by the gross national product an EMERGY to dollar ratio is found for that country. This can be used to estimate the EMERGYthat goes with paid services. The EMERGY per person is a useful measure of total contributions to the person's existence. Rural people receive more EMERGY basis for their existence directly without money payment than city people. In this case money does not measure their relative standard of living.

The benefits from buying and selling may be inferred from the relative magnitudes of The EMERGY in the trade. The balance of EMERGY is very different from the balance of money payments. Money evaluates only human services, since money is only paid to people. The EMERGY evaluation includes all inputs including those of human service, of fuels, and environment.

Policy Criteria

The EMERGY was used to choose between alternative plans and policies. Alternatives with higher EMERGY inputs increase an economy's vitality and competitive position. It may be expected that in the trial-and-error process of open markets and human individual choices, the pattern that generates more EMERGY will tend to prevail and be copied. Recommendations for the future likely to be successful go in the direction of the natural tendencies as predicted by selecting that which maximizes EMERGY.

Choice Between Alternatives Using Net EMERGY Benefit

To distinguish between an old systems and a proposed new system, the change in EMERGY contribution is estimated. See Figure 3. After a complex diagram is drawn to identify the main sources, components, and processes, a simpler diagram is drawn of the new system, the old system, and the connections with the larger system. Then an EMERGY analysis table is evaluated with a line for each input. Flows that use previous stored reserves are included.

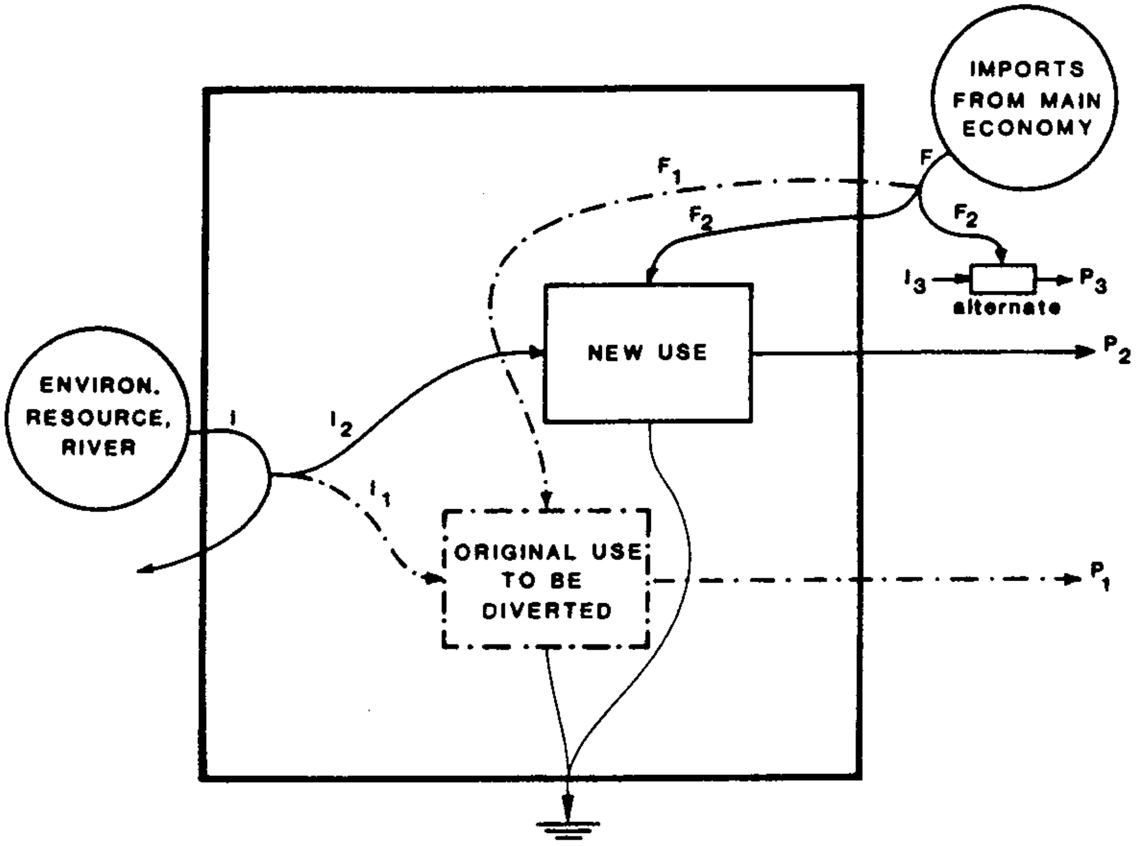
Then the change in EMERGY contribution due to the changed system is calculated. The change in EMERGY contribution between one system and another is:

$$\text{Change in contribution} = P2 - P1 \qquad (1)$$

where P2 is the EMERGY contribution of the new system, P1 is the EMERGY contribution of the older system.

The contribution of the new system or proposed new system (P2) may be compared with an alternative investment of the same economic inputs (P3). The alternative is estimated as the sum of the economic input (F_2) plus the regional matching of environmental resources that may be expected ($I_3 = F_2/I_R$). The investment ratio I_R was defined in the methods section as the ratio of the EMERGY flow from the economy to that supplied free from the environmental resources.

$$P3 = F_2/I_R + F_2 \qquad (2)$$



Old : $P_1 = I_1 + F_1$

New: $P_2 = I_2 + F_2$

Alternate: $P_3 = F_2 + F_2/I_R$

Figure 3. Generic diagram for identifying EMERGY flows to be evaluated in considering alternatives in choices and management of an economic sector involving environmental resources.

Comparison is made by subtracting the alternate EMERGY contribution (P3) from the EMERGY contribution of the new systems (P2).

$$\text{Contribution difference} = P2 - P3 \qquad (3)$$

Another comparison can be made between the new system and the contribution with the most potential. The potential EMERGY contribution (P4) is estimated by multiplying the available environmental resource contribution (I) by the investment ratio (I_R);

$$P4 = I_R * I \qquad (4)$$

$$\text{Comparison with Potential} = P2 - P4 \qquad (5)$$

If comparisons are made in EMERGY units, solar emjoules per year, the dollar magnitude (Macroeconomic Value) of the change is obtained by dividing by the solar EMERGY/$ ratio. For 1986 the U.S. ratio was 2.0 E12 solar emjoules/$.

An alternate procedure is to express the flows in macroeconomic $ before making the Net Benefit Calculations.

Successful new projects would be expected to be an increase in EMERGY contribution over the past and over alternatives available in the region. If the evaluation of the new system is less than the potential, it means that environmental potentialities are being wasted and ultimately a better system could emergy, subject to delays due to inertia, political events, and other factors. A hypothesis, largely untested as yet, is that trial and error eventually develops the maximum EMERGY system. Our EMERGY analyses may help find the maximum EMERGY pattern sooner.

In Section V the maximum EMERGY criterion for selection of alternatives is applied.

Methods for Characterizing Energy and Complexity of River Networks

Two procedures were used to show properties of the river network. First, the hierarchy of converging streams was measured by the gravitational potential energy used in successive segments. Segments were classified according to stream order and the energy used at one order to generate the next was calculated. Thus, solar transformities were determined for different orders of streams from headwaters to mouth. These express in solar EMERGY units the concentration that takes place in solar energy from global processes causing rains and runoffs in the Mississippi Basin. The higher the transformity of the stream, the greater the contribution of the river to the cities and floodplains that use the river.

Second, the information content in units of macroscopic entropy in the branching was calculated using Shannon formulae. These were statistically correlated with age, rainfall, and runoff by Diamond (1984). As a measure of water system complexity, the Information (Entropy) measure may indicate locations for maximum interaction of humanity and nature.

II. OVERVIEW OF ENVIRONMENT AND ECONOMY OF THE MISSISSIPPI BASIN

Howard T. Odum

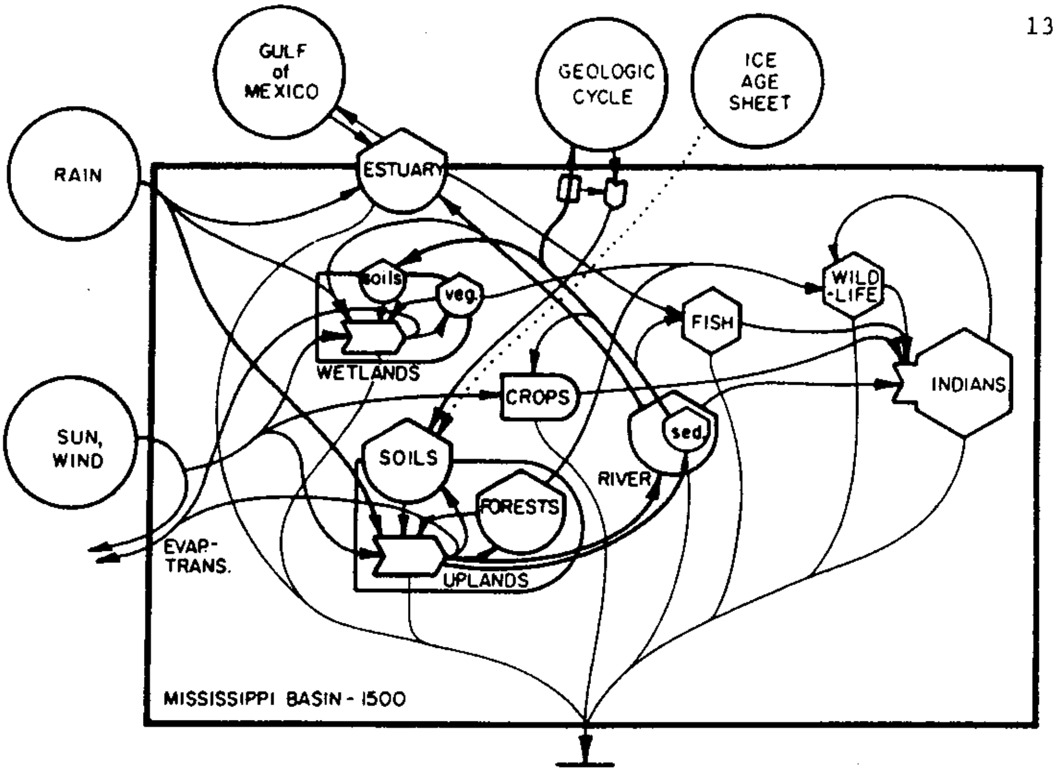
Using energy network diagrams to gain systems overview, two contrasting energy systems diagrams are given in Figures 4 and 5. Figure 4 represents the Mississippi River Basin prior to European colonization, operating on renewable resources. Figure 5 represents the pattern of urban human society and its pattern of landscape now at the end of the 20th century with a system dominated by the EMERGY of slowly renewable mineral resources at this very special time when total resource use may be at its peak. In the figures the main categories of subsystem are arranged from left to right according to the successive transformations in the convergence of energies. Main categories of causal influences (energy sources), subsystems, and processes are included in the diagrams. The two systems do not appear consistent because in selecting major systems some fall out or appear as major or minor components.

<u>A Producing Regime.</u> In the earlier diagram (Figure 4) prior to European colonization, the convergence of rains and snows to form the river network was the dominant source of EMERGY, controlling the spatial organization of organisms, people, geological processes, and chemical cycles on the surface of the landscape. The cycle of sediments from the uplands washing to the sea drives the sedimentary cycle, with the isostatic uplift of the mountains around the basin replacing the masses lost by erosion. Contributed from below are heat energies driving earth convection which also contribute to the sedimentary cycle of earth.

Main ecosystems are shown, much aggregated: the water-rich forests of the Appalachian Mountains grading through drier climate regimes into prairies and short-grass plains to the divide of the Rocky Mountains. In the lower river, vast areas of swamps and marshes absorbed the annual surges of floods from meltwaters of northern snows. The precolonial times represented in Figure 3 were mainly times of production, storage, and maintenance of geologic and biologic products.

Here human settlements of American Indians were part of the main categories of ecosystems on the watersheds and wetlands of the River. Although at the top of the hierarchy of wildlife, exerting many control influences on landscape through patterns of land use and fire, the humans were not controlling the main flows of EMERGY of the river, the sedimentary cycle, or the rich storages later to dominate the new processes.

<u>Storage-Using Regime.</u> Present in the first diagram but the basis for reorganizing the Basin's system as represented in the second diagram, were massive storages of earth products, storages accumulated by the prior geological and environmental work. There were deep beds of soil-forming materials deposited by earlier ice ages, wind-blown loess, clays and the soils formed by ice scrapings transported south from Canada, massive mountain structures, sculptured river basin forms, rich soils and heavy forests on uplands and in floodplains, large reservoirs of water in the Great Lakes, river lakes, and ground waters. The rich minerals underground stored by cumulative biogeochemical processes were the coal, oil, natural gas, salt



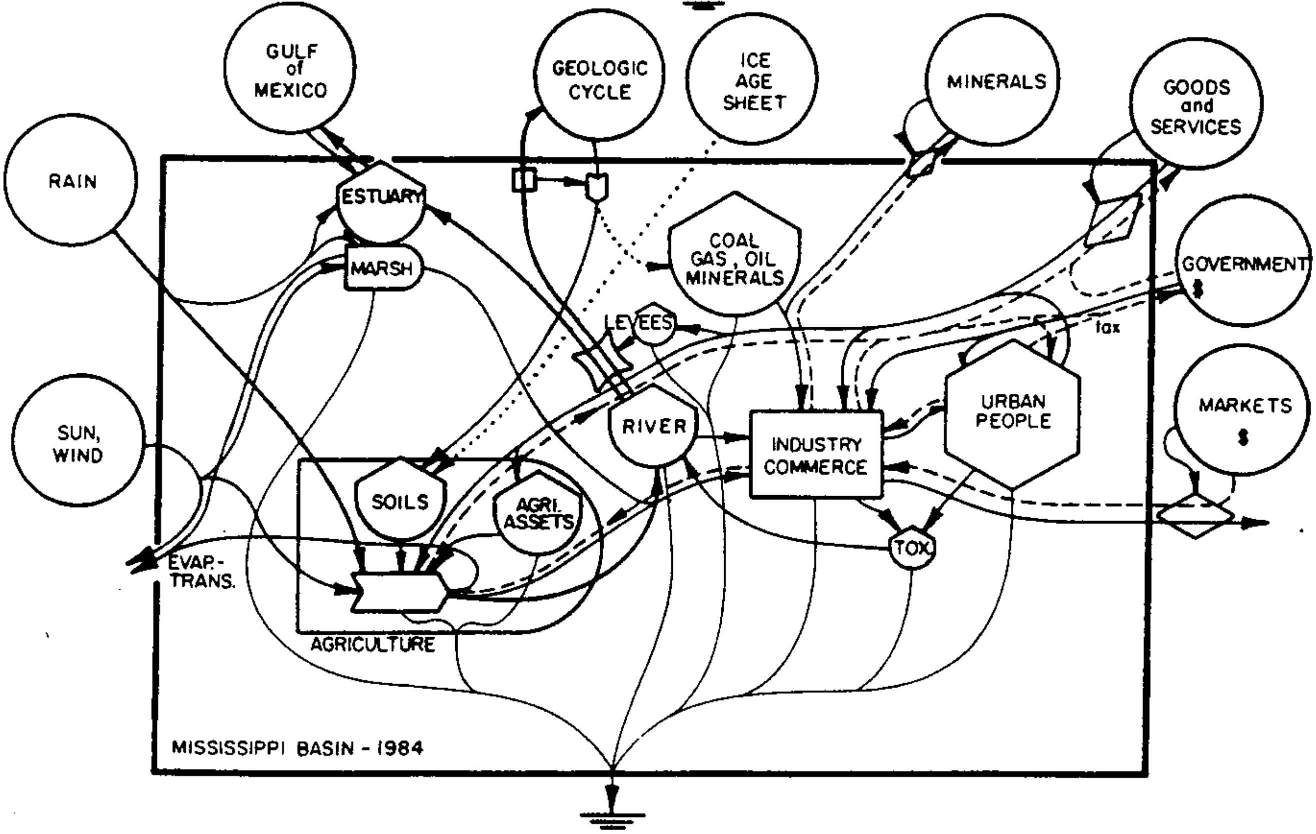


Figure 4. Energy systems overview of the Mississippi Basin in 1500. River line has been darkened.

Figure 5. Energy systems overview of the Mississippi Basin in 1984. TOX = toxic substances; river lines have been darkened.

beds, sulfur, and limestones--then a part of slow sedimentary cycle, little used by processes on the surface.

Although still containing the renewable environmental drives of Figure 4, the overview of the Mississippi Basin in our current time (Figure 5) now has the prior storages under rapid consumption by the economy. Use of fuels, minerals, and soils supports the enormous and dominant urban settlements of humanity, the massive consumer, with enough energies to control many aspects of the great river, the atmosphere, water chemistry, land uses, and some geological processes.

In interpreting the early history of American Culture in the Mississippi Basin, the dominance of New Orleans economically and culturally seems to make sense because of the multiple EMERGIES converging at this point. These are augmented by additional resources imported by river-facilitated foreign imports.

Interpretation of later history finds new centers of EMERGY convergence in additional cities oriented to the distribution of the rich soils, minerals, and fuels for new industries using the river network in new ways for massive water consumption, transportation, and waste processing. Electric lights seen in night views of the region from satellite reveal the high EMERGY centers of human activity and the hierarchical organization of the region with many towns, fewer cities, and only a few urban centers.

Among the possibilities that must be considered in anticipating the future is the return of the system of Figure 5 to that of Figure 4 as the slowly renewable resources now supporting the consumer society will soon be too small to sustain all the urban concentrations.

In Section III that follows the remaining major resource storages and renewable resources are evaluated in EMERGY units so as to infer what is important at the present and in the future.

III. ENERGY ANALYSIS OF THE MISSISSIPPI RIVER BASIN

Craig Diamond and H.T. Odum

Energy analysis was used to make an overview of the Mississippi River Basin. Main features and processes were related with energy network diagrams and were evaluated in units of EMERGY in which energies of varying types are transformed into the equivalent energy of a single type (Odum and Odum, 1983). Flows and storages of available energy were calculated in Calories (kilocalories), as physical heat, potential energy, or chemical potential. Using transformities established by Odum and Odum (1983) all energies were converted to solar equivalents (solar emcalories).

Energy analysis seeks to evaluate the relative magnitudes of the flows and storages of energy which both support and are generated within systems. Placing all values in EMERGY units in equivalent calories of one type, e.g., solar emcalories, permits comparisons among such flows and storages. Energy analysis also reflects the relative importance of and contribution of these flows and storages to the stability of the system and its ability to support further growth and compete with other systems.

Methods

For most physical parameters, an outline of the Mississippi River Basin (defined by the U.S. Water Resources Council, 1978) was superimposed over maps presented in Odum (1983). The boundary of the Basin at the coast was taken to be the 19,000 ppm surface salinity line, which includes all of the estuaries and reefs. The upper boundary was taken to be 1000 m for the evaluation of the vertical diffusion of wind energy. A 1 m depth, for evaluation of soils, was used as a lower boundary. Areas between isopleths were measured using a planimeter and summed for regions differing in solar intensity, precipitation, runoff, wind speed, elevation, soil type, and surface heat flow.

Information on erosion rates, land use (agricultural, urban, and forest), and groundwater supplies was obtained from the Water Resources Council. Data for wave height, tides, and salinity were taken from a study on the Delta region by Costanza (1983). Estimates of mineral reserves were done on an areal basis using the percent of each reserve region within the Basin. Varying quality of reserves within a given region was ignored except for the evaluation of coal which included substantial volumes of lignite.

Data regarding the use of fuels and fertilizers and the production and consumption of electricity, minerals, and agricultural products were taken from the U.S. Statistical Abstract (1983). Where states were not wholly contained within the Basin, approximate boundaries were drawn to county lines for which population data were available. Fuel and electrcitiy use, along with estimates for the returns of taxes, could then be done using per capita values for each state.

Where information was available only at the federal level, i.e., imports and exports of goods and services within the world market, the Basin's share was determined in the following manner: with respect to consumption and imports, the assumption was made that the Basin, because of the extent of its population and size, is representative of the U.S. as a whole, and its percentage of the U.S. population was used as a factor; with respect to exports of grains, the assumption was made that the Basin's share was proportional to its percentage of U.S. production totals for each dominant grain. Exports of manufactured goods were based on the Basin's proportion of employees in the industrial sector.

Procedural Details

A complex diagram containing all major subsystems of the Basin was prepared to determine the interactions governing production and consumption and the contribution of renewable and non-renewable resources. An aggregated diagram, featuring all inflows and outflows in EMERGY of one type was also prepared. General categories, such as all imports, indigenous non-renewables, etc., were then used to calculate indices which can be used for comparisons with other parts of the globe.

Standard formulae of physics and chemistry were used to determine the actual Calorie value of work done on the system and the potential energy of system storages. Flows out of the system were evaluated similarly. The formulae used are presented as footnotes.

Transformities for the flows and storages evaluated were taken from Odum and Odum, 1983; Odum, 1986. The transformities measure energy quality. Actual Calorie values were multiplied by the transformities to give EMERGY values in Solar Equivalent Calories.

Sources and flows were aggregated into categories: renewable sources, minerals and fuels, imported goods and services, exports, etc. Overview indices were calculated using the values obtained by aggregating. Some of the indices evaluated were total energy used, percent of all energy that is renewable, ratio of imports to exports, exports minus imports, fuel use per capita, fraction of use that is not paid for, and an estimate of the region's carrying capacity at the current standard of living.

Results

A complex overview diagram of the Mississippi River Basin is presented as Figure 6. Sources of energy and subsystems are oriented from left to right in order of increasing energy quality and concentration. The river system is at the heart of the diagram, increasing in quality as it raeches the port cities and then losing some of its energy quality as it moves past the estuaries and out to sea. River energy with its sediment load interacts with deep earth cycle energy to build the basin landform which is also eroded by weathering and the river.

Land use categories are connected to the river system, beginning with undeveloped highlands and plains and increasing in energy quality with developed agricultural and floodplain properties. Flood plains were found to be the highest quality of land in that they receive the sediments and nutrient-rich waters from lands above them.

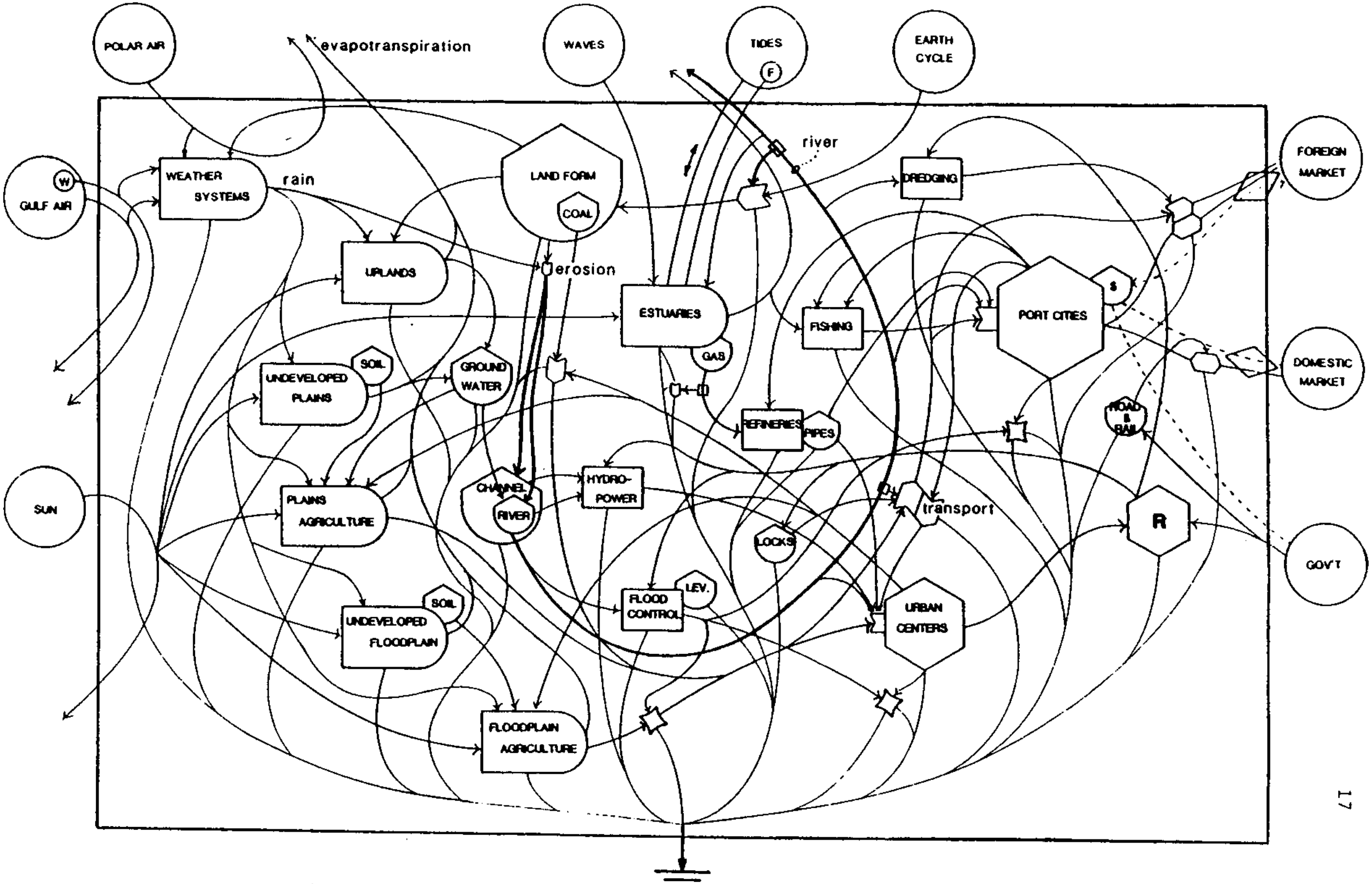


Figure 6. Complex energy diagram of the modern system of the Mississippi Basin. R, river management agencies; W, water vapor.

To the right of the river system are the government agencies, U.S. Army Corps of Engineers (CoE), Tennessee Valley Authority (TVA), and Bureau of Land Management (BLM), that manipulate the river's activity. Urban centers and floodplain agriculture are protected from flooding; regional and international commerce is augmented by the dredging of nearshore, main stem, and tributary channels; hydropower is made available for industry. Reserves of fossil fuels are shown feeding into urban processes and the extraction of gas and oil is shown to impact the estuaries. Groundwater, another important storage, is being tapped to provide energy for agriculture.

Based on Table 2, the chemical potential of rainfall over the Basin is the largest inflow of renewable energy. The direct use of fossil fuels is nearly seven times the value of all renewable sources. Goods and services, representing the general transfer of items evaluated primarily by their dollar value rather than actual energy content, are the largest flows both into and out of the system. The extensive use of the Basin as an agricultural tool is evident from the relatively high embodied energy of grain and animal products. Similarly, the Basin is used as a resource base in terms of the amount of fuel exported to the remainder of the U.S. and the world market.

Coal remains a huge storage of energy for the Basin. Combined storages of alternate fuels (oil, gas and forest wood) constitute only about two percent of the EMERGY of coal. Actual Calories of uranium are shown to be of even greater value than coal, but the estimates of tonnage are less reliable than those of coal and the concentrations at this time are considered too low to be economically competitive.

From sedimentary rock weathering and from past deposits of glaciers, deep beds of soil resources are the most valuable long-range resource. The EMERGY in soil is that of the clay materials and that of the soil profile that ecosystems build with those materials. The clay-rich earth materials that erode from croplands are mainly redeposited in floodplains where they may continue to contribute to productivity, but those unnecessarily lost out to sea represent loss of economic potentials. The topsoil profiles take several hundred years to develop and erosion of these represents a loss of nature's previous work for that period of time. However, when the earth materials of the profile (clays) are lost out to sea, materials are lost that required several thousand years to develop. In Table 2 both were evaluated, but only the more valuable earth loss (item #7) was included in regional totals so as to avoid double counting erosion.

Figure 7 is an aggregated diagram of the Basin that includes all major storages and sources of energy. The values are in solar emcalories and were taken from Tables 2 and 3. The derivations of these values are shown in the footnotes to the tables.

Indices and Discussion

An energy analysis of the Mississippi River Basin is similar to an analysis of the entire U.S. economy. Indices and ratios for the Basin and the U.S. as a whole are assembled in Tables 4 and 5. The results in Table 2 and

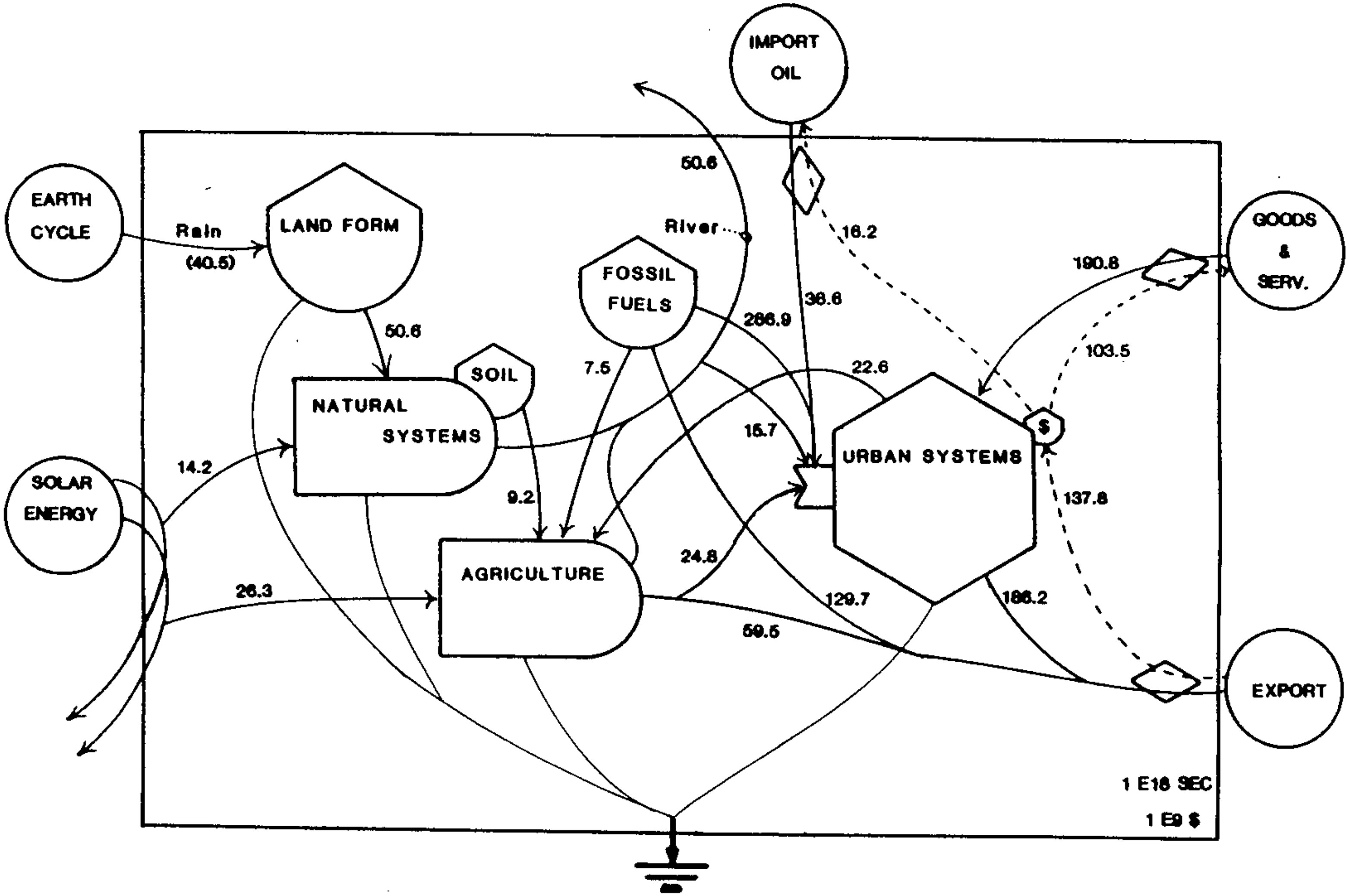


Figure 7. Aggregated diagram of the Mississippi Basin with solar EMERGY values written on principal pathways. See Tables 2 and 3.

Table 2. EMERGY flows of the Mississippi River Basin.

Footnote	Item	Energy Cal or g/yr	Transformity SE Cal/Cal or Cal/g	Solar EMERGY (E 18 SE Emcal/yr
1	Direct sunlight	4.51 E 18	1	4.51
2	Kinetic energy of wind	8.59 E 15	623	5.35
3	Tides	1.01 E 12	23,564	0.02
4	Geopotential of runoff	1.01 E 15	23,564	23.80
5	Chem. potential of rain	2.62 E 15	15,444	40.46
6	Waves	5.75 E 12	25,889	0.15
7	Net loss of earth	1.75 E 14 g	2.89 E 5 SE Cal/g	50.58
8	Net loss of topsoil	1.45 E 14	6.30 E 4	9.15
9	Coal consumed	1.87 E 15	3.98 E 4	74.23
10	Oil consumed	2.30 E 15	5.30 E 4	121.69
11	Gas consumed	1.83 E 15	4.80 E 4	87.60
12	Electricity (non-fuel) cons.	2.99 E 14	15.90 E 4	47.54
13	Earth cycle	1.16 E 15	2.90 E 4	33.77
14	Major crops produced	3.00 E 16	6.80 E 4	80.08
15	Animal products	1.08 E 14	4.24 E 5	42.36
16	Fish harvested	6.37 E 11	1.51 E 7	9.60
17	Minerals produced	1.82 E 13 g	2.03 E 5 SE Cal/g	3.70
Imports				
18	Nitrogen	4.09 E 12 g	1.00 E 6 SE Cal/g	4.09
19	Phosphorus	2.17 E 12 g	4.78 E 6 SE Cal/g	10.35
20	Potassium	2.27 E 12 g	4.57 E 5 SE Cal/g	1.04
21	Oil	6.91 E 14	5.30 E 4	36.63
22	Goods	--	--	7.18
23	Services	--	--	183.59
Exports				
24	Coal	1.83 E 15	3.98 E 4	72.83
25	Gas	1.18 E 15	4.80 E 4	56.64
26	Grain	5.30 E 14	6.80 E 4	36.04
27	Goods	--	--	3.20
28	Animal products	--	--	22.34
29	Services			182.97

Footnotes to Table 2.

1. Direct sunlight:

Average insolation value was measured to be 383.73 ly/day using maps developed by Visher (1954 quoted in Odum et al., 1983).

Area of basin is 3.22 E 12 m^2 (U.S. Water Resources Council, 1978).

(Avg. insolation)(area)

(383.73 ly/day)(10 Cal/m^2·ly)(3.22 E12 m^2)(365 day/yr)

= 4.51 E18 Cal/yr

2. Wind:

Average eddy diffusion coefficient was determined to be 14.74 m^2/s using data from Swaney (1978).

Average vertical wind gradient was determined to be 4.42 E-3/s using data from Swaney (1978).

(height)(density)(diff. coefficient)(wind gradient)^2(area)

(1 E 3 m)(1.23 kg/m^3)(14.74 m^2/s)(4.42 E-3/s)^2(3.22 E 12 m^2)

(3.154 E 7 s/yr)(2.389 E-4 Cal/joule) = 8.59 E 15 Cal

3. Tides:

Mean tidal range is 0.24 (Costanza et al., 1983).

Area of estuarine habit is 2.02 E 6 ha (Costanza et al., 1983).

(0.5)(area)(tides/yr)(height)^2(density)(gravity)

(0.5)(2.02 E14 cm^2)(730/yr)(23.9 cm)^2(1.025 g/cm^3)(980 cm/sec^2)

= 4.23 E22 erg/yr

= 1.01 E12 Cal/yr

Footnotes for Table 2 (cont.)

4. Geopotential of rain:

Average elevation was measured to be 2549 ft (776.93 m) using maps developed by Hunt (1967 as quoted by Odum et al., 1983).

Average runoff value was calculated to be 6.83 in/yr based on data from the U.S. Water Resources Council (1978) - see Appendix A

(area)(avg. elevation)(runoff)(density)(gravity)

$(3.22\ E\ 12\ m^2)(776.93\ m)(0.173\ m)(1\ E\ 3\ kg/m^3)(9.8\ m/sec^2)$

$= 4.25\ E\ 18\ J/yr$

$= 1.01\ E15\ Cal/yr$

5. Chemical potential of rain (Gibbs free energy):

Average rainfall over the Basin is 31.46 in/yr (0.799 m/yr) based on maps developed by NOAA (1977 as quoted by Odum et al., 1983). Since average runoff is 6.83 in/yr (0.173 m/yr), rainfall evapotranspired is taken to be 0.626 m/yr.

Average temperature over the Basin is 55°F (13°C) and 70°F (21°C) in the Delta region (NOAA, 1977 as quoted by Odum et al., 1983).

Average salinity in the estuarine and nearshore regions of the Delta is 19.4 ppt (19,440 ppm)(Costanza, 1983).

G = Gibbs free energy per gram = $(RT \log_e C_2/C_1)/(m.w.)$

$(1.99\ E{-}3\ Cal/°K \cdot mole)(286°K)\ln(999{,}990/965{,}000)/(18\ g/mole)$

$= 1.13\ E{-}3\ Cal/g$

Over the basin: (area)(rainfall)(G)

$(3.22\ E12\ m^2)(0.626\ m/yr)(1\ E\ 6\ g/m^3)(1.13\ E{-}3\ Cal/g) = 2.27\ E15\ Cal/yr$

Gibbs free energy at the delta:

$(1.99\ E{-}3\ Cal/°K \cdot mole)(294°K)\ln(999{,}990/980{,}600)/(18\ g/mole)$

$= 6.36\ E{-}4\ Cal/g$

Footnotes for Table 2 (cont.)

$(3.22\ E\ 12\ m^2)(0.173\ m/yr)(1\ E\ 6\ g/m^3)(6.36\ E\text{-}4\ Cal/g)$

$= 3.55\ E\ 14\ Cal/yr$

Total = 2.62 E 15 Cal/yr

6. Waves:

Shoreline was measured to be 257 km.

Wave velocity derived from the square root of the product of gravity and shoaling depth (3.12 E 8 m/yr)

Mean wave height is taken from data by Thomson (1977 as quoted by Odum and Odum et al., 1983).

$(length)(1/8)(density)(gravity)(height)^2(velocity)$

$(2.57\ E\ 7\ cm)(1/8)(1.025\ g/cm^3)(980\ cm/sec^2)(4.9\ E\ 1\ cm)^2$

$(3.12\ E\ 10\ cm/yr)$

$= 2.42\ E\ 23\ erg/yr$

$= 5.75\ E12\ Cal/yr$

7. Net loss of earth calculated as the difference between rate of earth formation from rocks and loss of earth offshore. Average rate of earth formation, 31.2 $g/m^2/yr$ (Odum and Odum, 1983) was used for Mississippi Basin. Outfall rate of suspended solids, 2.43 E14 g/yr (Costanza, 1983) based on 10 yr data from U.S. Geological Survey plus dredging loss:

Dredging loss used the mean of two estimates: (1) 7.96 E12 g/yr from Ocean Dumping (U.S. Army Corp of Engineers). (2) calculation where 30% of offshore dumping was in New Orleans area: density of mixed sands and silts was 2.81 g/cm^3; 8.78 E7 yd^3 dumped offshore annually (Armstrong and Ryner, 1978):

$(0.3)(8.78\ E7\ yd^3)(2.81\ g/cm^3)(.765\ m^3/yd^3)(1\ E6\ cm^3/m^3) = 5.66\ E13\ g/yr$

Mean dredging loss: $(5.66\ E13 + 7.96\ E12)/2 = 3.22\ E13\ g/yr$

Footnotes for Table 2 (cont.)

Total outflow:

(0.322 E14 g/yr dredging loss + 2.43 E14 g/yr suspended outflow =

= 2.75 E14 g/yr

Net earth loss:

(2.75 E14 g/yr outflow) - (31.2 $g/m^2/yr$)(3.22 E12 m^2) = 1.75 E14 g/yr

8. Energy in net loss of topsoil:

Erosion rates and areas of land type are reported in Appendix B. Mature range and forest areas assumed to have no net loss, hence production equals erosion for these areas. Loss of topsoil from crop areas, 8.97 E14 g/yr (Appendix B). Typical soils are 3% organic matter, and 5.4 Cal/g is empirically derived (Odum and Odum, 1983).

(8.97 E14 g/yr)(0.03)(5.4 Cal/g) = 1.45 E14 Cal/yr

Footnotes for Table 2 (cont.)

9, 10, 11, 12. Fuels consumed:

Refer to Appendix C.

Consumption data are from the Energy Information Administration (1983) Data for states entirely within the Basin are reported in Section I. Figures for states not entirely within the Basin (Section II) were derived as follows: Using maps from Rand McNally & Co. (1978), basin boundaries were outlined conforming to county boundaries. 1970 Census values for all counties within the Basin were summed and then divided by the state census total, giving a percentage of population within the Basin for each state. This percentage was applied uniformly to consumption values for each fuel type. Where percentage values were less than 1, the total of residents was multiplied by that state's average per capita energy use value.

Fuel	E 12 BTU (0.252 Cal/BTU)	E 12 Cal
Coal	7415	1869
Oil	9128	2300
Gas	7244	1825
Electricity	1187	299

Note: Electricity is the sum of nuclear generated, hydropower and transfers.

13. Earth Cycle:

Surface heat flow was calculated to be 4.8 E-2 W/m^2 using contour maps in Sorenson (1979).

(heat flow)(area)

(4.8 E-2 W/m^2)(1 joule/sec·W)(2.389 E-4 Cal/joule)(3.154 E7 sec/yr)

(3.22 E12 m^2) = 1.16 E 15 Cal/yr

Footnotes for Table 2 (cont.)

14. Major Crops:

Production values are from Appendix E.

Calorie values are from Composition of Foods, U.S. Agricultural Handbook No. 8 (Watt and Merril, 1975).

Energy = (mass)(energy/unit mass)

Corn: (1.62 E 14 g)(3.55 Cal/g) = 5.75 E 14 Cal

Wheat: (4.67 E 13 g)(3.30 Cal/g) = 1.54 E 14 Cal

Soybeans: (4.46 E 13)(4.03 Cal/g) = 1.80 E 14 Cal

Sorghum: (1.57 E 13 g)(3.32 Cal/g) = 5.21 E 13 Cal

Total = 9.61 E 14 Cal

Transformity for industrial corn is 6.8 E 4 SE Cal/Cal

(9.61 E 14 Cal)(6.8 E 4 SE Cal/Cal) = 65.35 E 18 SE Cal

Hay: Transformity for hay should be between that of native grasses and industrial crops. Based on local price of $30 per 1200 lbs, the transformity is 1.07 E 4 SE Cal/Cal. The mean of the two other transformities is 3.62 E 4. (2.63 E 14 Cal)(1.07 E 4 SE Cal/Cal) = 2.81 E 18 SE Cal

Pasture Grass: Range acreage is 2.674 E 8 acres (U.S. Water Resources Council, 1978). Average net primary production of temperate grasslands is 600 $g/m^2 \cdot yr$ (Whittaker, 1975).

(2.674 E 8 acres)(4047 m^2/acre)(600 $g/m^2 \cdot yr$) = 6.49 E 14 g/yr

(6.49 E 14 g/yr)(4.25 Cal/g) = 2.76 E 15 Cal/yr

Transformity for grass biomass is 4.32 E 3 SE Cal/Cal (Odum, 1983).

(2.76 E 15 Cal/yr)(4.32 E 3 SE Cal/Cal) = 11.92 SE Cal/yr

Total Cal = 3.00 E 16 Total SE Cal = 80.08 E 18

Footnotes for Table 2 (cont.)

15. Energy in animal products = (mass)(energy/mass)

Production values are from Appendix F.

Calorie values are from Watt and Merril, 1975.

Cattle: (1.07 E 13 g)(4.28 Cal/g) = 4.58 E 13 Cal

Hogs: (8.31 E 12 g)(4.36 Cal/g) = 3.62 E 13 Cal

Sheep: (3.03 E 11 g)(3.31 Cal/g) = 1.00 E 12 Cal

Broilers: (2.16 E 12 g)(2.39 Cal/g) = 5.16 E 12 Cal

Turkey: (6.23 E 11 g)(2.39 Cal/g) = 1.49 E 12 Cal

Eggs: (1.13 E 12g)(1.63 Cal/g) = 1.84 E 12 Cal

Total = 9.15 E 13 Cal

Transformity for animal products was based on caloric conversion rates of 1 Cal cattle per 7 Cal grain (64.4%) and 1 Cal hog per 5 Cal of grain (34.4%). Value is 6.23.

(6.23)(6.8 E 4 SE Cal/Cal) = 4.24 E 5 SE Cal/Cal

(9.15 E 13 Cal)(4.24 E 5 SE Cal/Cal) = 38.80 E 18 SE Cal

Milk: Transformity for milk products is 2.2 E 5 SE Cal/Cal (Odum, 1983)

(2.49 E 13 g)(0.65 Cal/g) = 1.62 E 13 Cal

(1.62 E 13 Cal)(2.2 E 5 SE Cal/Cal) = 3.56 E 18 SE Cal

Total Cal = 1.08 E 14 Cal   Total SE Cal = 42.36 E 18

16. Fish harvested = (mass)(energy/mass)

Harvest for Louisiana area is 1290 E 6 lb (1975-81 avg)

Harvest for Mississippi River and tributaries is 73 E 6 lb (U.S. Statistical Abstract, 1983)

Total is 1363 E 6 lb (6.18 E 8 kg)

(6.18 E 11 g)(1.03 Cal/g) = 6.37 E 11 Cal

Note: Commercial fish only - sport fishing not included.

Footnotes for Table 2 (cont.)

17. Mineral production = (mass)(solar EMERGY/g)

Production values are from the U.S. Statistical Abstract, 1983.

Transformity for elements is 2.03 E 5 SE Cal/g (Odum, 1983)

Mineral	Mass E 9 g
Bauxite	499.0
Copper	5.4
Salt	13,600.0
Sulfur	3,592.8
Land	150.0
Zinc	160.0
Uranium	181.4
Total	18,188.6 E 9 g

(1.82 E 13 g)(2.03 E 5 SE Cal/g) = 3.70 E 18 SE Cal

Footnotes for Table 2 (cont.)

18, 19, 20. Fertilizers consumed:

Values are from Appendix D.

21. Oil imports:

Based on difference between production (Appendix I) and consumption (Appendix C).

(6,374 E 12 BTU) - (9,117 E 12 BTU) = - 2,743 E 12 BTU

(2,743 E 12 BTU)(0.252 Cal/BTU) = 6.91 E 14

Note: This figure represents net imports. Much foreign oil is delivered to lower river port cities for processing and is exported out of the Basin.

22. Imported goods:

Data is from the U.S. Statistical Abstract, 1983. Values are for 1980. Mill products have transformities that include labor. Other imports are approximated under Services (Footnote 23) in terms of dollar/energy ratio.

Item	World Quantity E 12 g	Energy (Cal/g)	Transformity SE Cal/Cal	Solar Emergy (E 18 SE Cal)
Iron Ore	28.3	8.05 E-3	6.01 E 7	13.69
Bauxite	13.9	1.56 E-2	1.32 E 7	2.86
Steel Products	16.3	2.16 E-2	1.97 E 7	6.93
Aluminum	0.6		(3.89 E 6 SE Cal/g)	2.34
			Total	25.82

Assuming standard of living of the Basin is representative of the U.S. average and Basin is 27.8% of U.S. population:

(25.82 E 18 SE Cal)(0.278) = 7.18 E 18 SE Cal.

Footnotes for Table 2 (cont.)

23. Imported service

a) Fuel: Basin imported 2754 E 12 BTU of oil (4.75 E 8 bbl). Average price per barrel in 1980 on the world market was $34.00 (1980) so final cost was $16.15 E 9.

($16.15 E 9)(9.08 E 8 SE Cal/$) = 14.66 E 18 SE Cal

b) Agricultural products: Based on known exports of $23.90 E9 minus relative exports of $12.91 E9 (Appendix G) and $10.99 E9 imported from the rest of the U.S.

($10.99 E 9)(6.21 E 8 SE Cal/$ for USA = 6.82 E18 SE Cal

Based on U.S. imports of $15.77 E 9 for foods, Basin share would be $4.38 E 9.

($4.38 E 9)(9.08 E 8 SE Cal/$ for the world) = 3.98 E 18 SE Cal

c) Manufactured goods: Based on U.S. imports (excluding fuel and cattle) of $161.72 E 9, Basin share would be $44.96 E 9.

(44.96 E 9)(9.08 E 8 SE Cal/$) = 40.82 E 18 SE Cal

d) Relative services: From Appendix G imported services from the rest of the U.S. were $26.86 E 9.

($26.89 E 9)(6.21 E 8 SE Cal/$) = 16.68 E 18 SE Cal

c) From Appendix G the sum of federal benefits is $162.05 E 9.

($162.05 E 9)(6.21 E 8 SE Cal/$) = 100.63 E 18 SE Cal.

Total is 183.59 E 18 SE Cal.

Footnotes for Table 2 (cont.)

24, 25. Coal and Gas Exports:

Based on the difference between production (Appendix I) and consumption (Appendix C).

Coal: (14,654 E 12 BTU) - (7,405 E 12 BTU) = 7,249 E 12 BTU

(7,249 E 12 BTU)(0.252 Cal/BTU) = 1.83 E 15 Cal

Gas: (11,911 E 12 BTU) - (7,234 E 12 BTU) = 4,677 E 12 BTU

(4,677 E 12 BTU)(0.252 Cal/BTU) = 1.18 E 15 Cal

26. Grain exports

Values are from Appendix J.

Corn: (68.76 E 9 kg)(3.55 E 3 Cal/kg) = 2.44 E 14 Cal

Wheat: (37.06 E 9 kg)(3.30 E 3 Cal/kg) = 1.22 E 14 Cal

Soybeans: (34.07 E 9 kg)(4.03 E 3 Cal/kg) = 1.37 E 14 Cal

Sorgham: (8.11 E 9 kg)(3.32 E 3 Cal/kg) = 0.27 E 14 Cal

Total = 5.30 E 14 Cal

27. Exported Goods

a) Petroleum products to world market (UN International Trade Statistics, 1980): (1.43 E 7 Ton)(10.7 E 6 Cal/Ton) = 1.53 E 14 Cal

Basin was responsible for 36.1% of U.S. production.

Assuming similar refining capacity, the contribution to the U.S. world export should be 36.1% of the total.

(1.53 E 14 Cal)(0.361) = 5.52 E 13 Cal

(5.52 E 13 Cal)(5.30 E 4 SE Cal/Cal) = 2.93 E 18 SE Cal

b) Iron and Steel Products (UN International Trade Statistics, 1980):

(4.5 E 6 Tons)(2.16 E 4 Cal/Ton) = 9.72 E 10 Cal

Assume Basin contributes according to its percentage of the U.S. population (9.72 E 10)(0.278) = 2.70 E 10 Cal.

(2.70 E 10 Cal)(1.01 E 7 SE Cal/Cal) = 2.73 E 17 SE Cal

Footnotes for Table 2 (cont.)

28. Animal products

Basin exports of meat and dairy based on the difference between Basin production and 27.8% of U.S. total production, assumed to be Basin consumption level.

(Production - Consumption)(Cal/g)

Cattle: (1.07 E 13 g - 5.06 E 12 g)(4.28 Cal/g) = 2.42 E 13 Cal

Hogs: (8.31 E 12 g - 2.95 E 12 g)(4.36 Cal/g) = 2.34 E 13 Cal

Sheep: (3.03 E 11 g - 9.76 E 10 g)(3.31 Cal/g) = 6.80 E 11 Cal

Broilers: (2.16 E 12 g - 1.96 E 12 g)(2.39 Cal/g) = 4.80 E 11 Cal

Turkeys: (6.23 E 11 g - 3.87 E 11 g)(2.39 Cal/g) = 5.64 E 11 Cal

Eggs: (1.13 E 12 g - 9.61 E 11 g)(1.63 Cal/g) = 2.76 E 11 Cal

Total = 4.96 E 13 Cal

(4.96 E 13 Cal)(4.24 E 5 SE Cal/Cal) = 21.03 E 19 SE Cal

Milk: (2.49 E 13 g - 1.57 E 13 g)(0.65 Cal/g) = 5.96 E 12 Cal

(5.96 E 12 Cal)(2.20 E 5 SE Cal/Cal) = 1.31 E 18 SE Cal

Total = 22.34 E 18 SE Cal

Footnotes for Table 2 (cont.)

29. Exported Services:

a) From Appendix G, estimated export of services as a function of relative difference in economic sectors across the U.S. is $33.07 E 9.

($ 33.07 E 9)(6.21 E 8 SE Cal/$) = 20.54 E 18 SE Cal

b) Value of exported Coal:

Basin produced 69% of U.S. Coal (560 E 6 Tons out of 815 E 6 total.

U.S. exports were 71.8 E 6 Tons (U.S. Statistical Abstract, 1983).

(71.8 E 6 Ton)(0.69) = 49.58 E 6 Ton

Export price is $52.87/Ton.

(49.58 E 6)($52.87) = $2.62 E 9

Exports into the remainder of the U.S. equaled 227.2 E 6 Tons

Domestic price is $26.00/Ton.

(227.2 E 6)($26.00) = $5.91 E 9

Total = $8.53 E 9

($8.53 E 9)(6.21 E 8 SE Cal/$) = 5.30 E 18 SE Cal

c) Value of exported grain:

From Appendix J total value is $23.90 E 9.

($23.90 E 9)(6.21 E 8 SE Cal/$) = 14.84 E 18 SE Cal

d) Contribution to overall U.S. exports (1980 data)

Total exports is $216.67 E 9.

After value of grains, coal, ores, and animal products, the remainder is $176.31 E 9. Assumption is that the Basin produces an average mix of export commodities.

Based on Basin percentage of manufacturing employment (0.2794)

($176.31 E 9)(0.2794) = 49.26 E 9

($49.26 E 9)(6.21 E 8 SE Cal/$) = 30.59 E 18 SE Cal

Footnotes for Table 2 (cont.)

e) Value of exported meat:

Based on export volume (Footnote 27) as a percentage of total U.S. output times gross product value.

Cattle: 7.896 E 9

Hogs: 4.470 E 9

Sheep: 0.224 E 9

Broilers: 0.123 E 9

Turkeys: 0.215 E 9

Eggs: 0.160 E 9

Milk: 2.637 E 9

Total $15.74 E 9

($15.74 E 9)(6.21 E 8 SE Cal/$) = 9.77 E 18 SE Cal

f) Value of natural gas exports:

Based on the difference between production and consumption; fraction exported multiplied by the total market value

11553 E 9 ft^3 - 7026 E 9 ft^3 = 4527 E 9 ft^3

(4527 E 9 ft^3)/(20379 E 9 ft^3) = 0.222

(0.222)($32.7 E 9) = 7.26 E 9

($7.26 E 9)(6.21 E 8 SE Cal/$) = 4.51 E 18 SE Cal

g) Value of taxes

From Appendix H, Federal taxes were $156.88 E 9

($156.88 E 9)(6.21 E 8 SE Cal/$) = 97.42 E 18 SE Cal

Total = 182.97 E 18 SE Cal

Table 3. Storages within the Mississippi River Basin.

Foot-note	Item	Energy (Cal)	Transformity (SE Cal/Cal)	Solar EMERGY (E 21 SE (Cal)
1	Oil	1.36 E 16	5.30 E 4	0.72
2	Gas	2.62 E 16	4.80 E 4	1.25
3	Coal	3.22 E 18	3.98 E 4	128.16
4	Topsoil	3.40 E 17	6.30 E 4	21.42
5	Biomass (forests)	4.98 E 16	3.23 E 4	1.61
6	Groundwater	2.30 E 16	4.11 E 4	0.94

Footnotes for Table 3.

1. Oil:

Quantity of oil and gas liquids from Appendix K.

The equivalence for oil is 5.80 E 6 BTU/bbl .

The equivalence for liquids is 4.1 E 6 BTU/bbl .

The equivalence for dry gas is 1,031 BTU/ft^3.

(7.37 E 9 bbl)(5.80 E 6 BTU/bbl)(0.252 Cal/BTU) = 1.08 E 16 Cal

Liquids:

(2.68 E 9 bbl)(4.10 E 6 BTU/bbl)(0.252 Cal/BTU) = 2.77 E 15 Cal

Total liquid hydrocarbons = 1.36 E 16 Cal

2. Gas:

Quantity of dry gas is from Appendix K.

Dry Gas:

(1.01 E 14 ft^3)(1,031 BTU/ft^3)(0.252 Cal/BTU) = 2.62 E 16 Cal.

3. Coal:

See Appendix L

Footnotes for Table 3 (cont.)

4. Soil:

Quantity of organic matter is from Appendix M.

(6.30 E 16 g organic)(5.4 Cal/g organic) = 3.40 E 17 Cal

5. Biomass:

From Appendix N Forest Biomass is 1.11 E 13 kg.

(1.17 E 13 kg)(1 E 3 g/kg)(4.5 Cal/g) = 4.98 E 16 Cal.

6. Chemical Potential of Groundwater (Gibbs free energy): $G = (RT \log_e C_2/C_1)/(\text{m.w.})$

Surface storage figures are averages. Groundwater storages are "available", not estimated, maximums. Both are based on data in Nation's Water Resources, 1978.

Sub-basin	Surface (E 9 gal)	Ground (E 12 gal)	Totals (E 12 gal)
Ohio	5,161	383	388
Tennessee	3,600	530	534
Upper Miss.	4,231	2,243	2,247
Lower Miss.	2,034	1,272	1,274
Missouri	27,161	445	472
Arkansas	9,853	499	509
Total	52,040	5,372	5,424

Mean value of dissolved load in water is 150 ppm (Odum, 1983).

$$\text{Gibbs free energy} = (1.99\text{ E-3 Cal/mole}\cdot{}^\circ\text{K})(286^\circ\text{K})/\ln\left(\frac{999,850}{965,000}\right)(18\text{ g/mole})$$

$$= 1.12\text{ E-3 Cal/g}$$

(Volume)(density)(G)

$$(5,424\text{ E 12 gal})(3.785\text{ E-3 gal/m}^3)(1\text{ E 6 g/m}^3)(1.12\text{ E-3 Cal/g})$$

$$= 2.30\text{ E 16 Cal}$$

Table 4. Summary of annual EMERGY flows for the Basin.

R	Renewable sources: rain + tide = 40.48 E18 sec
N_o	Dispersed non-renewables: earth + organics = 59.73 E18 sec
N_1	Concentrated non-renewables: oil + coal + gas + nuclear + minerals = 275.83 E18 sec
N_2	Export non-renewables: gas + coal = 129.47 E18 sec
N	All non-renewable sources: 465.03 E18 sec
F	Imported minerals and fuels: oil + fertilizers + transfers = 58.75 E18 sec
G	Imported goods: 7.18 E18 sec
P_2I	Imported services: 183.59 E18 sec
I	Dollars paid for imports: $249.14 E9
E	Dollars received for exports: $259.89 E9
P_1E	Exported services: 182.97 E18 sec
B	Exported products grain + goods + meat = 61.58 E18 sec
X	Gross Domestic Product: $800.76 E9

sec = solar emcalories

Table 5. Basin overview indices (E 18 SE Cal).

(1) Renewable EMERGY flow

$R = 40.48$

(2) Indigenous non-renewable flow

$N = 465.03$

(3) Flow of imported EMERGY

$F + G + P_2I = 249.52$

(4) Total EMERGY inflows

$R + F + G + P_2I + N = 755.03$

(5) Total EMERGY used, U

$R + N_0 + N_1 + F + G + P_2I = 625.56$

(6) Total exported EMERGY

$B + P_1E + N_2 = 347.02$

(7) Fraction of energy used derived from home sources

$(N_0 + N_1 + R)/U = 376.04/625.56 = 0.601$

(8) Exports minus imports

$(B + P_1E + N_2)-(F + G + P_2I) = 374.02 - 249.52 = 124.50$

(9) Ratio of exports to imports

$(B + P_1E + N_2)/(F + G + P_2I) = 374.02/249.52 = 1.499$

(10) Fraction used that is renewable

$R/U = 40.48/625.56 = 0.065$

(11) Fraction of use that is purchased

$(F + G + P_2I)/U = 249.52/625.56 = 0.399$

(12) Fraction used that is imported service

$P_2I/U = 183.59/625.56 = 0.293$

(13) Fraction of use that is free

$(R + N_0)/U = 100.21/625.56 = 0.160$

Table 5 (cont.)

(14) Use per unit area

625.56 E 18/3.22 E 12 m^2 = 1.94 E 8 SE Cal/m^2

625.56 E 18/1.24 E 6 mi^2 = 5.04 E 14 SE Cal/mi^2

(15) Use per capita in 1975

625.56 E 18/60.21 E 6 = 1.04 E 13 SE Cal/capita

(16) Renewable carrying capacity at current living standards

(R/U)(population) = (0.065)(60.21 E 6) = 3.91 E 6 people

(17) Ratio of indigenous sources to imports

$(R + N_0 + N_1)/(F + G + P_2I)$ = 376.04/249.52 = 1.507

(18) Fuel use per person

(283.52 E 18)/(60.21 E 6) = 4.71 E 12 SE Cal/person

(19) Fuel use (plus nuclear and transfers) per person

(315.40 E 18)/(60.21 E 6) = 5.24 E 12 SE Cal/person

(20) Fraction of use that is electricity

120.01/625.56 = 0.192

Figure 7 indicate a system dominated by fossil fuel use and also by input of human services from a larger, external economy.

Table 4 is a summary of annual flows for the Basin, grouped into general categories such as all renewable sources, all imports, all high quality sources, etc. Non-renewables, concentrated for use in urban and industrial processes, are the largest flow. Table 5 presents these genralized flows in the form of indices for comparison with other regions and nations. Index (13) suggests that fifteen percent of the energy supporting the activities of the Basin would not appear in general accounting procedures. Index (16) suggests that the Basin could support less than four million people, at approximately the current standard of living, using only renewable energies.

Earth materials and soil organics were evaluated separately. Earth and clays represent materials accumulated by the slow process of predominantly abiotic weathering while topsoil is a storage created by the interaction of weathered rock and biological activity at a rate approximately 10 times faster. Over a longer time frame, topsoil may be considered a renewable resource. The EMERGY of eroded earth within the Basin should be a sizeable fraction of the chemical potential of rain (solar input); human activities have accelerated this loss.

Through extensive use of soils and fuels, the Basin appears to be exporting energy since the EMERGY in the net loss of clay and topsoils is greater than that in the inflows of rainfall and tides. The use of concentrated energies in the form of fossil fuels, fertilizers, hydropower, and nuclear power is approximately an order of magnitude larger than the rnewable energy flows of the Basin. These concentrated energies were double the value of imported services which equalled the value of exported services (183 E18 SEC/yr).

The Basin's reputation as the world's breadbasket is evident from the EMERGY value of grains, which is about 12% of all the EMERGY used for all purposes. Production of cattle, hogs, and sheep requires about 52% of all grain produced. About 95% of the remaining grain is exported to the world market or to the remainder of the U.S. About 55% of the Basin's animal products are exported. In addition to its role as a grain producer, the Basin exports large volumes of coal and gas. The energy value of these fuels is approximately that of the oil consumed by the Basin on a yearly basis.

Compared with the entire U.S., the Basin is more fuel-intensive: power use per unit area is 1.9 E8 SEC/m^2 versus about 1.7 E8 SEC/m^2; fuel use per person was 1.0 E13 SEC versus 6.9 E12 SEC; about 40% of all energy was purchased compared to a U.S. averaage of 23%; and only 6% of the total that was renewable versus 12% for the U.S. Percentage of electricity use was about the same for the Basin and the U.S. Energy consumption differences are also evident from the ratio of exports to imports, which is about 1.5 for the Basin versus 0.45 for the U.S.

Based on present rates of indigenous consumption and the estimate of storage, there is approximately a six-year reserve remaining for oil a fourteen-year reserve for gas, and a 1725-year reserve of coal. These figures do not include exports, which halve these time periods for the Basin alone. If coal were the only fuel supplying the Basin's fossil fuel needs, there is approximately a 450-year reserve. At an annual growth rate of 2%, the reserve would last about 325 years. If the Basin must supply energy to the rest of the U.S. at the current rate of total consumption for coal and gas, then the reserves are estimated to be only 310 years. An increasing reliance on coal and hydropower may be anticipated as the other fossil fuels become depleted.

At 1978 rates of withdrawal there are 1760 years worth of groundwater remaining. However, in the Missouri and Arkansas regions where available storage is low and depletion rates are high, there is an estimated 323 years of water remaining. An increase in consumption of 2% per year would deplete Basin-wide reserves in less than 400 years.

Soil reserves, based on loss of topsoil evaluated as organic material to a depth of one meter, are estimated at over 850 years. The EMERGY in the net loss of earth materials (river-discharged clays) is about five times as great as topsoils since it requires longer periods of time and, consequently, more solar energy to weather rock.

Since most of the Basin's activities require the interaction of fossil fuels, an overall decrease in output would follow fuel depletion. Pressure for maintenance of the river for navigation and commerce may actually increase, since trains and other transportaiton modes are more fuel intensive (Bayley et al., 1977).

Human energies have been oriented to match those of the watershed. Major hydroelectric systems have been located where the geopotential is greatest. Much of the TVA system occurs on a fourth-order river, which is close in geopotential to that of a fifth-order segment within a seventh-order system. Several dams exist on the Ohio, the Missouri (Fort Peck and Garrison Dams), and the Kansas (Tuttle Creek Dam) Rivers where they are order five.

Conversion of potential energy of water to kinetic energy and then into friction and heat depends on the stream order as defined with Figure 8. Use of water potential energy in friction and bottom work is greatest at order four and decreases nearly uniformly towards the extreme orders. This provides some justification for the size of many upstream cities such as Des Moines, Pittsburgh, Nashville, Chattanooga, and Minneapolis, which are on either fourth-order streams or the point of confluence for a fifth-order stream. The size of New Orleans, relative to the others, can be explained by its proximity to large energy reserves, its international port status whereby it receives many energies from a larger economic system, and the inputs of tidal and biotic energies from the Gulf. No major cities exist on tributaries of order three or less.

Flux of geopotential energy converges, i.e., increases, to order five and then decreases downstream. Cities such as St. Louis, Cincinnati, and Little Rock are then points of departure for energies accumulated in the watersheds above them. The greater geopotential per unit length may also provide a basis for more competitive industry in these cities, in contrast to their environs, since less power needs to be purchased from other sources.

Energies which converge within watersheds are transformed and fed back to the supply points. Maximum power in watersheds may be obtained from the central reaches which can then interact with energies located at the watershed extremes. Geopotential, transformed into electricity where available power is greatest, can be used for mining fuel reserves and pumping groundwater in regions of low stream order. The same energy is used for operating lock and dam structures that serve to move goods to locations beyond the lower reaches.

Total EMERGY is greatest at the Delta and lower floodplain where the watershed, the coast (tides, waves, fish, etc.), and external trade converge. Seafoods, sugar cane, natural gas and oil, citrus, cotton, export grains, and imports represent some of the varied energies found near the Delta. A variety of energy sources are required to maintain cultural diversity which is evident from the cosmopolitan makeup of cities such as New Orleans and Baton Rouge versus regions like the Corn Belt (Iowa and Illinois). Locations where a mix of human knowledge and culture can interact with several energy sources, transform the greatest quantities of energy which may then be redistributed to the upstream sources where energy is less concentrated.

IV. ENERGY DISTRIBUTION IN THE MISSISSIPPI RIVER

Craig Diamond

As rainwaters of the Mississippi Basin drain to the sea, the potential energy of these elevated waters carves the land into a hierarchical network, converging waters from smaller streams into larger ones. This network is a resource upon which the economy depends, and locations of human settlements, industries, hydroelectric uses and waste disposal are related to the availability of the water energy to make these functions economic. This chapter shows the distribution of energy availability to which human activities can be coupled for maximum benefit. These results are from a Masters thesis by Diamond (1984).

The converging of many little streams into a few large ones is represented in Figure 8, which follows the customary way of naming segments into first order, second order, third order, etc. (Horton, 1945). The numbers of segments of different order in the Mississippi Basin are given in Tables 6 and 7. As shown in Figure 9, it takes many small first order segments to support and converge energy to larger segments with more water and head energy downstream. Figure 10 shows the approximate slope of the river with small headwaters steeper than large segments downstream.

Figure 11 shows the total energy in elevated water (geopotential) for each class of streams. The total energy decreases downstream as the potential is converted into water motion and then into friction and heat, but the energy that is passed to the next larger stream size is more concentrated and can support more human activities. Going downstream the power expended per order increases to a maximum in the 6th order streams. Within the entire watershed, this maximum occurs in 4th order rivers (Table 8).

Transformity was defined in Table 1 as the energy of one type required to generate a unit of another. It is a measure of resource value. The river network is driven by the energies of the world cycles of water and earth process which may be expressed as solar EMERGY. By dividing the solar EMERGY of the rains by the energy available in each segment, transformities for each segment result. These are given for each stream order in Table 8. Transformity increases 60 fold from headwaters to mouth. In this sense one gallon of the powerful, large-volume downstream waters is 60 times more valuable than an upstream gallon.

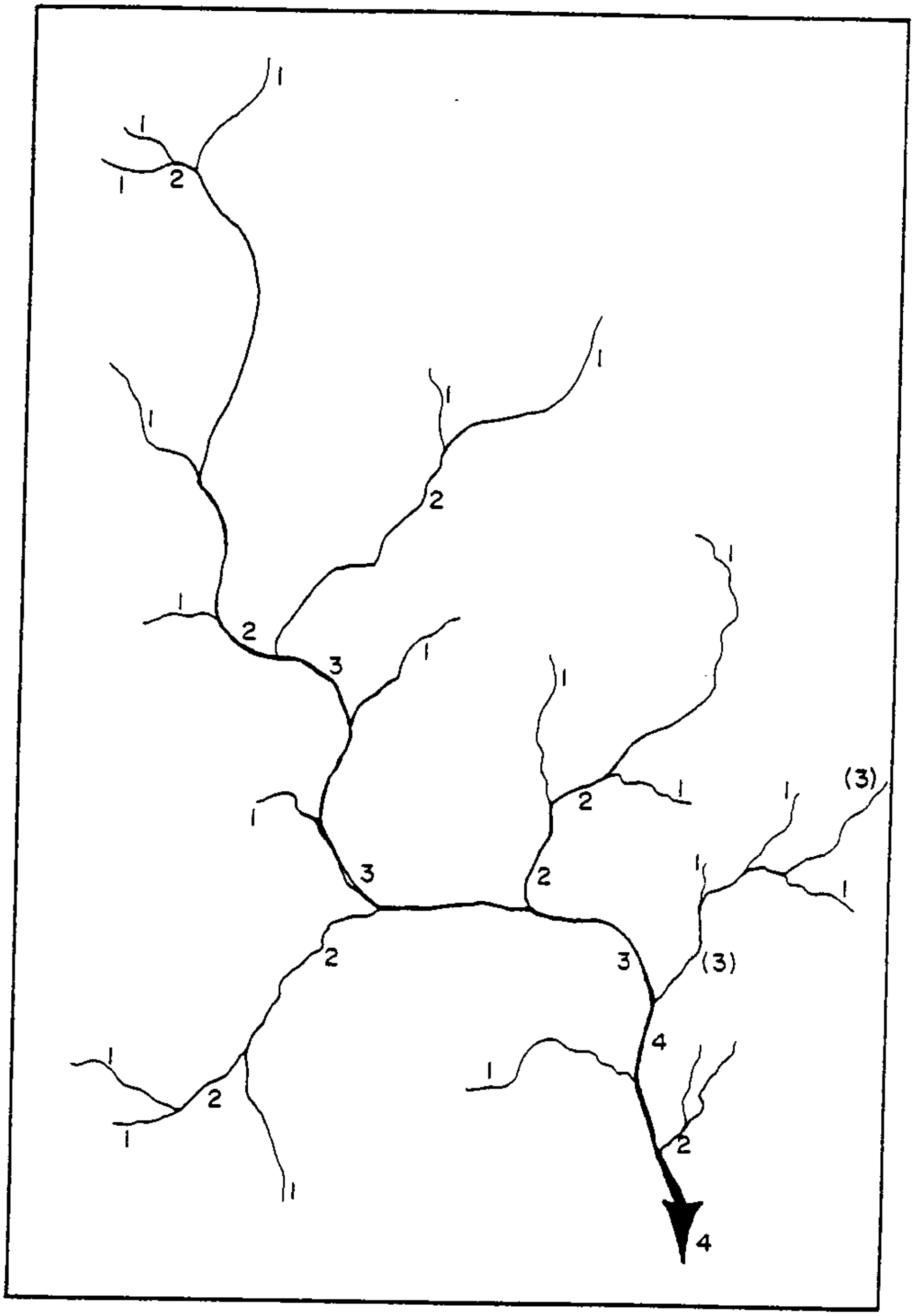


Figure 8. Hypothetical watershed with Strahler's modified Horton numbering scheme for stream order (Strahler, 1952, 1957).

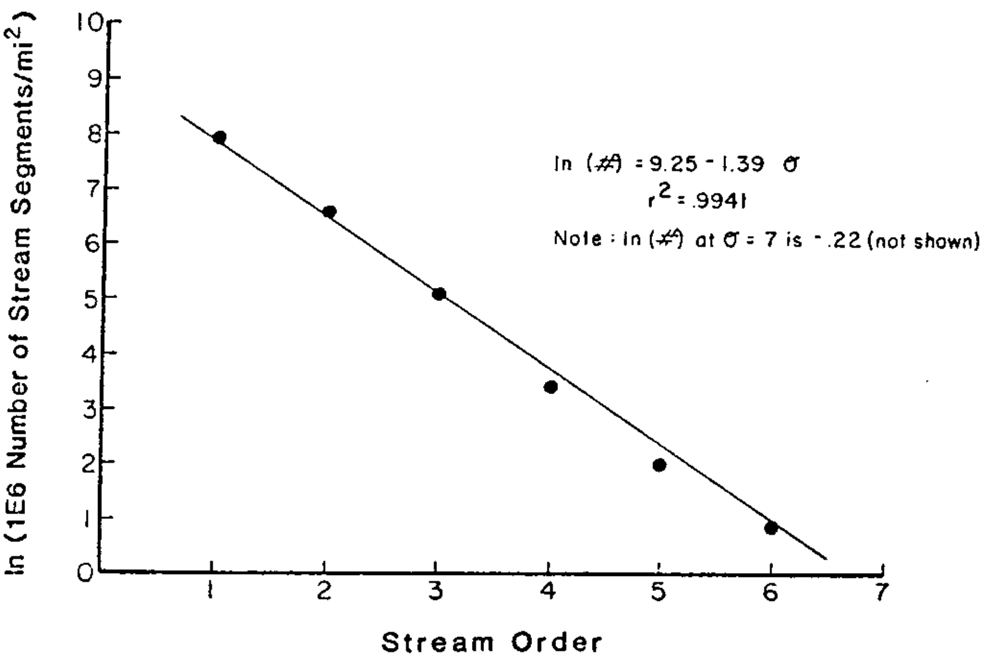


Figure 9. Logarithm of the number of stream segments per streams order as a function of stream order for the entire Mississippi River Basin.

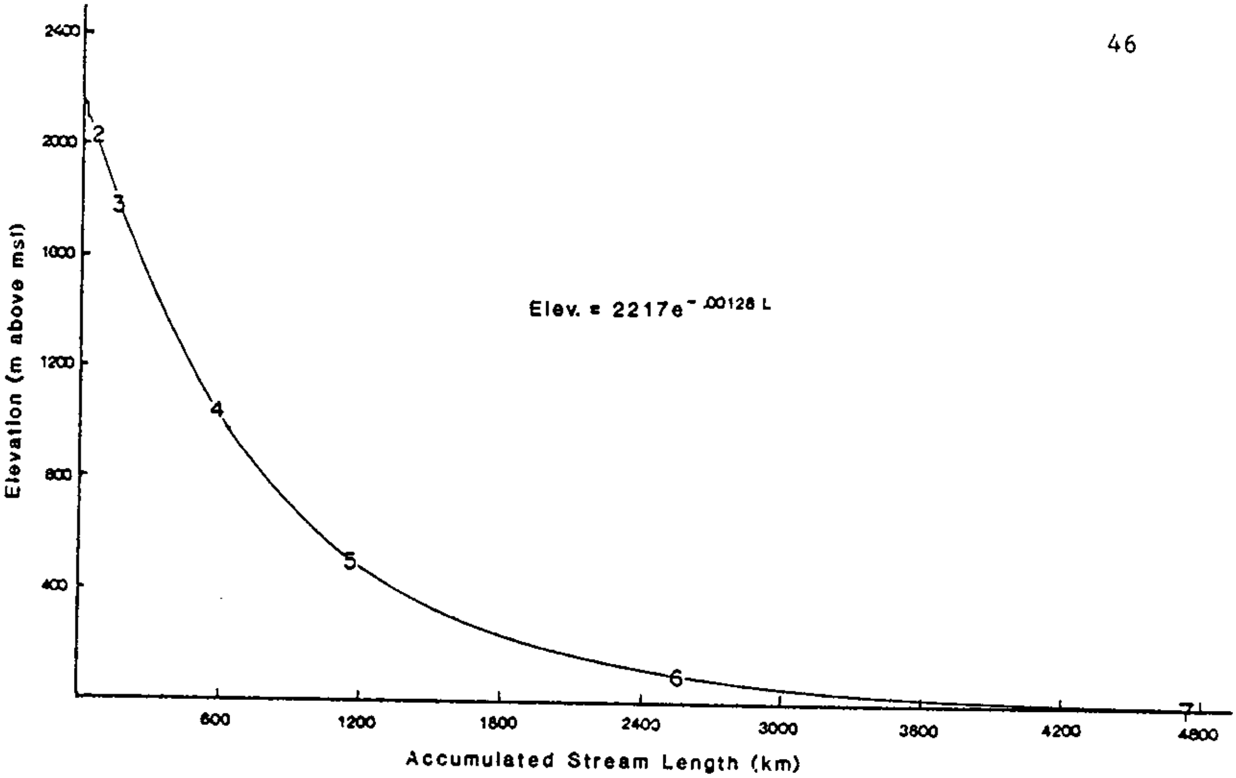


Figure 10. Approximate profile of the Mississippi River Basin. Numbers describe distance from source and elevation for each stream order.

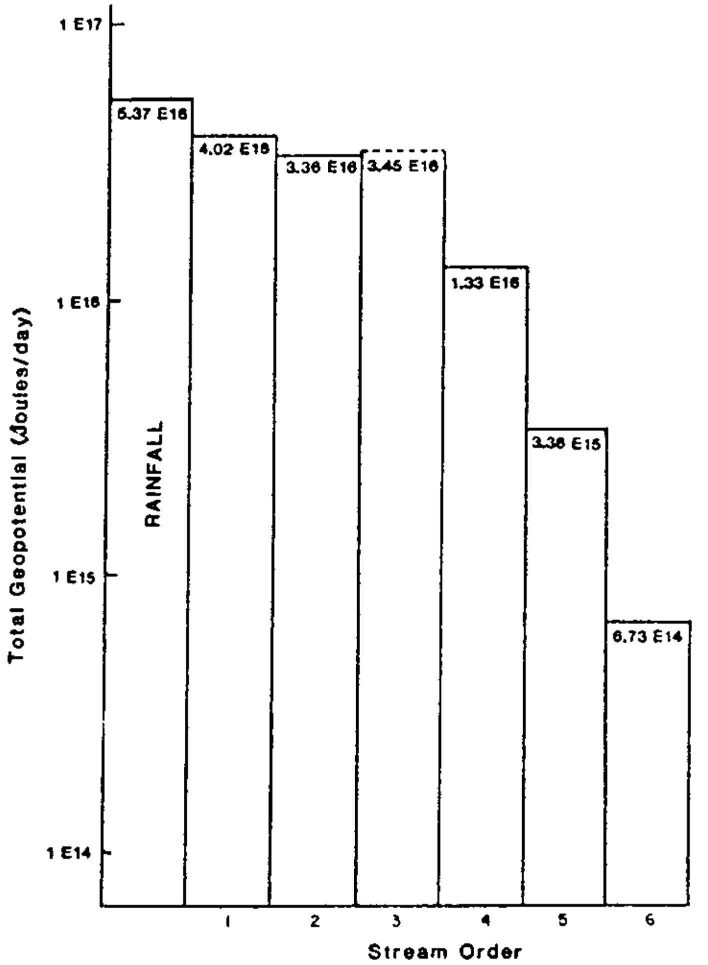


Figure 11. Total geopotential flux per order within the Mississippi River Basin.

Table 6. Summary of stream distributions of the Mississippi River Basin.

Region	Stream Order 1	2	3	4	5	6	7
Ohio	550	138	32	7	2	1	0
Tennessee	183	39	9	1	0	0	0
Upper Miss.	776	191	42	11	2	1	0
Lower Miss.	320	83	19	2	0	0	0
Missouri	1060	271	60	12	3	1	0
Arkansas	638	180	50	7	2	0	0
U. Miss-Missouri	1836	462	102	23	5	2	(1)
Ohio-Tennessee	733	177	41	8	2	1	0
Total	3528	898	212	40	9	3	(1)

Note: Total reflects only the sum of the six individual regions.

Table 7. Mean area of drainage (mi^2), mean discharge (MGD), and mean length of stream segment per order (km).

Order	Mean drainage area per segment	Mean discharge per segment	Mean length per segment
1	185	142	20.5
2	611	493	38.3
3	4,850	2,552	104.5
4	25,117	8,569	422.2
5	71,763	19,937	730.6
6	239,787	63,799	1,418.0
7	717,200	124,000	2,373.0

Table 8. Geopotential power and transformity in the Mississippi River. See Figure 11.

Order* of stream	Power/segment E12 joules/day	Total power used E15 joules/day	Solar transformity solar emjoules/joule
Rain	--	--	8,888
1	.31	1.00	11,542
2	1.88	1.96	13,809
3	24.5	5.66	
4	239.0	10.60	34,887
5	400.0	5.98	138,095
6	966.0	4.89	689,450
7	437.0	2.07	

* See Figure 8.

V. ALTERNATIVES IN THE MISSISSIPPI BASIN

Howard T. Odum and Craig Diamond

When economic development reorganized land and water use in the Mississippi Basin, private and public projects were directed to divert the seasonal rhythm of river floods, adapt land for agriculture and cities, and channelize for navigation and oil drilling. Thus, changes for one purpose diverted resources from preexisting services of the river which maintained rich wetlands, fisheries, water quality and controlled annual floods. Whereas economic values of new developments were known, the indirect contributions of the river to the economy were not known.

In this chapter EMERGY analysis is used to compare alternatives. A larger EMERGY flow contributers more to the economy. EMERGY values are expressed in Macroeconomic $. What makes evaluations of benefit difficult is the way a change in one use causes changes in other connected pathways. Systems diagrams help identify the connections so that all the flows which change are evaluated. A general diagram of the benefit comparison procedure was given as Figure 3.

Net EMERGY Benefit Evaluation

Figure 3 illustrates the EMERGY comparisons used by equations (2), (4), and (6). A choice has a greater benefit and should prevail if it contributes more EMERGY P than the alternative. See explanation in Methods.

In Figure 3 the original system (in dashed lines) contributed P1, which was the sum of independent environmental input I1 plus economic input F1. The developed river system contributes EMERGY flow P2, which is the sum of independent inputs I2 and F2. Developed uses may draw more or less from the main economy indicated by flow F. The net benefit of a development is the contribution of the new system, P2 minus contribution of the old system, displaced P1.

The same Figure 3 also illustrates the comparison between contributions of a developed use (P2) and the standard alternate investment (P3). It can also be used to compare a developed use (P2) with the maximum possible contribution (P4), which includes environmental inputs and the standard ratio of matching economic inputs for the region.

We are accustomed to expect new developments to exceed the older ones because during times of cheap energy and economic growth more EMERGY is available to increase F over the previous systems, causing the new ones to have greater total EMERGY. However, some new developments, while increasing F, decreased I. Other developments diverted more from alternative investments (P3) than was increased by the development (P2). In times of declining availability and increasing costs of resources, alternatives which can use less economic inputs (F) and increase environmental use (I) may compete better.

Adequate evaluation of a sector may require integrating flows over a time so as to cover the initial periods of contstruction of the capital assets involved and the lifetime of service of the capital items. For example, evaluation of a highway would need to average flows starting with construction continuing through the life of the highway and its final disposition. Disposition might be replacement with a new item or returning the land or waters to an older system.

Previous Mississippi Basin Evaluations

Young, Odum, Day, and Butler (1974) made a preliminary analysis of the Atchafalaya Basin of the Mississippi, anticipating its greater volumes of water in coming years, considering the alternatives of raising levees and channelizing further or opening up more floodplain with essential housing and roads built up above flood levels. Evaluation methods were not fully developed, but enough was found to recommend the latter plan as eventually more economic.

Bayley et al. (1977) and Zucchetto et al. (1980) used energy analysis to compare Mississippi barge transport with rail transport and found less coal equivalents required per ton-mile using the barges. Their analysis included energies used for locks and dams and included embodied coal equivalents in goods and services. Their method used coal-to-dollar ratios for various commodities, but did not include the embodied energy in the work of nature, in raw materials, iron and items used in concrete.

Net EMERGY evaluations of coal mining, gas, fisheries and oil well examples in the Mississippi Basin were also made as cited below.

Table of EMERGY Evaluations of Mississippi River Use

As part of the evaluation of alternates concerned with use of the Mississippi River, a number of inputs, processes, storages, etc., were evaluated in EMERGY units and then expressed in macroeconomic dollars. These calculations are given in Table 9. Each line has a footnote with details on the source of data, assumptions, and calculation formulae. The table has column 1 indicating footnote; column 2 with item name; column 3 with raw data in grams, joules, or $; column 4 is the solar transformity in solar emjoules per joule, solar emjoules per gram, or solar emjoules per $. Column 5, which is the product of items in columns 3 and 4, is the solar EMERGY in solar emjoules per year; and finally column 6 is macroeconomic $ equivalent to the EMERGY in the previous column.

System Diagrams of Alternatives

In order to include every consideration, two diagrams of the whole system can be drawn and the differences evaluated. A diagram like Figure 5, except with more detail, could be used for the two evaluations. In practice, this procedure has so much complexity that it is hard to do and explain.

To focus on a particular question or problem without dealing with so much all at once, a simpler diagram can be drawn that has the pathways that are

Table 9 . Macroeconomic values in the Mississippi Basin. Some items are included within others.

Foot-note	Item	Data j,g,or$/yr	Transformity sej/unit	Solar Emergy E22 sej/yr	Macroeconomic value $E9/yr*
	ORIGINAL RIVER, Figure 12a				
1	River, chemical Energy	2.8 E18j	41068	11.5	52.2
2	River, Geopotential	4.26 E18j	23564	10.0	45.6
3	Floodplain water use	1.91 E18j	41068	7.87	35.8
4	Early transport use	2.41 E14j	41068	0.001	0.0045
	CURRENT RIVER, Figure 12b				
5	Floodplain water use	0.74 E18	41068	3.03	13.8
6	Econ. inputs, floodplain	2.45 E9$	2.2 E12	0.54	2.45
7	Sediment carried	1.35 E15g	1.71 E9	230.	1045.
8	Sediment lost to sea			127.	575.
9	Economic water use	1.79 E17g	4.1 E4	0.73	3.3
10	Rain in Agriculture	2.08 E17j	1.54 E4	0.32	1.46
11	Econ. inputs to Agricul.			3.47	15.8
	SHIPPING, Figure 12b				
12	Locks, channels costs	0.36 E9$	2.2 E12	0.08	0.36
13	Shipping $ (coal equiv.)	6.2 E16j	4.0 E4	0.25	1.13
14	Fuel use (coal equiv.)	1.58 E17	4.0 E4	0.63	2.87
15	River energy used	4.03 E16j	4.1 E4	0.0426	0.43
	Total shipping inputs				4.79
	ALTERNATIVE RAILROAD TRANSPORT, Figure 12c				
16	Costs (services)	7.15 E9$	2.2 E12	1.57	7.14
17	Fuels used	5.74 E17j	5.3 E4	3.04	13.8
18	Land use diverted	6.34 E14j	1.54 E4	0.0049	0.022
	Total railroad inputs				19.962
	COMPARISON OF OIL AND GAS AND MARSH IN LOUISIANA				
19	Oil yield	3.34 E18j	5.3 E4	17.7	80.5
20	Gas yield	7.81 E18j	4.8 E4	37.5	170.5
21	Oil and gas sales	23.7 E9$	2.2 E12	5.2	23.7
22	Coastal land loss	8.22 E12g	1.71 E9	1.4	6.4
23	Fisheries	1.24 E15j	8.0 E6	0.99	4.5
24	Coal transport savings		4.0 E4	16.4	74.7

* 1983 U.S. dollars obtained by dividing Solar EMERGY by 2.2 E12 sej/$ or 5.26 E8 solar emcalories per $.

Footnotes for Table 9

1 EMERGY of chemical potential energy refers to the same energy evaluated as geopotential energy in item #2.

River volume

$(6.83\ \text{in/yr runoff})(3.22\ \text{E12 m}^2)(2.54\ \text{cm/in})(.01\ \text{m/cm}) = 5.59\ \text{E11 m}^3\text{/yr}$

Gibbs free energy

$(5.59\ \text{E11 m}^3\text{/yr})(1\ \text{E6 g/m}^3)\ (5\ \text{j/g}) = 2.8\ \text{E18 j/yr}$

Footnotes for Table 9 (cont.)

2 Geopotential Energy which goes into Kinetic Energy during flow: refers to the same evaluated as chemical energy in item #1: 776.9 m average elevation; gravity, 9.8 m/sec^2

$$(5.59\text{ E11 m}^3/\text{yr})(776.9\text{ m})(1\text{ E3 kg/m}^3)(9.8\text{ m/sec}^2) = 4.26\text{ E18 j/y}$$

3 Geopotential energy in water used by original floodplains (9.71 E10 m^2) and deltaic plain (2.9 E10/ m^2 (areas from Costanza et al., 1983): annual volume of water used estimated as 2 m transpiration: (2m^3/m^2/yr)(12.61 E10 m^2) = 2.52 E11 m^3/yr; fraction of geopotential energy taken as the fraction of water used: (2.52 E11m^3/5.59 E11 m^3 = .45; transformity used is for geopotential-kinetic energy used in delivery of waters. Physical energy from footnote 2:

$$(4.26\text{ E18 j/y})(.45) = 1.91\text{ E18 j/yr}$$

4 Estimate of 0.01% of the river flow used by boats. Water is used while it is affected by the displacement. (0.0001 used)($45.3 E9/yr) = 0.045 E8$

5 Calculation of water use by floodplain as in footnote 3 with smaller areas (4.9 E10 m^2)(2 m^3 trans./m^2/yr) = 0.98 E11 m^3/yr water fraction: .98/5.59 = .175

$$(4.26\text{ E18 j/y})(.175) = 7.4\text{ E17 j/y}$$

6 Economic inputs to unlevied floodplains for forest wood, crayfish production, other products, assumed $500/ha/yr

(4.9 E6 ha)($500/ha/yr) = $2.45 E9

7 Sediments carried; See Appendix B; 13.45 E14 g/yr

8 Sediments lost to sea; Fraction of water not passing through floodplain, 0.55 from footnote 3.

9 Economic water use estimated from population (U.S. Statistical Abstract) and Expressed as Gibbs free energy

$$(60.2\text{ E6 ind})(440\text{ gal/ind/day})(365\text{ days})(3700\text{ g/gal})(5\text{ j/gal}) = 1.7\text{ E17 j/yr}$$

10 Floodplain agriculture on 90% of 7.71 E10 m^2 former floodplain and deltaic plain; Gibbs free energy in annual transpiration, 3.0 E10 j/ha/yr

$$(7.71\text{ E6 ha})(.9)(3\text{ E10 j/ha/yr}) = 2.08\text{ E17 j/yr}$$

11 Inputs per hectare from energy analysis of corn (Odum, 1984). Sum of solar emergy inputs from economy per hectare including: direct fuel, indirect fuel in machinery, services, pesticide, phosphate, nitrogen, potassium and seed (Odum, 1985), 500 E13 sej/ha/yr

$$(7.71\text{ E6 ha})(.9)(5.0\text{ E15 sej/ha/yr}) = 3.47\text{ E22}$$

12 1972 costs of locks and channels including maintenance and amortized replacement costs quoted from Sharpe after Bayley et al. (1977); converted to 1983 $ by multiplying by 2.9:

($134.9 E6/yr)(2.9) = $0.36 E9 (services)

13 Shipping costs of barge companies, operation, and maintenance including accidents, 268 btu coal equivalents/ton-mile (Bayley et al. (1977)

(229 E9 ton-mile/yr)(268 btu coal/ton-mile)(1013 j/btu) = 6.2 E16 j/y coal

14 Fuel used in barge travel; 680 btu coal equiv./ton-mile (Bayley et al., 1977)

(229 E9 ton-miles/y)(680 btu/ton-mile)(1013 j/btu) = 1.58 E17 coal j/yr

15 Water volume displaced by annual shipping:

(10)(5.84 E8 tons/yr)(2000 lb/ton)(454 g/lb)/(1E6 g/m^3) = 5.30 E8 m^3/yr

Fraction of River used by shipping assumed to be ten times displacement.

(5.30 E8 m^3/yr)/(5.6 E11 m^3/yr) = 9.46 E-3 (1%)

This fraction take of items in Line 2:
Fraction of River geopotential energy: (9.46 E-3)(4.26 E18 J/yr) = 4.03 E16 J/yr
Fraction of River EMERGY: (9.46 E-3)(10 E22 sej/yr) = 4.26 E20 sej/yr
Fraction of Macroeconomic Value: (9.4 E-3)(45.6 E9 $/yr) = 4.31 E8 $/yr

16 Railroad shipping costs (services and labor); Ton mile rate from U.S. Statistica. Abstract:
(229 E9 ton-miles/yr)($.0312/ton-mile) = $7.15 E9 ($1983)

17 Fuel use per ton-mile, U.S. Statistical Abstract, 1983 including diesel, electric, and coal-fueled trains

(3942 E6 Gal/y diesel)(34776 Cal/gal)(4186 j/Cal) = 5.74 E17 j/y

(5.74 E17 j/y)(5.3 E4 sej/j) = 3.04 E22 sej/y

(3.04 E22 sej/y)/(2.2 E12 sej/$) = 13.8 E9 $/y

18 Environmental use taken as the EMERGY of lands
13202 miles in 5th-, 6th-, and 7th-order streams as rail equivalent.
Width assumed 30 m; area used:
(13202 miles)(1548 m/mile)(50 m) = 1.02 E9 m^2
Emergy in productivity taken as that of transpiration, .626 m/yr

(1.02 E9 m^2)(.626 m/yr)(1E6 g/m^3)(5 j/g)(1.54 E4 sej/j Gibbs energy)

= 4.92 E19 sej/yr; (4.19 E19 sej/yr)/(2.2 12 sej/$) = $.022 E9

19 Oil production in Louisiana; mean 1976-1980 (U.S. Statistical Abstract)
(533 E6 bbl/yr)(6.28 E9 j/bbl) = 3.34 E18 j/y

20 Gas production in Louisiana; mean 1976-1980 (7181 E9 cubic ft/yr)(1.033 E6 j /cubic ft) = 7.81 E18 j/yr

21 Services estimated from prices
(3.34 E18 j/y oil)($3.72/1 E9 j) = $12.4 E9 (1980)
(7.81 E18 j/yr gas)($1.45/1 E9 j) = $11.3 E9 (1980)
Total: $ 23.7 E9

21 Loss of marsh lands due to canals blocking normal sedimentation and organic production processes maintaining marsh lands; wetland loss 1.02 E8 m^2/yr; (Scaife, Turner and Costanza (1983).
Area of deltaic plain wetland 1.275 E10 m^2; 1 cm/yr accretion diverted; 14.2% dry matter; 27.3% of dry is Carbon (Costanza, et al., 1983); organic estimated as twice carbon, 54.6% organic and 45.4% mineral of dry weight.
Land rate loss mineral sediment:
(1.275 E10 m^2)(.454)(.142)(1E4 g/m^2/yr) = 8.22 E12 g/yr

22 Urban services on floodplain; New Orleans, 1983: 2.831 E6 people; $8017/income per capita (U.S. Statistical Abstract, 1985).
Urban EMERGY use using U.S. per capita rate
(29 E15 sej/person)(2.8361 E6 people in New Orleans) = 8.22 E22 sej/yr

23 Sustained fishery production involving life cycles of oysters, shrimp, and finfishes includes life off shore and nursery stages in wetland areas. Estimates of productivity, transformaties and areal bases for fisheries were given by Bahr, Day, and Stone (1982). Water areas:
77 E9 m^2 continental shelf
31 E9 m^2 inshore estuarine-wetland area
16.8 E9 m2 of the inshore area is water-covered
receive sun, wind, ocean currents, and especially the distributaries of the river. The fishery harvest inshore is 2.67 E4 metric tonnes dry weight. EMERGY inputs generating this production are estimated as one of the products of the EMERGY flux, primarily of the river.
River, Gibbs energy, footnote 1 ----------------- 11.5 E22 sej/yr
part in 108 E9 m^2 out of
Direct Sun (108 E9 m^2)(5.91 E9 j/m^2/yr) = 0.063 E22 sej/yr
Waves, Table 2, footnote 6 ---------------------- 0.068 E22 sej/yr
Tide, Table 2, footnote 3 ----------------------- 0.0083 E22 sej/yr
EMERGY of river used in the study area calculated as proportion that the study area was of total river area:
(3.1 E10 m^2/36.0 E10 m^2) =0.086;
(.086)(11.5 E22 sej/yr) = 9.89 E21 sej/yr
Solar transformity of gross production of 2.11 E18 j/yr:
(9.89 E21 sej/yr)/(2.11 E18 j/y) = 4687 sej/j

24 Energy savings using river transport of fuels; total fuels used in Mississippi Basin from Table 2: 118.68 E22 sej/yr; equivalent coal = 1.01 E9 ton: 1000 miles or 1.01 E12 ton-miles;
Savings by water ($20.94 - 4.0 E9)/(299 E9 ton-miles) = 0.074 $/ton-mile
Savings: (1.01 E12 ton-mile)(.074 $/ton-mile) = $74.7 E9

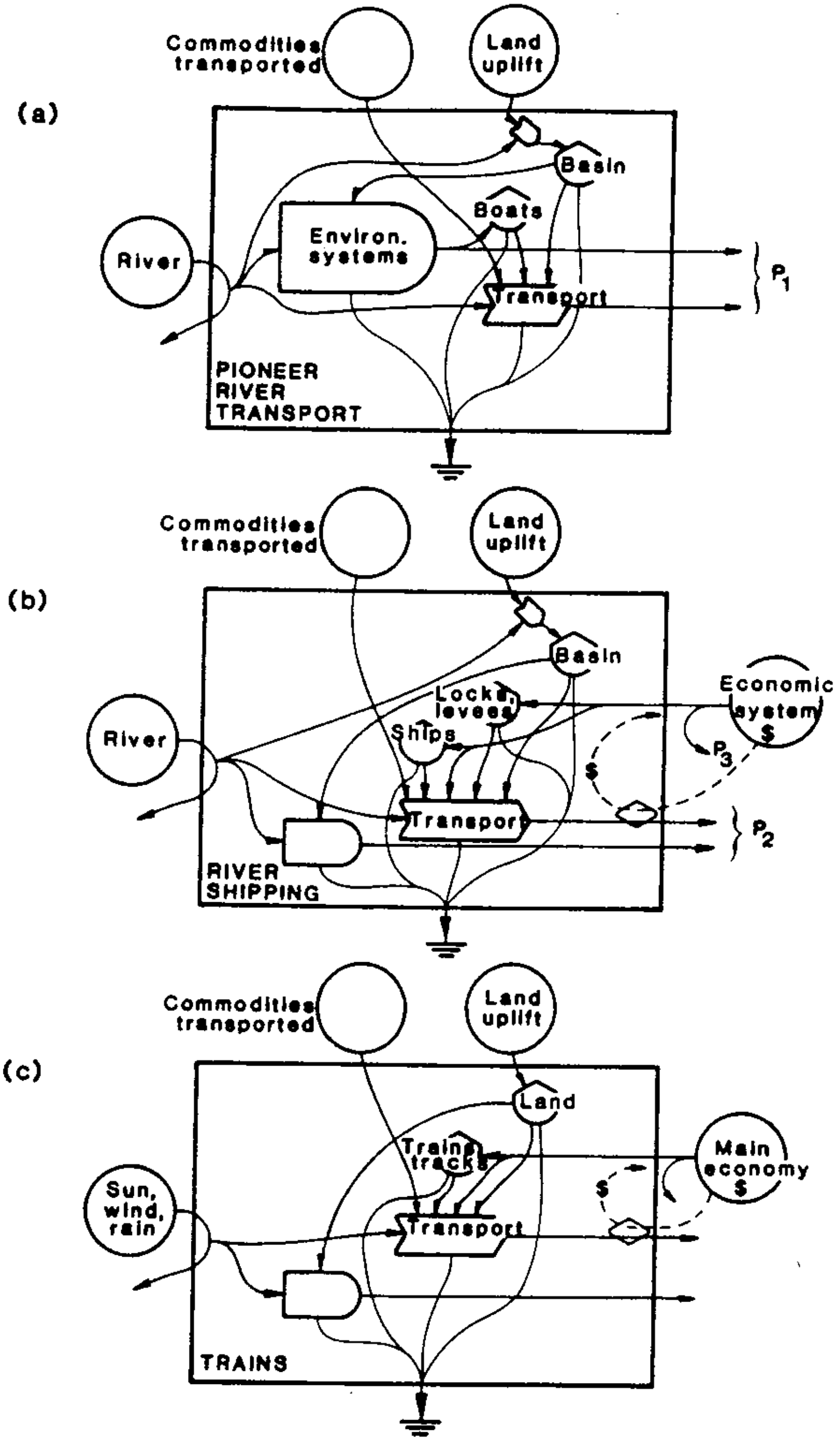


Figure 12. Main pathways involved in river transport. (a) Small boats on an unmodified river; (b) transport on a river modified with levees, channels, and locks; (c) railroad alternative to river transport.

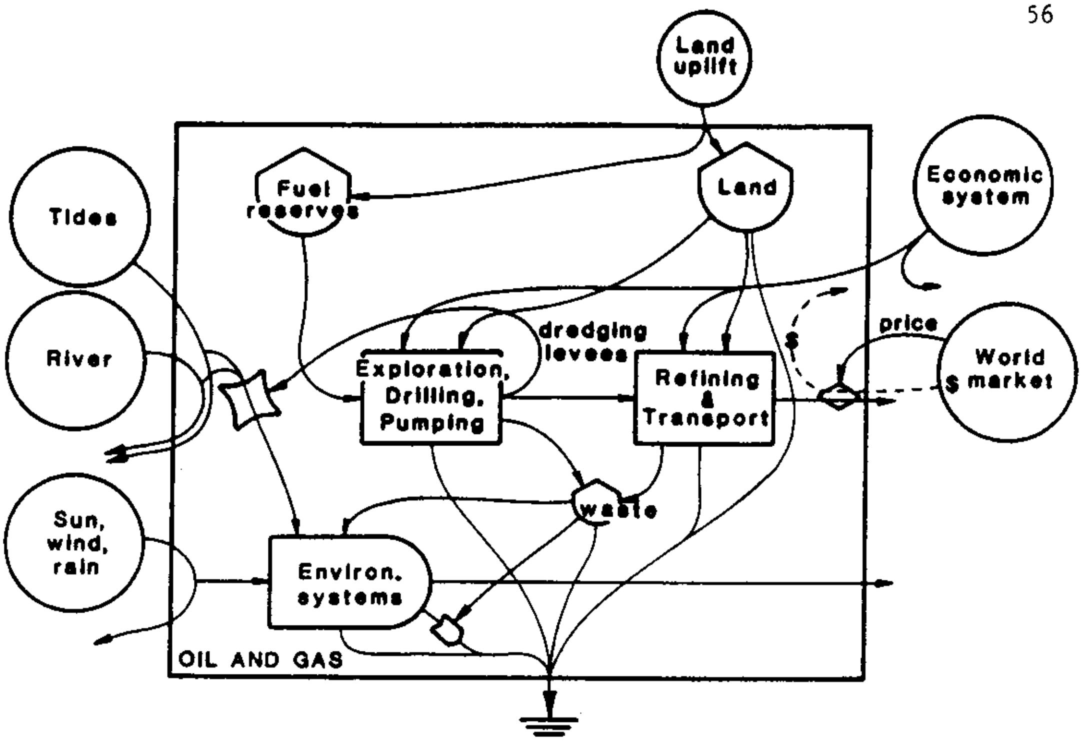


Figure 13. Overview of oil and gas production and environmental interactions.

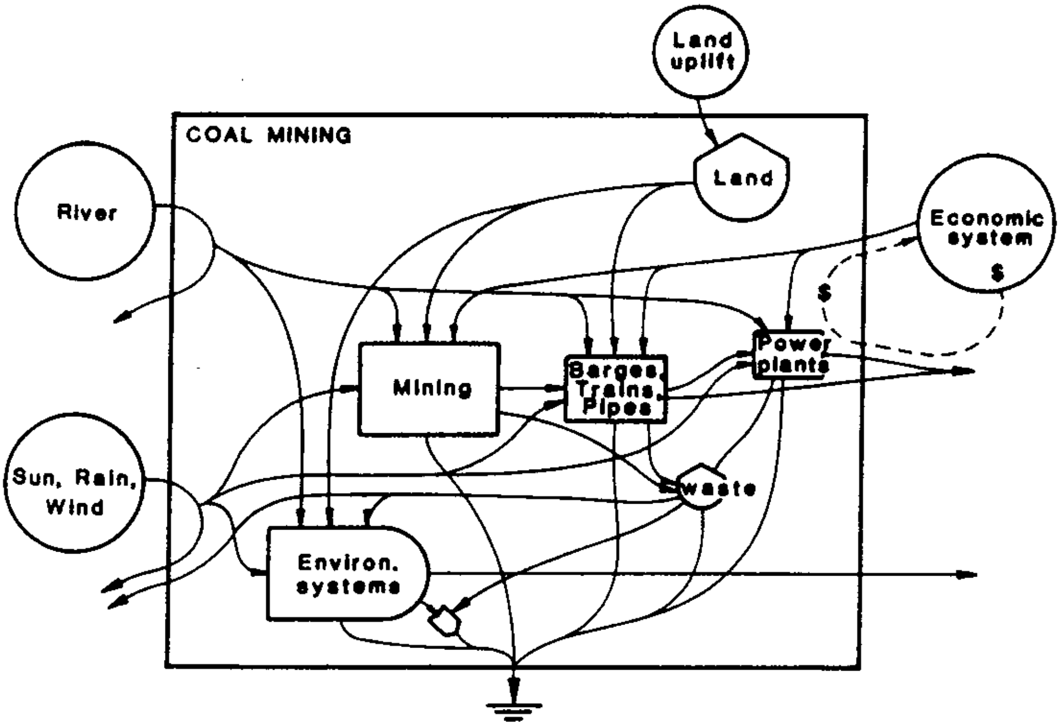


Figure 14. Overview of coal production and environmental interactions.

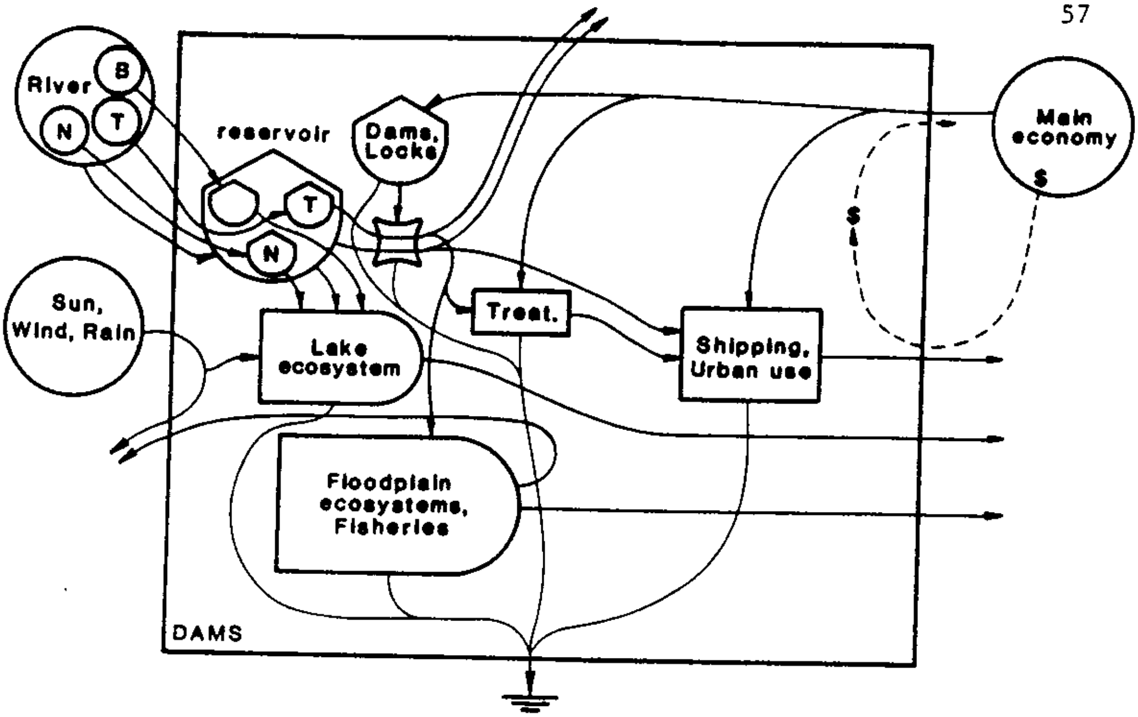


Figure 15. Overview of dams and reservoirs and the change in environmental processes involving the rivers.

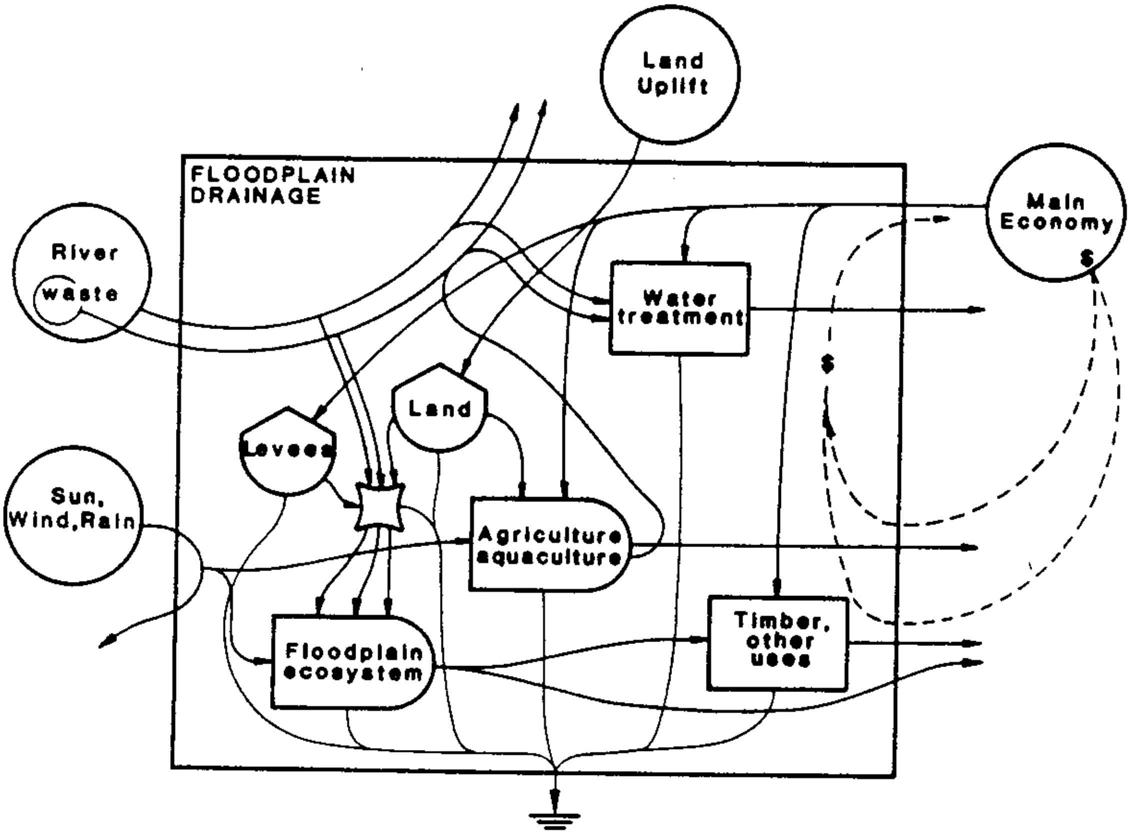


Figure 16. Overview of development of floodplains for agriculture and urban use by excluding river waters.

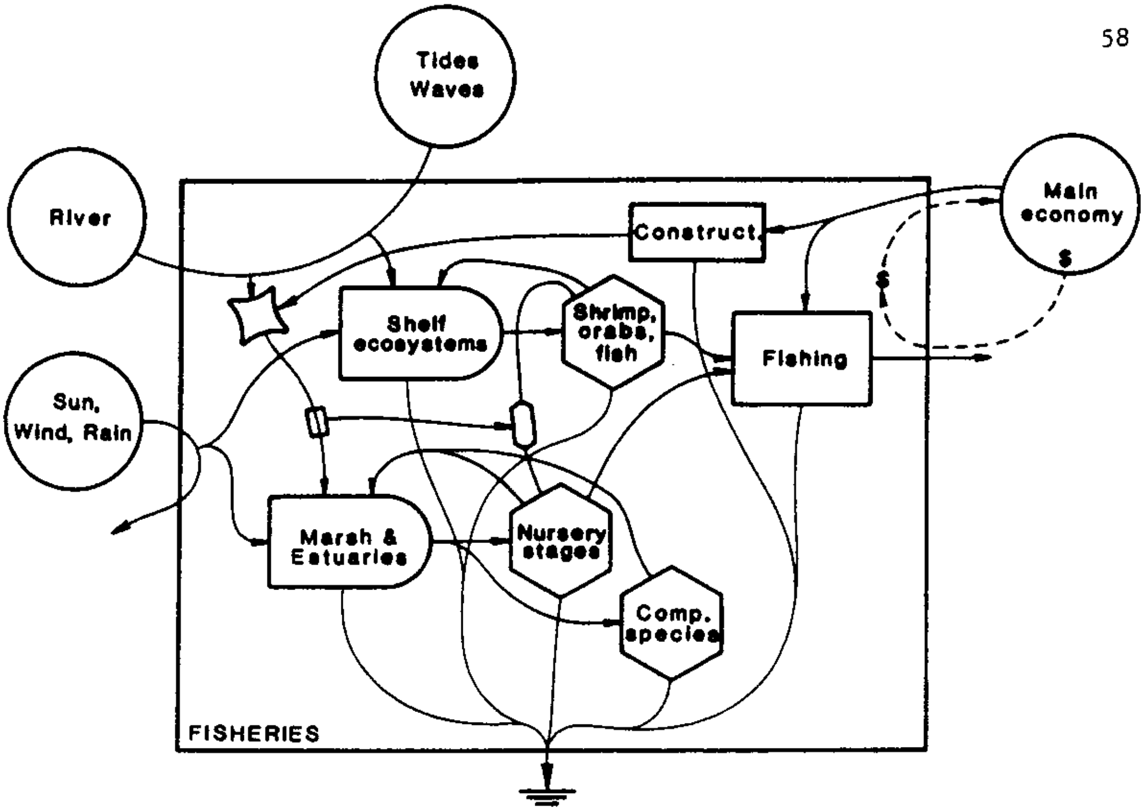


Figure 17. Overview of fisheries exploitation and associated environmental changes.

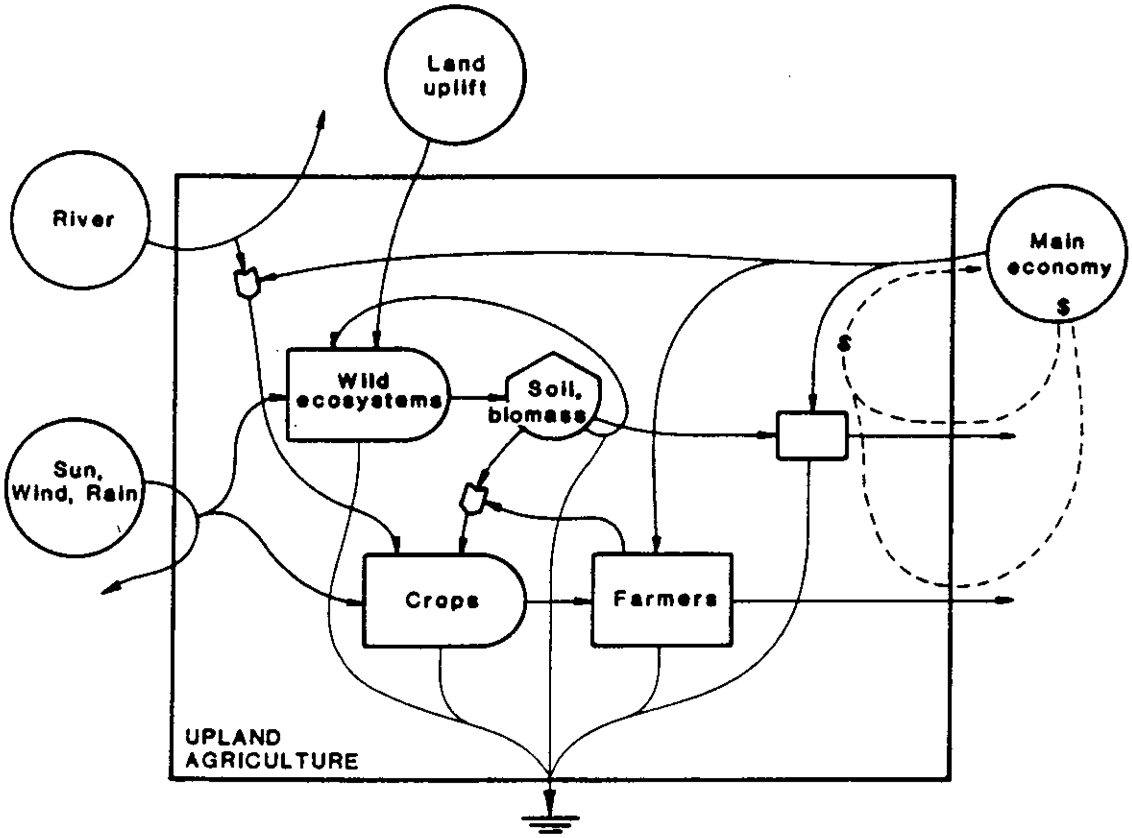


Figure 18. Overview of development of intensive upland agriculture and its environmental consequences.

Table 10 . Comparisons of short range macroeconomic values of river management,* omitting sediment resource.

	Footnotes Table 10	P1, Before Development E9 $	P2, After Development E9 $	DP Change E9 $
RIVER AND FLOODPLAIN SYSTEMS				
Environmental Inputs, I				
Water to the floodplain	3, 5	35.8	13.8	
Coastal land increments	21	6.4	0	
River used in transport	4, 15	0.0045	0.43	
Leveed floodplain agricul.	15	0	1.46	
Total I		I1: 42.205	I2: 15.69	
Change in environmental macrovalue (I2 - I1) =				- 26.51
Economic Inputs, F				
Locks, Levees	8	0	0.36	
Shipping costs	9	0	1.13	
Fuels in shipping	10	0	2.87	
Agriculture on floodplain	1, 6	3.86	15.8	
Urban floodplain inputs	22	0	37.4	
Water treatment	9	0	2.93	
Total F		F1: 3.86	F2: 60.49	
Change in Economic Inputs (F2 - F1):				+ 56.63
Total contributions: Old System:		P1: 46.1		
New System:			P2: 76.18	
Alternative Development (F2 + F2/IR):			P3: 69.13	
Contribution of Potential Development (IR * I1):			P4: 295.7	
BENEFIT COMPARISONS:				
Change between new and old:			P2 - P1 =	+ 30.1
Comparison with alternative development:			P2 - P3 =	+ 7.1
Comparison with potential development:			P2 - P4 =	-226.6

* See Figure 3 for diagram of relationships of environmental inputs I, economic inputs F, and contributions to the system P.

Table 11. Comparisons of long range macroeconomic values of river management*

	Footnotes Table 10	P1, Before Development E9 $	P2, After Development E9 $	Change E9 $
RIVER AND FLOODPLAIN SYSTEMS				
Environmental Inputs, I				
Water to the floodplain	3, 5	35.8	13.8	
Sediment to floodplain	7, 8	1045.	470.	
Coastal land increments	21	6.4	0	
River used in transport	4, 15	0.0045	0.43	
Leveed floodplain agricul.	15	0	1.46	
Total I		I1: 1087.205	I2: 485.69	
Change in Environmental Macrovalue (I2 - I1) =				- 601.52
Economic Inputs, F				
Locks, Levees	8	0	0.36	
Shipping costs	9	0	1.13	
Fuels in shipping	10	0	2.87	
Agriculture on floodplain	1, 6	3.86	15.8	
Urban floodplain inputs	22	0	37.4	
Water treatment	9	0	2.93	
Total F		F1: 3.86	F2: 60.49	
Change in Economic Inputs (F2 - F1):				+56.63
Total contributions: Old System:		P1: 1091.065		
New System:			P2: 546.18	
Alternative Development (F2 + F2/IR):			P3: 69.13	
Contribution of Potential Development (IR * I1):			P4:7609.	
BENEFIT COMPARISONS:				
Change between new and old:			P2 - P1 =	- 544.9
Comparison with alternative investment			P2 - P3 =	+ 477.1
Comparison with potential development			P2 - P4 =	- 7062.8

* See Figure 3 for diagram of relationships of environmental inputs I, economic inputs F, and contributions to the system P.

changing and their connections with inputs. The whole system diagram is still done first to make sure everything has been considered. Then a net EMERGY benefit table can be evaluated, including the items in the smaller diagram.

Figure 12 through Figure 18 are diagrams for evaluating some economic use of the Mississippi River. Each includes the economic inputs to development as well as those environmental or economic sectors which are changed by the new use of the river. The contributions to the joint economy of humanity and nature are shown emerging from the diagram to the right. Where the old system is diagrammed, the output is labelled P1 as in Figure 12a. Where the new system is diagrammed, the contribution is P2. See Figure 11.

The systems overview diagrams were used to determine which pathways needed to be evluated in Table 9. Then the diagrams were used to determine how to add or subtract EMERGY values to compare alternatives or evaluate impacts.

Comparison of Present River with Undeveloped Pattern

Figure 11 compares the primitive, pioneer river with the present river system which is channelized, narrowed with levees, and controlled in upper reaches with locks and dams. Table 11 is the same as Table 10 except that it includes erosion and redeposition of sediments, valuable in the long run.

Much of the large EMERGY of the river originally went with nearly half of the water into the floodplains generating $35.8 billion macrovalue. Some economic inputs were attracted as wood, furs, and seasonal agriculture was harvested between floods.

In the present river most of the floodplain has been converted to agriculture and urban development and the river channelized and deepened. $14.8 billion of environmental work is still done in the remaining floodplains, $6.8 billion of river capacity is used by the shipping industry, but the rest of the water that used to do work on the floodplains shoots into the sea. On the drained lands, intensive agriculture inputs have $15.8 macrovalue. Table 11 includes $37.4 billion macrovalue input as economic support of New Orleans, a city on the floodplain.

The new annual macrovalue of the developed system (P2) with $82.55 billion is greater than the old pattern of $46.1 billion, even when corrected for alternative environmental uses. Economic development usually increases the total value because additional outside inputs are attracted with investments.

The new contribution (P2) is $13.4 E9 more than alternative investments (P3). See Table 10.

However, the loss of $20 billion in environmental work in the process is also a loss of potential for attracting additional matching economic inputs. The potential of the river is seven times the original annual environmental value which is $296 billion.

Floodplain Services

Figure 16 diagrams some of the floodplain's processes developing products, cleansing waters, accepting sediments and wastes, and enriching agriculture between floods. Activities that can be economic and attract outside fuels and monies include forestry, water, fur, aquaculture, recreation, and fishery nurseries recycling. Floodplain contributions evaluated are in Table 9.

Floods

The annual flood is a potential resource that was effectively used by the original floodplain and deltaic system. By diking, channelizing, and making economic developments that were not adapted to the flood cycle, a benefit was often turned into a stress, a drain on part of the system, a pathological state. Floods caused by a development and the costs of dealing with them are a drain and count negatively, although the new values obtained from the diked lands are an alternative benefit. See agriculture and urban items in Table 9. Flood protection is part of the costs of the new system. The flood resource that is now shunted to the sea instead of being absorbed into beneficial production on the floodplains is a waste in the present system that can be changed by returning more areas to floodplain use.

Comparing Transportation Alternatives

Next consider transportation more marrowly (Figure 12; Table 9). The pioneer transport (Figure 12a) derived nearly everything from the river and its floodplain including wood for the boats, whereas the modern system (Figure 12b) uses large inputs from the economic system directly and indirectly based on fuels. The current system diverted the river from some of its natural roles in the floodplain.

If no water management is required, EMERGY required from the economy for water shipping uses only $4 billion (1.13 + 2.87), whereas for the same ton-miles $20.9 billion (13.8 + 7.14) are required by railroad (Table 9). The example shows why water transportation seems cheaper, since the river supplies physical energy evaluated at $.43 billion, whereas the EMERGY supplied by the land is only $.022 billion (Railroad, Table 9).

If transportation evaluations include river use, locks and levees, shipping costs, and fuels, the total is $4.79 billion per year, which is much less than the loss of floodplain value (35.8 - 13.8 - $22 billion). In other words, the diversion of the floodplains is not justified for transportation reasons only.

The water transportation may be compared with alternative train transportation (Figure 12c) using EMERGY evaluations in Table 9. The railroad alternative diverted land for use with small annual EMERGY, compared to the water transportation diversion of high EMERGY waters. Rail transport uses less EMERGY contribution from the environment and more from the economy.

Oil and Gas

Rapid development of oil and natural gas resources dominated economic development within the Mississippi Basin in this century, particularly in Louisiana and Oklahoma. Notice, for example, the high EMERGY contribution per year from Louisiana alone (Table 10, $151 billion/yr macrovalue). The priority given to oil and gas operations is understandable considering the maximum EMERGY principle which predicts the take-over by systems that can contribute more EMERGY flow. However, large environmental macrovalues were inadvertently lost by a failure to value their contributions.

In addition to impacts of briny bleedwater, drilling muds, and oil spills, oil and gas operations in the deltaic plain cut the marshes with networks of barge channels and fill lines. See Figure 13. These shielded the marshes from receiving their sediment and nutrients that helped produce organic sediment from marsh plants. With some deltaic compaction and subsidence, the diversion of the river sediments is causing the marsh lands to be replaced with water at a very rapid rate (Scaife, Turner, and Costanza, 1983). In Table 9 footnote 21, this loss of land accretion is partially evaluated as $6.4 billion macroeconomic value. Although small compared to the oil and gas contribution, it is large enough to justify better conservation measures to prevent this problem in future operations and to justify a large restoration effort to return the free flow of the delta waters.

Because the net EMERGY yield ratio of U.S. oil and gas is now much lower than those in OPEC nations, oil will come increasingly from foreign sources. See net EMERGY calculation of a Gulf oil operation (Odum et al., 1976) and Cleveland and Costanza (1983). Water transportation becomes increasingly important in keeping the net EMERGY yield of fuels reaching final users competitively low compared to other nations. See below.

Coal Mining and Transport

Use of coal is related to the river's role in making transport cheaper. Coal mining is diagrammed in Figure 14. Net EMERGY yield ratio in Wyoming strip mines is 40.1, but after rail transport for 1000 miles, the net EMERGY ratio drops to 6/1 (Ballentine, 1976), more typical of most available energy sources. These were made with the assumption that vegetational recovery after some land reclamation effort required 50 to 100 years. If much longer times are required to develop landscape productivity, much lower net energy ratios result. Ballentine found that where coal is to be transformed to electricity, this should be done before transport. The rest of the coal to be used for various heat sources should be sent as coal. However, with river transport, higher net EMERGY ratios are avalable throughout the basin, thus maintaining a higher economic activity in other sectors.

In Table 9 footnote 24, we are given the savings if all the fuel use of the Basin was from transported coal. There are 14% savings in fuel, which has almost this much effect on the whole economy of the Basin.

Dams and Lakes

In the upper waters of the Basin there are many dammed reservoirs which serve as water supply reservoirs and means of keeping the river navigable with locks. See relationships in Figure 15. Maintaining uniform lake levels eliminates floodplain ecosystems and thereby the means of cleansing waters and depositing sediments over broad area to stimulate biological production of the land. By their longer time constant, the lakes accumulate nutrients and toxic substances. Although larger boats are facilitated, the use by smaller boats is hindered. Ice break-up is delayed. The free downstream drift of boats, waters and sediment is prevented. Table 9 includes costs of dams and locks.

Concrete has large EMERGY supplied with cement (3.43 E10 sej/gram) and steel (1.78 E9 sej/gram) in addition to that evaluated as construction fuels and services.

Water Used in the Economy, Water Treatment

In footnote 9 the economic water use for the whole basin was estimated as about 6% of the whole river discharge with macrovalue of $3.3 billion. Many of the waters are returned to the river with lower capacity, and increased toxicities. Because of the return of part of that water to the river without floodplain action, water treatment costs are increased. Some of this is an unnecessary input that could have gone into other uses if more environmental services were retained. See footnote 25.

Fisheries

Coastal fisheries are diagrammed in Figure 17 which includes interaction of wetlands and the continental shelf. Bahr, Day and Stone (1982) quantitatively relate main populations to the primary production of Mississippi River coastal waters and wetlands. In Table 9 footnote 23 the river EMERGY input per area of nursery was calculated so as to relate the river EMERGY to fish production. The annual macroeconomic value of the river prorated over the area studied was $4.5 billion. Additional fisheries involved the freshwater wetlands and migrations up and down stream. Part of the decline of fisheries is related to the loss of area of marshes for interaction of larvae and food chains.

When the river EMERGY of the nursery was related to stages in the food chain using the plant production transformities supplied by these authors, the following solar transformities were obtained:

Item	Concentration factor*	Solar transformity
gross production	1	4,687 sej/J
dispersed algae	2	9,374 sej/J
dispersed organic matter	4	18,748 sej/J
zooplankton, microzoa	30	140,610 sej/J
dispersed herbivores	300	1,406,100 sej/j
upper consumers	1700	7,967,900 sej/J

* gross production units required per unit.

Upland Agriculture and Erosion

Intensive agriculture characterizes the Mississippi Basin producing corn, wheat, soybeans, cattle beef and dairy products, fowl, and hogs, as itemized in the Appendix. Figure 18 is a simplified representation of the relationship between the wild ecosystems developing soil that is rotated into crop production, particularly in the drier western part of the Mississippi-Missouri Basin where river waters and ground waters are used for irrigation. However, the rising costs of electricity for pumping, and the lowering of water tables due to years of pumping, are making this less competitive.

Details of soil erosion and runoff are given in Appendices A and B. Because of the intensity of farming and the elimination of part of the floodplains, part of the mineral clays go directly into the sea. An estimate of the loss of clay materials of soils in Table 9 is larger even than the fuels. Based on the fraction of water through the floodplains, nearly half of that eroded from the uplands is deposited at sea.

General Recommendation

The evaluation of various flows in Table 9 on a macroeconomic dollar basis shows a set of environmental contributions that have been lost from the economy and potential developments that could be made by reincorporating these. The evaluation of floodplain alternatives in Table 10 is an example. Nearly 3.5 times the economic development is possible by refitting the pattern of humanity to use the river flooding resource instead of shunting it to sea. A general policy of opening up more floodplains to the river again is needed, diking people in rather than diking the river out. With a period of more coal use just ahead, the river transportation system needs to be retained for its net EMERGY benefit, but not at the expense of the floodplain changes needed.

VI. OVERVIEW SIMULATION MODEL

Craig Diamond

One approach to understanding the processes and dynamics of a system is the use of a simulation study. A model which contains the dominant elements of a system and the pertinent pathways by which these elements interact may provide useful estimates of system behavior over a time frame of interest. Such a model can be translated to a set of differential equations which can then be solved using either a digital or analog computer.

Figure 19 represents an overview minimodel, using H.T. Odum's energy language, of the Mississippi River Basin (a list of energy language symbols and their meanings is included as Figure 2). Figure 20 shows the values of flows and storages in Calories and dollars. The system contains five storages: soil (S), water (G), fossil fuels (F), urban assets (A), and financial capital (D). The storage of assets is in EMERGY (1 E18 solar equivalent Calories), dollars are in $ E9, and the remaining storages and flows are in 1 E15 Calories.

Systems inputs include sunlight, which is flow limited and is competed for between natural and agricultural systems; rainfall (R); imported fuels (a function of relative prices); and imported goods and services (a function of available funds). System exports are fossil fuels, goods and services, and agricultural surplus.

Production of soil is shown as a byproduct of sun and rain interaction. The assumption is that soil nutrients are produced at relatively constant rates via abiotic processes. Changes in land use effect the level of sunlight available for natural systems, thereby altering the quantity of soil produced. Soil is depleted by agricultural practice above the natural rate of turnover.

Water storage is another byproduct of solar-driven processes and reflects the volume of ground and surface waters after evapotranspiration in undeveloped regions. Outflows include Mississippi River discharge, consumption by agriculture, and urban net use. Geopotential of water over land (for hydroelectric) is added in a variant of the basic model. At a macro level water storage reflects all systems dependent on maintaining average volumes over time, i.e., wetlands and non-perched bodies of water.

Fossil fuels are taken to be nonrenewable resources which, in the basic model, feed only the urban interaction. Fuels used by agriculture are calculated by a function of the relative price - world market price over domestic production price, available fuel reserves and assets. Since the Basin's assets will be proportional to those of the entire U.S., it may be assumed that export of domestic fuels will be similarly related. Imports are controlled by available dollar resources and the inverse price function. As world prices increase, system imports decrease (although purchases continue if funds exist) and exports increase accounting for substitution of basin fuels for foreign fuels in the domestic market.

Urban assets are generated by an autocatalytic relation using renewable and nonrenewable resources. Byproducts of this interaction are marketable

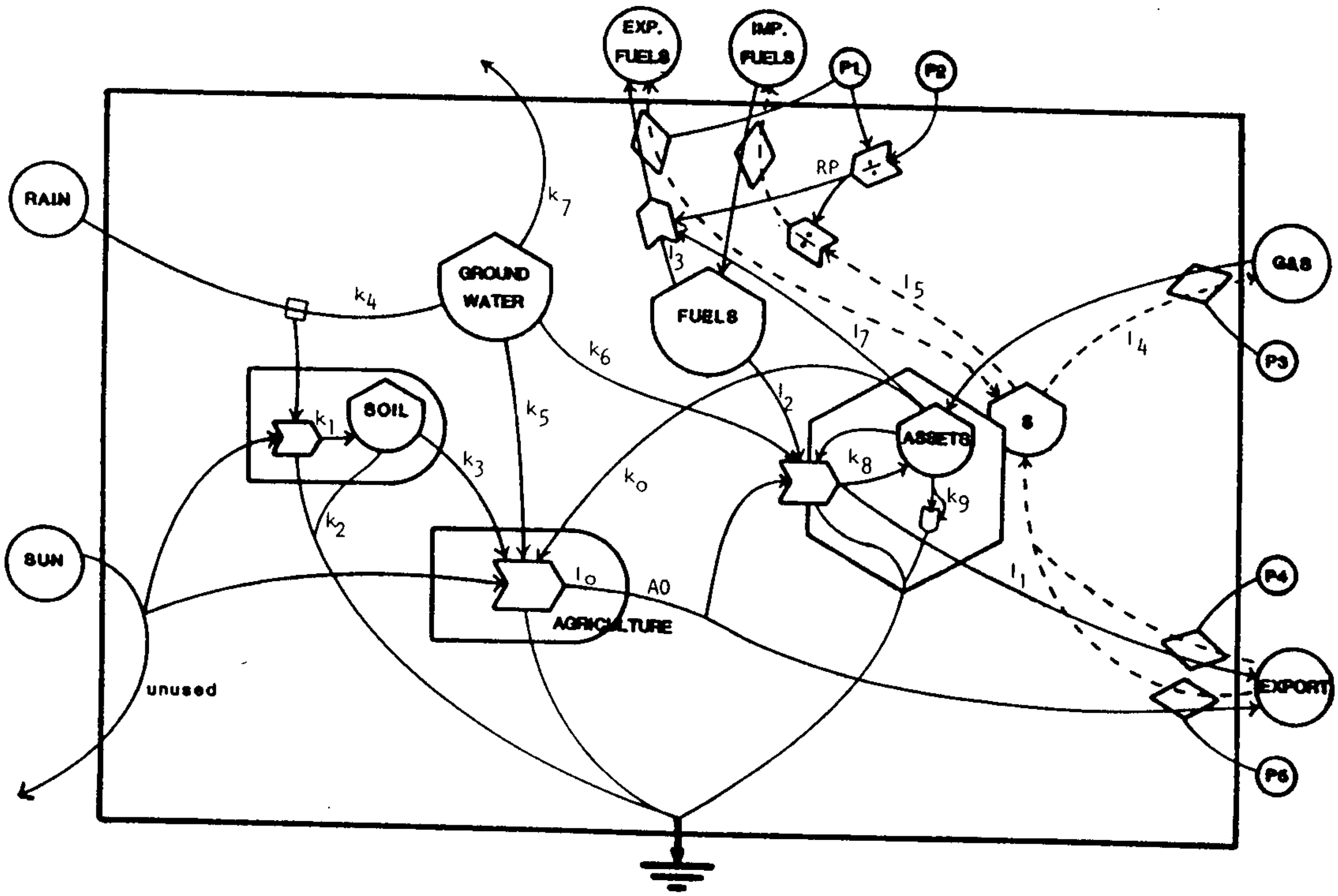


Figure 19. Overview simulation model of the Mississippi River Basin using energy language symbols. Accompanying differential equations are listed in Table 12.

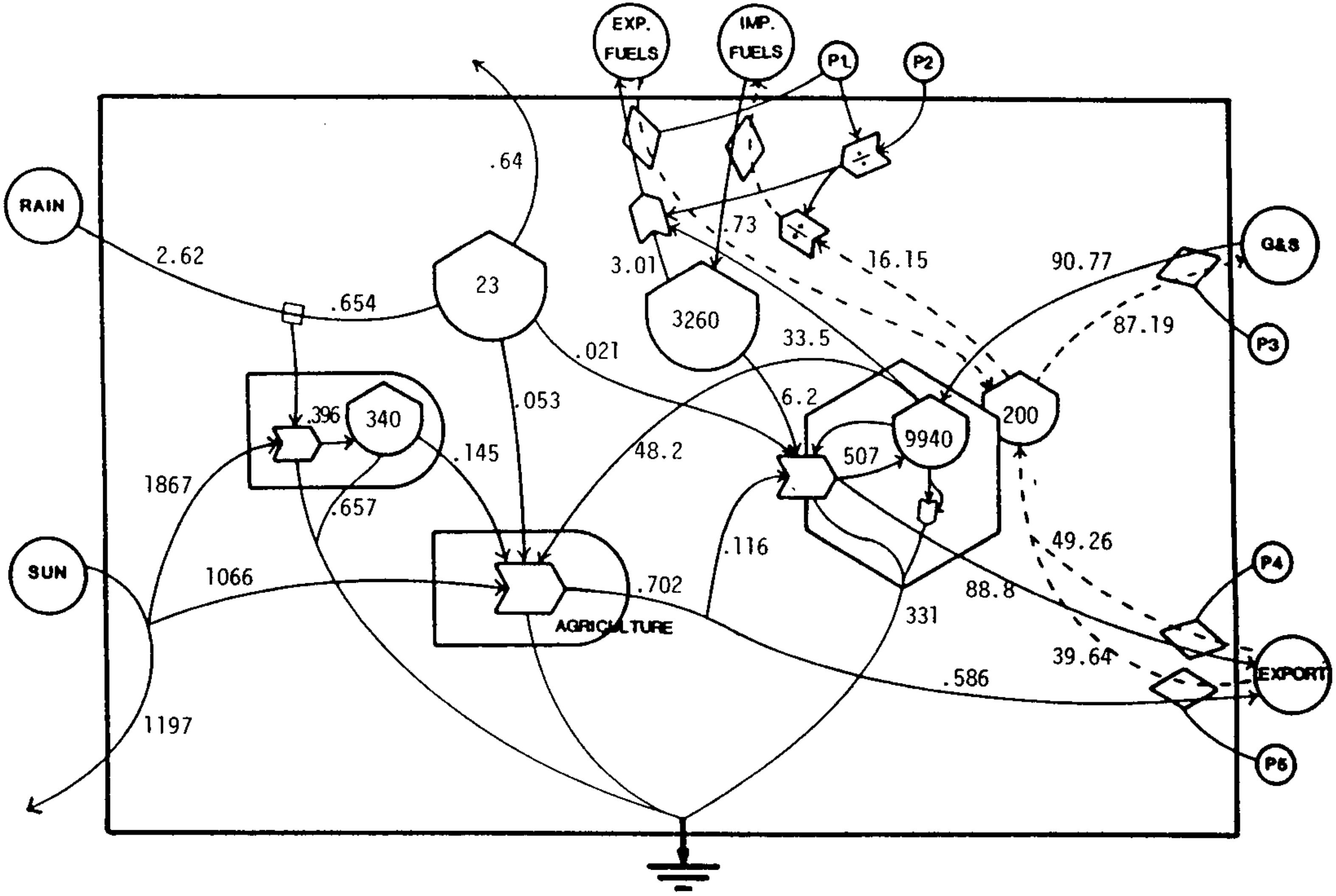


Figure 20. Overview simulation model of the Mississippi River Basin given in Figure 19 and Table 13. Numbers are initial calibration values. Fuels, water, soil, sun and agricultural output are in units of E15 kilocalories per year. Assets and related flows are in units of E18 solar equivalent kilocalories per year; dollar flows are in units of billion dollars per year.

Table 12. Differential equations for Model A 1 (accompanies Figure 11).

$$\dot{S} = \frac{k_1*L*R}{1+C_1*R+C_2*G*S*A} - k_2*S - \frac{k_3*L*G*S*A}{1+C_1*R+C_2*G*S*A}$$

$$\dot{G} = k_4*R - \frac{k_s*L*G*S*A}{1+C_1*R+C_2*G*S*A} - \frac{k_6*AO*A*F*G}{1+C_3*A*F*G} - k_7*G$$

$$\dot{A} = \frac{k_8*AO*A*F*G}{1+C_3*A*F*G} - k_aA^2 - \frac{k_0*L*G*S*A}{1+C_1*R+C_2*G*S*A} + \frac{l_4*D}{P_3} - l_7*F*RP*A$$

$$\dot{D} = \frac{l_1*AO*A*F*G*P_4}{1+C_3*A*F*G} + \frac{AO*P_5}{1+C_3*A*F*G} + l_3*F*RP*A*P_1 - l_4*D - \frac{l_5*D}{RP}$$

$$\dot{F} = \frac{l_5*D}{RP*P_2} - \frac{l_2*AO*A*F*G}{1+C_3*A*F*G} - l_3*F*RP*A$$

Table 13. BASIC program for simulation of the standard model of the Mississippi River Basin.

```
10 REM  SIMULATION PROGRAM FOR MODEL A.1
15 DIM T(300),A1(300),F1(300),G1(300),GP1(300),S1(300),AO1(300)
20 CLS
30 PRINT "MODEL A.1"
35 LINE (160,0)-(640,200),,B
36 LINE (161,1)-(638,199),,B
40 FOR I=1 TO 4
42 FOR J=-1 TO 1
45 LINE (155,40*I+J)-(160,40*I+J)
50 LINE (160+96*I+2*J,200)-(160+96*I+2*J,203)
65 NEXT J
70 NEXT I
100 REM  INITIAL CONDITIONS
110 S=340 : REM  SOIL ORGANICS
120 G=23: REM  TOTAL GROUNDWATER
130 F=3260 : REM  TOTAL FUELS
140 A=9940 : REM  TOTAL ASSETS
150 D=200 : REM  DOLLARS
160 L=4130 : REM  SUNLIGHT
170 R=2.62 : REM  RAIN (CHEM. POT.)
200 REM  PRICES AND COEFFICIENTS  (1 E9 $/1 E18 SEC)
210 P1=5.246 : REM  DOMESTIC FUEL
220 P2=22.09 : REM  IMPORTED FUEL, TRANSFERS, NUCLEAR
230 P3=.961 : REM  IMPORTED GOODS AND SERVICES
240 P4=.5547 : REM  EXPORTED GOODS AND SERVICES
250 P5=67.64 : REM  AGRICULTURAL EXPORTS
260 C1=1.145 : REM  NATURAL SYSTEMS LIMITING FACTOR
270 C2=2.389E-08 : REM  AGRICULTURAL SYSTEMS LIMITING FACTOR
280 C3=6.778E-09 :REM  URBAN SYSTEMS LIMITING FACTOR
300 REM  INITIAL FLOWS
310 J1=.396 : REM  SOIL PRODUCTION
315 J2=.657 : REM  SOIL RESPIRATION
320 J3=.145 : REM  AGRIC. CONSUMPTION OF SOIL PLUS EROSION
325 J4=.654 : REM  INFLUX OF WATER CHEM. POTENTIAL
330 J5=.053 : REM  AGRIC. CONSUMPTION OF WATER
335 J6=.021 : REM  URBAN CONSUMPTION OF WATER
340 J7=.64 : REM  OUTFLOW OF WATER CHEM. POTENTIAL
345 J8=507 : REM  URBAN PRODUCTION
350 J9=331 : REM  URBAN DECAY
355 J0=48.2 : REM  FEEDBACK TO AGRI-CULTURAL SYSTEMS
360 I1=88.8 : REM  URBAN EXPORT
365 I2=6.2 : REM  FUEL CONSUMPTION
370 I3=3.01 : REM  FUEL EXPORTS
375 I4=87.19 : REM  COST OF IMPORT GOODS AND SERVICES
380 I5=16.15 : REM  COST OF IMPORT FUELS
384 I7=33.48 : REM  MINING
390 AO=.702 : REM  AGRICULTURAL OUTPUT
```

Table 13 (cont.)

```
400 REM  CALCULATION OF PATHWAY COEFFICIENTS
405 DN=1+C1*R+C2*S*G*A : REM  DENOMINATOR FOR NON-URBAN PRODUCTION FUNCTIONS
410 SP=L*R/DN : REM  SOIL PRODUCTION
420 AP=L*S*G*A/DN : REM  AGRICULTURAL PRODUCTION
425 DU=1+C3*A*G*F : REM  DENOMINATOR FOR URBAN PRODUCTION FUNCTIONS
430 UP=AO*A*F*G/DU : REM  URBAN PRODUCTION
435 RP=1+.25*P2/P1 : REM  RELATIVE FUEL PRICE
440 K1=J1/SP
445 K2=J2/380 : REM HISTORICAL LEVEL
450 K3=J3/AP
455 K4=J4/R
460 K5=J5/AP
465 K6=J6/UP
470 K7=J7/G
475 K8=J8/UP
480 K9=J9/(A*A)
485 K0=J0/AP
490 L1=I1/UP
495 L2=I2/UP
500 L3=I3/(F*RP*A)
505 L4=I4/D
510 L5=I5*RP/D
515 L0=AO/AP
520 L7=I7/(F*A*RP)
1000 REM  SIMULATION LOOP
1010 DT=2
1020 Y=300
1030 FOR I=1 TO Y STEP DT
1100 DN=1+C1*R+C2*S*G*A
1110 SP=L*R/DN
1120 AP=L*A*G*S/DN
1130 AO=L0*AP
1140 DU=1+C3*A*F*G
1150 UP=AO*A*F*G/DU
1160 RP=1+.25*P2/P1
1200 DS=K1*SP-K2*S-K3*AP
1210 DG=K4*R-K5*AP-K6*UP-K7*G
1220 DA=K8*UP-K9*A*A-K0*AP+L4*D/P3-L7*RP*F*A
1230 DD=L1*UP*P4+P5*AO/DU+P1*L3*RP*F*A-L4*D-L5*D/RP
1240 DF=-L2*UP-L3*RP*F*A+L5*D/(RP*P2)
1300 S=S+DS*DT
1310 G=G+DG*DT
1320 A=A+DA*DT
1330 D=D+DD*DT
1340 F=F+DF*DT
1500 GOSUB 2000
1600 NEXT I
1700 END
```

Table 13 (cont.)

```
2000 REM  PLOTTING SUBROUTINE FOR ZENITH SYSTEM
2005 T(INT(I))=INT(I)
2010 X=160+I*480/Y
2020 PSET (X,200-A/100) : REM  ASSETS ARE RED
2025 A1(INT(I))=(200-A/100)/2
2030 PSET (X,200-F/17.5) : REM  FUEL IS YELLOW
2035 F1(INT(I))=(200-F/17.5)/2
2040 PSET (X,200-G*4) : REM  GROUNDWATER IS BLUE
2042 G1(INT(I))=(200-G*4)/2
2045 GP=L1*UP*P4+AO*P5/DU+L3*RP*F*P1*A
2050 PSET (X,200-GP*2) : REM  GDP IS PURPLE
2055 GP1(INT(I))=(200-GP*2)/2
2060 PSET (X,200-S/2) : REM  SOIL IS GREEN
2065 S1(INT(I))=(200-S/2)/2
2070 PSET (X,200-AO*100) : REM  AG. OUTPUT IS WHITE
2075 AO1(INT(I))=(200-AO*100)/2
2100 RETURN
```

Table 14. Initial Storage Values for Simulation.

Storage	Name	Value and Basis
S	Soil	3.40 E17 Cal See Footnote 4 to Table 3.
G	Water	2.30 E16 Cal See Footnote 6 to Table 3.
A	Assets	9.94 E18 SEC (20)(GDP)(6.21 E8 SEC/$) where GDP = $800 E9. Factor of 20 was used in previous studies as an estimator of urban value.
F	Fuel	3.26 E21 Cal Sum of Oil, Gas and Coal storages. See Footnotes 1-3 to Table 3.
$	Dollars	$200 E9 (.25)(GDP) where .25 reflects an average turnover rate of 4 times per year.

Table 15. Initial Flow Values for Simulation.

Flow	Name	Value and Basis
L	Sunlight	4.13 E15 Cal/yr (.914)(4.53 E15 Cal/yr) Average insolation over all non-urban land. See Footnote 1 to Table 2.
R	Rain	2.62 E15 Cal/yr See Footnote 2 to Table 2.
J1	Production of Soil	6.57 E14 Cal/yr (2.04 E3 Cal/m^2)(3.22 E12 m^2) Avg. rate taken from Odum and Odum, 1983.
J2	Natural Soil Losses	6.57 E14 Cal/yr Steady state value assumed for non-agricultural lands (60.2% of total).
J3	Agricultural Soil Losses	1.45 E14 Cal/yr Net loss of topsoil. See Footnote 8 to Table 2.
J4	Influx of Chem. Pot. of Water	6.54 E14 Cal/yr Sum of Basin outflow and surface water consumption for agricultural and urban use.
J5	Agricultural Water Use	5.30 E13 Cal/yr (9.35 E12 Gal/yr)(4.28 Cal/Gal) Instream use plus 3.07 E12 Gal/yr groundwater overdraft. Values from U.S. Water Resources Council, 1978.
J6	Urban Water Use	2.10 E13 Cal/yr (4.05 E12 Gal/yr)(4.28 Cal/Gal) Instream use plus 1.15 E12 Gal/yr reservoir evaporation. Values from U.S. Water Resources Council, 1978.
J7	River Outflow	6.40 E14 Cal/yr (5.71 E17 g/yr)(1.12 E-3 Cal/g) Calorie value based on 150 ppm dissolved solids. Discharge data from Costanza, 1983.
J8	Urban Production	5.07 E20 SEC/yr Based on net growth of 1.8% after depreciation, imports, and feedbacks.
J9	Urban Depreciation	3.31 E20 SEC/yr (.033/yr))(9.94 E21 SEC) Based on a turnover period of 30 years.
J0	Feedback to Agriculture	4.82 E19 SEC/yr Sum of embodied energy in fuel, fertilizer, and labor.

Table 15 (cont.)

I1	Export of Manufactured Goods	88.8 E19 SEC/yr
I2	Fuel Consumption	6.02 E15 Cal/yr Sum of oil, gas and coal used. See Footnotes 9-11 to Table 2.
I3	Fuel Exports	3.01 E15 Cal/yr Sum of coal and gas exported. See Footnotes 24 and 25 to Table 2.
I4	Cost of Imported Goods and Services	$87.19 E9/yr Sum of all imported services except for fuel. See Footnote 23 to Table 2.
I5	Cost of Imported Fuels	$16.15 E9/yr See Footnote 23 to Table 2.
I6	Depreciation Due to Pollution	1.32 E20 SEC/yr Used in Model B only.
I7	Feedback to Mining Industry	3.35 E19 SEC/yr ($53.9 E9/yr)(6.21 E8 SEC/$) Value is the portion of the GDP generated by mining sector. See Appendix G.
AO	Agricultural Output	7.02 E14 Cal/yr Sum of grain and animal exports and grain and animal products consumed. See Footnotes 14,15, and 29 to Table 2.

Table 16. Simulation Constants and Prices.

Constant	Name	Value and Basis
C1	Soil Production Limiting Factor	1.145 Based on average albedo of 25%.
C2	Agricultural Limiting Factor	2.389 E-8 Based on average albedo of 35%.
C3	Urban Limiting Factor	6.778 E-9 Based on consumption of 1.16 E14 Cal/yr of agricultural output versus 5.86 E14 Cal/yr exports.
P1	Price of Exported Fuel (Domestic)	$5.246 E9/1 E15 Cal
P2	Price of Imported Fuel	$22.09 E9/1 E15 Cal
P3	Price of Imported Goods and Services	$0.961 E9/1 E18 SEC

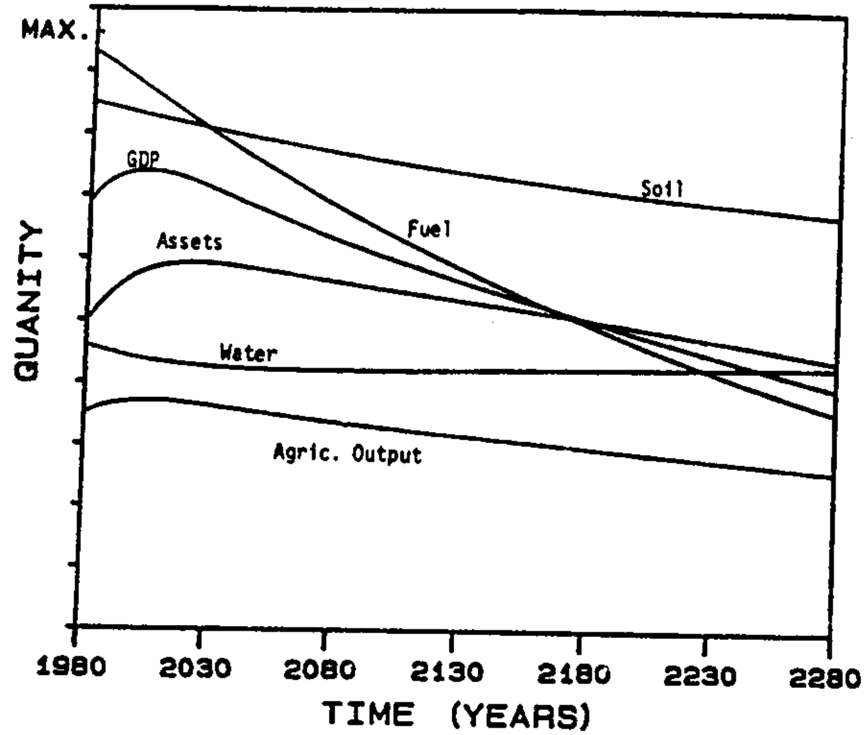


Figure 21a. Simulation of the model in Figure 19 with values as calibrated in Figure 10.

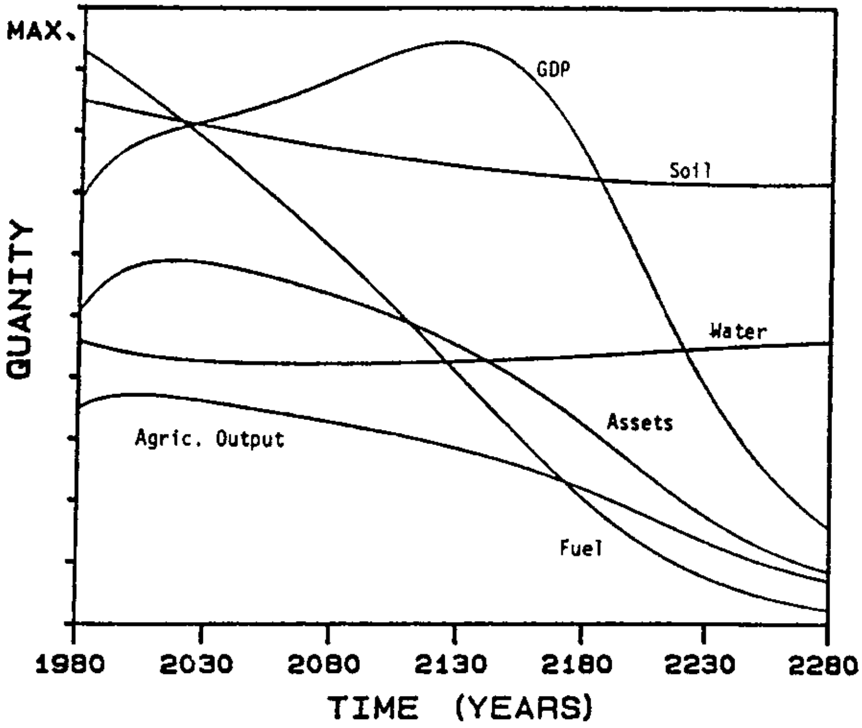


Figure 21b. Simulation of the model in Figure 19 with 2% per year increase in cost of fuel.

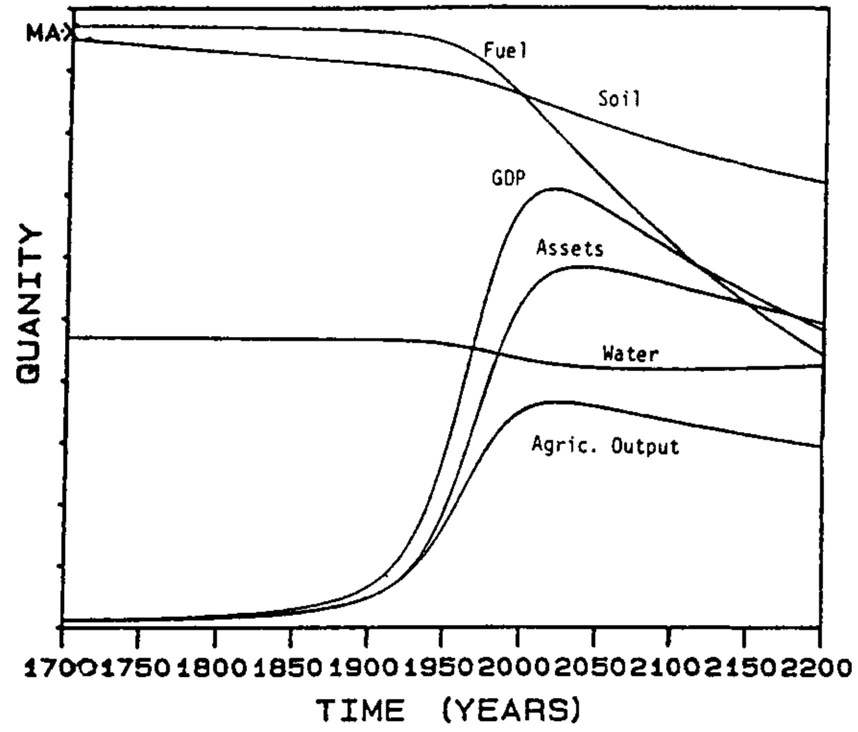


Figure 21c. Simulation of the model in Figure 19 over a 500-year period with initial values of assets and dollars set at 1% of current values and fuel and soil set 10% higher than current values.

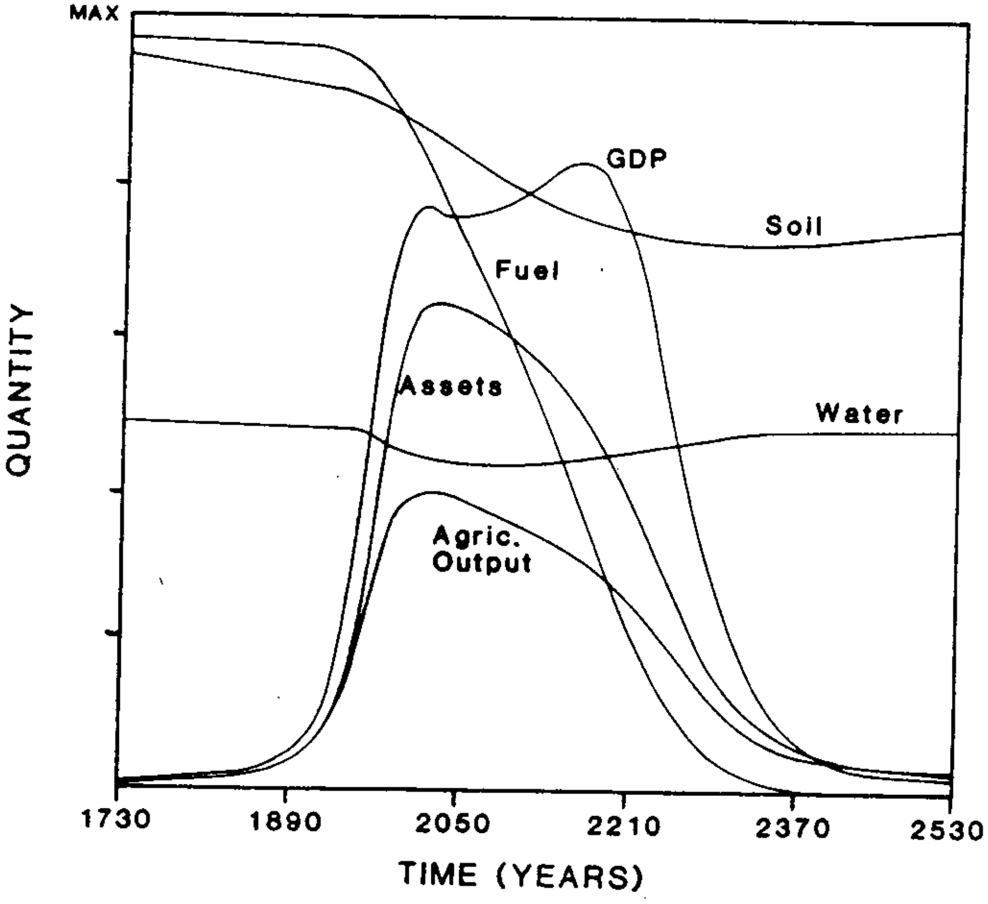


Figure 21d. Simulation of the model in Figure 19 over an 800-year period with a 2% increase in fuel costs.

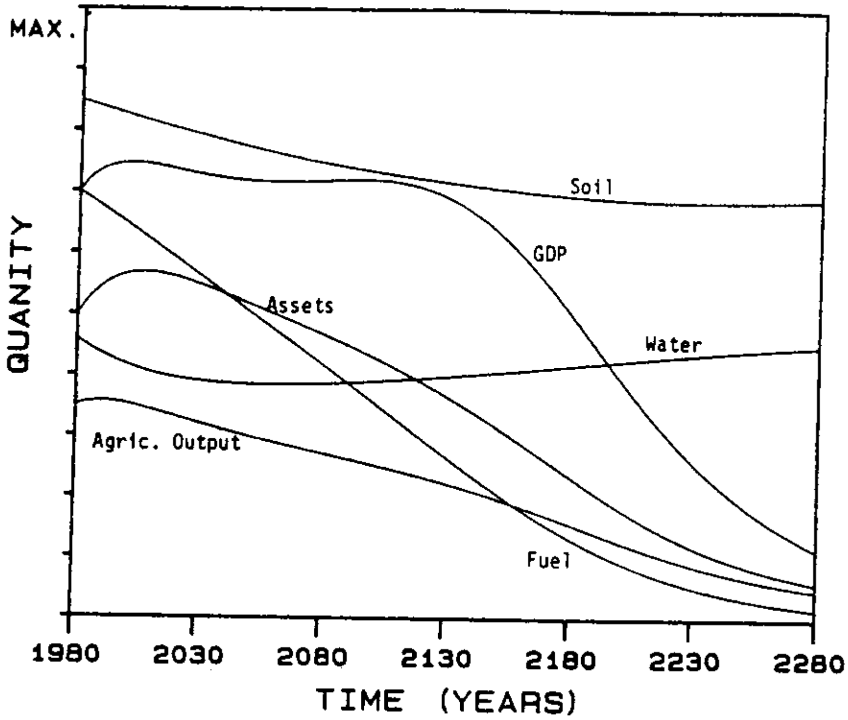


Figure 21e. Simulation of the model in Figure 19 with 25% increase in estimate of present fuel reserves, with 2% increase per year in cost of imported fuel, addition of a pathway of increased depreciation of assets as a function of fuel use representing pollution, and a 2% per year increase in the costs of outside goods and services.

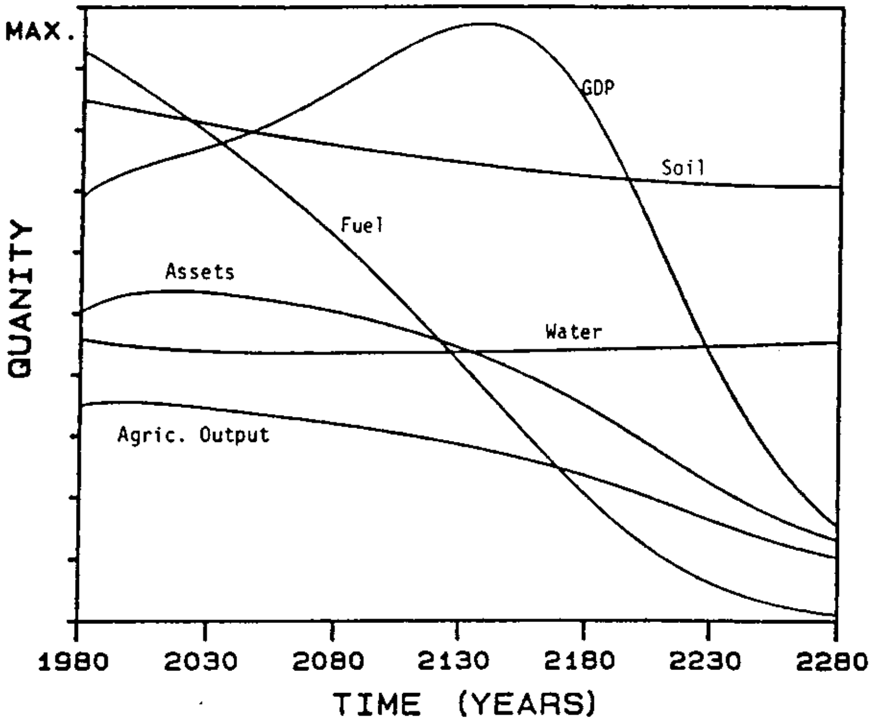


Figure 21f. Simulation of the model in Figure 19 with 2% increase in fuel cost and an additional pathway providing more hydropower as an alternative of fuel use.

exports which, in conjunction with surplus produce, generate the capital required for external fuels, goods, and services. Since goods and services are considered to be high-quality energies, they are added directly to urban assets. The value of goods, services and assets was determined by the EMERGY of their approximate dollar value rather than an estimate of the actual calories. Odum (1983) has shown that high-quality items which use substantial fuels, labor and information in their production are represented reasonably well, in terms of EMERGY, by their dollar value and the dollar-energy translation.

Simulation Program and Results

Table 12 reports the differential equations used in the basic model. The computer program for the simulation, written in BASIC, is presented as Table 13. The calibration of initial values of flows and state variables is described in Tables 14-16. Pathway coefficients are calculated within the program to insure accuracy. Soil, fuel, water, urban assets, agricultural output, and gross domestic product (the sum of fuel, manufactured goods, and agricultural sales) are plotted for 300 years, beginning with 1980, in each simulation.

Figure 21a is the result of the basic model with no changes to system inputs or to internal pathways. Agriculture and GDP reach their maximum values by 2010, decline to current values by 2030 and continue to decline thereafter. Urban assets peak around 2025. Water supplies continue to shrink until 2040, while soil storages do not begin to recover until the end of the 23rd century. Basin civilization succeeds in tapping about 60% of its fuel reserves during this period.

Figure 21b describes the impact of a constant increase of 2% per year in the real price of imported goods, services, and fuels. Agriculture peaks before 2010, while assets increase until 2025. GDP reaches a temporary maximum, following growth in assets, before a dramatic increase occurs as a result of accelerated fuel sales. Soil and water reserves attain slightly higher final levels since assets and agriculture are drawn down substantially once fuel supplies shrink. Most of the fuel has been exported, along with greater internal consumption, to account for diminishing foreign supplies.

A historical simulation is shown in Figure 21c. Initial values for state variables were estimated for the year 1700: Fuel, soil and water are near maximum values, while assets were set at 2% of the current level to account for population and small settlements. The accuracy of the basic model is borne out by the magnitude and location of the developed peaks which occur around 2020. 1700 as a starting year was an arbitrary date, and a figure 50 years either way could have been chosen. A longer-term model, 800 years, is depicted in Figure 21d. Water reserves stabilize near 2400, while soil stocks do not begin to recover until 2300.

Figure 21e describes the effects of increased soil erosion and water consumption as a function of higher fuel supplies, to account for optimistic estimates, and an increase in foreign fuel prices. Agriculture and GDP peak by 1995, while assets continue to grow until 2020. Water supplies recover by the end of the simulation, while soil stocks just begin to increase. Only about 5% of fuel reserves remain.

Figure 21f shows a variation of the model in which the urban production function uses the sum of water and fuel energies rather than their product. Consumption of fuel causes increased depreciation of capital through pollution. The overall behavior is similar to that shown in Figure 20 but assets, agriculture, and GDP conclude at much higher levels since they can depend on a separate, renewable energy source.

VII. PERSPECTIVES ON THE FUTURE

The future trends for the Mississippi River Basin should be considered on several scales: the response of the Basin's economy to the world trends; the effect of loss of resources within the Basin, and the successional changes in the cities, rural land uses, and water management as a new maturity develops at a lower energy level.

The worldwide decline of net energy of fuels and other nonrenewable resources is predicted to gradually decrease the availability of raw imports to fuel the industrial economies. At the same time net energy of oil and gas in Louisiana, Oklahoma, and elsewhere in the Mississippi Basin also will decline, raising cost. The proportion of the EMERGY due to the River will increase again. These predictions are based on simulations shown in Figure 21 also.

The massive structural diversion of the river's pattern of floods, floodplains, distributaries, sediment deposition and marine estuaries has moved the system away from the self-maintaining steady state patterns natural to the river. As changes have accumulated, the pattern of navigation locks, channels, levees, and floodplain agriculture will become increasingly costly to maintain. As the rich energy resources for each movement and engineering decline, a point is reached at which the river goes back to its natural pattern. People once again will fit their settlements to the water's hierarchical network. The massive channelization and levees of a single navigation route will be replaced with multiple distributaries like the Atchafalaya. The ships will become smaller, and major ports and shipping will reorganize around the energy availabilities of the natural river.

Some of the lands now eliminated from annual flooding once again will receive waters, enriching deposits of sediment, and become floodplain forests or wetland agriculture. A greater percentage of the waters will receive the filtering action of these floodplains so that water qualities improve. The practice of building up and diking around human settlements, agricultural plots, roads, etc., will replace the more expensive practices of holding the river in one narrow channel. With wider areas to absorb the normal floods, the height and hazard will be less, and heights of dikes necessary for local protection will be less in most places.

Upland agriculture, now among the world's most intensive in inputs of machinery, chemicals, services, etc., becomes less intensive as greater areas of land are used at lower yield per unit area, with more use of labor, and smaller and less expensive machinery. The increased costs of inputs ultimately due to the declining net energy of world resources make intensive agriculture too expensive. World markets will shift to more local self sufficiencies. Increasing costs of fertilizers and pesticides increase practices of rotation and use of flood deposited sediments.

Fresh waters will be better distributed to the Louisiana salt marshes. As the abandoned network of oil barge channels is recaptured by estuarine circulation, restored marsh productivity can counteract subsidence.

Three factors may work to increase the stocks of fishes, crabs, and shrimps: (1) restored wetland production, (2) decreased fishing pressure due to rising fuel prices, and (3) restored migratory fish runs as upstram habitats improve.

Whereas the total trade of agricultural products, oil, petrochemicals, and manufactured goods may decrease, the percentage of the trade that is river-processed may increase, since river energies will not be diminished. However, river energy will be spread over a wider channel again. The industrial structure for processing oil may be used less and less as imported oils become too expensive, and the exporting countries develop their own installations for refining and manufacture.

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APPENDIX A. RUNOFF RATES IN THE MISSISSIPPI RIVER BASIN.

Sub-basin	Runoff in/yr	% Total Area		Contribution (in/yr)
Ohio	19	12.95		2.46
Tennessee	21	3.40		0.71
Upper Miss.	4	14.41		0.58
Lower Miss.	8	8.23		0.66
Missouri	3	41.31		1.24
Arkansas	6	19.64		1.18
			Total	6.83
				(0.173 m)

Source is U.S. Water Resources Council (1978).

APPENDIX B. EROSION WITHIN THE MISSISSIPPI RIVER BASIN.

Sub-basin	Cropland (E 11 m^2)	$g/m^2 \cdot yr$	E 14 g/yr	Range and Forest (E 3 acres)	Ton/area·yr	E 6 ton/yr
Ohio	1.45	1,250	1.81	57,138	0.4	22.86
Tennessee	0.22	1,250	0.27	17,936	0.3	5.38
Upper Miss.	2.74	1,000	2.74	36,117	0.6	21.67
Lower Miss.	0.98	1,000	0.98	37,027	0.3	11.11
Missouri	4.44	500	2.22	191,711	1.5	287.57
Arkansas	1.89	500	0.95	100,104	1.0	100.10
Totals			8.97 E 14 g/yr			4.49 E 8 Ton/yr (4.48 E 14 g/yr)
Total soil loss is 13.45 E 14 g/yr						

Area of cropland, range and forest is from U.S. Water Resources Council (1978)

Rate of erosion for crops is from Larson (1983) in Odum (1983).

Rate of erosion for range and forest is from U.S.W.R.C. (1978).

APPENDIX C. ENERGY USE IN BASIN, 1981. E 12 BTU.

State		Coal	Gas	Petrol	Nuclear	Hydro	Elect.	Total
I Arkansas		102	272	316	99	13	1	803
Iowa		254	260	377	24	10	49	974
Kansas		213	440	347	0	0	-35	965
Kentucky		675	204	450	0	27	-51	1,305
Missouri		538	291	558	0	7	-21	1,373
Nebraska		100	142	199	65	12	-13	505
Oklahoma		155	690	456	0	12	-55	1,258
S. Dakota		38	23	107	0	55	-30	193
Tennessee		562	229	504	51	61	228	1,635
II Alabama	(11%)	68	31	52	28	7	-24	162
Colorado	(94%)	266	204	303	8	14	-1	794
Georgia	(1%)	5	3	7	1	0	0	16
Illinois	(35%)	280	381	474	113	1	7	1,256
Indiana	(78%)	888	397	558	0	4	-12	1,835
Louisiana	(95%)	25	1,739	1,385	0	0	179	3,328
Maryland	(<1%)	0	0	1	0	0	0	1

APPENDIX C (cont.)

State		Coal	Gas	Petrol	Nuclear	Hydro	Elect.	Total
Minnesota	(93%)	238	254	458	103	10	48	1,111
Mississippi	(74%)	61	185	275	0	0	70	591
Montana	(90%)	58	49	135	0	106	-46	302
New Mexico	(7%)	14	14	16	0	0	-11	34
New York	(1%)	1	3	8	1	2	0	15
N. Carolina	(3%)	20	5	20	2	1	1	49
N. Dakota	(32%)	58	11	46	0	19	-51	83
Ohio	(64%)	1,004	571	860	31	0	93	2,559
Penn.	(32%)	470	257	428	50	2	-20	1,187
Texas	(6%)	54	242	206	0	1	-5	498
Virginia	(6%)	16	9	41	12	0	11	89
W. Virginia	(94%)	828	143	195	0	10	26	1,202
Wisconsin	(40%)	133	133	188	42	9	11	516
Wyoming	(87%)	291	62	158	0	8	-183	336
Totals		7,415	7,244	9,128	630	391	166	24,974

APPENDIX D. FERTILIZER USE.

Values are 1970-1978 averages, E 3 tons

State		Nitrogen	Phosphorus	Potassium
Iowa		776	416	422
Indiana		391	275	376
Illinois		743	477	575
Kansas		535	178	
Missouri		332	182	215
Nebraska		596	149	
Ohio		291	253	294
Minnesota	a)	284	181	199
Wisconsin	a)			186
Texas	a)	142	54	
	Total	4,090	2,165	2,267

Source: National Waterways Study, 1981

Note: These states were factored by the percentage of their area in the Basin: Minnesota (65%), Wisconsin (70%) and Texas (20%).

APPENDIX E. AGRICULTURAL OUTPUT.

State	Corn	Wheat (E 9 kg)	Soybeans
Arkansas		1.04	2.79
Colorado b)	2.50	2.43	
Illinois	33.30	2.01	9.47
Indiana	16.36	1.46	4.25
Iowa	41.21		8.65
Kansas	3.74	10.30	1.00
Kentucky	3.27	0.48	1.27
Louisiana			2.06
Minnesota a)	10.79	1.99	2.70
Mississippi a)		0.17	1.17
Missouri	4.77	2.49	4.34
Montana b)		3.71	
Nebraska	18.87	2.73	1.73
N. Dakota a)	0.39	3.81	
Ohio	10.31	1.84	3.45
Oklahoma		5.30	
Pennsylvania a)	4.17	0.34	
S. Dakota	4.35	1.92	
Tennessee	1.16	0.57	1.61
Texas a)	0.64	4.09	0.08
Wisconsin a)	6.18		
Totals	162.01	46.68	44.57

Source: U.S. Statistical Abstract, 1983.

Note: All values reported are at 14% moisture content.

All values represent three year average: 1979-1981.

Original values reported in E 6 bushels. Conversion based on 1.25 ft^3/bushel and 44.8 lb/ft^3 for corn, 48 lb/ft^3 for wheat and soy. (56 lb/bushel and 60 lb/bushel)

a) These values have been factored by the percent area of the state within the Basin: Minnesota (65%), N. Dakota (55%), Texas (20%), Mississippi (50%), Wisconsin (70%), Pennsylvania (35%).

APPENDIX F. ANIMAL PRODUCTS (E 6 kg).

	Cattle	Hogs	Sheep	Milk	Broilers	Turkey	Eggs
Arkansas	335	118	--	344	1,216	131	178
Colorado a)	243	26	26	192			12
Illinois	442	1,086	10	1,165		4	74
Indiana	303	757	7	1,020		57	129
Iowa	1,170	2,649	24	1,907		62	100
Kansas	1,014	313	14	619			30
Kentucky	442	201	1	994			26
Louisiana	213	26	1	433	188		33
Minnesota a)	399	545	10	2,945		145	71
Mississippi a)	148	34	--	187	261		42
Missouri	883	655	7	1,288	47	104	59
Montana	433	41	34				9
Nebraska	1,047	642	12	621			37
N. Dakota a)	180	24	8	232			3
Ohio	299	354	19	1,955	28	22	95
Oklahoma	900	58	5	501	92	14	21

APPENDIX F (continued)

	Cattle	Hogs	Sheep	Milk	Broilers	Turkey	Eggs
Pennsylvania a)	112	56	2	1,328	72	17	57
S. Dakota	656	306	46	785			31
Tennessee	376	188	1	1,000	116		46
Texas a)	432	31	28	324	83	13	21
Wisconsin a)	490	193	5	7,038	16	36	40
Wyoming a)	153	3	43				1
West Virginia					45	18	11
Totals	10,670	8,306	303	24,878	2,164	623	1,126

Source: U.S. Statistical Abstract, 1983 (1980 figures).

Note: Production values determined by the percentage of stock each state is of the U.S. total times the U.S. production total.

a) These states factored by their area in the Basin [50, 65, 50, 55, 35, 20, 70, 70, respectively].

APPENDIX G. IMPORT AND EXPORT SERVICES OF THE BASIN.

Table G.1. Portion of GDP generated per employee by sector (U.S. avg.).

Sector	Number of Employees (1 E 3)	Dollars per Employee ($ E 3)	Gross Product of Sector ($ E 9)
Agriculture	3,008	28.46	85.6
Manufacturing	20,173	31.92	644.0
Mining	1,131	112.47	127.2
Trade	20,551	23.00	472.7
Government	16,024	21.01	336.7
Services	18,592	20.81	386.9
Utilities	5,157	50.79	261.9
Finance	5,301	84.55	448.2
Construction	4,176	30.46	127.2
Totals	94,113		2,890.4

Table G.2. Gross Domestic Product of Basin.

Sector	Number of Employees (1 E 3)	Dollars per Employee ($ E 3)	GDP per Sector ($ E 9)
Agriculture	1,157	28.46	32.93
Manufacturing	5,628	31.92	179.93
Mining	479	112.47	53.92
Trade	5,638	23.00	129.67
Government	4,439	21.01	93.26
Services	4,659	20.81	96.95
Utilities	1,453	50.79	73.80
Finance	1,254	84.55	106.03
Construction	1,125	30.46	34.27
Totals	25,832		800.76

Dollars per employee is based on U.S. averages.

Table G.3. Employment (1 E 3) by Sector.

State	Total	Agr.	Mfg.	Trade	Gov't	Services	Utilities	Finance	Const.
U.S.	94,113	3,008	21,304	20,551	16,024	18,592	5,157	5,301	4,176
Alabama	154	15	43	30	32	23	8	6	7
Arkansas	803	63	216	160	138	117	43	32	34
Colorado	1,308	105	212	292	228	250	77	75	69
Georgia	19	3	4	3	4	2	1	1	1
Illinois a)	1,549	113	351	331	232	289	86	96	51
Indiana a)	1,674	77	503	354	262	257	79	76	66
Iowa	1,164	74	238	275	210	209	54	59	45
Kansas	1,010	61	206	228	187	174	63	48	43
Kentucky	1,299	106	323	258	227	215	67	52	51
Louisiana	1,569	22	303	351	291	274	125	71	132
Maryland	3	1	--	1	1	--	--	--	--
Minnesota	1,718	79	351	409	278	355	92	91	63
Miss.	641	34	173	121	138	90	30	24	31
Missouri	2,025	54	433	466	333	405	138	109	87
Montana	277	20	30	67	64	51	21	12	12
Nebraska	663	38	96	163	131	121	47	41	26

Table G.3 (continued)

State	Total	Agr.	Mfg.	Trade	Gov't	Services	Utilities	Finance	Const.
New Mexico	34	1	4	7	9	7	2	2	2
U.S.	94,113	3,008	21,304	20,551	16,024	18,592	5,157	5,301	4,176
New York	73	1	13	15	13	18	4	7	2
N. Carolina	75	3	25	14	12	11	4	3	3
N. Dakota	85	5	8	21	20	17	5	4	5
Ohio a)	2,757	88	780	584	420	528	135	127	95
Oklahoma	1,257	64	294	278	237	202	69	59	54
Pennsylvania	1,542	30	429	316	226	322	83	77	59
S. Dakota	263	26	29	64	58	52	13	11	10
Tennessee	1,802	56	516	373	309	307	86	78	77
Texas	380	11	84	90	60	65	23	21	26
Virginia	136	6	26	28	31	25	7	6	7
W. Virginia	611	24	160	123	123	95	39	21	26
Wisconsin	802	34	219	173	128	150	36	38	24
Wyoming	193	7	38	43	37	28	16	7	17
Total	25,832	1,157	6,107	5,638	4,439	4,659	1,453	1,254	1,125

Note: Manufacturing includes mining.

Table G.4. Total exports and imports by sector.

	Agr.	Mfg.	Mining	Trade	Gov't	Services	Utilities	Finances	Const.
(1) U.S. avg.	3.19	21.43	1.21	21.83	17.03	19.75	5.48	5.63	4.44
(2) Basin	4.48	21.79	1.85	21.83	17.18	18.04	5.62	4.85	4.36
(3) Diff	1.29	0.36	0.64	--	0.15	-1.71	0.14	-0.78	-0.08
(4) Exp. Imp.	333.23	92.99	165.32	--	38.75	-441.72	36.16	-201.49	-20.67
(5) Exp. $	9.48	2.97	18.59	--	0.81	-9.19	1.84	-17.04	-0.63

Exports (+) = 33.07 E 9

Imports (-) = 26.86 E 9

Net = 6.21 E 9

Notes: (1) Percentages of employees per sector (from Table G.1).

(2) Percentages of employees per sector (from Table G.2).

(3) Difference between (1) and (2).

(4) Number of export employees (1 E 3): Difference in percentages times total number of employees.

(5) Total export dollars ($ E 9): Number of export employees times dollars generated per employee (from Table G.1).

APPENDIX H. GOVERNMENT FINANCE.

	1981 Total Fed. Aid ($ E 6)	1984 Federal Taxes ($ E 9)
Alabama (11%)	164	0.78
Arkansas	887	3.63
Colorado (94%)	960	7.98
Georgia (1%)	22	0.11
Illinois (35%)	1,613	12.75
Indiana (78%)	1,349	10.95
Iowa	961	6.99
Kansas	774	6.35
Kentucky	1,433	6.85
Louisiana	1,643	10.42
Maryland	9	0.01
Minnesota (93%)	1,650	9.73
Mississippi (74%)	812	2.84
Missouri	1,663	11.75
Montana (90%)	404	1.50
Nebraska	517	3.59
New Mexico (7%)	50	0.18
New York (1%)	104	0.48
N. Carolina (3%)	57	0.34
N. Dakota (32%)	102	0.43
Ohio (64%)	2,384	18.45
Oklahoma	1,043	7.52
Pennsylvania (32%)	1,564	9.69
S. Dakota	356	1.21
Tennessee	1,910	9.32
Texas (6%)	249	2.57
Virginia (6%)	112	0.85
W. Virginia (94%)	885	3.75
Wisconsin (40%)	920	4.45
Wyoming (87%)	279	1.41
Total	24,876	156.88

Footnotes to Table H.

Source: U.S. Statistical Abstract, 1983

Note: Percentage values are based on population of each state residing within the Basin.

Assume remainder of federal budget accrues benefits to citizens proportionally. Budget is $599.3 E 9; Aid is $94.8 E 9 and foreign service expense is $11.1 E 9, so balance is $493.40 E9. Basin percentage is 27.8%: $137.17 E 9.

Inflow = 137.17 + 24.88 = 162.05

Outflow = 156.88

Net = +$5.17 E9

APPENDIX I. OIL, GAS AND COAL PRODUCTION.

State	Oil (E 6 bbl)	Gas (E 9 ft^3)	Coal (E 6 tons)
Arkansas	19	108	0.5
Colorado a)	30	160	4.9
Illinois	24	1	56.5
Indiana	5		27.2
Kansas	58	800	0.5
Kentucky	6	63	145.2
Louisiana	533	7,181	
Mississippi a)	20	59	
Missouri			5.6
Montana	31	49	22.1
Nebraska	6	3	
N. Dakota	28	30	7.7
Ohio	11	113	43.7
Oklahoma	152	1,800	2.9
Pennsylvania			85.6
Tennessee			8.2
Texas b)	61	720	1.1
Virginia			18.8
W. Virginia	2	153	104.7
Wyoming a)	113	313	24.1
Totals	1,099	11,553	559.3

All values are 5-year averages: 1976-1980.

Source: U.S. Statistical Abstract, 1983

Oil: (1,099 E 6 bbl)(5.80 E 6 BTU/bbl) = 6,374 E 12 BTU

Gas: (11,553 E 9 ft^3)(1,031 BTU/ft^3) = 11,911 E 12 BTU

Coal: (559.3 E 6 ton)(26.2 E 6 BTU/ton) = 14,654 E 12 BTU

Notes: a) and b) see Appendix K.

APPENDIX J. GRAIN USE OF THE BASIN.

Crop	Change in Stock (E 9 kg)	Production (E 9 kg)	Internal Consumption (E 9 kg)	Animal Feed (E 9 kg)	Exports to Other States (E 9 kg)	World Exports (E 9 kg)	Value of State Exports ($ E 9)	Value of World Exports ($ E 9)
Corn	2.33	162.01	5.32	85.60	19.20	49.56	2.03	6.45
Wheat	1.46	46.68	4.58	3.58	7.48	29.58	1.04	4.70
Soybeans	0.70	44.57	8.05	1.75	15.63	18.44	3.87	4.80
Sorghum	0.57	15.70	0.08	6.94	2.78	5.33	0.32	0.69
Hay	--	18.20	--	18.20	--			
						Sum:	7.26	16.64

Source: U.S. Statistical Abstract, 1983. All figures are 3-yr averages: 1979-1981.

Notes: Values for change in stock and world exports are based on Basin percentage of U.S. total production.

Production values are from Appendix E.

Consumption value based on Basin percentage of U.S. population (27.8%).

Feed value based on Basin percentage of total U.S. animal output (66.0%).

Exports to states based on difference between production, storage and other values.

APPENDIX K. OIL AND NATURAL GAS RESERVES.

State	Oil (E 3 bbl)	Gas Liquids (E 3 bbl)	Gas (E 6 ft^3)
Arkansas	93,439	7,279	1,728,271
Colorado a)	214,016	58,613	289,432
Illinois	155,318	--	376,876
Indiana	22,256	--	45,401
Kansas	361,570	388,078	11,950,564
Kentucky	38,188	41,132	771,544
Louisiana	3,470,628	1,622,834	57,501,756
Mississippi a)	107,098	6,885	530,657
Montana	152,670	4,697	1,106,270
Nebraska	31,307	627	59,158
N. Dakota	149,629	49,090	405,944
Ohio	125,268	--	1,350,581
Oklahoma	1,186,553	279,795	12,435,333
Pennsylvania	50,563	446	1,651,898
S. Dakota	1,504	--	--
Tennessee	1,910	--	--
Texas b)	474,621	83,939	4,974,133
Virginia	--	--	56,393
W. Virginia	30,009	83,833	2,273,273
Wyoming a)	703,604	52,641	3,148,726
Totals	7,370,151 (7.37 E 9 bbl)	2,679,889 (2.68 E 9 bbl)	100,656,210 (1.01 E 14 ft^3)

Source: Energy Information Handbook, U.S. Congress. 1977.

Notes: a) Values for Colorado, Mississippi and Wyoming based on percent area of resources within the Basin using maps in the above reference. Percentages were 85%, 50% and 85%, respectively.

b) Value for Texas was based on an area of resource within the Basin which was equivalent to 40% of Oklahoma's total area of resources. The assumption is that N. Texas deposits are closer in nature to Oklahoma resources in terms of concentration than those deposits in coastal Texas.

APPENDIX L. COAL RESERVES.

State	E 12 BTU
Arkansas	16,509
Colorado a)	214,477
Illinois	1,707,285
Indiana	276,188
Iowa	75,007
Kansas	39,091
Kentucky	664,056
Maryland	27,253
Missouri	246,670
Montana b)	3,760,759
N. Dakota a,b)	2,711,225
S. Dakota	80,568
Ohio	548,007
Oklahoma	33,649
Pennsylvania c)	620,880
Tennessee	25,654
Virginia a)	45,661
W. Virginia	1,029,335
Wyoming a)	656,320
Total	12,778,594 (1.28 E 19 BTU) = 3.22 E 18 Cal

Source: Energy Information Handbook, U.S. Congress. 1977.

Note: All values are for demonstrated reserves only.

a) Values for Colorado, Wyoming, N. Dakota and Virginia were based on percent area of each state's reserves within the Miss. Basin using maps from the above reference. Percentages were 60%, 40%, 90% and 40%, respectively.

b) Values include energy for lignite at 8,687 BTU/lb for Montana (99,372 E 6 tons); 6,723 BTU/lb for N. Dakota (201,638 E 6 tons);

Footnotes to Appendix Table L (cont.)

6,723 BTU/lb for S. Dakota (5,992 E 6 tons).

c) Value based on bituminous reserves only, since this is the dominant coal type of the western part of the state.

APPENDIX M. ORGANIC CONTENT OF SOILS.

Soil Type	Nitrogen Content (E 6 g/ha)	Organic Content (E 4 g/m^2)	Area (E 1/m^2)	Subtotal (E 16 g)
Red and yellow	4.47	0.89	4.99	0.45
Gray-brown podzols	7.16	1.43	3.61	0.52
Prairie	16.80	3.36	6.44	2.16
Chernozem	17.94	3.59	4.15	1.49
Chestnut	11.98	2.40	4.57	1.09
Brown	8.97	1.79	3.25	0.58
Undetermined			5.22	
			Total	6.30

Note: Undetermined soil represents 16.2% of the total area.

Areas were measured using maps by Hunt (1972) in Odum et al. (1983).

APPENDIX N. BIOMASS IN FORESTS.

Sub-Basin	Forested Acres (E 3)
Ohio	43,143
Tennessee	14,404
Upper Mississippi	24,473
Lower Mississippi	27,099
Missouri	29,937
Arkansas	33,545
Total	172,601 (6.99 E11 m^2)

Based on USDA (1949) vegetation maps, the forested areas of the Basin are primarily oak-hickory except for the lower Miss. sub-basin which is primarily cypress-tupelo. Average value for mid-west oak-hickory communities is 13.79 kg/m^2 (Odum, 1983) and average value for southern bottomland forest/cypress-gum is 26.85 kg/m^2.

(145,502 E 3 acres)(4,047 m^2/acre)(13.79 kg/m^2) = 8.12 E 12 kg

(27,099 E 3 acres)(4,047 m^2/acre)(26.85 kg/m^2) = 2.94 E 12 kg

Total = 1.11 E 13 kg