Evaluation Overview of the Cache River and Black Swamp in Arkansas

Howard T. Odum, Silvia Romitelli, and Robert Tighe

Final Report on Contract #DACW39-94-K-0300
Energy Systems Perspectives for Cumulative Impacts Assessment
between Waterways Experiment Station, U.S. Dept. of the Army,
Vicksburg, Miss. and University of Florida

Center for Environmental Policy
Environmental Engineering Sciences
University of Florida, Gainesville, 32611

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Part I was a progress report entitled Energy Systems Perspectives on Cumulative Impacts in the Black Swamp, Cache River Arkansas (H.T.Odum and R. Tighe, Sept .30, 1994). It contained energy systems diagrams aggregating the Black Swamp as a whole. To show qualitatively how complex interactions developed cumulative impact, diagrams with highlighted pathways were supplied for each of 6 functional sectors of the system that had been recognized to be of concern: (a) waters, (b) sediments, (c) biodiversity, (d) forestry, (e) fisheries, and (f) deer. If the user has been taught the symbols and their meaning, inspection of these networks provides a quick guide to components and interactions which have to be considered in permitting. The appendix contained the equations for each of the models and highlighted impact relationships. These equations show the impact relationships in mathematical form, a translation of the energy language diagrams, ready for simulation. An example is the simulation of impact on groundwater in the Black Swamp included in this final report.

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ABSTRACT

This is the second and final report applying energy systems methods for overview, evaluation, and management of watersheds, with the Cache River in Arkansas as an example. The first report included systems models (diagrams and mathematical expressions) for showing environmental, ecological, and economic interactions in the Cache River watershed, and a portion of its floodplain known as the Black Swamp, for synthesizing knowledge and understanding cumulative impacts.

This second report uses the systems overviews to evaluate influences and processes affecting the area on 3 scales, from the large scale down: (1) the state of Arkansas, (2) the Cache River watershed, and (3) the Black Swamp. Emergy and emdollars were used to determine what is important for environmental management and permitting. (Emergy is the available energy in units of one kind of energy previously used up directly and indirectly to make a product or service. Emdollars (em$) are the part of the gross economic product due to an emergy contribution).

Policy for decisions on environment can be based on the maximum empower principle, which defines choices as best which maximize empower and emdollar contributions of environment and the economy together. (Empower is the rate of emergy use per year). Decisions on permitting of a development proposal should be those that maximize the emdollar production of the system.

The state evaluation showed Arkansas to have a high level of indigenous real wealth (a high emergy/money ratio, and high emergy levels per person) compared to the United States as a whole. About 37% of the state's total emdollars were contributed by water, soils, natural gas and other local resources and 63% from fuels, goods, and services purchased from out of state. Only 11% was renewable. Twice as much real wealth (emergy) was sold out of state as rice and other commodities than was received in monetary payments.

Evaluation of the Cache River watershed with its intensive rice production showed about half of the area's total emdollars were contributed by ground and river water uses and half from fuels, goods, and services purchased from out of the area. Forty two percent of the production was unsustainable, based on non-renewable use of soils and groundwater storages.

Evaluation of the Black Swamp showed annual contributions to a hectare were: 1608 em$ in the inflow of sediments and 4847 em$ as organics.

Physical energy contributed 449 em$ (geopotential energy used up). Forest productivity contributed $372 em$ using the chemical potential energy of water used by forests for their evapotranspiration. Swamp based fish production was 633 em$.

Per hectare, the Black Swamp, with 7640 em$/year, was more valuable than the average Cache River watershed area with 4111 em$/year and the average for Arkansas with 4738 em$/year. For permitting, the burden of proof is on a developer to show that a proposed economic use of a swamp area will generate a greater annual emdollar value.

Since energy systems models define mathematical equations, the models can be calibrated with observed data and simulated to determine the consequences of the relationships shown in the model. A model of the water budget of the Black Swamp and its groundwater was calibrated and simulated considering several "what if" alternatives. Cutting forest, and diverting the river had small effects on the groundwater compared to the larger effect of direct pumping. However, large cumulative impacts on the forest resulted from the three factors affecting the water budget together.

As with any initial overview evaluation, closure was obtained by using whatever estimates and approximations were readily available. The numerical results therefore are uneven and preliminary, inviting refinement by specialists with better data.

INTRODUCTION

Understanding watersheds and their ecosystems requires that their roles in the surrounding economy and landscape be quantitatively evaluated. Since maximum economic benefits are not achieved by diminishing the life support functions of watersheds, decisions by those planning and authorizing developments need to be made according to the principle of maximizing the real wealth productivity of both the ecosystems and the dependent economy. This paper overviews and evaluates the developed Cache River watershed in Arkansas and the contributions of the original floodplain forest ecosystem now represented by a remnant, the Black Swamp.

Energy systems diagrams are used to identify and summarize the main components and processes on three scales shown in Figures 1-3: (1) State of Arkansas; (2) Cache River Watershed; and (3) Black Swamp. Then the principal contributions to real wealth in these systems are evaluated with EMERGY, spelled with an "m", and expressed as emdollars for comparison with economic values on a common basis. Patterns over time are explored with simulation models. Those considering changes in the watershed can use the results by comparing emdollars of existing environmental and economic contributions with emdollars of the systems to result from proposed changes. Changes which do not increase emdollar value should not be authorized.

Cumulative Impacts

Most cumulative impact evaluations have been concerned with the effects accumulating on one property of the landscape, such as groundwater or biodiversity. By contrast, a systems overview of an ecosystem in relation to its surroundings shows the interplay of all variables on each other. By expressing each variable in a measure that applies to them all, it is possible to add up all impacts, or examine them separately to identify principal actions. This study evaluates various changes taking place in the Cache River watershed that impact the floodplain forest remnant represented by the Black Swamp.

Simulating Impacts

Quantitative estimates of impacts of changes and proposed changes can be obtained by computer simulation of overview models, calibrated with local values for flow and storages. Included in this study is an example of the simulation of ground water response with an overview model that has water flows, storages, and interactions highly aggregated so that the process and result are easily understood. Overview assessment and decision making require simplicity, while including details considered to be important. Simulating aggregate water responses for this purpose, to learn "what if," is different from the detailed and expensive simulation of water distribution spatially. Each approach has its place in impact evaluation, depending on the scale of the questions.

Concepts

Emergy analysis is a procedure for environmental accounting of the cumulative work required for a product or service in units of one kind of energy. It allows the user to define the proportion of the regional economy due to a specific natural resource. It measures what an environmental resource is contributing to the regional economy. A brief explanation of emergy concepts and measures follows, with definitions summarized in Table 1.

Emergy and Energy Hierarchy

Because of the second energy law, all the processes of nature and the economy can be arranged in a series, representing the hierarchy of energy. All processes use up some of the potential of energy (its availability) to do work, dispersing that energy in degraded form. Therefore, the product of useful processes has less available energy in its output than its inputs. This means that processes may be arranged in an energy transformation series like Figure 4a. In each block, available energy is dispersed. Total energy flow (power) decreases from left to right, but becomes more concentrated. Examples are food chains, stages in the hydrological cycle, and steps in the production sectors of the economy.

Energy is abundant but low quality on the left, whereas energy is less but of higher quality on the right, capable of doing more per calorie. It would be misleading, if not wrong, to consider a calorie of energy on the right equivalent to one on the left. For example, a calorie of human service is many times more valuable than a calorie of sunlight. A calorie of a hawk's work in the ecosystem contributes and controls much more than a calorie of a leaf. It takes many calories on the left to make a calorie on the right.

However, energies of different kinds may be appropriately compared by expressing each in units of one kind of available energy previously used up. In the approach used in this report, solar energy is used. Thus, Solar Emergy is defined as the available solar energy previously used directly and indirectly to make a product or service. The unit of emergy is the emcalorie or the emjoule. Whereas joules of energy are in a piece of wood,

Table 1
Summary of Definitions

Available Energy =	Potential energy capable of doing work and being degraded in the process (units: kilocalories, joules, etc.)
Useful Energy =	Available energy used to increase system production and efficiency
Power =	Useful energy flow per unit time
EMERGY =	Available energy of one kind previously required directly and indirectly to make a product or service (units: emjoules, emkilocalories, etc.)
Empower =	EMERGY flow per unit time (units: emjoules per unit time)
Transformity =	EMERGY per unit available energy (units: emjoule per joule)
Solar EMERGY =	Solar energy required directly and indirectly to make a product or service (units: solar emjoules)
Solar Empower =	Solar EMERGY flow per unit time (units: solar emjoules per unit time)
Solar Transformity =	Solar EMERGY per unit available energy (units: solar emjoules per joule)

emjoules refer to the available energy that was previously used up to make the wood. We sometimes call emergy the "energy memory."

Maximum Empower Principle and Environmental Management

The flow of useful emergy is also called empower (Table 1). The maximum power principle has long been advocated as a general principle for self organizing systems, including those of nature and of the economy. Stated so as to represent different kinds of energy appropriately, this principle is: Self organizing systems develop designs of components and relationships that maximize the intake and efficient use of emergy. Designs with more empower displace those with less.

Consequently, either by reason or by trial and error, the landscape with environment and economy will develop maximum empower designs. Public attitudes, environmental management and permitting, to be successful in the long run, need to arrange for maximum empower during development.

Transformity

Whereas the energy flow decreases through an energy transformation series, the emergy flow stays the same or increases if more inputs are added. Transformity is defined as the emergy per unit energy. It increases from left to right (Figure 4a). It is a measure of energy quality. Transformities are useful for making calculation of emergy from data on energy. Solar emergy = (energy)(solar transformity).

Empower Density

Self organizing systems develop centers of energy processing. Hierarchical centers have high concentrations of empower. The spatial concentration of empower is measured as areal empower density. For example, on a small scale, empower is concentrated in trunks of trees and in the bodies of animals. On a large scale empower is concentrated in flowing streams and human settlements.

Empower of Arkansas, the Cache River Basin, and the Black Swamp

As summarized in Figure 4b, sunlight, tides, and heat from the deep earth drive the geobiosphere, including the state of Arkansas. From the global processes, rains, geological contributions, and inputs from the economy operate the Cache River watershed. Climatic inputs and river waters operate the Black Swamp. In Figure 4b these are arranged from left to right in order of decreasing energy flow but increasing transformity.

Emdollars and Real Wealth

Figure 5 shows the main inputs to the economy of any area, including those free from the environment and those purchased and transported in. Through many processes and transformations these inputs develop the real wealth of the area such as forests, clean waters, clothing, food, housing, transport, information and aesthetics. Within that area the money circulating among the people facilitates efficient buying and selling, often measured by the gross economic product. Since emergy measures the real wealth on a common basis, dividing the annual emergy use by the gross economic product provides a useful emergy/money ratio for relating real wealth to money. The emdollar is defined as the emergy divided by the emergy/money ratio. Emdollars put environmental resource contributions on a common basis with contributions purchased by the economy. Environmental management can maximize empower by arranging developments and permits so that they maximize emdollars of the economy and environment.

Emergy Indices

Various ratios of emergy flows are useful for evaluating a system and its potential. Two are defined in Figure 6. The emergy yield ratio is calculated by dividing the emergy of the yield (Y) flowing into the economy on the right by the feedback of emergy (F) the economy is supplying from the right. A system with a large net emergy ratio is contributing much more real wealth than it requires for the process. Examples are rich mineral deposits and abundant fresh waters. In recent years the main sources of fuels that operate the nation have a net emergy ratio between 4 and 10, fluctuating with prices of fuels (Odum, 1996).

The intensity of regional economic development and use of environment is given by an emergy investment ratio defined as the ratio of emergy purchased from the economy (F) to the emergy used free from the local environment (E). In wilderness parks the ratio is less than one. Typical development in the U.S. has an investment ratio of 7. By offering more free local inputs than usual, developments less than 7 tend to cost less, capture markets, and compete economically.

Study Areas

State of Arkansas

Arkansas, in the center of the United States, includes the Ozark mountain highlands on the west and the Mississippi River alluvial valley on the east. The latter includes the floodplain and old channels of the Mississippi River, as well as current streams and tributaries, such as the Cache River (Figure 1a).

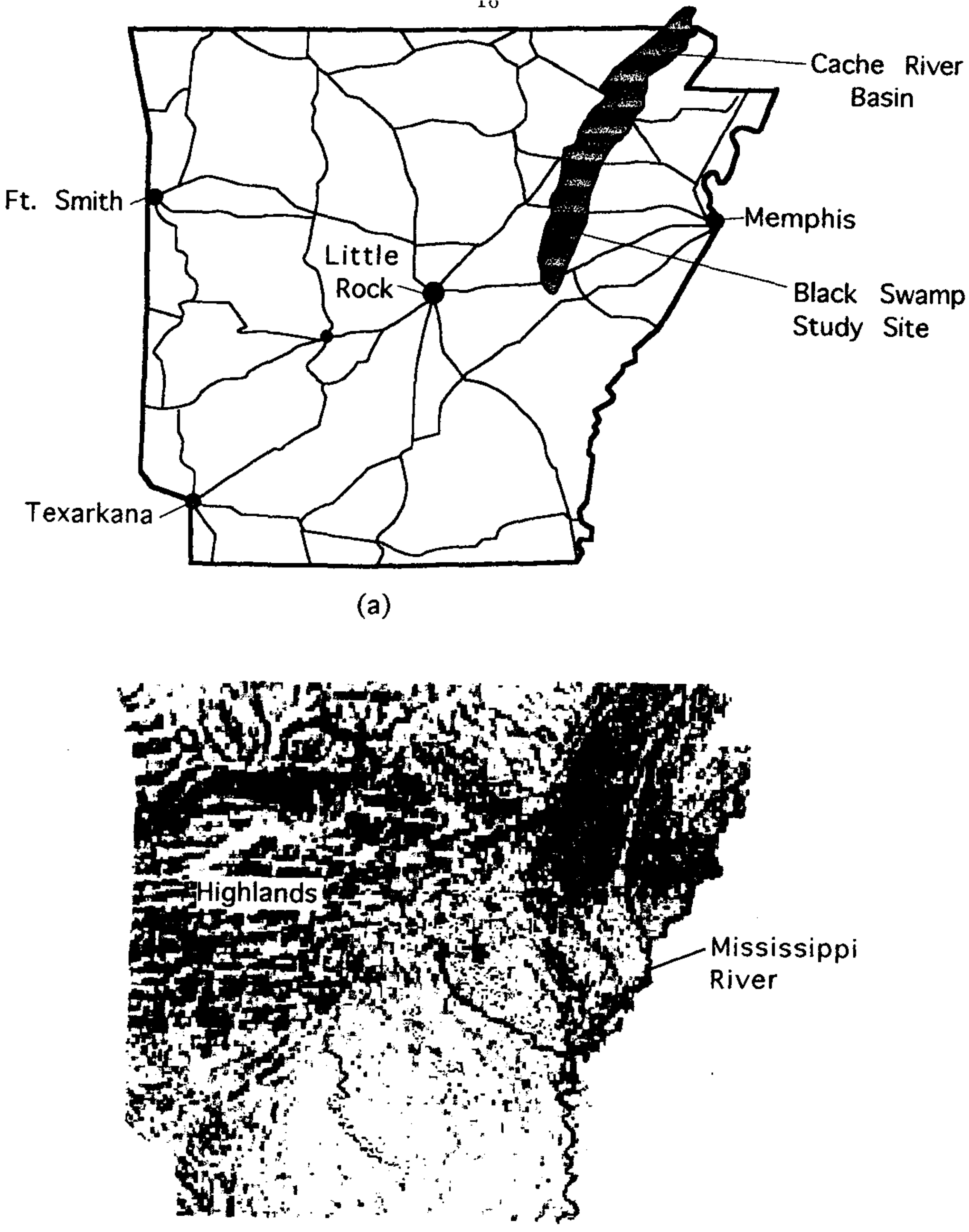


Figure 1. Three scales of watershed evaluation (1) as part of Arkansas; (2) the Cache River Watershed; (3) the Black Swamp.

Cache River Basin

The Cache River rises in southeastern Missouri, and flows south-southwest through northeast Arkansas to its confluence with the White River (Figure 2). It is one of several rivers traversing the Western Lowlands, an alluvial plain in the upper portions of the Mississippi River Valley. The landscape is flat and fertile, and has thus been conducive to the establishment of agriculture, primarily crops such as soybeans, rice, cotton, and wheat.

Beginning with initial clearing and drainage in the early part of this century, more than 80% of the former forestland of the Cache River basin has been converted to agriculture. Of the little natural area that remains, most is floodplain forest along the watercourses of the alluvial plain. In the Cache River basin, this is primarily concentrated in several clumps found along the lower portions of the river.

Black Swamp

The Black Swamp Wildlife management area is a part of the remaining bottomland hardwood area in the lower Cache River Basin (Figure 2). These are not virgin forests, but many patches have grown 100 or more years since cutting.

Background of Previous Studies

The Cache River Basin

The Cache River basin was the subject of a major Environmental Impact Statement (EIS)(COE 1974), based on proposals for renovation and extension of the previously completed channelization of portions of the river. The previous channel works occurred in the upper basin, for 89 miles from river mile 114 near the town of Grubbs to the headwaters of the river near Qulin, Missouri, and partial completion of the lower 10.5 miles of the river at its confluence with the White River (Figure 1). The Environmental Impact Statement (EIS) contains detailed information on various aspects of the ecology and economy of the basin, and some history of human use in the area.

Mauney and Harp (1979) studied the effects of this channelization on the fisheries of the Cache River and its main tributary Bayou DeView. They found a general decline in fish populations in those areas that were channelized, as compared to natural stretches of the streams.

Because of the drastic effect of rice irrigation on depleting the alluvial aquifer in extensively-farmed areas of the Western Lowlands, substantial

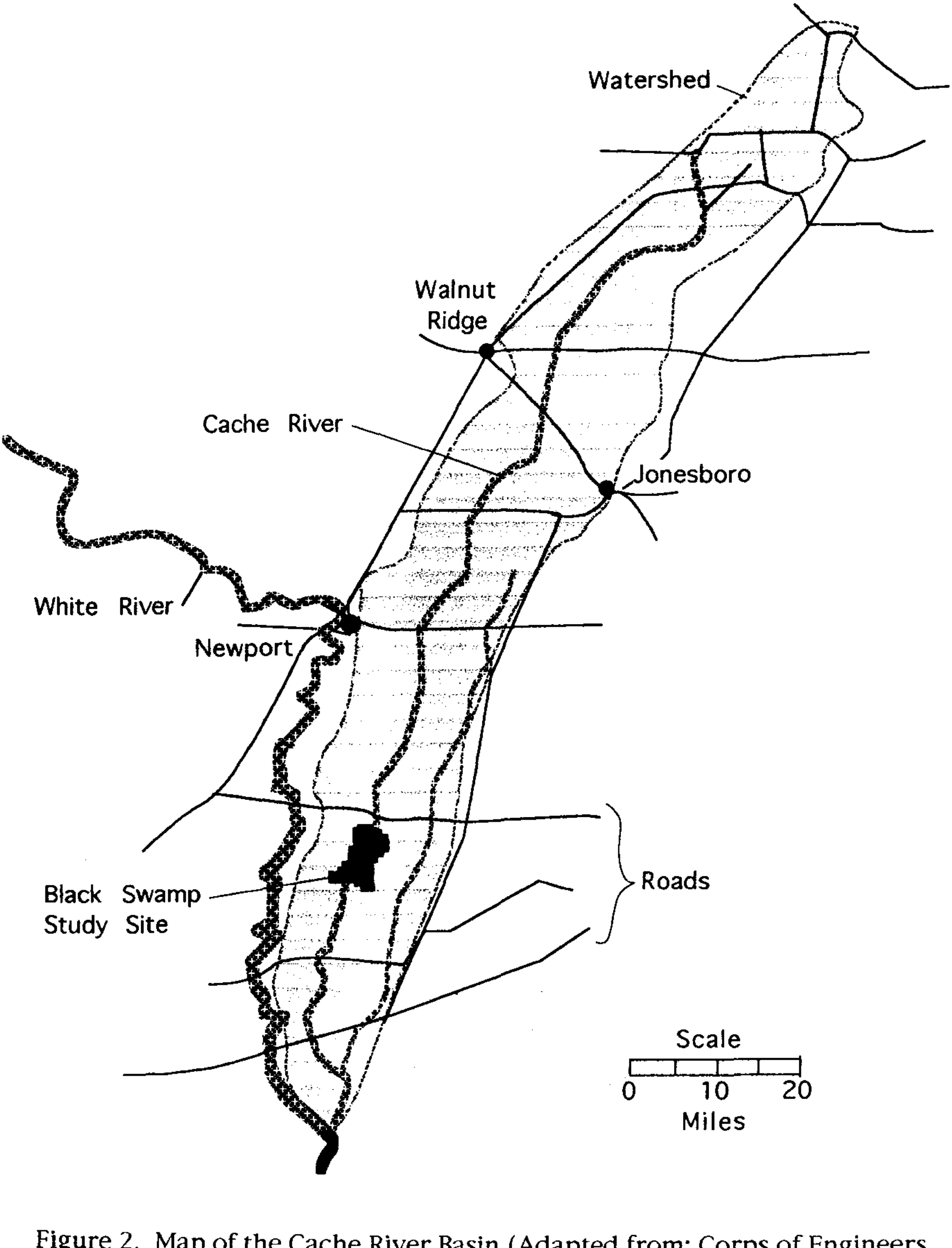


Figure 2. Map of the Cache River Basin (Adapted from: Corps of Engineers, 1974).

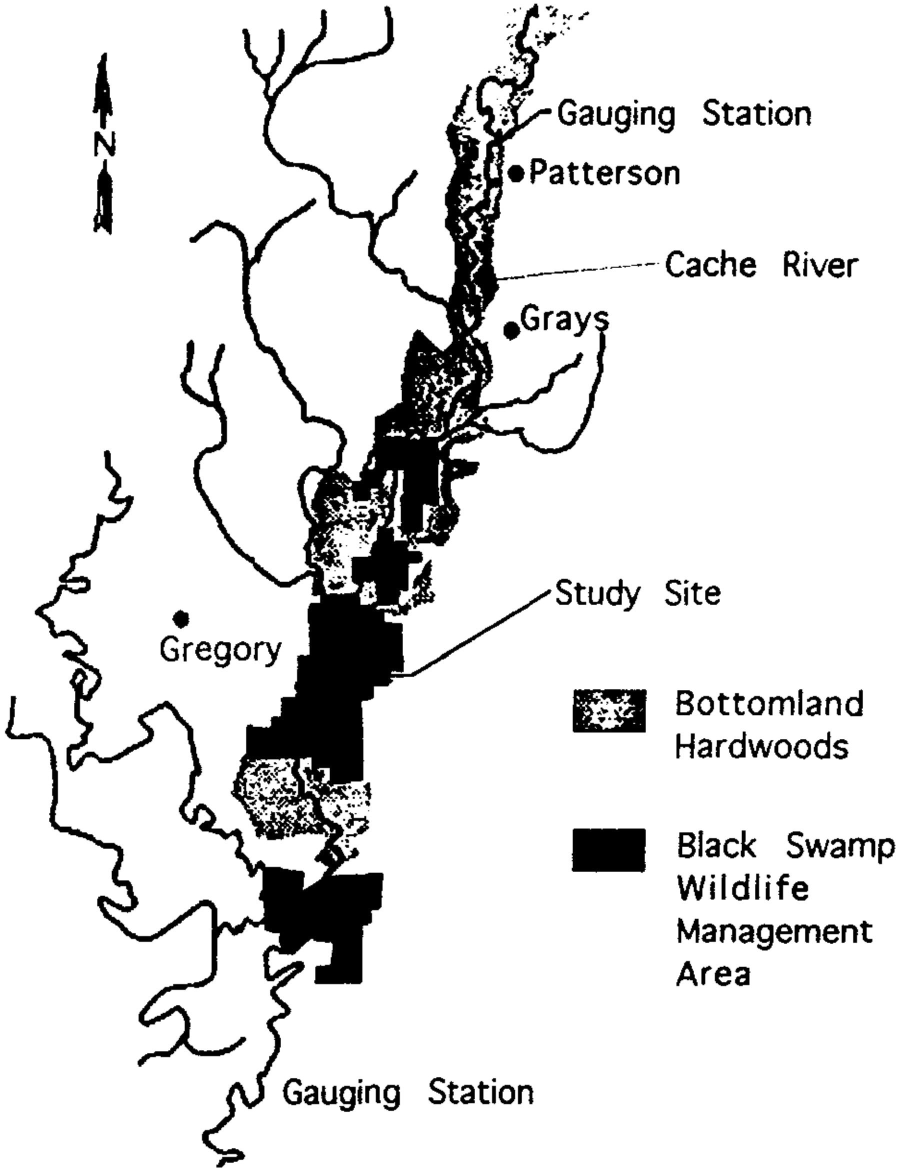
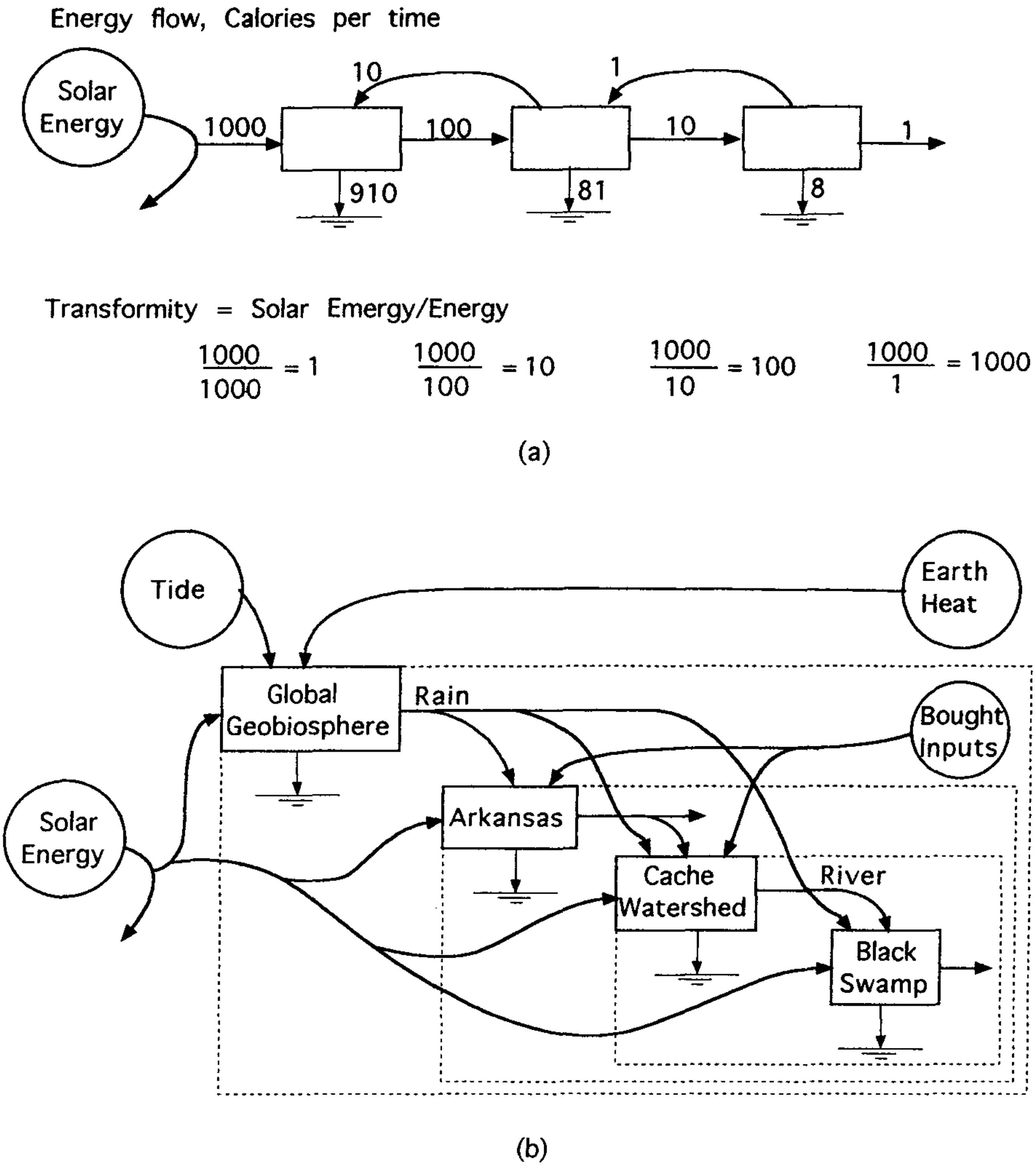


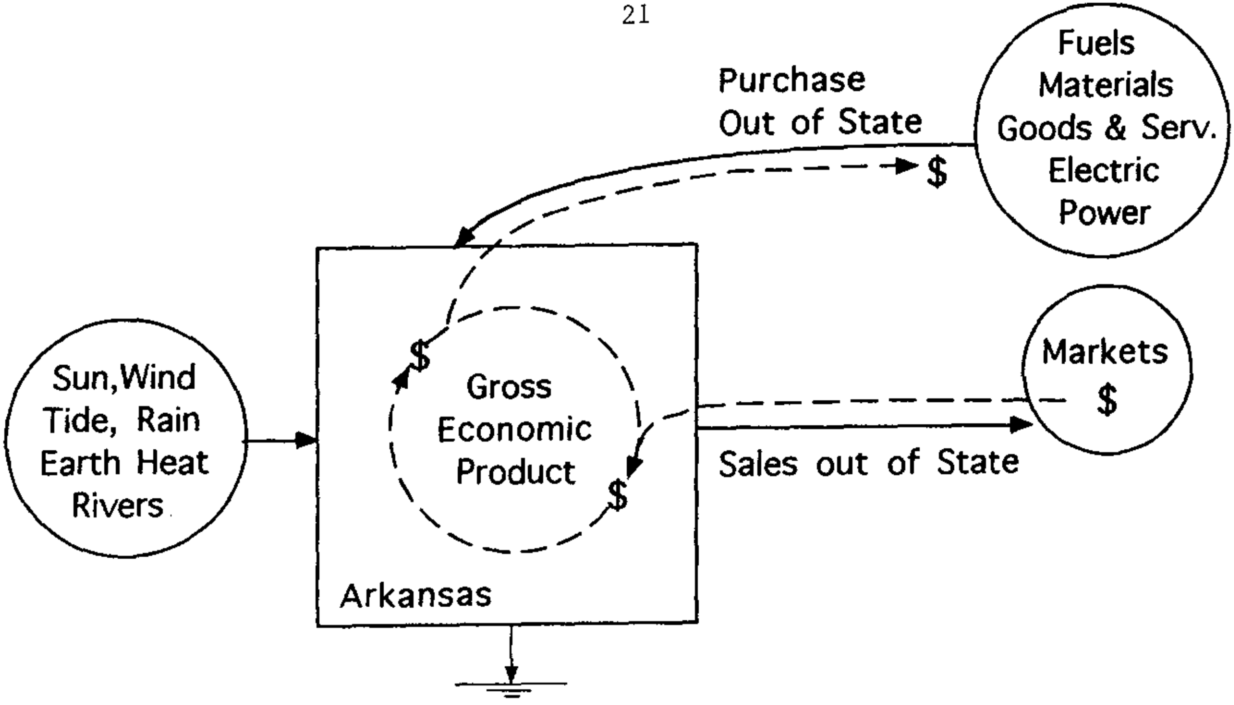
Figure 3. Map of the Black Swamp (Source: Baker and Killgore, 1994).



(a)

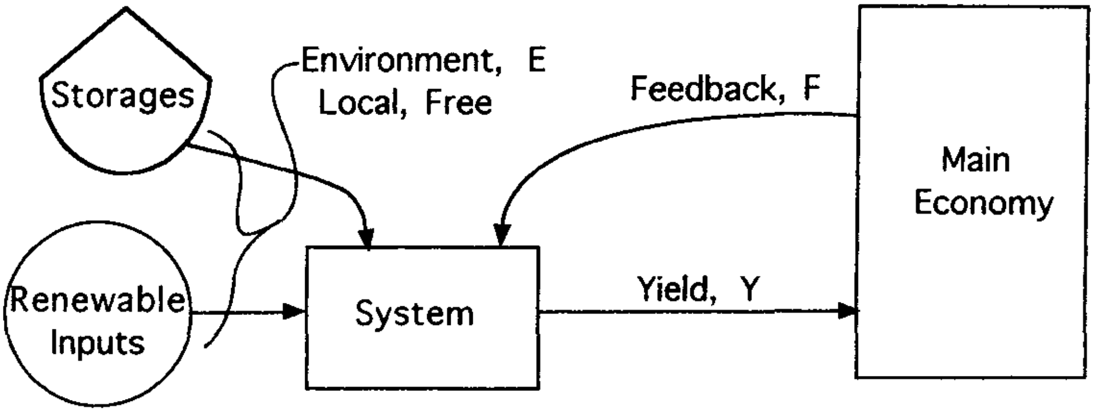
(b)

Figure 4. A series of energy transformations forming an energy hierarchy from left to right with each measured by its transformity. (a) Energy transformation series based on one energy source with calculation of solar transformity of energy of the flows downstream to the right; (b) main energy flows and transformations contributing to the Black Swamp.



$$\frac{\text{Empower Use}}{\text{Gross Economic Product}} = \text{Emergy/money Ratio}$$

Figure 5. Empower (emergy flow) and money circulation in a state. (a) Energy systems diagram; (b) emergy to money ratio used to evaluate emdollars of environmental contribution.



$$\text{Emergy Investment Ratio} = \frac{F}{E} \qquad \text{Emergy Yield Ratio} = \frac{Y}{F}$$

Figure 6. Emdollar indices used to evaluate environmental developments.

study was made of the hydrology of this region, including the Cache River basin. As early as 1953, an unreplenished decline of the aquifer in the western portions of Cross, Poinsett, and St. Francis counties was noted, as well as an alteration in the general flow direction of the aquifer in this area (Counts and Engler 1954).

Broom and Lyford (1982) and Ackerman (1989) modelled the interactions of irrigation and water movement throughout the surface and groundwater systems of the region. Their efforts showed the depletion of the aquifer affecting surficial hydrology of the region, capturing streamflow from the Cache River as a source of recharge for the lowered aquifer.

Smith and Saucier (1971) mapped and described the geomorphology of the Western Lowlands region as part of a larger effort to map the entire Mississippi River Valley Alluvial Plain. They provide descriptions of historic and current locations of the rivers of the region, and include a portfolio of maps showing plan-view and cross-section analyses of the geologic formations that currently occupy the area.

A special issue of the journal Wetlands in 1996 included 12 papers on the Cache River Basin and the Black Swamp, the results of an intensive study starting about 1987. The cooperative effort of the U.S. Army Corps of Engineers (COE), the U.S. Geological Survey (USGS), and several other Federal and State agencies (Clairain and Kleiss, 1989) was designed to consider biological, chemical, and physical aspects of bottomland hardwood ecosystems including work to assess fisheries, hydrology, sedimentation, spatial information, vegetation, water quality, and wildlife (Kleiss 1993, 1996).

In her summary of this special issue, Kleiss (1996) explains the way the clearing of bottomland hardwoods, first for soybeans and then for rice, with heavy groundwater pumping for part of the year, changed water levels, hydroperiod, and ecology for the remaining bottomland hardwoods in the rest of the basin. Kress, Graves, and Bourne (1996) mapped the land use changes, with forest cover decreasing from 65% to 15% from 1935 to 1975. Remaining forest, mostly on hydric soils, is fragmented with a large edge/area ratio.

Gonthier and Kleiss (1993) and Gonthier (1996) analyzed the records of groundwater wells located throughout the Black Swamp, which penetrated to varying depths in the underlying geologic units, including the alluvial aquifer and its overlying confining unit. Groundwater levels of the basins, including that under the bottomland hardwoods (Black Swamp), varied seasonally and year to year with the heavy pumping for rice agriculture. Floodplains that once received groundwater inputs were often recharging groundwaters. During periods of rising stream flow, the Cache River contributes recharge to the alluvial aquifer, while during falling stream levels the aquifer discharges to the river.

Walton and Chapman (1993) and Walton, Chapman, and Davis (1996) presented their spatial hydrologic simulation model of the watershed with 67 nodes synthesizing the interactions of precipitation, canopy interception, overland flow, channel flow, infiltration, evapotranspiration, and horizontal groundwater flow. The model generated a reasonable fit to a hydroperiod graph of number of days versus water level of the Cache River. The model provided an estimate of hydroperiod for sampling plots located throughout the swamp.

Wilber, Tighe, and O'Neill (1996) found the low river flows in summer to be related to drawdowns of the groundwater by rice agriculture and not to climate. At the end of summer, when pumping ceases, groundwater levels in the drawdown areas rise, albeit to levels lower than those preceding withdrawal.

Black Swamp

Walton, Davis, Martin and Chapman (1996), analyzing the hydrology of the Black Swamp, found that the highly channelized Cache River watershed had downstream constrictions, causing overbank flooding and wetland hydroperiod dependent on rains in the short-run. Nestler and Long (1994) and Long and Nestler (1996) found that the hydroperiod in the swamps has become erratic in dry periods with a loss of base flow that may be attributed to groundwater pumping.

Hupp and Morris (1990) found that, prior to the late 1940's, deposition of sediment in the swamp was consistent with normal sedimentation rates in other, unimpacted alluvial floodplains. After that time, however, sediment accumulation rates in the floodplain increased substantially, more than doubling from previous years. Kleiss (1996) measured the sediment budget and deposition for the Black Swamp, finding sedimentation at 1 cm/yr, removing 14% of the sediments from the river, most in the bottom of the floodplain. Main factors affecting sedimentation rate were flood duration, tree basal area and distance from the river.

With the help of a model of water detention on the floodplain Dortch (1996) evaluated the removal of suspended solids, total nitrogen, and total phosphorus from floodwaters. With a retention time of 5 days, sediment removal was 6.6%/day, total nitrogen 4.8% per day, and total phosphorus 0.58% per day, rates less than in marshes.

Boar, Delaune, Lindau and Patrick (1993) and Delaune, Boar, Lindau, and Kleiss (1996) measured denitrification process in the Black Swamp, finding that 9 parts per million nitrate nitrogen in floodwaters were reduced between 59 to 82% in 40 days. Experiments showed that the organic carbon available to the sediment process was a limiting factor.

Smith (1996), analyzing the vegetation with gradient ordination methods, found four main types in the Black Swamp, typical of southeastern United States. These were named by dominant trees and related to flood depth and duration:

In river-swamp forest with nearly continuous flooding:

1. <u>Water Tupelo and Bald Cypress,</u>

With 50% flooding, two types of lower hardwood swamp forest, with more species:

2. <u>Nuttall's Oak and Green Ash</u>
3. <u>Overcup Oak and Water Hickory</u>

With flooding 30% of the year, diverse backwater forest

4. <u>Willow Oak and Sweetgum</u>

Baker and Killgore (1994) and Kilgore and Baker (1996) evaluated the Black Swamp's role as a fisheries nursery by study of fish populations and larval fish abundance. The fish community was comprised almost entirely of flood-exploitative species. Larval fishes of 35 taxa were found, more in the floodplain than in the river, and more in years of greater flood area.

Wakeley and Roberts (1994, 1996) evaluated small bird populations in transects across the Black Swamp and related these to the gradient of water flooding and the four vegetation types, including analysis of structural characteristics of vegetation, snags, tree heights, etc. Because of the fragmented patchiness with edge, more birds were found in the Black Swamp than in some continuous forest. Although number of species in the four types of habitat was similar, the dominant species were different and arranged on a scale of water gradient. Birds were fewer in winter; migrants were a small percentage.

Content of This Study

This study includes energy systems models, emergy, and emdollar evaluations of the state of Arkansas, the Cache River Watershed and a hectare of Black Swamp. Included is an example of simulation of an overview model. Because overview models at the level of human verbal thinking are relatively simple, calibrating and simulating can be done in a day or two and does not require a major project authorization. A model of the Black Swamp interaction with waters was simulated to evaluate potential impacts of some changes in watershed management on ground water and other variables.

METHODS

Developing Systems Models from Verbal Concepts

Energy System Diagramming

Developing an overview model starts with the drawing of a diagram of the system of interest. After defining the physical boundary, important outside sources are listed and drawn around the boundary from left to right in order of their transformity, which marks their position in the energy hierarchy (sun, wind rain, river, geology, fuel, chemicals, goods, services, tourists, market, etc.). The main internal components and processes in the system are identified and drawn inside the system frame, such as forest, agriculture and industrial producers, urban areas, water storages, etc. Pathways, interactions, and money transactions are connected. The first diagram may be complex because minor components and processes may be included. Next the diagram is simplified to those parts and pathways that are found to be most important.

Emergy and Emdollar Evaluation

Emergy analysis tables were prepared on three scales: the state using 1992 data on Arkansas, the watershed and the swamp. For each system an emergy evaluation table was prepared with a line item for each input, output, and other items of special interest. An emergy evaluation table typically has 6 columns: (1) number of the line item and its footnote, (2) the name of the item to be estimated, (3) data in units of energy, mass or cost, (4) emergy per unit, (5) solar emergy and (6) emdollars. Energy flows are calculated from standard formulae from physics, chemistry, geology, economics, engineering, etc. Emergy per unit was obtained from previous emergy studies (Table 2).

Solar emergy of each line item was estimated by multiplying the data in column 3 by the solar emergy per unit from column 4. Finally, the real wealth value in emdollars was calculated by dividing emergy by the emergy/money ratio of the country, state or region. Emergy/money ratio was obtained by dividing the gross economic product by the total contributing emergy used by that system. Finally, summations and indices defined in Table 1 and Figure 6 were calculated to interpret the condition of the system. Full explanation of methods is given in a recent book on environmental accounting (Odum 1996).

Table 2
Emergy per Unit

Item	Value and Unit	Source
Direct sunlight	1 sej/J	a
Wind	1.5 E3 sej/J	a
Rain chemical potential	1.81 E4 sej/J	a
Runoff geopotential	2.8 E4 sej/J	a
River geopotential	2.8 E4 sej/J	a
Earth cycle	3.4 E4 sej/J	a
Coal	4.0 E4 sej/J	a
River chemical potential	4.8 E4 sej/J	a
Natural gas	4.8 E4 sej/J	a
Petroleum	5.4 E4 sej/J	a
Sorghum & cotton	6.0 E4 sej/J	b
Topsoil losses	7.4 E4 sej/J	a
Groundwater	1.6 E5 sej/J	c
Electricity (nuclear)	1.7 E5 sej/J	a
Rice & soybean	1.7 E5 sej/J	b
Hydroelecetricity	1.7 E5 sej/J	a
Wheat	2.2 E5 sej/J	b
Poultry	7.0 E5 sej/J	b
Migrants birds	9.7 E5 sej/J	b
Livestock production	2.0 E6 sej/J	c
Fish production	2.0 E6 sej/J	a
Forest products	2.8 E8 sej/J	c
Soil losses	1.0 E9 sej/g	a
Bromine	1.0 E9 sej/g	d
Potassium	1.1 E9 sej/g	a
Phosphorus	3.9 E9 sej/g	a
Nitrogen	4.6 E9 sej/g	a
Pesticides	1.48 E10 sej/g	a

a	Odum, 1996
b	Romitelli, Appendix B
c	Brown and McClanahan, 1995
d	As fluorite, Brown and McClanahan, 1995

Simulating Impacts

Starting with an overview systems diagram previously drawn, a simplified model diagram was drawn retaining the components of interest, the impacting influences, and the important pathways. In this study, as an example, groundwater fluctuations were observed as the Black Swamp system was impacted by different water-related processes. The simplified model of the Cache River system included pathways delivering influence from outside and from other parts of the system.

Equations for each of the storage compartments of the diagram were written following the nearly automatic translation of the systems symbols to mathematical form. Each equation has positive terms for flows into storage and negative terms for flows going out.

To calibrate the model, quantitative values for the inputs, storage and flows were fed into the model using summary data where available. Otherwise, data from similar systems were used or indirectly calculated from relationships between variables (e.g., retention time = ratio between volume of storage and flows).

A spreadsheet program was used to estimate the values of coefficients (the k's in the program equations). Values of flows and storages were assigned to each variable in the mathematical terms for flows. After the terms were set equal to the flows, the term was manipulated with k's on one side equal to the numerically evaluated expression on the other side. The calculations were built into the spreadsheet so that changing one value automatically changed all other places affected. For example, Appendix Table 1 was used for the calculation of coefficients of the groundwater impact model. Explanations were given in footnotes to the spreadsheet table for each item.

The program for the simulation of cumulative impacts on groundwater in the Black Swamp is written in QBASIC and included as Appendix Table A2. It includes statements to introduce the starting variables, the coefficient values, the equations for change on each iteration, and plotting statements. The model was run first with the calibration data to simulate pre-impact conditions operating in steady state conditions. Then the main program was modified to include statements that would simulate impacting actions, including groundwater pumping, river diversion and forest cutting.

To simulate effects of groundwater pumping, values of Jg were reduced by increments of 1 E7 m^3. This represents decrease of about 30, 60 and

90% of the outside groundwater flows feeding the alluvial aquifer below the Black Swamp. River diversion was simulated by deducting equal incremental volumes of 2 E7 m^3/month from the Cache River inputs (Jc). These represent reductions of 17, 35 and 52% of the average flow of Cache River now running through the Black Swamp. Forest cutting was simulated, reducing starting values of the hardwood forest biomass (B) by increments of 5 E4 tons. It simulates cutting 13%, 26%, and 39% of original forest.

Graphs of groundwater levels and other variables over time obtained from simulation are included as Appendix Tables A1-A11. From these a table of impact changes was prepared summarizing the many runs. See Odum (1983, 1996) for more extensive explanations of the methodology of energy systems modelling and simulation.

RESULTS

Arkansas

Energy Systems Diagram

Figure 7a is the overview model of the state of Arkansas with the water components and flows darkly shaded.

Emdollar Evaluation Tables

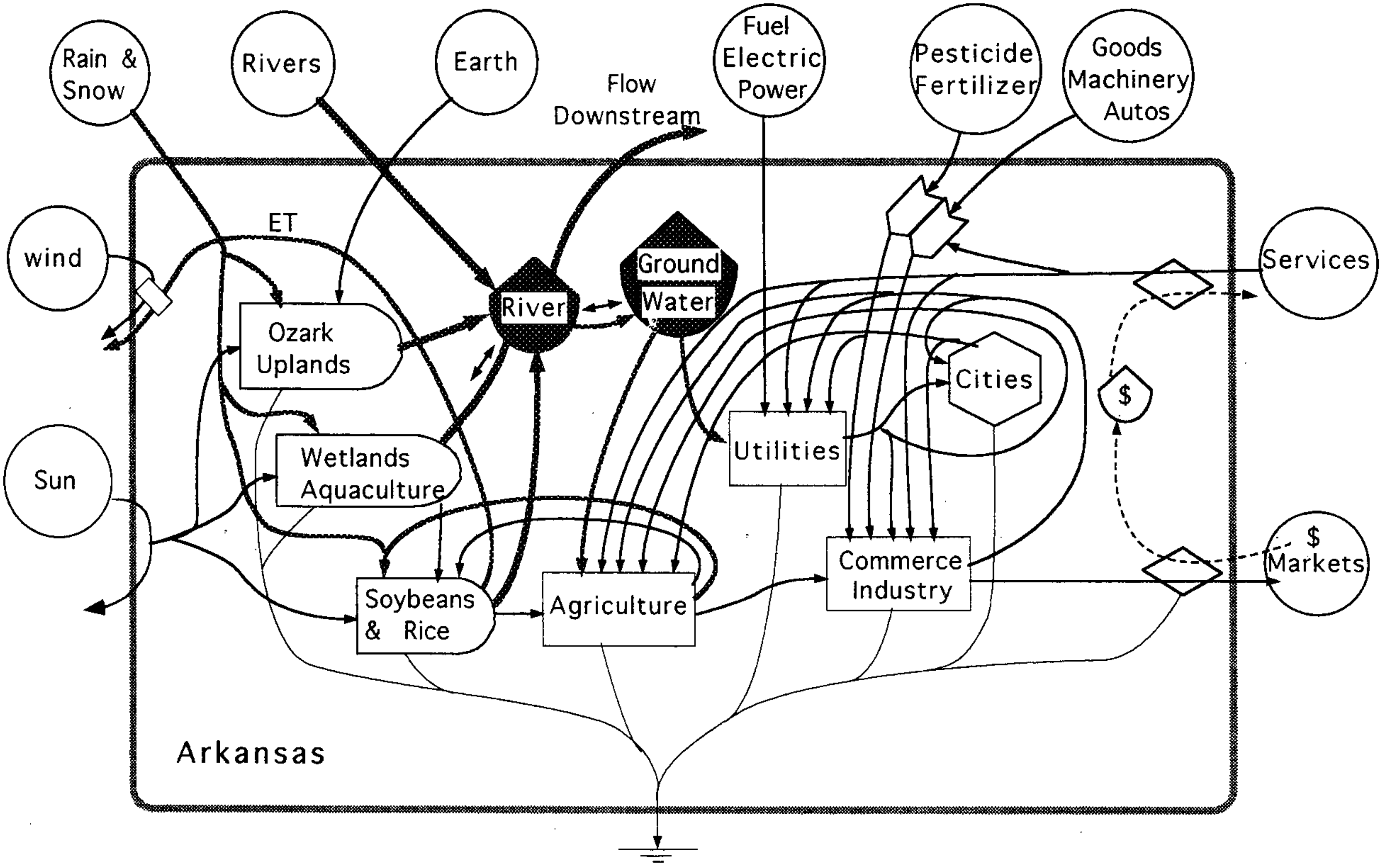
Table 3 has the energy and emdollar evaluation of the important sources, imports, and exports. Table 4 has the exchanges with the rest of the United States based on the percentage of workers in various occupations. Contributions to real wealth from the tables are shown in bar graph form in Figure 8 from left to right in order of their transformity (position in natural energy hierarchy). Major contributions come from the rain's chemical and geopotential energy, the fossil fuels used within the state, and the goods and services purchased from outside the state. Rainfall over the land does work on the landscape which is measured as runoff geopotential. Arkansas has an uneven relief with mountains and plateaus over its west side and the Mississippi floodplain in its east side. Therefore, it has a relatively high runoff geopotential (~30% of its renewable emergy). The state has a diversified economy with important industrial agriculture requiring imports of pesticides and fertilizers. Fuels represents 31% of state imports. Goods and services are 46% of state imports. The state exports meat and services embodied in its agricultural and industrial production.

Emergy Indices

State indices derived from the emergy evaluation tables are listed in Table 5. Arkansas is 58% self sufficient. Its ratio of resources added by the economy to the environmental renewable resources is 2.9. With 48 inches of rain, water is 13% of the state's annual source of real wealth.

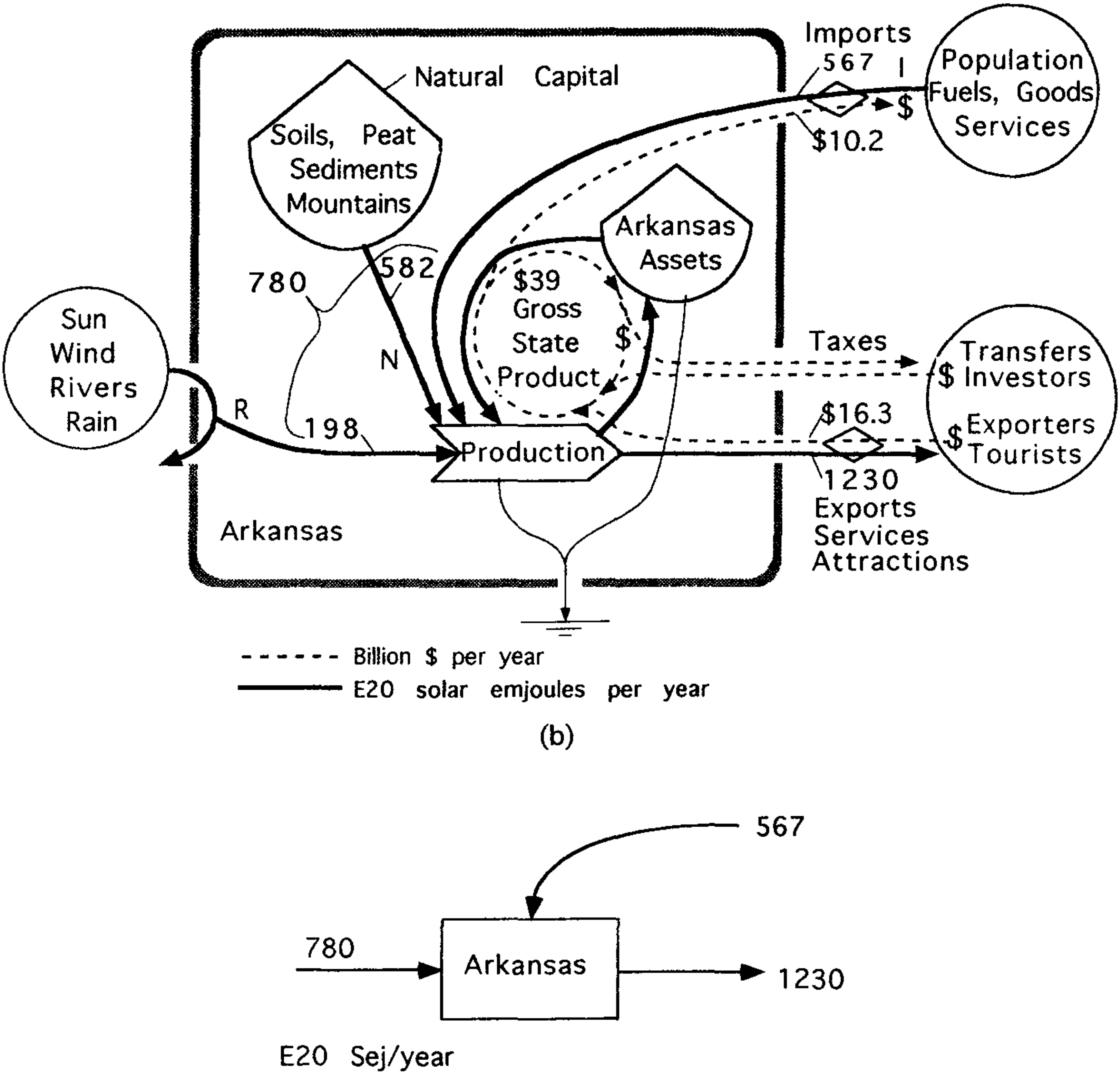
Comparisons

The emergy basis for the state is summarized in an aggregated diagram in Figure 7b. Arkansas has a higher percentage of its economic basis supplied from environmental emergy than the more developed states of Florida and Texas, but less than that of Alaska and Maine. The state is also relatively rich in non-renewable mineral resources that are intensely used by the economy. Its natural gas reserves provides the amount used by the state and supply the state with 28% of its energetic needs (EIA, 1994).



(a)

Figure 7. Energy systems diagram of Arkansas with main empower inputs in solar emjoules per year. (a) Complex diagram; (b) aggregated summary; (c) three arm summary.



(b)

$$\text{Solar Emergy/Money} = \frac{1347\ \text{E20 sej/year}}{39\ \text{E9 \$/year}} = 3.45\ \text{E12 sej/\$}$$

(c)

Figure 7 (continued)

Table 3
Annual Emergy Flows of Arkansas

Note	Item	Data	Units J, g, $/yr	Emergy/Unit sej/unit	EMERGY E20 sej	1990 Emdollars E6 Em$
Renewable Resources						
1	Direct sunlight	793 E20	J	1	8	230
2	Wind	1.51 E18	J	1496	23	653
3	Runoff geopotential	8.55 E16	J	27874	24	690
4	Rain chemical pot.	7.91 E17	J	18199	144	4174
5	Inflow river geopot.	9.77 E16	J	27874	27	789
6	Inflow river chem. pot.	7.12 E15	J	48459	3	100
7	Earth cycle	1.35 E17	J	34377	46	1344
					198	
Indigenous Renewable Energy						
8	Rice & soybean	9.71 E16	J	1.70 E5	165	4785
9	Wheat	1.32 E16	J	2.20 E5	29	845
10	Sorghum & cotton	1.40 E16	J	6.00 E4	8	243
11	Poultry	1.38 E16	J	7.00 E5	97	2808
12	Livestock production	6.34 E15	J	2.00 E6	127	3675
13	Forest products	8.13 E12	g	2.75 E8	22	648
14	Fish production	8.71 E13	J	2.00 E6	2	50
15	Hydroelec.	3.67 E16	J	1.70 E5	62	1811
					513	

Table 3 (continued)

Indigenous Non-renewables Resources						
16	Groundwater	2.88 E16	J	1.60 E5	46	1336
17	Bromine	1.71 E11	g	1.31 E10	22	650
18	Coal	1.33 E15	J	3.98 E4	1	15
19	Natural gas	2.32 E17	J	4.80 E4	111	3228
20	Petroleum	6.44 E16	J	5.30 E4	34	990
21	Soil losses	1.34 E13	g	1.00 E9	134	3892
22	Topsoil losses	2.44 E16	J	7.40 E4	18	522
23	Electricity (nucl.)	1.27 E17	J	1.70 E5	215	6243
					582	16876
Imports						
24	Coal	2.32 E17	J	3.98 E4	92	2673
25	Petroleum	2.38 E17	J	5.30 E4	126	3654
26	Nitrogen	1.32 E11	g	4.60 E9	6	176
27	Phosphorus	6.99 E9	g	3.90 E9	0	8
28	Potassium	6.82 E10	g	1.10 E9	1	22
29	Pesticides	5.60 E10	g	1.48 E10	8	240
30	Goods				9	263
31	Services	1.85 E10	$	1.75 E12	324	9386
					567	16421
Exports						
32	Poultry	1.35 E16	J	7.00 E5	94	2730
33	Livestock	3.99 E15	J	2.00 E6	80	2313
34	Goods				2	61
35	Services	2.24 E10		3.45 E12	774	22440
					1231	35675

Footnotes for Table 3

Area of the State = 1.35 E11 m^2

1. Sunlight: 385 ly/day = 3850 kcal/m^2/day (Weather Atlas of US)
   Energy = (3850 kcal/m^2/day)(1.35 E11 m^2)(365 days/yr)(4186 J/kcal) = 7.93 E20 J/yr

2. Wind energy
   Calculated as Odum, 1996, Appendix B, with eddy diffusion coefficient and vertical gradient coefficient (Odum, Diamond and Brown, 1987)
   = (height)(density)(diff coefficient)(wind gradient)(area)
   = (1000 m)(1.23 kg/m^3)(14.74 m^3/m^2/s)(4.42 E-3 m/s/m)^2 (area)(sec/yr) = 1.51 E18 J/yr

3. Rain geopotential energy
   = (area)(runoff/yr)(ave elev gradient)(1000 kg/m^3)(9.8m/s^2)
   average rain = 48 in/yr = 1.22 m/yr
   Energy
   ((1.34 E9 m^2)(450m) + (1.78 E10 m^2)(390 m) + (2.67 E10 m^2) (120 m) + (8.92 E10 m^2)(75 m))(0.50 m)(1000 kg/m^3)(9.8 m/s^2)
   = 8.55 E16 J/yr

4. Rain chemical potential
   (Water used in evapotranspiration) = 55 in (Weather Atlas of US)
   pan coefficient = 0.85 (Scott, H.D. et al., 1987)
   = 46.75 in/yr = 1.19 m/yr
   Energy = (area)(evaporation)(1 E6 g/m^3)(4.94 J/g) = 7.91 E17 J/yr

5 River geopotential
   Major Inflowing rivers - Arkansas and Mississippi Rivers
   Flow in Arkansas River = 872 m^3/s (Water Data-USGS, 1971)
   Change in elevation (210 m - 30.5 m)
   Energy = (volume)(density)(height in - height out)(gravity)
   = 4.84 E16 J/yr
   Flow in (Mississippi River) = 13300 m^3/s
   Change in elevation: (45 - 21 m)
   = 9.86 E16 J/yr
   Assumed 1/2 used in the State = 4.93 E16 J/yr
   Total River Geopotential = 9.77 E16 J/yr

Footnotes for Table 3 (continued)

6. River phemical potential in major inflowing rivers:
Arkansas River flow = 872 m^3/s
Gibbs Free Energy in = 4.92 J/g (200 mg/l dissolved solids)
Gibbs Free Energy out = 4.88 J/yr (400 mg/l dissolved solids)
Energy = (volume)(density)(Gibbs Free Energy)
Energy in = 1.35297 E17
Energy out = 1.34472 E17
In - Out = 8.24982 E14
Mississippi River flow = 13300 m^3/s
Energy in = 2.06 E18
Energy out = 2.05 E18
In - out = 1.26 E16 J/yr
Arkansas state total = 6.29 E15 J/yr
Total river chem potential = 7.12 E15 J/yr

7. Earth Cycle Energy = (land area)(heat flow/area)
= Assumed heat flows = 1 E6 $J/m^2/yr$
Energy = 1.35 E17 J/yr

Notes 8-10. Agricultural production data on Arkansas from Census of Agriculture (1992): Sorghum 5.93 E8; wheat 9.59 E8; rice 3.42 E9; cotton 3.43 E8; soybeans 2.70 E9
Energy calculated as in Odum, H.T. et al.(1987)
Energy = (mass)(energy/unit)

8. Rice and Soybeans
Rice = (3.43 E11 g)(3.60 kcal/g)(4186 J/kcal) = 5.17 E15 J/yr
Soybeans = (2.70 E12 g)(4.03 kcal/g)(4186 J/kcal) = 4.56 E16 J/yr
Total = 5.07 E16 J/yr

9. Wheat (3.42 E12 g)(3.30 kcal/g)(4186 J/kcal) = 4.73 E16

10. Sorghum and Cotten
Sorghum = (9.59 E11 g)(3.32 kcal/g)(4186 J/kcal) = 1.33 E16 J/yr
Cotton = (2.70 E12 g)(4.0 kcal/g)(4186 J/kcal) = 4.52 E16 J/yr
Total = 5.86 E16 J/yr

Footnotes for Table 3 (continued)

Notes 11-12. Animal production data for Arkansas from Census of Agriculture (1992): Cattle 1.63 E6; cattle sold 8.18 E5; hogs & pigs 7.25 E5; pigs sold 2.02 E6; sheep 1.20 E4; chicken 2.21 E7; broilers 8.62 E8
Calculated as in Odum, H.T. et al. (1987)
Energy = (annual production mass)(energy/mass)

11. Poultry Broilers
= 2.13 kcal/g (US Department of Agriculture Handbook 8)
(number produced)(1.8 kg/animal)(2.13 kcal/g)(4186 J/kcal)
= 1.38 E16 J/yr

12. Livestock
Energy contents from US Department of Agriculture Handbook 8
Beef = 2.92 kcal/g; pork = 3.76 kcal/g

(Cattle sold)(3.5 E5 g/animal)(2.92 kcal/g)(4186 J/kcal)
= 3.48 E15 J/yr

Pigs: (pigs sold)(9 E4 g/animal)(3.76 kcal/g)(4186 J/kcal)
= 2.86 E15 J/yr

13. Forest Production Data from US Department of Agriculture - Southern Forest Experimental Station, Vissage, J.S. and P.E. Miller - Southern Pulpwood production, 1990

Pulpwood production for 1990;
4.99 E6 cords = 6.38 E8 ft^3 = 1.81 E7 m^3
Density assumed 450 kg/m^3 (specific density = 0.45)

Forest production = 8.13 E9 kg/yr = 8.13 E12 g/yr

Energy = (weight)(3.6 kcal/g)(4186 J/kcal)
= 1.23 E17 J/yr

14. Fish production data from Census of Agriculture, 1992, on fish sales in Arkansas: 4.45 E7 lb = 2.02 E7 kg
Energy = (mass)(energy/mass)
= (92.02 E10 g fish)(1.03 kcal/g)(4186 J/kcal) = 8.71 E13 J/yr

Footnotes for Table 3 (continued)

15. Hydroelectricity production data from EIA - Electrical Power Annual (1992) = 3.48 E13 Btu
Energy = (3.48 E13 Btu)(1055.87 J/yr/Btu) = 3.67 E16 J/yr

16. Groundwater data from US Geological Survey
Open File Report 91-203 on 1989 water use for Arkansas:
Groundwater consumption:
4.25 E3 = million gal/day = 5.88 E9 m^3/yr
Chemical potential energy of groundwater:
(volume)(1 E6 g/m^3)(4.9 J/g) = 2.88 E16 J/yr

17. Bromine data from The Mineral Yearbook, 1992
Bromine production = 1.71 E5 ton/yr = 1.711 E11 g/yr

18. Coal production data for Arkansas from Energy Information Administration - Coal production (1992)
= 4.60 E4 short ton = 4.17 E4 ton/yr
Energy = (41731.2 ton)(3.18 E10 J/ton) = 1.33 E15 J/yr

19. Natural gas production data for Arkansas from Energy Information Agency/ Natural gas annual 1992, Vol. 1
= 2.11 E11 cubic feet
= (2.11 E8 thsd cubic ft)(1.1 E9 J/thsd cubic feet) = 2.32 E17 J/yr

20. Petroleum production data for Arkansas from Energy Information Administration/Petroleum Supply Annual 1992, Vol. 2
= 1.026 E7 barrels
Energy produced:
= (10260 E3 barrels)(6.28 E9 J/barrel) = 6.4433 E16 J/yr

21. Soil loss erosion in Arkansas cropland = 500 g/m^2/yr (Odum et al., 1983); cropland area = 2.69 E10 m^2
(500 g/m^3/yr)(2.69 E10 m^2) = 1.34 E13 g/yr

22. Topsoil Energy Losses:
Assuming 3% organic content and 5.4 kcal/g
(Soil weight per year)(organic fraction)(5.4 kcal/g)(4186 J/kcal)
= 9.10 E15 J/yr

Footnotes for Table 3 (continued)

23. Electricity (nuclear) data from EIA- Electrical Power Annual, 1992
Nuclear energy = 1.20 E14 Btu
(1.20 E14 Btu)(1055.87 J/Btu) = 1.27 E17 J/yr

24. Coal import data for Arkansas from Energy Information Administration - State Energy Data Report, 1992
= 12536 E3 short tonn = 220.7 trillion Btu
Coal energy use = (220.7 E12 Btu)(1055.87 J Btu) = 2.33 E17 J/yr
Coal Imported = (use - produced) = 2.32 E17 J/yr

25. Petroleum import data from Energy Information Administration/ Petroleum Supply Annual 1992, Vol. 2
4.29 E7 barrels = 2.29 E14 Btu = 2.38 E17 J/y

Notes 26-28. Fertilizers estimated for crops and area planted: using kilograms per hectare as follows:

	N	P_2O_5	K_2O	
Sorghum	37.8	3.4	0.9	(Pimentel, 1980)
Wheat	89.7	1.12	0	(Pimentel, 1980)
Rice	134.5	0	33.6	(Pimentel, 1980)
Cotton	40.0	16.0	17	(Kohee & Lewis, 1984)
Soybeans	5.61	0	33.6	(Pimentel, 1980)

26. Nitrogen use in kilograms/yr:
For sorghum 5.28 E6; wheat 2.96 E7; rice 7.42 E7; cotton 1.54 E7; soybeans 7.19 E6
Total N used (g/yr) = 1.32 E11 g/yr

27. Phosphorus use in kilograms/yr:
Sorghum 4.75 E5; wheat 3.70 E5; rice 0; cotton 6.14 E6; soybeans 0.
Total P use = 6.99 E9 g/yr

28. Potassium use in kilograms/yr:
Sorghum 1.26 E5; wheat 0; rice 1.85 E7; cotton 6.52 E6; soybeans 4.30 E7
Total P used = 6.82 E10 g/yr

Footnotes for Table 3 (continued)

29. Pesticides data for Arkansas from US Dept. of Commerce, Bureau of Census, 1994 - 1992 Census of Manufactures - Agricultural Chemicals
= 2.02 E8$/yr
Average price of pesticides
= 3.60 $/kg pesticides
Weight of pesticides used in the State = Expenses/Average Price
= 5.60 E7 kg = 5.60 E10 g/yr

30. Goods imported into Arkansas were estimated as a fraction of U.S. imports of basic mineral and metal production in 1992. Arkansas population is 0.94% of U.S. population.

U.S. Imports (1994 US Statistical Abstract):

Item	Quantity	Emergy/g	Emergy, sej/yr
Iron Ore	1.25 E13 g	1.00 E9	1.25 E22
Steel Prod.	1.73 E13 g	2.64 E9	4.57 E22
Aluminum	1.16 E12 g	1.60 E10	1.86 E22
Copper ref	2.89 E11 g	6.80 E10	1.97 E22
			9.64 E22

Emergy = (9.64 E22 sej/yr)(0.0094) = 9.06 E20 J/y

31. Services supplied to Arkansas with imports

a. Services with fuels

	Btu	$/1 E6 Btu	$ Expenditures
Coal	2.17945 E14	1.66	3.62 E8
Petroleum	2.28576 E14	7.82	1.79 E9
Total			2.15 E9

b. Services with imported manufactured goods estimated as fraction of U.S. imports for 1992 less petroleum, meat, and gas;
Arkansas population 0.94% of U.S. population
(4.76 E11 dollars)(0.0094) = 4.46 E9 $/yr

Footnotes for Table 3 (continued)

c. Relative services imported from other parts of U.S. as given in Table 4 = 1.02 E10 $

d. Federal benefit to Arkansas in 1992 = 1.69 E9 $

Total imported services = 1.85 E10 $/yr

Notes 32-33. Animal production sold out of state estimated as the difference of production and consumption in the State. Per capita consumption from 1994 US Stastitistical Abstract - Data as boneless weight with data on pounds divided by 0.70, the percent of meat in the whole animal weight

32. Poultry broiler sales out of state:

Production	1.55 E12 g
Consumption per capita	1.80 E4 g
Consumption	4.3 E10 g
Weight exported	1.51 E12 g

Broiler energy exported:
(1.51 E12 g exported)(2.13 kcal/g)(4186 J/kcal) = 1.35 E16 J/yr

33. Livestock sales out of state:

	Beef	Pork
Production	2.86 E11 g	1.81 E11 g
Consumption per capita	4.07 E4 g	3.11 E4 g
Consumption	9.75 E10 g	7.45 E10 g
Weight exported	1.89 E11 g	1.07 E11 g

Cattle energy:
= (1.89 E11 g)(2.92 kcal/g)(4186 J/kcal) = 2.31 E15
Pork energy:
= (1.07 E11 g)(0.76 kcal/g)(4186 J/kcal) = 1.68 E15
Total Livestock exports = 3.99 E15 J/yr

34. Goods exports were estimated as fraction of U.S. exports of iron and steel products in 1992 5.3 E6 tons (1994 US Statistical Abstract)
Weight = (5.3 E6) (907 kg/ton)(1 E3 g/kg) = 4.81 E12 g
Emergy = (4.8 E15 g)(4.65 E9 seJ/g) = 2.24 E22 sej
In proportion to population
Iron & Steel products from Arkansas
= (2.24 E25)(0.0094) = 2.10 E20 sej/yr

Footnotes for Table 3 (continued)

35. Services exported = (value of total production)(percent exported)
a. Animals exported:
(production 2.44 E9 $/yr)(0.85 exported) = 2.08 E9 $/yr
b. Foreign Export from Arkansas in 1992 = 1.32 E9 $
(1994 Statistical Abstract of the United States)
c. Relative exports to other States from Table 4 = 1.63 E10 $
d. Federal Taxes in 1992 = 2.75 E9 $
(1994 Statistical Abstract of the United States)
Total Export = 2.24 E10 $/yr

Table 4
Export and Import Exchange Between Arkansas and Other States

	Agr.	Min.	Constr.	Manuf.	Transp.	Wholes.	Retail	Finance	Serv.	Gov't
U.S. average	0.03	0.01	0.06	0.17	0.07	0.04	0.17	0.07	0.35	0.05
State average	0.01	0	0.04	0.24	0.05	0.05	0.18	0.04	0.23	0.16
Difference	-0.02	-0.01	-0.02	0.07	-0.02	0.01	0.01	-0.03	-0.12	0.11
$/employee	34579	149096	34365	50971	58460	75550.89	26341	125580	25541	116726
#/employees	-18729	-9365	-18729	65552	-18729	9365	9365	-28094	-112375	103011
Export/import $	-6.48 E8	-1.40 E9	-6.44 E8	3.34 E9	-1.1 E9	7.08 E8	2.47 E8	-3.5 E9	-2.9 E9	1.2 E10

Imports: -1.02 E10 $/yr

Exports: 1.63 E10 $/yr

Net Export: -6.14 E9 $/yr

(Calculation done considering the difference in percent of employment per sector for U.S. and State and the relative contribution of employee of each sector to the country GNP)

Footnotes for Table 4

EXPORTS

1. Animal production (GOODS)

	Production grams	Per capita consump	State consump	Export	Energy J/yr
Beef	5.56 E11	114044.8	2.73 E11	2.83 E11	5.07 E15
Pork	1.81 E11	72640.0	1.74 E11	7.59 E9	1.76 E14
Broiler	2.16 E12	50303.2	1.2 E11	2.04 E12	2.04 E16
Total	2.89 E12			2.33 E12	2.56 E16

Production = (number of animals)(average weight)
Assuming average weights for
Cattle = 680 kg
Pork = 90 kg
Broiler = 2.5 kg

Per capita consumption (Data from 1994 US Statistical Abstract, pounds of commodity consumed per capita in 1992, Table 220)
Information was given in terms of boneless weight. Therefore, pounds in commodity per capita was divided by a factor (0.25 or 0.3), assumed to be the percent of meat in the whole animal weight.
State consumption = (per capita)(State population)
Export = production - consumption

Energy = (weight (g))(caloric content (kcal/g))(4186 J/kcal)
Caloric content of cattle = 4.26 kcal/g
Pork = 5.53 kcal/g
Broiler = 2.39 kcal/g

2. Value of animal exports (SERVICES)
Value of total production = 2.44 E9 $
Percent exported = 3.19 E12/3.76 E12 = 0.848
Value Exported = (value of total production)(percent exported)
= 2.07 E9 $

Footnotes for Table 4 (continued)

3. Grain exported (GOODS)

	Production grams	Internal comsumption	Protein produced
Sorghum	5.93 E11	0	4.74 E10
Wheat	9.59 E11	1.5 E11	1.15 E11
Rice	3.42 E12	1.83 E10	4.79 E11
Cotton	3.43 E11	0	1.37 E10
Soybeans	2.7 E12	0	9.18 E11
Hay	2.11 E12	0	2.32 E11
Total	1.01 E13	1.69 E11	1.81 E12

Protein produced = (production)(percent protein)
% protein: Sorghum, 8%; Wheat, 12%; Rice, 10%; Cotton, 4%; Soybean, 34%; Hay, 11%

Animal Consumptiom **1

	Production grams	Prot weight % protein	Feed prot/ grams	Tot feed prot weight	protein
Beef	5.56 E11	0.2	1.11 E11	15.5	1.72 E12
Pork	1.81 E11	0.13	2.36 E10	10.5	2.48 E11
Broiler	2.16 E12	0.2	4.31 E11	5.5	2.37 E12
					4.34 E12

**1 from Pimentel, 1979

** Considering that 60% of protein come from another source that is not grains, (Pimentel, 1979), we have:
Protein for feeding = (0.4)(total feeding protein)
= 1.74 E12 g/protein
Therefore, the amount required for feeding is about the same amount that is produced in the State.
NO NET GRAIN EXPORT

4. Export of Services
State Foreign Export (SERVICES)
(1994 Statistical Abstract of the United States)
Foreign Exports in 1992 = 1.32 E9 $
Relative exports to other States (SERVICES), According with Table 1
= 1.63 E10 $

Footnotes for Table 4 (continued)

5. Value of taxes (SERVICES) (referring to 1992 taxes)
(1994 Statistical Abstract of the United States)
Federal Taxes = 2.75 E9 $
TOTAL SERVICES EXPORTED = 2.24 E10 $

6. Iron and Steel Products (GOODS)
U.S. Export of Iron and Steel products in 1992 (from 1994 US Statistical Abstract)
= 5.3 E6 tons
(5.3 E6)(907 kg/ton)(1 E3 g/kg) = 4.81 E12 g
(4.8 E15 g)(4.65 E9 sej/g) = 2.24 E22 sej
Considering the State contribution proportional to its population contribution to U.S.:
Iron/Steel products from Arkansas = (2.24 E25)(0.0094)
= 2.1 E20 sej

IMPORTS - SERVICES
1. Value of the fuels

	Btu	$/1 E6 Btu	Expenditures $
Coal	2.18 E14	1.66	3.62 E8
Petroleum	2.29 E14	7.82	1.79 E9
Total			2.15 E9

2. Manufactured goods (SERVICES)
Calculating U.S. imports for 1992 less petroleum, meat, and gas
= 475697 million dollars
Estimating the amount shared by the State, considering the percent of U.S. population living in Arkansas (0.94% of U.S. population)
Therefore, the share of foreign imports
= 4.46 E9 $

3. Relative Services
Considering the relative services imported from other parts of U.S. (as shown in Table 1)
Relative services = 1.02 E10 $

Footnotes for Table 4 (continued)

4. Federal benefits
Federal aid for Arkansas in 1992 = 1.69 E9 $
Therefore, total imported Services = 1.85 E10 $

5. Imports (GOODS)
Imports of basic mineral and metal products by U.S. in 1992 (1994 US Statistical Abstract)

Item	Quantity g	Energy	Transformity	Emergy J/yr
Iron Ore	1.25 E13		1.00 E9	1.25 E22
Steel Prod	1.73 E13		2.64 E9	4.57 E22
Aluminum	1.16 E12		1.60 E10	1.86 E22
Copper ref	2.89 E11		6.8 E10	1.97 E22
				9.64 E22

Considering the State is 0.94% of U.S. population, the amount of Emergy imported for basic mineral and metals for Arkansas is:
Basic minerals = (9.64 E22)(0.0094)
= 9.06 E20 J/y

Table 4.1.a
State GDP Generated per Employee by Sector

Sector	Number of Employees*	Gross State Product# E9 $	Dollars per employee	% of total employees
Agriculture	5641	2	354547	0.01
Construction	34565	1	28931	0.04
Manufacturing	228683	10	43729	0.24
Wholesale trade	46527	2	42986	0.05
Retail trade	167215	4	23921	0.18
Finance	37676	5	132710	0.04
Services	212954	5	23479	0.23
Transportation	49915	4	80136	0.05
Mining	3286	2	608643	0.00
Government	150000		0	0.16
	936462			

* 1992
\# 1990

Table 4.1.b
U.S. Employment per Industry, 1992

Sector	Employees thousands	GNP E9 $	Dollars per employee	% of total employees
Agriculture	3210	111	34579	0.03
Mining	664	99	149096	0.01
Construction	7013	241	34365	0.06
Manufacturing	19972	1018	50971	0.17
Transportation	8245	482	58460	0.07
Wholesale	4765	360	75551	0.04
Retail sale	19589	516	26341	0.17
Finance	7764	975	125580	0.07
Services	40758	1041	25541	0.35
Government	5620	656	116726	0.05
	117600	5499	46760	

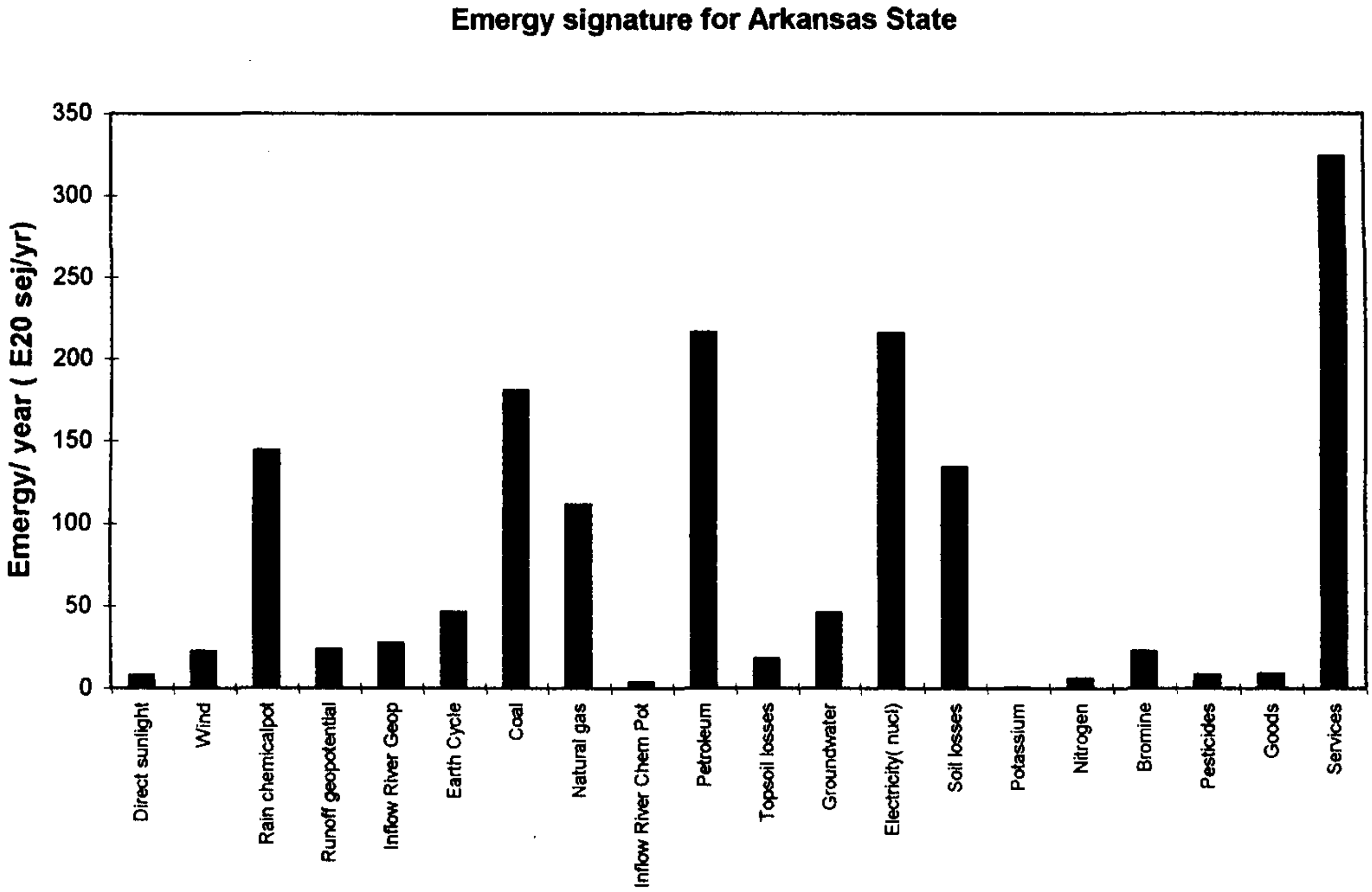


Figure 8. EMERGY signature of environment and economy in Arkansas.

Table 5
Emergy Indices for Arkansas

Item	Name of index	Expression*	Quantity
1	Renewable use	R	1.98 E22 sej/y
2	Indigenous non-renewable	N	5.82 E22 sej/y
3	Imported emergy	I	5.67 E22 sej/y
4	Total emergy used U=R+N+I	U	1.35 E23 sej/y
5	Total exported emergy	E	1.23 E23 sej/y
6	Emergy used from home sources	(N+R)/U	0.58
7	Imports-exports	I-E	-6.64 E22 sej/y
8	Ratio of export to imports	E/I	2.17
9	Fraction used, locally renewable	R/U	0.15
10	Fraction of use purchased outside	I/U	0.42
11	Fraction used, imported service	Import ser./U	0.24
12	Ratio of economic to free	(U-R-N)/(R+N)	0.73
13	Use per unit area (1.35 E11 m^2)	U/area	9.98 E11 sej/m^2
14	Use per person (2.39 E6 persons)	U/population	5.64 E16 sej/indiv.
15	Arkansas State Econ. Product (1990)	GSP	39 E9 $/yr
16	Ratio of emergy use to GSP, Ark.	U/GSP	3.45 E12 sej/$
17	Ratio of emergy use to GNP for U.S.	U/GNP	1.75 E12 sej/$

* For letters see Figure 7. U = sum of inputs = R + N + I.

Cache River Basin

Energy Systems Diagram

Figure 9a is the overview model of the Cache River Basin with an overlay diagram of the water components and flows given in Figure 9b. The basin is rural with a few human settlements. Groundwater-irrigated rice and some catfish aquaculture are based on the large water volumes.

Emdollar Evaluation Tables

Table 6 has the emergy and emdollar evaluation of the important sources, imports, and exports. Table 7 has the exchanges with the rest of the United States based on the percentage of workers in various occupations. Contributions to real wealth from the tables are shown in bar graph form in Figure 10 from left to right in order of their transformity (position in natural energy hierarchy).

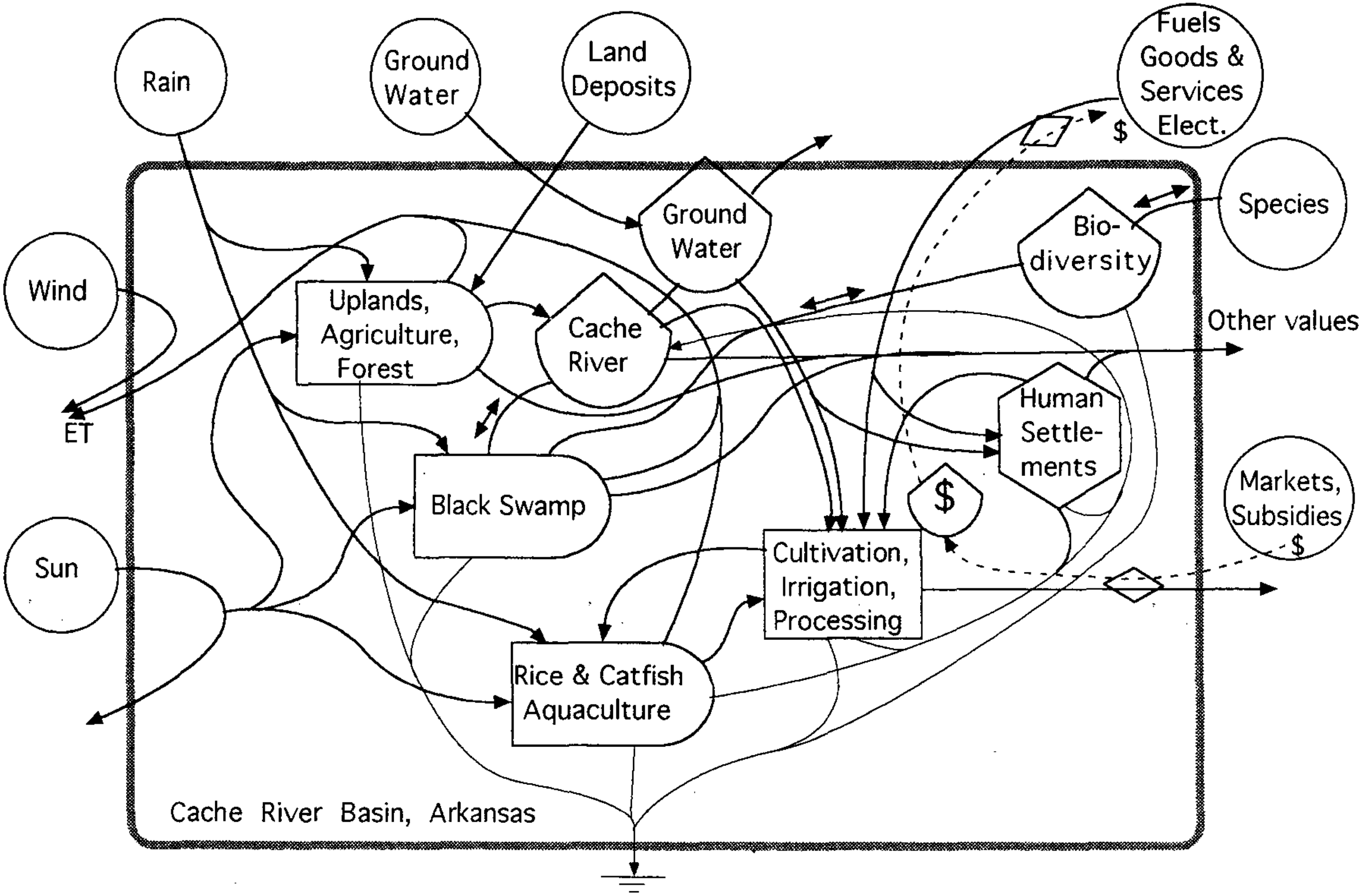
Cache River Basin is well served by rain (~48 in) during the whole year, and with high evapotranspiration rates during summer and early fall months. The Cache River basin is basically a flatland, and water has little geopotential energy. The water evapotranspired by vegetation measures the contribution of rain chemical potential. Rain chemical potential emergy is the highest source of natural renewable emergy.

The Cache River basin is basically an agricultural area largely based on indigenous soils and waters. The intensive agriculture of recent years has used soils and groundwater faster than their normal rate of restoration. Groundwater has been nonrenewable with about 70% of the recharge of the Mississippi river valley alluvial aquifer diverted to irrigation in 1972 (Ackerman, 1989). Groundwater emergy represents, respectively, 28% and 26% of non-renewable energy used in the state and the basin. Soil formed in the past makes up about 74% of the nonrenewable emergy use and 28% of total emergy use in the basin. The agricultural production depends on goods and services, fuel, and fertilizers brought into the basin from outside. Goods and services make up about 24%.

Outside sales of grain carry high emergy, much more than is in the buying power of the money received. Both areas export much more emergy than they import.

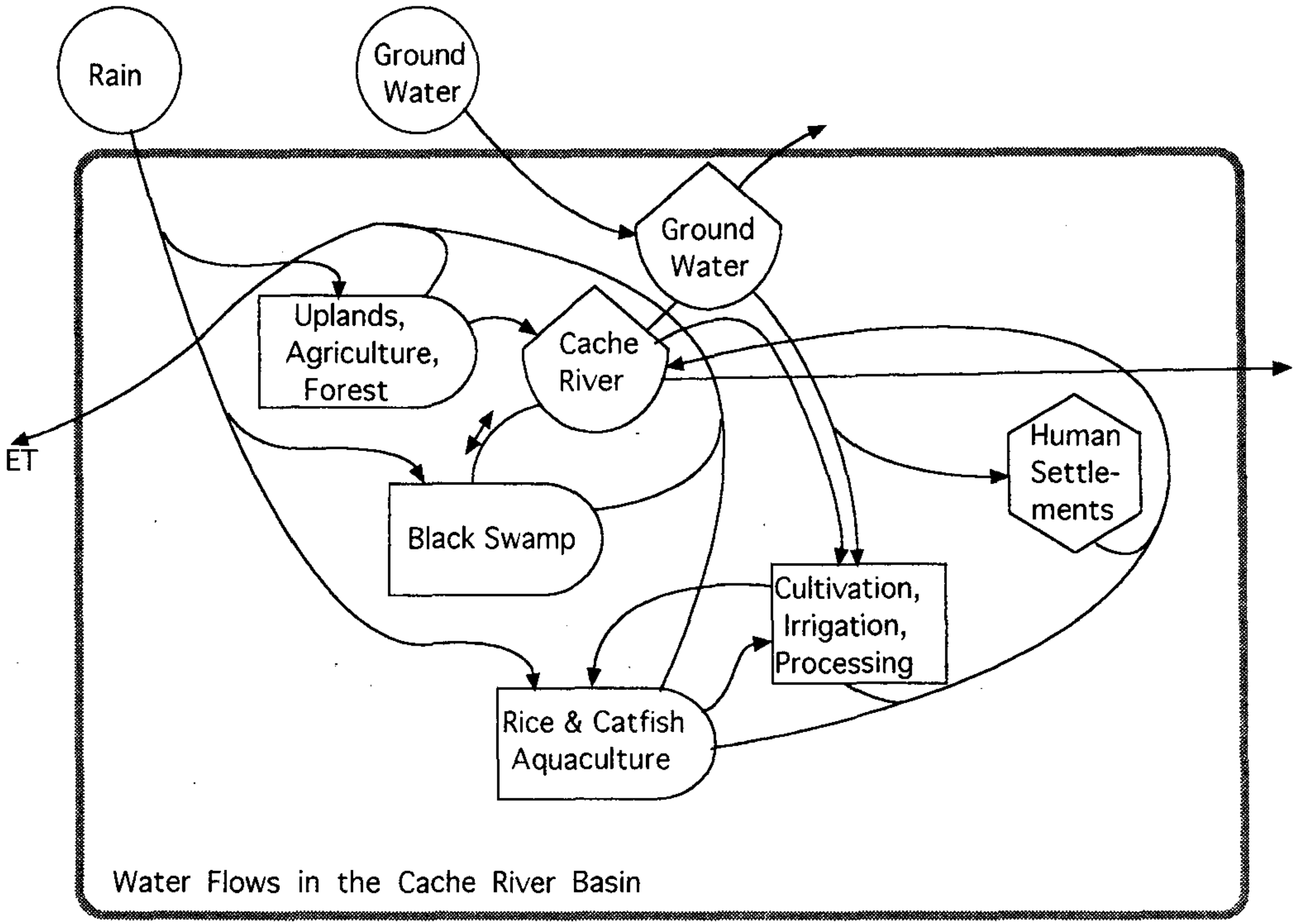
Emergy Indices

Indices for the Cache River Basin derived from the emergy evaluation tables are listed in Table 8. Although rural, the basin is only 48% self sufficient. Its ratio of resources added by the economy to the



(a)

Figure 9. Energy systems diagram of the Cache River Watershed (a) with main empower inputs in solar emjoules per year (b) water budget overlay.



Water Budget Overlay Diagram for Cache River Model

(b)

Figure 9 (continued)

Table 6
Annual Emergy Flows of the Cache River Basin

Note	Item	Data & Units	Emergy/unit	Emergy E20 seJ	U.S. Em$* E6
Renewable Resources					
1	Direct sunlight	2.87 E19 J/yr	1	0.29	8
2	Wind	5.45 E16 J/yr	1496	0.81	24
3	Rain geopotential	4.29 E15 J/yr	10488	0.45	13
4	Rain chemical pot.	2.86 E16 J/yr	18199	5.21	151
5	Earth cycle	4.88 E15 J/yr	29000	1.41	41
Indigenous Renewable Energy					
6	Rice and soybeans	1.24 E16 J/yr	1.70 E5	21.08	611
7	Wheat	1.30 E15 J/yr	2.20 E5	2.86	83
8	Others	1.84 E15 J/yr	6.00 E4	1.11	32
9	Poultry	4.24 E12	7.00 E5	0.03	1
10	Livestock prod.	4.37 E13 J/yr	2.00 E6	0.87	25
11	Fish prod.	2.53 E12 J/yr	2.00 E6	0.05	1
				26.00	754
Indigenous Non-renewable Energy					
12	Losses of earth	1.54 E12 g/yr	1.00 E9	15.4	448
13	Losses of topsoil	1.05 E15 J/yr	7.40 E4	0.78	22
14	Groundwater	3.62 E15 J/y	1.60 E5	5.79	168
				22.01	638
Imports					
15	Coal used	8.43 E15 J/yr	3.98 E4	3.35	97
16	Natural gas	8.65 E15 J/yr	4.80 E4	4.15	120
17	Petroleum	1.09 E16 J/yr	5.30 E4	5.79	168
18	Electricity	6.93 E14 J/yr	1.70 E5	1.18	34
19	Nitrogen	1.66 E10 g/yr	4.19 E9	0.70	20
20	Phosphorus	5.18 E8 g/yr	1.42 E10	0.07	2
21	Potassium	8.08 E9 g/yr	9.50 E8	0.08	2
22	Pesticides	5.03 E9 g/yr	1.48 E10	0.74	22
23	Goods & services	5.95 E8 $/y	2.3 E12	13.69	397
				29.75	862
Exports					
24	Rice & soybeans	1.20 E16 J/yr	1.70 E5	20.33	589
25	Goods & services	7.57 E8	3.45 E12	26.11	757
				46.43	1346

*U.S. $ 1990

Footnotes to Table 6

Area of the Cache basin = 4.88 E9 m^2

1. Direct sunlight
   Insolation for Arkansas (from US Env. Data Serv. 1975: Weather Atlas of the US) = 385 Langleys/day = 3850 kcal/m^2/day
   Energy = (3850 kcal/m^2/day)(4.88 E9 m^2)(365 days)(4186) J/kcal
   = 2.87 E19 J/yr

2. Wind calculated with eddy diffusion coefficient and vertical gradient coefficient (Odum, Diamond and Brown, 1987; Odum, 1996)
   Energy = (height)(density)(diff coefficient)(wind gradient)(area)
   = (1 E3 m)(1.23 kg/m^3)(14.74 m^2/s)(4.42 E-3 /s)(4.88 E9 m^2)
   = 3.15 E16 J/yr = 5.45 E16 J/yr

3. Rain geopotential with average rainfall = 48 in/yr = 1.22 m/yr
   Elevational gradient = 483 ft = 147.22 m
   Energy = (area)(rain/yr)(elev. gradient)(1000 kg/m^3)(9.8 m/s^2)
   = 4.29 E15 J/yr

4. Rain chemical potential as water used in evapotranspiration
   Evaporation = 55 in (from US Env. Data Serv. 1975: Weather Atlas of the US)
   Pan coefficient = 0.85 (Scott, H.D. et al., 1987)
   Water evapotranspired = 46.75 in = 1.19 m/yr
   Energy = (area)(water evaportranspired)(1 E6 g/m^3)(4.94 J/g)
   = 2.86 E16 J/yr

5. Earth cycle energy = (land area)(heat flow/area)
   = 4.88 E15 J/yr
   where heat flows assumed = 1 E6 J/m^2/yr

Notes 6-8. Agricultural Production

For the main crops of Arkansas, data from Census of Agriculture, 1992 were multiplied by the percent area of each county in the basin. Production was estimated in kg/yr:
Sorghum 9.30 E7; wheat 9.42 E7; rice 4.98 E8; cotton 2.06 E7; and soybeans 2.90 E8
Energy = (mass)(energy/unit) calculated as in Odum et al. (1987)

Footnotes for Table 6 (continued)

6. Rice and soybeans
Rice = (4.98 E11 g)(3.60 kcal/g)(4186 J/kcal) = 7.51 E15 J/yr
Soybeans = (2.90 E11 g)(4.03 kcal/g)(4186 J/kcal) = 4.89 E15 J/yr
Total weight: 7.88 E11 g; Total energy: 1.24 E16 J/yr

7. Wheat
(9.42 E10 g)(3.30 kcal/g)(4186 J/kcal) = 1.30 E15 J/yr

8. Others
Sorghum = (9.30 E10 g)(3.32 kcal/g)(4186 J/kcal) = 1.29 E15 J/yr
Cotton = (2.06 E10 g)(4.0 kcal/g)(4186 J/kcal) = 3.44 E14 J/yr
Hay = (1.64 E10 g)(3.0 kcal/g)(4186 J) = 2.06 E14 J/yr
Total energy: 1.84 E15 J/yr

Notes 9-10. Animal Production
Data from Census of Agriculture,1992 for Arkansas.
Production data for the main animals were multiplied by the percent area of each county in the basin. Energy was calculated
= (animals sold)(mass of each)(energy/mass) as in Odum et al. (1987)
Number of animals sold per year in Cache River Basin:
Cattle 13215; cattle sold 6964; hog & pigs 4514; pigs sold 9831; sheep129; broilers 2.64 E5

9. Poultry energy
= (number of broilers)(2.5 E3 g/animal)(2.39 kcal/g)(4186 J/kcal)
= 4.24 E12 J/yr

10. Livestock
Cattle = (cattle sold)(3.5 E5 g/animal)(2.92 kcal/g)(4186 J/kcal)
= 2.98 E13 J /yr
Pigs = (pigs sold)(9 E4 g/animal)(3.76 kcal/g)(4186 J/kcal)
= 1.39 E13 J/yr
Total: 4.37 E13 J/yr

11. Fish production data from Census of Agriculture,1992 for Arkansas.
Production data for fish production in counties of the basin were multiplied by the percent area of each county:
Production = 5.87 E5 kg/yr
Energy = (grams fish)(1.03 kcal/g)(4186 J/kcal) = 2.53 E12 J/yr

Footnotes for Table 6 (continued)

12. Losses of earth
Cropland Erosion = 500 $g/m^2/yr$
Cropland area = 3.09 E9 m^2
Soil Losses = (500 $g/m^2/yr$)(3.09 E9 m^2) = 1.54 E12 g/yr

13. Topsoil Losses = 1.54 E12 g/yr
Typical soils are = 3% organic matter and 5.4 kcal/g org.
Energy
= (loss per year)(organic fraction)(5.4 kcal/g)(4186 J/kcal)
= 1.05 E15 J/yr

14. Groundwater data from Arkansas Summary for 1989
(US Geological Survey- Open File Rep 91-203)
Total water use = 0.39 E8 m^3/yr
Chemical potential of basin groundwater
(volume/yr)(1 E6 g/m^3)(4.9 J/g) = 3.62 E15 J/yr

15. Coal data from Energy Information Administration - State Energy Data Report for1992:
State consumption = 12536 E3 short ton = 220.7 trillion Btu
Consumption in proportion to basin area, 0.036 fraction of state area
Energy:
(220.7 E12 Btu/yr)(0.036) = 7.98 E12 Btu/yr = 8.43 E15 J/yr

16. Natural gas consumption data from State Energy Data report 1992.
Arkansas total = 225 billion cubic feet = 226.6 trillion Btu
Consumption in proportion to basin area, 0.036 fraction of state area.
Energy = (226.6 E12 Btu)(0.036) = 8.19 E12 Btu/yr = 8.65 E15 J/yr

17. Petroleum data from Energy Info Administration - State energy data report for1992:
Arkansas consumption = 53115 E3 barrels = 286.3 trillion Btu
Consumption in proportion to basin area, 0.036 fraction of state area
Energy = (286.3 E12 Btu)(0.036) = 1.04 E13 Btu/yr =1.09 E16 J/yr

18. Electrical power data from Energy Information Administration
4707 million Kwh = 155.7 trillion Btu
Consumption in proportion to basin area, 0.036 fraction of state area
Energy: (155.7 E12 Btu)(0.036) = 5.63 E12 Btu/yr = 6.93 E14 J/yr

Footnotes for Table 6 (continued)

Notes 19-21. Fertilizers
Calculated considering occupied areas and the fertilizer concentrations (kg/ha) used in the different cultures

19. Nitrogen used in the basin = 1.66 E7 kg/yr

20. Phosphorus applied in the basin = 5.18 E5 kg/yr as P_2O_5

21. Potassium applied in the basin = 8.08 E6 kg/yr as K_2O

22. Pesticides chemicals in the basin; 3.6 $/pesticides from Table 3;
(expenditure $)(1000)(basin % of state area) = 1.81 E7 $/yr
weight in kg/yr = (chemicals costs in $)/3.6 $/kg of pestcides
= 5.03 E9 g/yr

23. Goods and services brought into Arkansas estimated from costs
a. Services with imported fuels, estimated from coal, petroleum, electricity and natural gas consumption = 2.32 E8 $/yr

b. Services with foreign imports:
(4.49 E9 $/yr)(0.94% of state population in basin) = 4.21 E7 $/yr

c. Purchases from other states of the U.S. based on relative employment in different economic sectors in the basin compared with averages outside, as given in Table 7.1 = 3.50 E8 $/yr

d. Federal services estimated as percent (in population terms) of the federal transfer payments to Arkansas in 1992 = 1.69 E9 $ (1994 US Statistical Abstract)
= (0.009)(transfers to Arkansas) = 1.59 E7 $/yr
Total Imported Services = (a + b + c + d) = 5.95 E8 $/yr

24. Exports: Rice and soybeans energy calculated as:
(product weight)(caloric content in kcal/g)(4186 J/kcal)
Rice: 4.98 E11 g/yr yields 7.50 E15 J/yr
Soybeans: 2.64 E11 g yields 4.45 E15 J/yr
Total energy 1.20 E16 J/yr

Footnotes for Table 6 (continued)

25. Goods and services leaving the basin:

a. Foreign grain exports: 0.09 percent (basin proportion of state population) of Arkansas foreign exports of grains; prices from 1994 US Statistical Abstract - table 1113 Principal Crops - production, supply and disappearance, 1989/1993 = 1.54 E8 $/yr

b. Basin foreign exports (services)
Arkansas contribution to U.S. foreign exports: 1.32 E9 $/yr
Basin contribution: 1.24 E7 $/yr

c. Relative exports to other parts of U.S. using Table 6.1, computing the relative differences in employment in economic sectors between the basin and average for the U.S. = 5.61 E8 $/yr

d. Services equivalent to tax money estimated as a fraction of federal taxes paid by the state = 2.75 E9 $/yr
Basin federal taxes - 2.58 E7 $/yr

Total services going out of the basin = 7.53 E8 $/yr

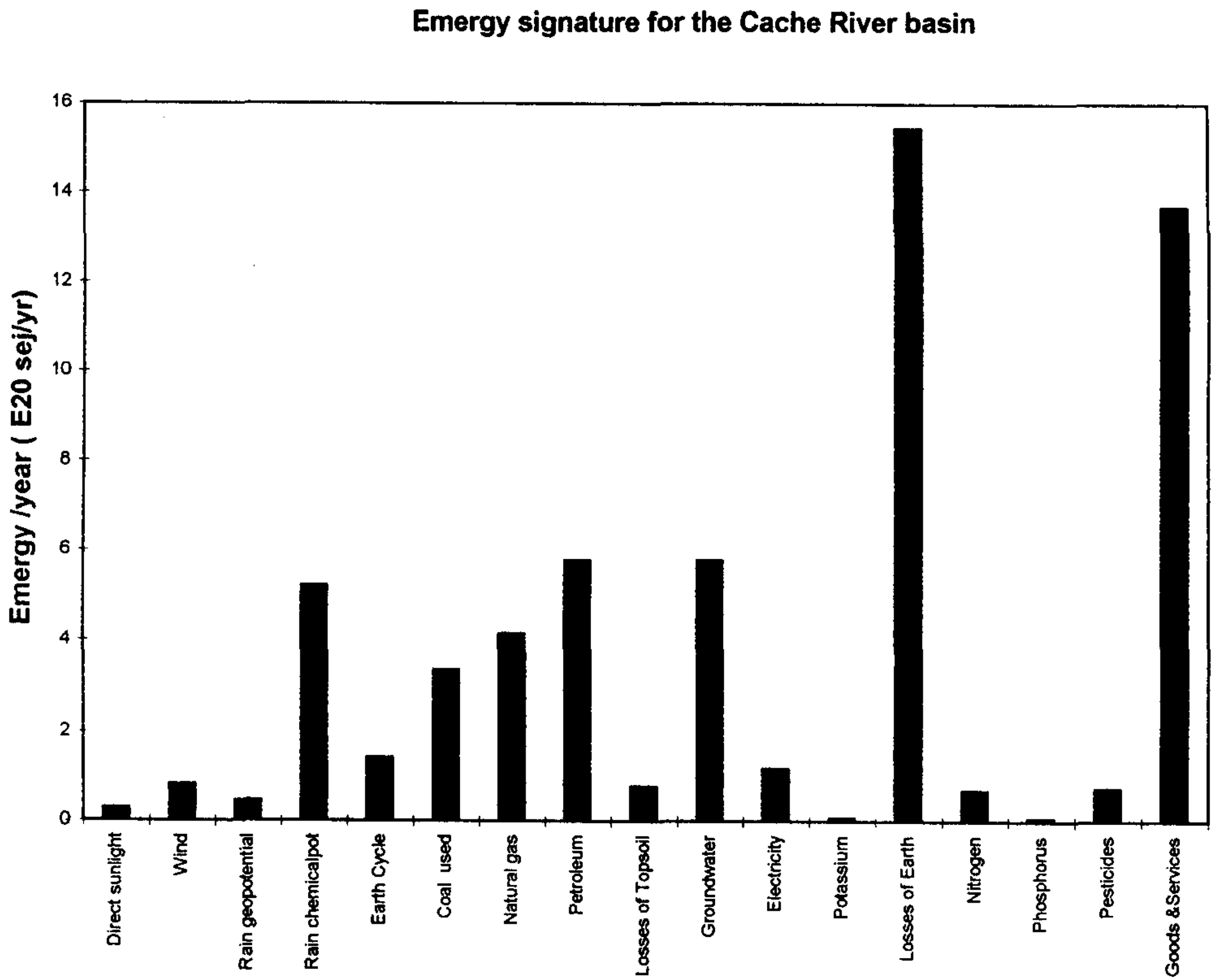


Figure 10. EMERGY signature of environment and economy of the Cache River Watershed.

Table 7
Exchange Between Other Parts of the U.S. and the Cache River Basin Estimated from the Percent of Employees in Occupational Sectors

	Agr.	Mng.	Constr.	Manuf.	Transp.	Wholes.	Ret.	Fin.	Serv.	Govt.
U.S. average	0.03	0.01	0.06	0.17	0.07	0.04	0.17	0.07	0.35	0.05
Basin	0.01	0	0.03	0.3	0.04	0.05	0.17	0.03	0.19	0.18
Differences	-0.02	-0.01	-0.03	0.13	-0.03	0.01	0	-0.04	-0.16	0.13
$/employee	34579	149096	34365	50971	58460	75551	26341	125580	25541	116726
#/employees	-497	-249	-746	3233	-746	249	0	-995	-3979	3233
Exp/Imp	-1.72E7	-3.71E7	-2.56E7	1.65E8	-4.36E7	1.88E7	0.00E0	-1.25E8	-1.02E8	3.77E8

Imports: 3.50 E8 $

Exports: 5.61 E8 $

Net Export: 2.11 E8 $

($/employee - portion of the GNP generated by employee by sector in U.S.)

Footnotes For Table 7

IMPORT SERVICES

1. Value of imported fuels

	Btu	$/1 E6 Btu	Total Expend.
Coal	7.979 E12	1.66	1.325 E7
Natural Gas	8.192 E12	3.44	2.818 E7
Petroleum	1.035 E13	7.82	8.094 E7
Elecricity	5.629 E12	19.56	1.1 E8
			2.32 E8 $

2. Manufactured goods (Services)

Estimating the amount of foreign goods imported by Arkansas
Estimated foreign goods imports by Arkansas = 4.49 E9 $
Basin = 0.94% of state population
Therefore, imports of manufactured goods (Services) = 4.21 E7 $

3. Relative services

Imports from U.S. outside basin (based on relative differences on different industrial sectors in the basin and outside, as shown in Table 3a)
Relative services = 3.50 E8 $

4. Federal benefits (Services)

Estimating as percent (in population terms) of the Federal Aid transferred to Arkansas
Federal Aid to Arkansas, 1992 = 1.69 E9 $ (1994 US Statistical Abstract)
Basin Aid = (0.009385)(Arkansas Fed Aid) = 1.59 E7 $

TOTAL IMPORTED SERVICES = 5.95 E8 $

EXPORTS

1. Grain exported

	Production g/yr	Consumption	Remaining production
Sorghum	9.30 E10	0	9.299 E10
Wheat	9.42 E10	4.48 E9	8.9746 E10
Rice	4.98 E11	5.45 E8	4.9785 E11
Cotton	2.06 E10	0	2.0554 E10
Soybeans	2.90 E11	0	2.8982 E11
Hay	1.64 E10	0	1.637 E10
	1.01 E12		1.0073 E12

Footnotes for Table 7 (continued)

Consumption calculated as per capita consumption of flour and cereal multiplied by number of persons in the basin

Animal Feeding

	# of animals	Weight (grams)	Feed protein ratio (g/g)	Protein
Beef	20179	1.37 E10	15.5	4.254 E10
Pig	14345	1.29 E9	10.5	1.762 E9
Broiler	264181	6.6 E8	5.5	7.265 E8
				4.503 E10

	Production	Protein content	Protein available	Protein for feeding	Production available
Sorghum	9.299 E10	0.08	7.44 E9	7.44 E9	0
Wheat	8.9746 E10	0.12	1.08 E10	0	8.9746 E10
Rice	4.9785 E11	0.1	4.98 E10	0	4.9785 E11
Cotton	2.0554 E10	0.04	8.22 E8	0	2.0554 E10
Soybeans	2.8982 E11	0.34	9.85 E10	8.76 E9	2.6406 E11
Hay	1.637 E10	0.11	1.80 E9	1.80 E9	0
			1.69 E11	1.80 E10	

Considering 60% of needed protein is coming from other sources,
protein needed for animal = 1.8 E10 g
(assuming that protein is provided by hay and sorghum and soybeans)

Grain production available for export

	Production (grams)	Energy J/yr	Sales $
Wheat	8.97 E10	1.25 E15	1.07 E7
Rice	4.98 E11	7.5E15	6.46 E7
Cotton	2.06 E10	3.44 E14	2.49 E7
Soybeans	2.64 E11	4.45 E15	5.39 E7
		1.35 E16	1.54 E8

(Grain Prices from 1994 US Statistical Abstract, Table 1113)
Principal Crops- production, Supply and Disappearance, 1989/1993
Grain Export (GOODS) = 1.35 E16 J/yr
Grain Export (SERVICES) + 1.54 E8 $

Footnotes for Table 7 (continued)

2. Animal Production

	Weight (grams)	Internal consumption	Exp/ imp.	Energy J/yr
Beef	1.37 E10	8.14 E9	5.58 E9	9.997 E13
Pig	1.29 E9	5.34 E8	7.57 E8	1.752 E13
	1.50 E10		6.34 E9	1.175 E14

Animal Prod (GOODS) = 1.175 E14 J/yr

Counties	Sales/county 1000 $	% basin	Sales-basin 1000 $
Butler	3538	0.095755	338.78
Clay	3127	0.354792	1109.43
Craighead	3248	0.303259	984.99
Greene	5001	0.462598	2313.45
Jackson	1979	0.450701	891.94
Lawrence	6354	0.15494	984.49
Monroe	832	0.228013	189.71
Poinsett	1794	0.183625	329.42
Prairie	7286	0.068496	499.06
Woodruff	372	0.695715	258.81
			7900.07

Total Sales = 7.9 E6 $
Export = (% exported)(total sales) = 3.34 E6 $
Animal Prod (SERVICES) = 3.34 E6 $

3. Basin Foreign Exports (SERVICES)
Taken as percent (in population terms) of Arkansas foreign exports:
Arkansas contribution to U.S. foreign exports = 1.32 E9 $
Basin contribution = 1.24 E7 $

4. Relative Exports to others parts of U.S. (SERVICES)
Calculated as shown in Table 3a, computing the relative differences between Basin and average U.S. in employment in different industry
Relative Exports from Basin = 5.61 E8 $

5. Value of Taxes (SERVICES)
Estimating as percent of Federal Taxes paid by the State
Arkansas Federal Taxes = 2.75 E9 $
Basin Federal Taxes= 2.58 E7 $

EXPORTS (SERVICES) Total = 7.57 E8 $

Table 8
Emergy Indices for Cache River Basin

Item	Name of Index	Expression	Quantity
1	Renewable use	R	5.66 E20 sej/y
2	Indigenous non-renewable	N	2.20 E21 sej/y
3	Imported emergy	I	2.98 E21 sej/y
4	Total emergy used, U=R+N+I	U	5.74 E21 sej/y
5	Total emergy exported	E	4.64 E21 sej/y
6	Emergy from home sources	R+N/U	0.48
7	Imports - exports	I- E	-1.67 E21 sej/y
8	Ratio of exports/imports	E/I	1.56
9	Fraction locally renewable	R/U	0.10
10	Fraction purchased	I/U	0.52
11	Fraction imported services	Imp ser/U	0.24
12	Ratio of economic to free	(U-N-R)/(R+N)	1.06
13	Use per unit area (4.87 E9 m^2)	U/area	1.18 E12 sej/m^2
14	Use per person	U/population	8.0 E16 sej/person

environmental renewable resources is 5.3. Water use is 20% (10% groundwater) of the total source of real wealth, but the agricultural economy based on the water including the imported inputs to agriculture is 45% of the total emergy budget.

Comparisons

Emergy Indices of the Cache River basin were compared with those for the whole Mississippi River basin in Table 6 (Diamond, 1984; Odum, Diamond and Brown, 1987). The Cache River basin like the Mississippi River basin used half of its emergy from home sources, but just 10% were locally renewable. Compared to the rest of the state the Cache River basin used less emergy from home (~48%), although a larger fraction came from renewable resources (18%). Like the Mississippi basin and Arkansas as a whole, the Cache River basin was an emergy exporter. The ratio between exports and imports was 2.17 for the state, 1.50 for the Mississippi basin, and 1.56 for the Cache River basin. Imported services were 24% for the state, 29% for the Mississippi basin and 24% for the Cache River basin. Annual emergy use per area in the Cache River basin(1.12 E12/m^2/yr) was greater than in the Mississippi basin and Arkansas state (~9 E11/m^2). Emergy per person was very high (8 E16 sej/person) compared to that in the larger areas of Arkansas and the United States as a whole.

Black Swamp

Energy Systems Diagram

Figure 11 is an overview model of the main parts and processes in a hectare of Black Swamp. An efforts was made to include the parts and processes considered important by those making recent studies such as those in the special issue of the Wetlands Journal in 1997.

Emergy Evaluation Tables

Typical emergy flows were evaluated in Table 10 and represented in the bar graph as a function of transformity in Figure 12. Water transpiration and work of physical motions of water were the principal basis for this ecosystem. There were also inputs by human managers and users.

Emergy Indices

Managed for its natural characteristics the ratio of economic inputs to the natural environmental value was small (0.25), a ratio less than found in national parks.

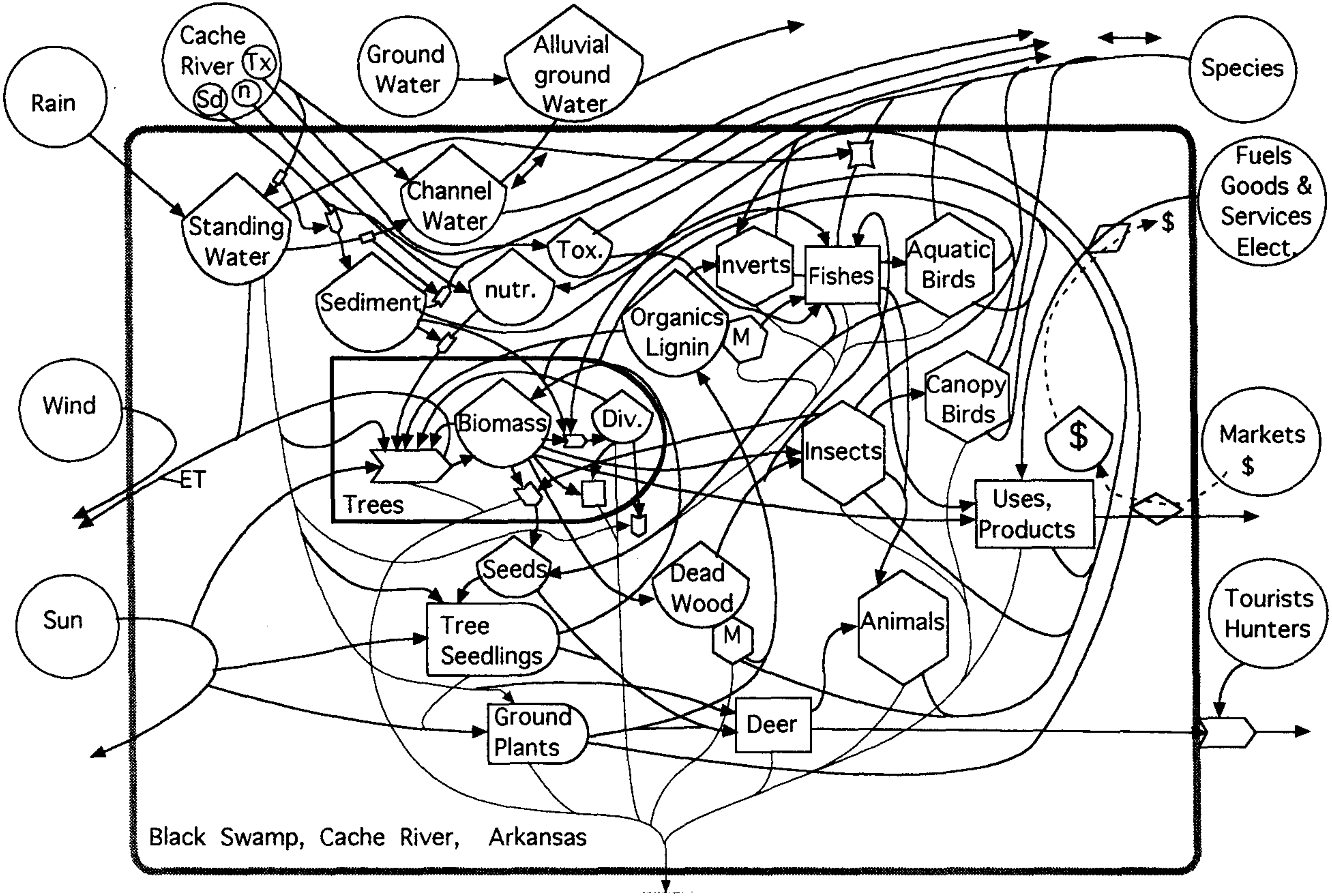


Figure 11. Energy systems diagram of the Black Swamp with main empower inputs in solar emjoules per year.

Table 9
Annual Emergy Flow in the Black Swamp

Note	Item	Raw units J, g, $	Emergy per unit sej/unit	Solar Emergy E16 sej/yr	Emdollars! 1992 E3 $/yr
1	Solar energy, J	9.26 E16	1	9	27
2	Wind energy, J	1.76 E14	1496	26	76
3	Rain chemical pot., J	9.48 E13	18199	173	500
4	River geopotential, J	5.37 E13	27764	149	432
5	River chem potential, J	4.80 E13	48459	232	674
6	Forest evapotransp, J	9.23 E13	18199	168	487
7	Migratory birds, J	1.29 E11	9.70 E5	12.5	36
8	Fish influx, J	2.43 E10	1.00 E6	2.4	7
9	Recreational uses, $	1.75 E5	4.70 E12	82	239
10	Gross production, J	9.88 E13	33610*	332	
	Total Emergy =			414	1201

! 3.44 E12 sej/$

Area = 3888 acres (Coe, 1974) = 1.57 E7 m^2 =1573 ha

* Sum (#4 + #6 + #7+ #8) = 332 E16 sej/yr
Solar transformity = (3.32 E18)/(9.88 E13) = 33610 sej/J

1. Solar energy = 385 ly/day = 3850 kcal/m^2/day
(3850 kcal/m^2/d)(1.57 E7 m^2)(365 d)(4186 J/kcal) = 9.26 E16 J/yr

2. Wind energy
= (height)(density)(diffusion coefficient)(wind gradient)(area)
(1000 m)(1.23 kg/m^3)(14.7 m^2/s)(3.16 E7 s/yr)(0.0044/s^2)
(1.57 E7 m^2) = 1.76 E14 J/yr where diffusion coeff = 14.72 m^3/m/s
and wind gradient = 0.00442 m/s/m

3. Rain chemical potential:
(1.22 m precip)(1.57 E7 m^2)(1 E6 g/m^3)(4.94 J/g) = 9.48 E13 J/yr

Footnotes for Table 9 (continued)

4. River geopotential
Flow in and out = 1.37 E9 (from average USGS data, 1987-1993); (from Dortch, 1996, p. 361)
Elevation change = (57 m - 53 m) (from Walton et al., 1996)

Geopotential energy used:
(volume/yr)(1000 kg/m^3)(9.8 m/s^2)(4 m drop) = 5.37 E13

5. River chemical potential
Mean annual river flow (Patterson) estimated from 5-year data from US Geological Survey Water Data reports from Arkansas, 1987-1990 (1993). Flows from Dortch, (1996, p. 361)

Used chemical potential:
100 mg/l to 500 mg/l (Kadlec & Knight, 1996)
Change in total dissolved solids = 400 - 150 mg/l
(1.37 E9 m^3/yr)(1 E6 g/m^3)(4.925 - 4.89 J/g) = 4.79 E13 J/yr

6. Bottomland hardwood evapotranspiration
Evapotranspiration to pan evaporation ratio = 0.95 (cyp. riverine from Lugo A., 1990)
Pan evaporation = 55 in = 139.7 cm (from US Env. Data Serv. 1975: Weather Atlas of the US)
Assuming transpiration/pan evap = 0.85
Transpiration rates = 118.745 cm
Forest transpiration energy
= (1.187 m)(1.57 E7 m^2)(1 E6 g/m^3)(4.94 J/g) = 9.2 E13 J/yr

7. Birds migrants
Abundance of migrants during breeding season
1.5 birds/0.48 ha plot = 3.125 birds/ha
(3.125)(1573) ha = 4916 birds
Average weight = 19 g/bird = 9.5 g dry weight/bird
Bird dry weight/swamp = 4.67 E4 g dry wt
Respiration = (dry weight)(conversion factor)(236g/yr)
= 1.10 E7 g/yr (Costanza et. al, 1983)
Energy = (1.1 E7 g/yr)(5.6 kcal/g)(4196 J/kcal)(0.5 yr)
= 1.29 E11 g/seas

Footnotes for Table 9 (continued)

8. Fish Influx as larvae
Larvae in floodplain in spring = 1.81 ind./m^3
In spring + early summer = 1.33 ind./m^3
For the whole season assume = 1.0 ind./m^3
Volume of inundation water into the floodplain = 5.0 E6 m^3

Based on transects and water stages (Kleiss, 1996)
5.0 E6 larvae in spring; average larval weight = 2 g
Total weight = (2 g/ind.)(5 E6 ind) = 1.0 E7 g
Energy
= (1 E7 g)(0.2 dry)(5.8 kcal/g)(4186 J/cal)(0.5 yr) = 2.43 E10 J

9. Recreational uses
Area demand: 3.10 E6 man/hours (Corps of Engineers, 1974)
Rec. areas in the region = 78,000 acres
Black Swamp = 3880 acres
Black Swamp percent = 0.0497
Black Swamp share 5% of demand = 1.55 E5 man/hours
Energy
(1.55 E5 man/hour)(104 kcal/h)(4186 J/kcal) = 6.7478 E10 J/yr

Counting by trips
Trips demands for hunting/fishing = 116,900 trips/year
Black Swamp area = 5% available area in the region
Black Swamp's trips = 5845 trips/year
Estimated cost/trip = \$3.3/trip (Corps of Engineers, 1974)
Estimated expenses/trip = \$20.00/trip (assumed)
Total expenses = 175,350 \$/year
(Solar emergy)/(emergy/money for Arkansas)
In 1992 Emergy/money ratio = 4.70 E12 sej/\$

10. Black Swamp gross primary production
= (5900 tonne/swamp/yr)(1 E6 g/tonne)(4 kcal/g)(4186 J/kcal)
= 9.88 E13 J/yr

Table 10
Annual Emdollar Values in one Hectare of the Black Swamp
For value of 1.57 E3 hectares of Black Swamp, multiply by 1570

Item		Baseline Evaluation	River Diverted	River Channelized	Pumped Groundwater
1	Forest productivity	309	295	280	342
2	Sediment retention	1335	1135	0	1335
3	Organics retention	4023	3419	0	4023
4	Fish production	525	92	0	0
	Total	6192	4941	280	5700

* Emdollars calculated by dividing emergy values by Arkansas emergy/dollar ratio for 1992 = 3.45 E12 sej/$

Emergy per unit used to evaluate emergy:
Forest production 4916 sej/J
Sediment retention 1.7 E9 sej/gram
Organic matter retention 6.24 E4 sej/J
Fish production 2 E6 sej/J

1. Forest productivity:
Baseline evaluation: floodplain from inundation frequency in a natural floodplain (Brinson, 1990) with 25% transition
Floodplain =11.5 t/ha/yr; transition = 7 t/ha/yr; upland = 10 t/ha/yr
Production/ha = (0.25)(1 ha)(7t/ha) + (0.75)(1 ha)(11.5 t/ha)
= 10.375 t/ha/yr
Energy = (10.375 t/ha/yr)(1 E6 g/t)(5 kcal/g)(4186 J/kcal) = 2.17 E11 J/yr

Evaluation of swamp with diverted river: using upland, 15%; transition 30%; floodplain 55% with production, respectively: 10 t/ha, 7 t/ha, 11.5 t/ha.

Evaluation of channelized river: using upland, 80%; transition 20%; floodplain 0% with production, respectively: 10 t/ha, 7 t/ha, 11.5 t/ha.

Evaluation of pumped groundwater impact: using upland, 0%; transition 25%; floodplain 75% with production, respectively: 10 t/ha, 7 t/ha, 13 t/ha.

Footnotes for Table 10 (continued)

2. Baseline sediment retention 2.75 tonne/ha/yr
   River diversion 85% sediment retention
   Channelization 0% sediment retention
   Groundwater pumping, normal sediment retention

3. Baseline organic retention 1.07 E7 g/ha/yr
   River diversion 85% retention
   Channelization 0% retention
   Groundwater pumping, normal retention

4. Baseline fish production 187 kg/ha
   With river diversion 85%
   With channelization 0%
   With groundwater pumping 70%

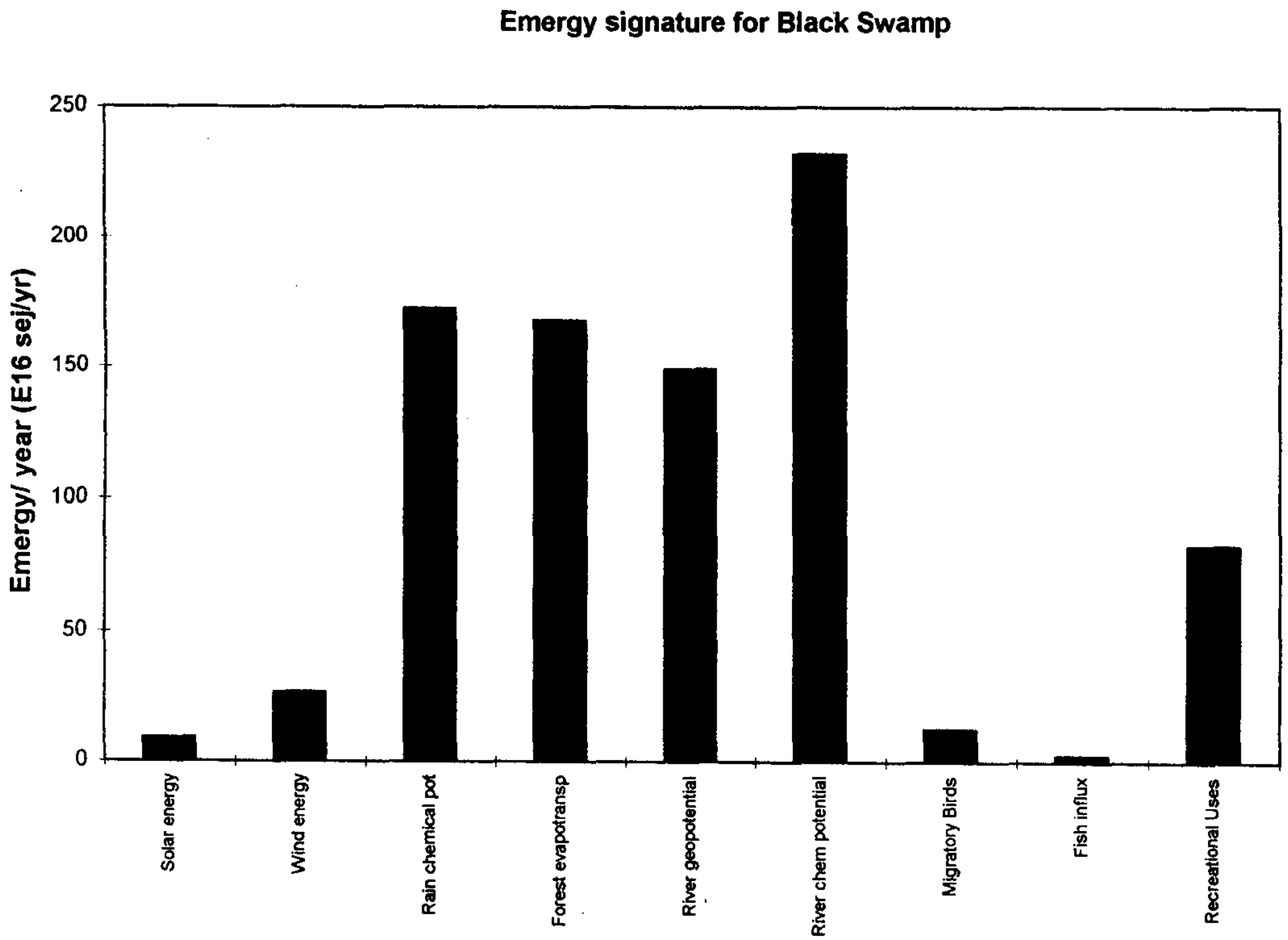


Figure 12. EMERGY signature of a hectare of Black Swamp Ecosystem.

Comparisons

The annual emergy uses and flows are high comparable with other more productive ecological systems.

Simulating Impacts

Diagram of the overview ground water model in Figure 13a has the equations beneath the diagram and the mathematical terms for each pathway or storage. Figure 13b has the values of flows and storages used in the calibration based on calculations in Appendix Table A1. The coefficients for the simulation model were calculated in Appendix Table A2.

Figure 14 has the results of simulating the model calibrated with pre-impact conditions. River water is the main water input to the swamp (Figure 14a). Average standing water in the swamp varied from less than 0.10 m in the summer to 1.20 m in the winter and early spring months. Water levels followed the annual sine-wave fluctuation supplied to represent sunlight, rain and river. When river waters receded, the water inputs to the swamp were provided by rainfall and groundwater. These inputs were critical for the forest production because they occurred during summer season when sunlight was maximum in the area.

The seasonal pulsing of sunlight and rain produces corresponding pulses in photosynthetic production (Figure 14b). Similar graphs were obtained for the several impact conditions (Appendix A), and these differences from the base calibration run are summarized in Table 11. To understand the impact interactions, the reader might use a finger to trace the pathways in the model (Figure 13a) to see how each management action causes the changed values reported in the summary Table 11.

The results of simulated effects of the various conditions on average gross primary production and the swamp are given in Table 3.1.

Included in Appendix A are 26 year simulations of the overview model (Figure 13a) for various conditions. Yearly fluctuations of the gross primary production are displayed in the top panel, forest biomass and water level of the swamp on the middle panel, and groundwater level and the groundwater influx into the underlying aquifer on the bottom panel. Impacts simulated separately were:

Pre-impacted conditions - Figure B.1.
Effect of cutting forest - Figure B.2.
Effect of lowering groundwater - Figure B.3.

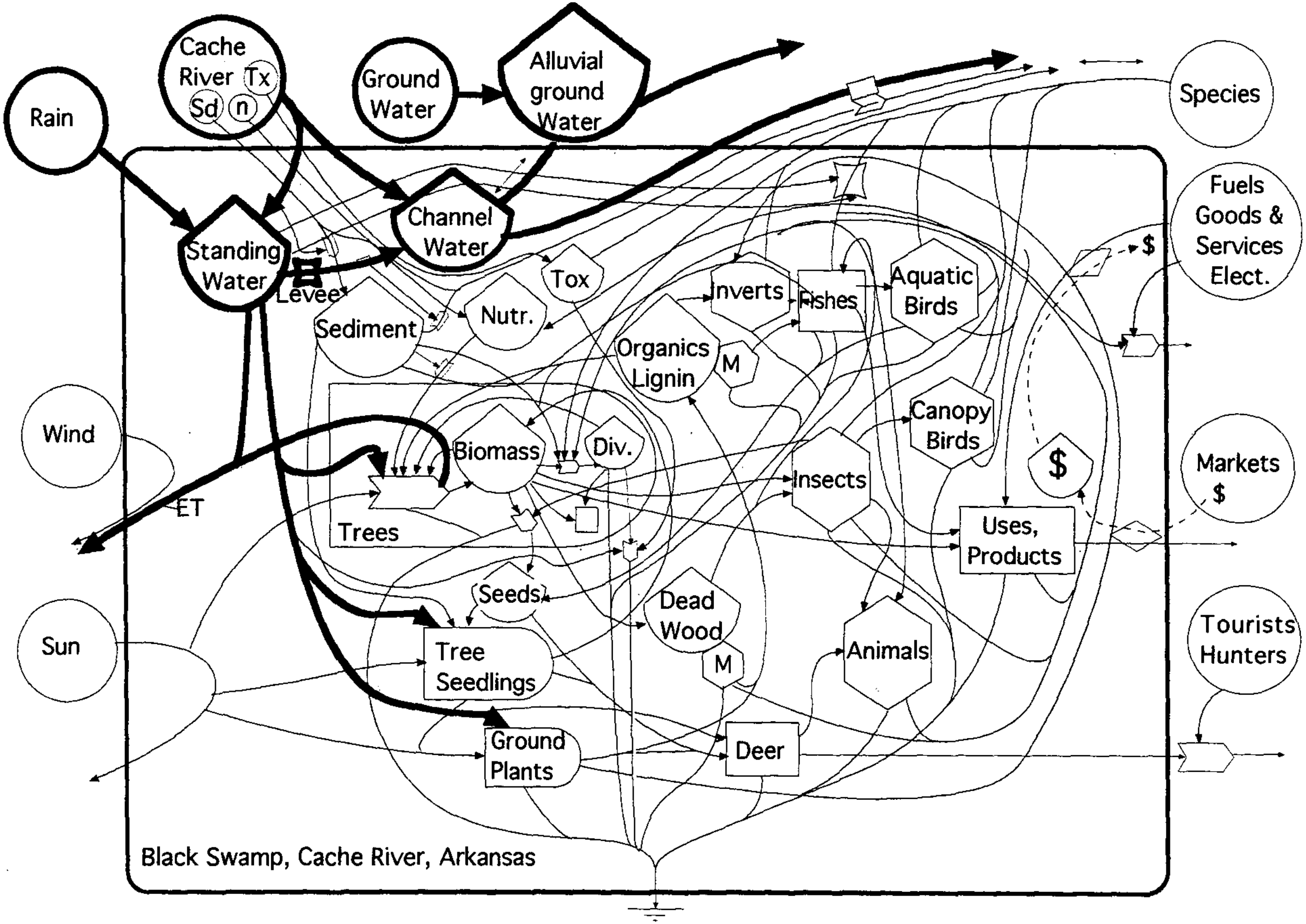


Figure 11 with water pathways highlighted.

Effect of diverting river flows - Figure B.4.

Simulation of combined actions (= cumulative impacts) were:

Effect of lowering groundwater and cutting forest - Figure B.5.
Effect of lowering groundwater and diverting river - Figure B.6.
Effect of diverting river and cutting forest - Figure B.7.
Effect of lowering groundwater, diverting river and cutting forest - Figure B.8.

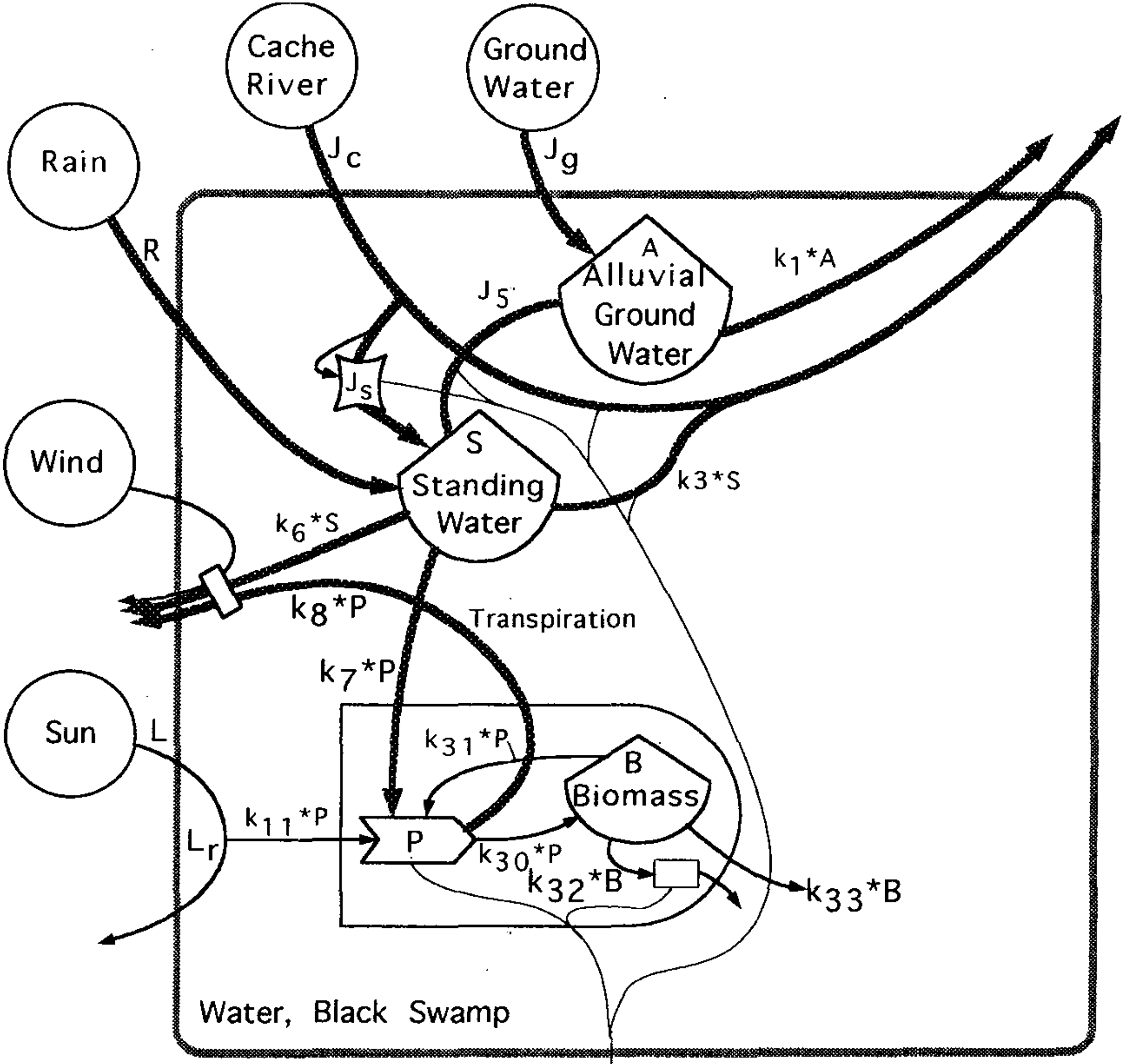
Simulated Effects of Separate Impacts

According to the model predictions, cutting 10 or 20% of the forest did not cause major impacts in the system production. In 7 to 10 years the forest returned to the pre-impact conditions.

Reducing groundwater inputs and lowering the average groundwater level in the area caused a 20% reduction in the groundwater inputs and caused forest production and biomass to be reduced to 67% and 74% of the pre-impacted values, respectively. Diverting 20% of river waters caused forest production and biomass to decrease to 61% and 69% of the pre-impacted conditions, respectively.

Simulation of Cumulative Impacts

Cutting biomass did not increase the larger impacts of lowering groundwater or diverting the river. However, there were cumulative synergistic effects of river diversion and lowering groundwater. Reducing these two water inputs by 20% caused the forest production and biomass to decrease to just 31% and 45% of the pre-impact values. The strongest impact came from a scenario with 20% reduction in forest biomass, groundwater and river water inputs. In this case, forest production and biomass were reduce to 28% and 39% of the initial conditions, respectively.



$$\text{Product: } P = Lr*S*B$$

$$L = 1 + 0.5*\mathrm{Sin}[(T+8)*0.523]$$

$$R = R_1 + R_2 *\mathrm{Sin}(T*0.523)$$

$$L_r = L/(1 + k_{11}*S*B)$$

$$J_c = J_o + J_1*\mathrm{Sin}[(T + 13)*0.523]$$

$$Js = k_4*[(J_c/J_{c1})-2]$$

$$J_5 = k5*\{ [(S/S1)-h0]-[(A/A_1) - h_1]\}$$

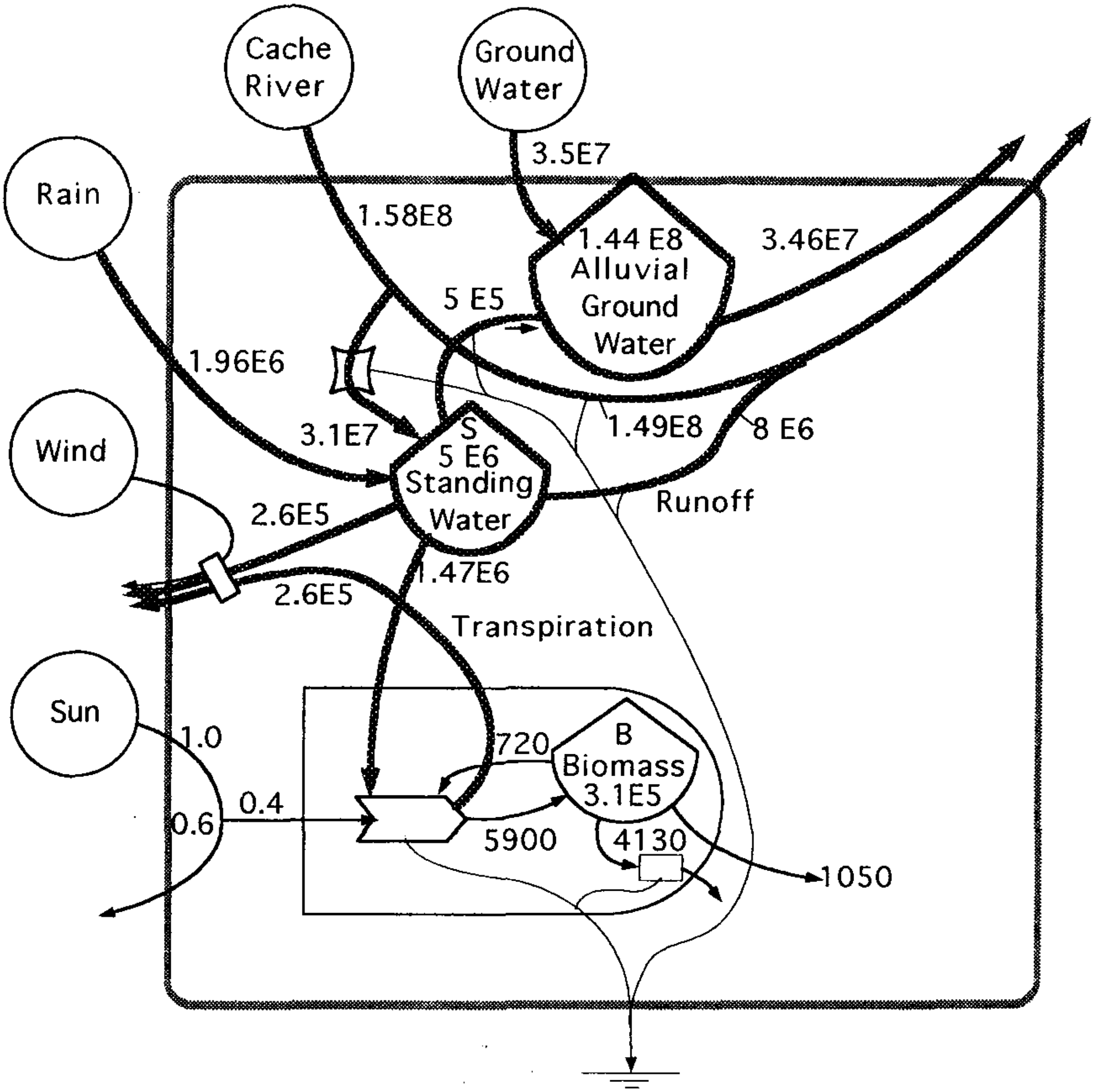
$$dA/dt = J_g - k_1*A + J_5$$

$$dB/dt = k_{30}*P - k_{31}*P - k_{32}*B - k_{33}*B$$

$$dS = R + J_s - k_7*P - K_3*S - k_6*S - J_5$$

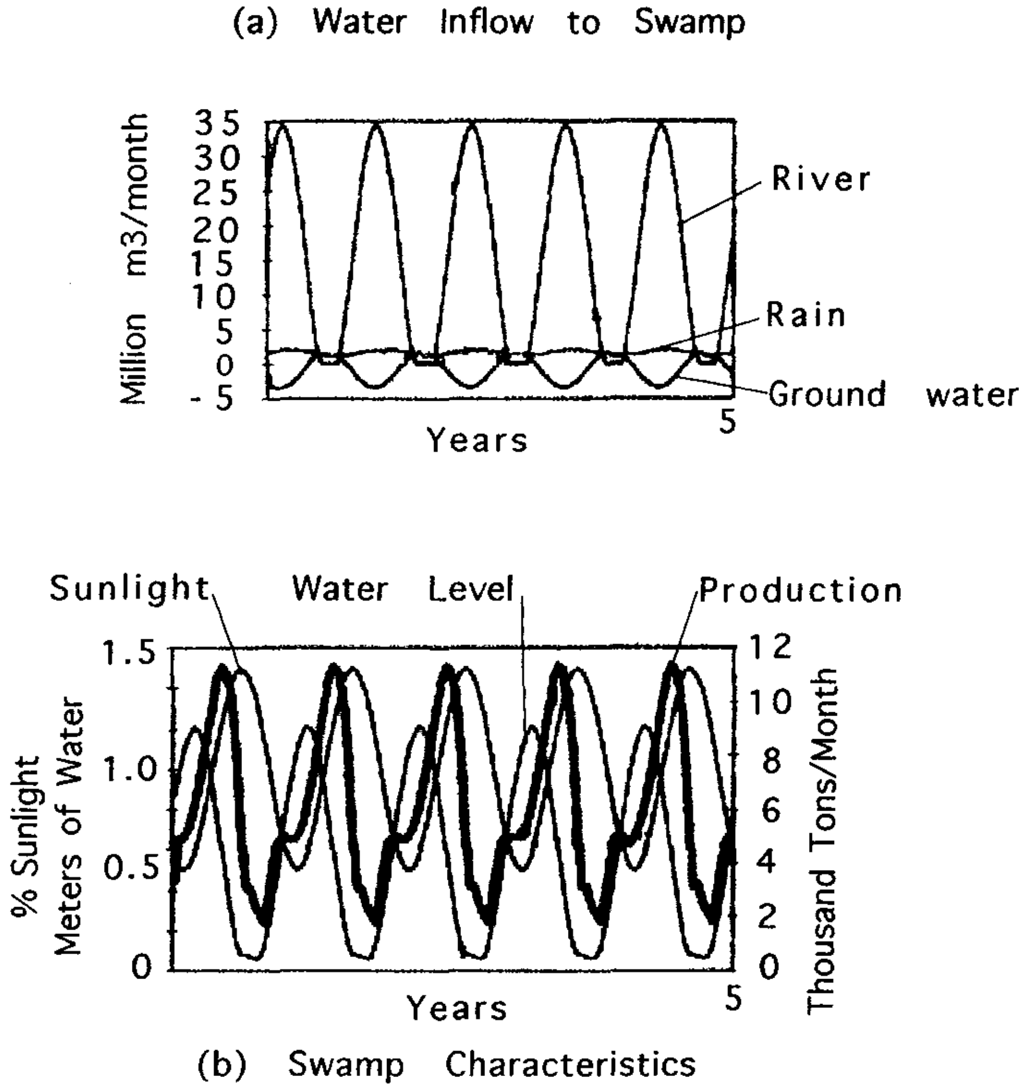
(a)

Figure 13. Overview simulation model of impacts on waters of the Cache River watershed affecting the Black Swamp. (a) With mathematical equations; (b) with values of flows and storages used for calibration from Appendix Table A1.



(b)

Figure 13 (continued)



(a) Water Inflow to Swamp

(b) Swamp Characteristics

Figure 14. Simulation of the Black Swamp water model in Figure 13a as calibrated with values in Figure 13b. (a) Water inputs; (b) sunlight, primary production, and water level. See Appendix Figures A1 - A8.

DISCUSSION

Principal Resources

Sunlight and its derived natural energy flows (wind, rain, etc.) work in many ways over the state and its river basin. However, it is in the form of rain that it provides higher emergy for these areas, and the way it will be taken into account in this analysis. Rain fallen over the land and working in the landscape is measured as runoff geopotential. The water evapotranspired by vegetation is measured as rain chemical potential. The state and the Cache River basin are well served by rain (~48 in) during the whole year and present high evapotranspiration rates during summer and early fall months. Therefore, rain chemical potential emergy is the highest source of natural renewable energy in both systems.

Arkansas has an uneven relief, with mountains and plateaus over its west side and the Mississippi floodplain in its east side. Therefore, it has a relatively high runoff geopotential (~30% of its renewable emergy). The Cache River basin is basically a flatland, and water has little geopotential energy there.

The state is relatively rich in nonrenewable resources. It has a good deal of mineral resources that are intensively used by the present economy. Its natural gas reserves provide the amount used by the state and supply the state with 28% of its energetic needs (EIA, 1994). The Cache River basin, however, has no fuel reserves and depends on imports to supply its energetic consumption.

The Cache River basin is basically an agricultural area, and therefore the indigenous nonrenewable resources most used in the area are soil and groundwater. Groundwater was taken as nonrenewable because about 70% of the recharge of the Mississippi River valley alluvial aquifer was already used by irrigation in 1972 (Ackerman, 1989). Groundwater emergy represents 22% and 14% of nonrenewable energy used in the state and the basin, respectively.

The most striking fact is the agricultural cost in terms of erosion in the Cache River basin. Soil formed in the past is now intensively used. Soil loss makes up about 84% of nonrenewable emergy used and 42% of total emergy used in the basin.

The agricultural production in the basin depends on imports of goods and services, fuel and fertilizers. Goods and services make up about 36% of the whole basin emergy import.

The state has a more diversified economy. However, it is still largely agricultural and dependent on some kind of imports. Fuels represent 31% of state imports. Goods and services make up 46% of state imports. The basin exports its high grain production and services embodied in such production. The state exports meat and services embodied in its industrial production. Both areas export much more emergy than they import.

Evaluating Change

Perspectives on the roles of various processes, inputs or impacts can be obtained by comparing the annual emdollars of different flows in the evaluation tables. Emdollars provide the resource contribution to the dollar economy, the gross economic product. For example, Table 10 gives the value of a hectare of Black Swamp and compares effects of river diversion, channelization, and strong groundwater pumping.

Another way to evaluate the impacts is to observe the effects of a changed input to a computer simulation model. The simulation automatically includes synergistic and cumulative impacts. Table 11 has the results of simulating the water model in Figure 13, showing the percentage decline in emdollar values for different impacts separately and together. Table 11 has the model's indications of impact on swamp forest productivity and biomass.

Use of Emergy Evaluation in Permitting

Emdollar evaluation allows environmental resources, their contributions to the economy, and the impacts to be placed on familiar monetary terms. Whereas the systems diagrams show pathways of contribution or impact, the evaluations give substance, indicating how important they are and their cumulative impacts, as we have shown with examples in Tables 9, 10, and 11 for the Black Swamp.

For those responsible for permits or other decisions about environment, Table 12 summarizes the steps to obtain an emdollar evaluation of a proposed action. By evaluating the changes anticipated in the environment and the associated economic development, the new may be compared with the pre-condition. The general guideline can be to authorize developments that maximize the annual emdollar production and use (including that of the environment and the economic uses).

Table 11
Simulated Effects on the Productivity and Biomass of the Black Swamp

Action & Impact Intensity	% of Initial Productivity	% of Initial Biomass
Cutting biomass		
0%	100	100
10%	99	97
20%	97	94
Diverting river flow		
0%	100	100
10%	79	84
20%	61	69
Lowering groundwater		
0%	100	100
10%	79	84
20%	61	74
Cutting biomass + Lowering groundwater		
0%	100	100
10%	80	81
20%	67	68
Cutting biomass + Diverting river flow		
0%	100	100
10%	79	80
20%	65	63
Diverting river flow + Lowering groundwater		
0%	100	100
10%	78	67
20%	58	45
Cutting biomass + Diverting river flow + Lowering groundwater		
0%	100	100
10%	59	64
20%	31	39

Table 12
Steps for Emdollar Evaluation of a Proposed Change
(See Also Previous Section on Concepts)

---

1. Identify the changes by looking at a systems diagram for the environmental system and its interface with economic use and impact. Diagrams are already available for most ecosystems and environmental use systems.

2. List the main changes. For example, replacing a swamp with a development will have items that are lost and items from the economy that will be added.

3. Obtain estimates of each of these in the normal every-day or scientific units. For example, estimates may be appropriate for area of land use changed, energy of sunlight, volume of water, number of ducks, dollars spent on construction, etc. It is desirable to evaluate any large storages--such as water, minerals, soil, forest wood, etc. It is also necessary to evaluate the annual contribution in amounts contributed per year.

4. Multiply each of these measures by the <u>emergy per unit</u> from unit emergy tables. For example, emergy per gram, emergy per individual, emergy per area, transformity (Table 1). The results of this step are <u>emergy of the stored quantities</u> and <u>annual emergy flows</u>.

5. Next divide the emergy values from step #4 by the emergy/money ratio for a recent year. The results are in emdollars. Emdollars include nature's contribution and the money paid to people on the same scale.

6. Finally compare the alternative proposals including the original condition to see which represent an increase in total emdollars. A proposal which decreases total emdollars should not be authorized. Instead, better designs for development may be found that use the work of nature and that of the economy in a symbiotic way (called ecological engineering).

Appendix A
Details of Impact Simulation

Appendix Table A1
Data Used for Calibration of the Water Simulation Model in Figure 13

Flows In and Out of Standing Water Storage (S):

1. Rainfall into the area (R)

   Average rainfall = 49.2 in (COE, 1974) = 1.25 m/yr
   Annual rainfall = (area)(average rain)
   = (10,000 m^2)(1.25) = 12,500 m^3/yr/ha
   Considering the Black Swamp area (1573.5 ha)
   = (12500 m^3/yr/ha)(1573.5 ha) = 19.7 E6 m^3/yr/swamp
   = 1.64 E6 m3/month
   Rainfall was varied during the year, with the sine equation:
   R = (R1 + R2)(sin t)(0.523)
   R1 = 1.60 E6 m^3/month
   R2 = 0.40 E6 m^3/month
   For the calibration month, R = 1.96 E6 m^3/month

2. Standing water storage (S)

   Assuming an annual average water level in the swamp of 0.30 m, the volume of water retained in the swamp
   = (water level)(area) = (0.3)(10000 m^2) = 3000 m^3/ha
   Considering the whole swamp
   Volume = (3000 m^3/ha)(1573.5 ha) = 4.72 E6 m^3/swamp
   Volume (assumed) = 5.00 E6 m^3/swamp

3. Evaporation and transpiration

   According to Lugo, A.E. (1990), evapotranspiration of riverine cypress in Florida = 95% of pan evaporation.
   Assumptions for the Black Swamp ecosystem:
   Evaporation = 15% of pan evaporation
   Evapotranspiraton = 85% of pan evaporation
   Cache R. area: average pan evaporation = 55 in ~1400 mm/yr
   Ground level evaporation E ~ 200 mm/yr = (0.2 m)(10000 m)
   = 2000 m^3/ha
   (2000 m^3/ha)(1573.5 ha) = 3,147,000 m^3
   = 3.15 E6 m^3/yr/swamp
   Canopy evapotranspiration (ET) = 1400 - 200 = 1200 mm/yr
   = (1.2 m/yr)(10000 m^2/ha) = 12000 m^3/ha/yr
   = (12000 m^3/ha/yr)(1573.5 ha) = 18.88 E6 m^3/yr/swamp
   = 1.47 E6 m^3/month

Appendix Table A1 (continued)

4. River flooding in the swamp

River water inflow is about 14 times the rainfall.
(Annual water budget for Black Swamp, Walton et al., 1996)
River inflow (~14)(1.96 E6 m^3) = 2.74 E7 m^3
Assumed = 3.0 E7 m^3/month

5. Runoff leaving the swamp

The flow needed to empty floodwaters in the swamp in a period of 4 to 6 months (flooding time).
Flows in = rainfall + river flooding
= 19.7 E6 m^3/yr + 89.24 E6 m^3/yr = 108.94 E6 m^3/yr
Flows out = evaporation + evapotranspiration + runoff
= 3.15 E6 m^3/yr + 18.88 E6 m^3/yr + runoff
Then Runoff = 108.94 E6 m^3/yr - 22.03 E6 m^3/yr
= 86.91 E6 m^3/yr = 7.25 E6 m^3/month
Assumed runoff for the calibration month (January)
= 8 E6 m^3/month.

6. Groundwater inflow

Groundwater draining to the alluvial water storage (A) found below the Black Swamp area assumed from the whole northwest zone of the Mississippi river valley alluvial aquifer (from its NW boundary to the east Crowley Ridge divide south to Black Swamp area), about 11,840 km^2 which represents 14.3% of the whole aquifer area.
Water budget estimated for the aquifer by Ackerman (1989)
Percent of the aquifer considered:
Flows in layer 1-whole aquifer-1178 cfs; NW zone-168.3 cfs
Flows in layer 3-whole aquifer-2065 cfs; NW zone-295 cfs
Total groundwater flowing into the storage (A) is 463.3 cfs
= 13.12 m^3/s = 413.77 E6 m^3/yr = 3.46 E7 m^3/month

Appendix Table A1 (continued)

7. Alluvial water storage
   The alluvial aquifer groundwater storage (A) was calculated as the volume of the water of the Mississippi River valley alluvial aquifer stored below the Black Swamp area. This volume was estimated from the average depth (30.45 m) and the average porosity (0.30) (Ackerman, 1989).
   Therefore: volume = (depth)(porosity)(area)
   = (30.45 m)(0.30)(10,000 m^2/ha) = 91350 m^3/ha
   = (91350 m^3/ha)(1573.5 ha/swamp) = 1.44 E8 m^3/swamp

8. Groundwater contribution to swamp
   Water flow calibrated from swamp to the aquifer during wet periods and from the aquifer to swamp in dry periods of late summer. Flow from swamp to the aquifer:
   = 5.0 E5 m^3/month (about 25% of rainfall)

9. Groundwater out of the alluvial storage (A) calculated as the water to balance other flows going in and out of the storage.
   Groundwater flow in = 3.46 E7 m^3/month + 5 E5 m^3/montth
   = 3.46 E7 m^3/month

10. Cache River flow into the Black Swamp (Jc)
    Average flow at Patterson (upstream gauging station)
    = 1000 cfs = 28.32 m^3/s
    Annual flow = (28.32 m^3/s)(365)(24)(3600 s/yr)
    = 8.93 E8 m^3/yr (7.44 E7 m^3/yr)

11. The inflow river was oscillated according to the equation:
    Jc = (J0 + J1)(sin ((t+13)(0.523))
    J0 = 1.2 E8 m^3/month and J1 = 5 E7 m^3/month

12. Storage of plant biomass (B) of riverine forest ranges from 100 to 300 ton/ha (Brinson, M.M., 1990). Standing biomass for bottonland forest at Black Swamp assumed 250 ton/ha.
    Total biomass = (standing biomass/ha)(area, ha)
    = (250 ton/ha)(1573.5 ha) = (393375 ha) = 3.93 E5 ha

Appendix Table A1 (continued)

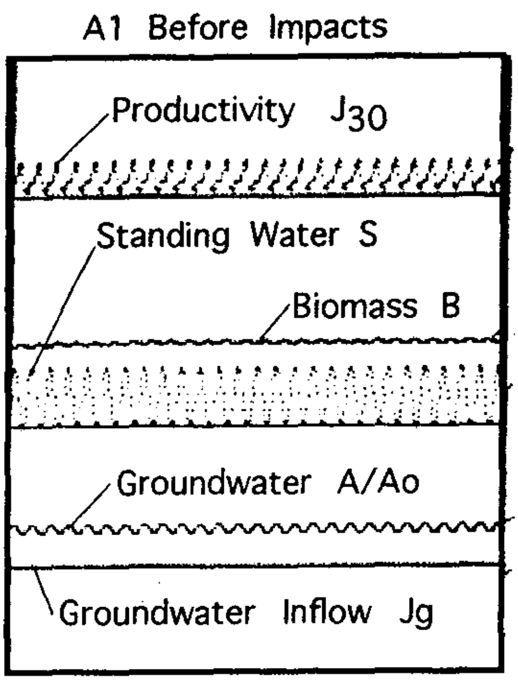
13. Gross production of biomass
    Net production in riverine forest like the Black Swamp
    13.5 ton/ha/yr, where litterfall is about 5.5 ton /ha/yr
    (Brinson, M.M., 1990). Respiration about 70% of gross
    production; net production about 30%; gross production
    = (13.5 ton/ha/yr)/0.3 = 45 ton/ha/yr
    (45 ton/ha/yr)(1573.5 ha) = 70807.5 ton/yr
    = 7.1 E4 ton/swamp = 5900 ton/month

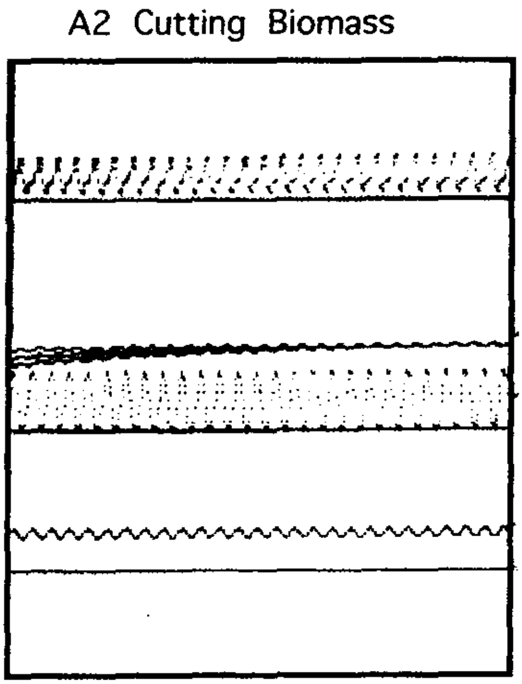
14. Biomass used in feeding back into production (Figure 13b)
    Net production of litterfall of riverine forest
    = (5.5 ton/ha/yr)(1573.5 ha/swamp) = 8654.25 ton/yr
    = 8.65 E3 ton/yr/swamp (720 ton/month)

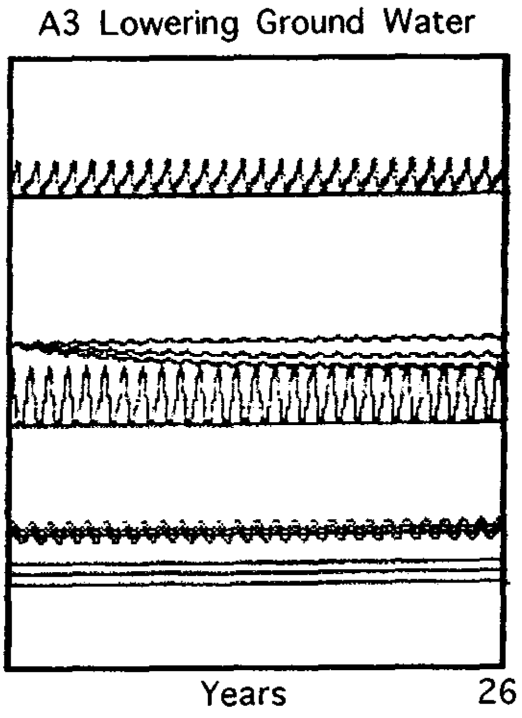
15. Net production to consumers equal the remaining net production
    (woody production - 8.0 ton/ha/yr)
    (8.0 ton/ha/yr)(1573.5 ha/swamp) = 12588 ton/yr/swamp
    = 1.26 E4 ton/yr/swamp (1050 ton/month).

16. Biomass production used by respiration about 70% of the gross
    production = (45 ton/ha/yr)(0.70)(1573.5 ha/swamp)
    = 49,565 ton/yr/swamp = 4130 ton/month

17. Sunlight: assumed forty percent of incident sunlight used by the
    trees. However, production of the tree biomass proportional to
    the 60% unused remainder (Lr) (Odum, H.T.,1983).
    Sunlight varied during the year with a sine function
    $L = (1 + 0.5)(\sin((t + 8)(0.523))$







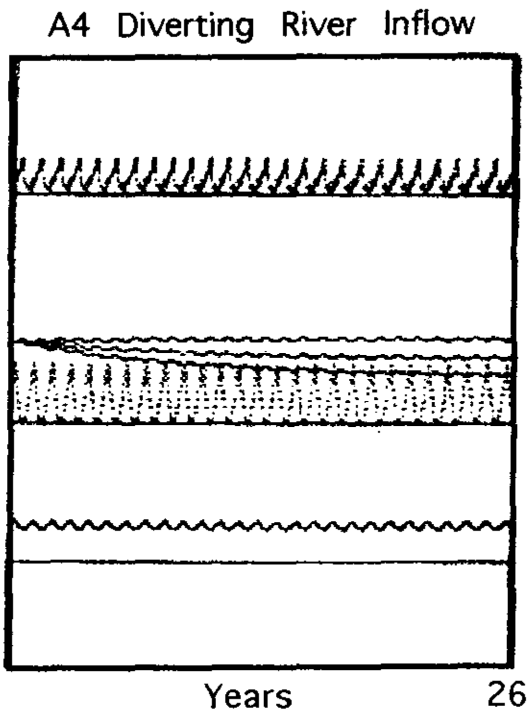
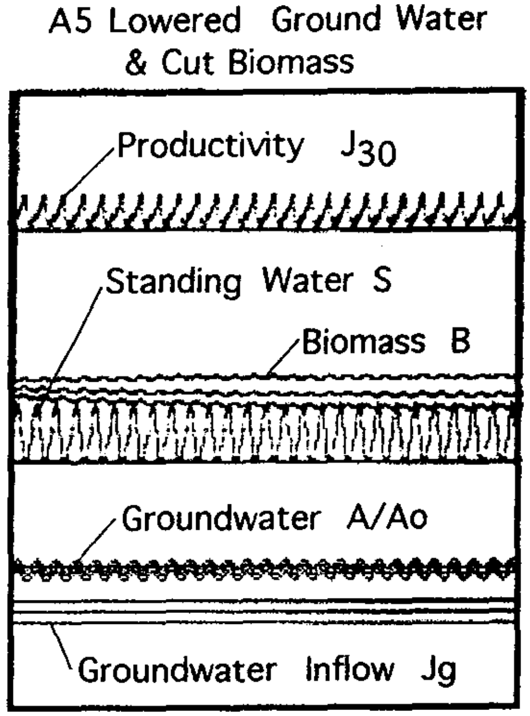


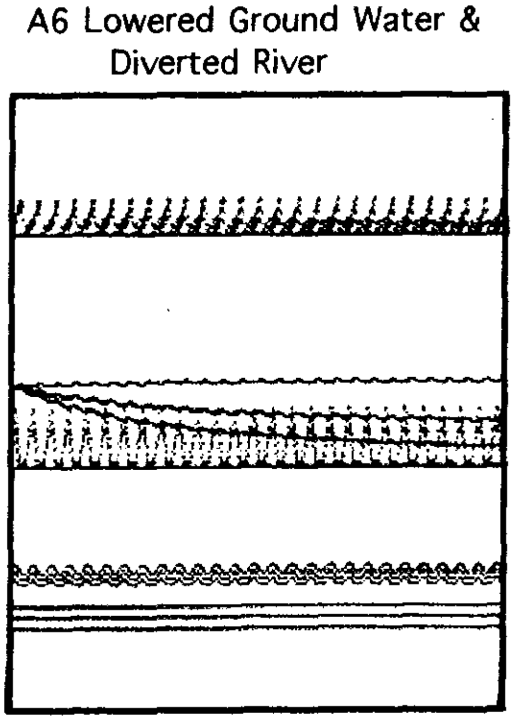
Figure A1. Simulation of the groundwater model with calibration conditions before impact.

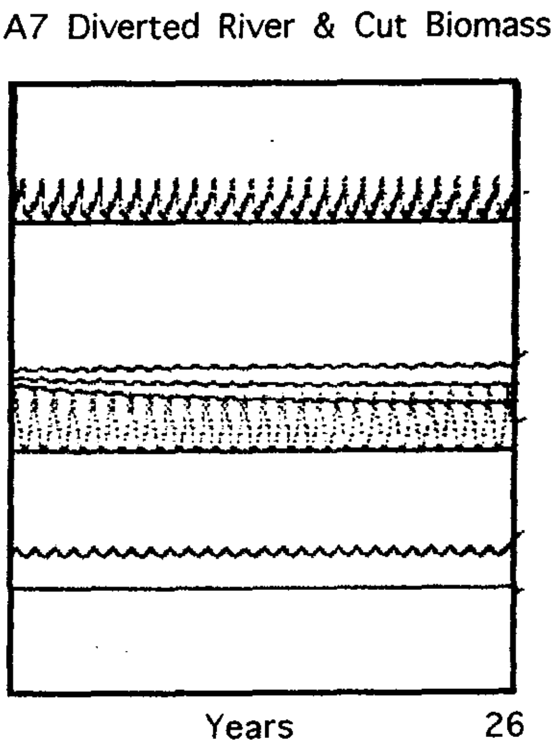
Figure A2. Impacts of cutting Biomass.

Figure A3. Impacts of lowering groundwater.

Figure A4. Impacts of diverting the river inflows.







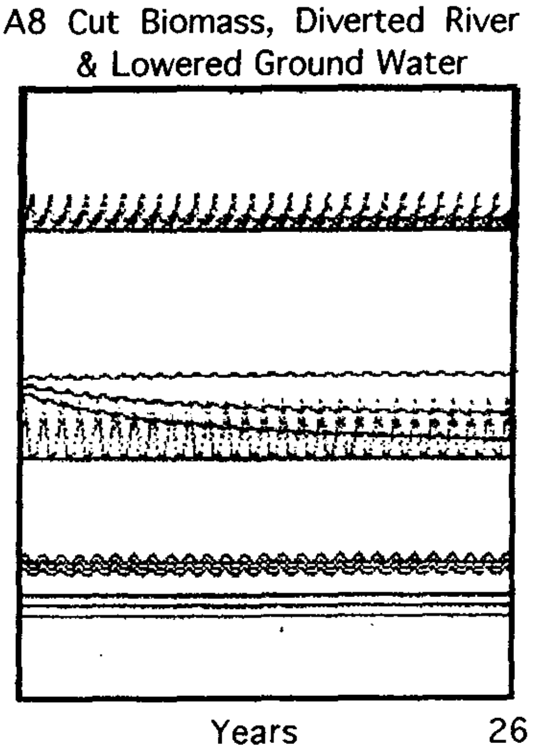


Figure A5. Cumulative impacts of lowering groundwater and cutting biomass.

Figure A6. Cumulative impacts of lowering groundwater and diverting river inflow.

Figure A7. Cumulative impact of cutting biomass and diverting river inflow.

Figure A8. Cumulative impacts of lowering groundwater, diverting river and cutting biomass.

Table A2
Calibration Values for the Water Simulation Model for the Black Swamp

Expression	Value	Coefficient	Value
R =	1.96 E6		
Jc* =	1.58 E8		
Jc1 =	3.94 E7		
Jg =	3.45 E7		
Lr =	0.6		
Jr =	1.36 E8		
S1 =	1.57 E7		
A =	1.44 E8		
B =	3.15 E5		
S =	5.00 E6		
A1 =	1.57 E7		
h0 =	2.00 E-1		
h1 =	9.12		
k1*A =	3.46 E7	k1 =	2.41 E-1
k3*S =	8.00 E6	k3 =	1.60 E0
k4*((Jc/Jc1)-2.0)) =	3.00 E7	k4 =	1.49 E7
k5*(((S/S1)-h0))-((A/A1)-h1))=	5.00 E5	k5 =	5.84 E6
k6*S =	2.625 E5	k6 =	5.25 E-2
k7*Lr*S*B =	1.47 E6	k7 =	1.56 E-6
k11*Lr*S*B =	0.4	k11 =	4.23 E-13
k30*Lr*S*B =	5900	k30 =	6.24 E-9
k31*Lr*S*B =	720	k31 =	7.62 E-10
k32*B =	4130	k32 =	1.31 E-2
k33*B =	1050	k33 =	3.33 E-3

Appendix Table A3
Black Swamp Water Simulation Program in BASIC

```
10 REM BSWF Calibrated without impacts
20 CLS
30 SCREEN 12
40 LINE (0, 0)-(319, 400), 3, B
41 LINE (0, 240)-(319, 240)
42 LINE (0, 90)-(319, 90)
45 REM OPEN "C:\excel\bswpre.dat" FOR OUTPUT AS #1
50 REM SCALING FACTORS
55 t = 0
60 DT = .5
70 S0 = 500000
80 B0 = 6000
85 A0 = 10000000
90 JG0 = 500000
91 JC0 = 2000000!
100 R0 = 500000
101 t0 = 1
102 L0 = .1
103 j40 = 500
110 REM INITIAL QUANTITIES
120 R1 = 1604671
125 R2 = 397671
135 Jc1 = 3.94E+07
136 J0 = 1.2E+08
137 J1 = 5E+07
140 JG = 3.45E+07
150 A = 1.444E+08
155 A1 = 1.57E+07
160 S = 5000000!
161 S1 = 1.57E+07
162 h0 = .2
165 h1 = 9.12
170 B = 315000
220 REM COEFFICIENTS
230 K1 = .241
240 K3 = 1.6
250 k4 = 1.49E+07
260 K5 = 5480000!
270 k6 = .0525
280 K7 = 1.56E-06
310 K11 = 4.23E-13
360 K30 = 6.24E-09
370 K31 = 7.62E-10
375 k32 = .013111
376 k33 = .003333
380 REM EQUATIONS
383 Jc = J0 + J1 * SIN((t + 13) * .523)
384 L = 1! + .5 * SIN((t + 8) * .523)
392 Js = k4 * ((Jc / Jc1) - 2!)
393 IF Js < 0 THEN Js = 0
```

Appendix Table A3 (continued)

```
395 R = R1 + R2 * SIN(t * .523)
400 Lr = L / (1 + K11 * S * B)
401 J5 = K5 * (((S / S1) - h0) - ((A / A1) - h1))
402 J7 = K7 * Lr * S * B
403 J3 = K3 * S
404 J11 = K11 * Lr * S * B
410 DA = JG - (K1 * A) + K5 * (((S / S1) - h0) - ((A / A1) - h1))
420 DS = R + Js - k6 * S - K7 * Lr * S * B - K3 * S - J5
430 DB = K30 * Lr * S * B - K31 * Lr * S * B - k32 * B - k33 * B
431 J30 = K30 * Lr * S * B
432 J32 = k32 * B
440 REM CHAngING EQUATIONS
450 A = A + DA * DT
455 IF A < 0 THEN A = 0
460 S = S + DS * DT
465 IF S < 0 THEN S = 0
470 B = B + DB * DT
475 IF B < 0 THEN B = 0
480 REM PRINT #1, USING "############.##"; R; L; Jc; S; S / S1; B; Js; J5; J7; J3;
J30; J32; A; A / A1; J11
490 REM PLOTTING EQUATIONS
500 PSET (t / t0, 400 - A / A1 * 10), 3
510 PSET (t / t0, 240 - S / S0), 2
520 PSET (t / t0, 240 - B / B0), 1
525 PSET (t / t0, 90 - J30 / j40), 3
526 PSET (t / t0, 400 - JG / JG0), 2
528 REM PRINT j5
530 t = t + DT
540 IF t / t0 < 320 GOTO 380
```

Appendix B
Calculation of Transformities

Transformities of Global Water Flows

Global chemical potential fresh water flows transformities were estimated following the same rationale that was applied for H.T. Odum (1996) in calculating transformities for other Earth processes (such as wind, rain, streams, waves, etc.). It is understood is that all these Earth processes are interdependent of each other and they require the whole empower budget contributing to the Earth (9.44 E24 sej/yr) to operate each individual process. As aggregated in Figure B1a, all the fresh water pathways are necessary to the global system and thus are coproducts of the total geobiospheric system.

A global water budget done by L'vovich, 1974 (in Gleick, 1993) was used to identify the average annual water flows in the pathways. According to the data, the global average flows are: Precipitation- 110,305 km^3/yr, evaporation- 71,475 km^3/yr, groundwater runoff- 11,885 km^3/yr, and surface water runoff- 26,945 km^3/yr (Figure B1b).

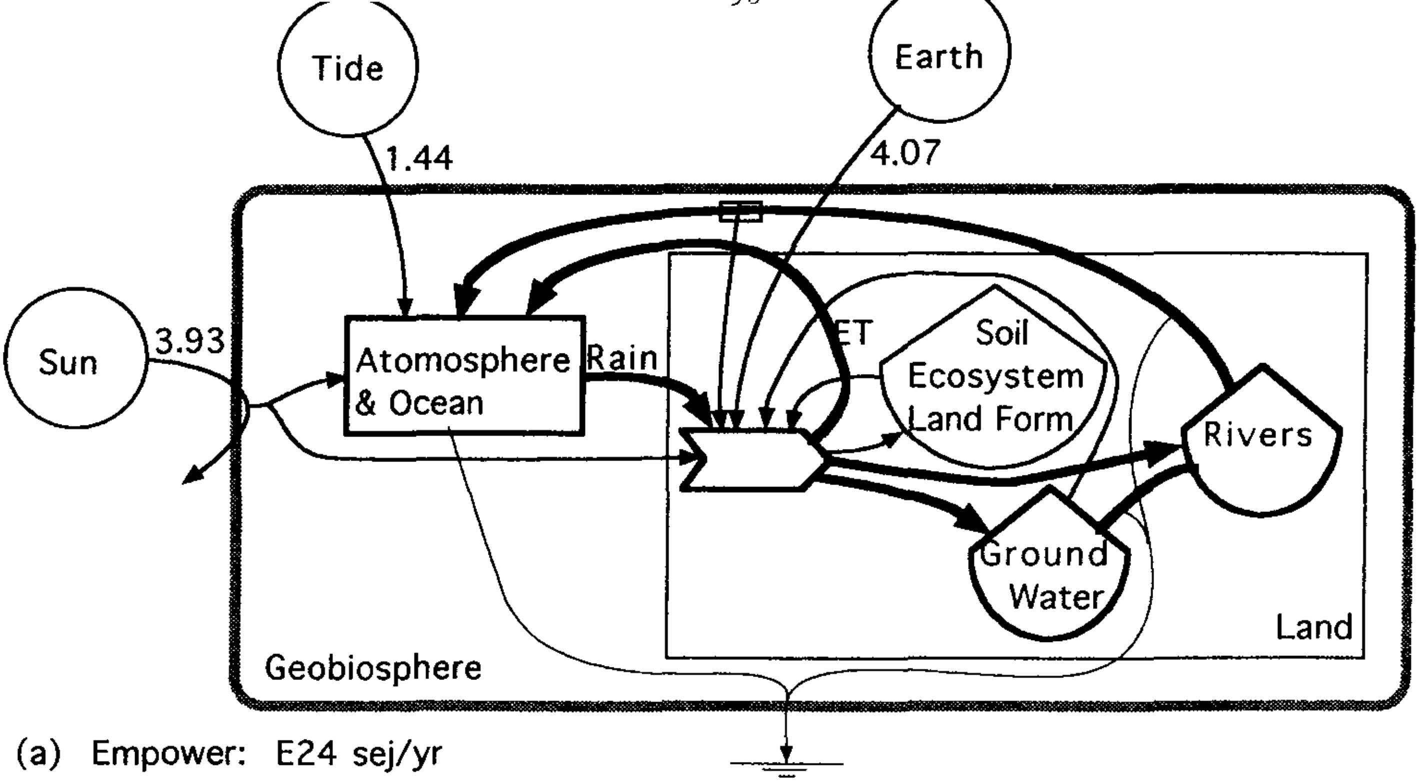
The chemical potential energy of the water flows was then calculated from the volume flows using the following equations:
Evapotranspiration (J/yr) = (m^3/yr)(1 E6 g/m^3)(Gibbs Free Energy, 4.94 J/g)
River flows (J/yr) = (volume/yr)(1 E6 g/m^3)(Gibbs Free Energy, 4.93 J/g)
Groundwater (J/yr) = (m^3/yr)(1 E6 g/m^3)(Gibbs free energy, 4.89 J/g).

The Gibbs Free Energy in the flows was estimated considering the free energy of the fresh water relative the to salty ocean water (Figure B2c). Concentrations of dissolved solids were assumed to be about 5 mg/l for precipitated/evaporated water, around 150 mg/l for river waters and around 342 mg/l for the groundwater (Lee and Fetter, 1994).

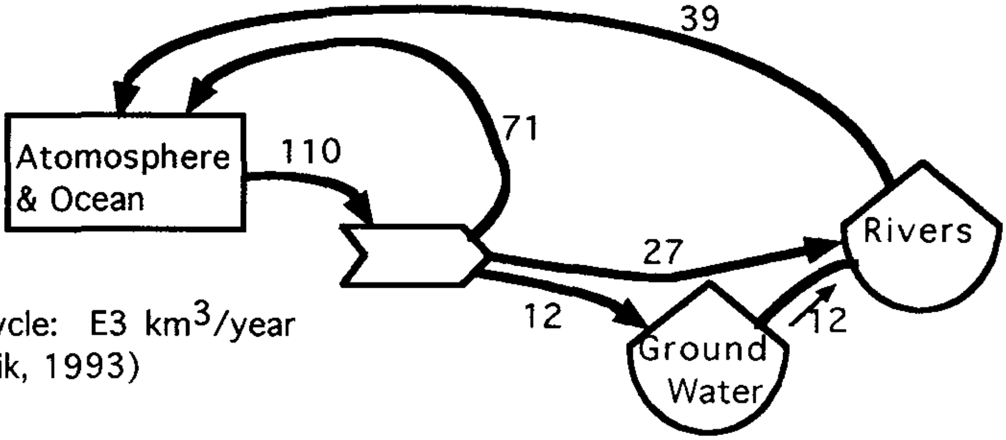
Transformities were calculated as emergy divided by energy.
Evapotranspired rain = (9.44 E24 sej/yr)/(3.53 E20 J/yr) = 26,735 sej/J

River waters = (9.44 E24 sej/yr)/(1.88 E20 J/yr) = 48,850 sej/J

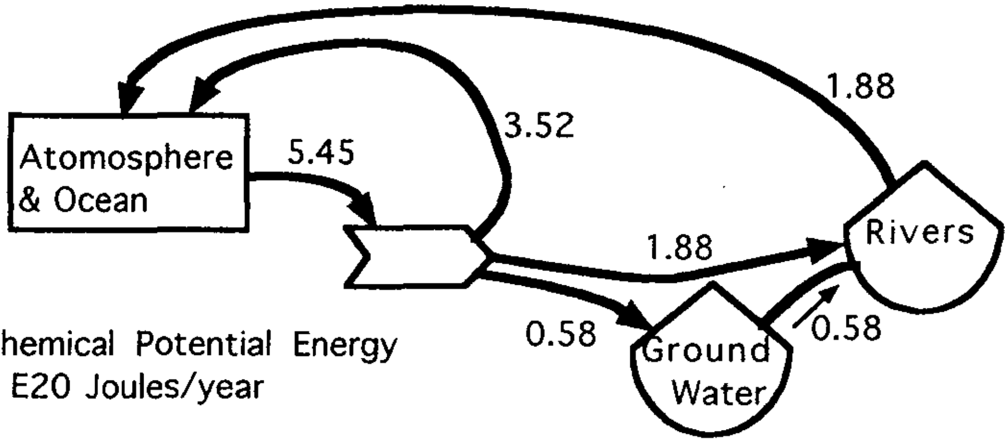
Groundwater = (9.44 E24 sej/yr)/(5.82 E19 J/yr) = 162,165 sej/J



(a) Empower: E24 sej/yr



(b) Global Water Cycle: E3 km^3/year
by L'vovic (Gleik, 1993)



(c) Flow of Chemical Potential Energy of Water: E20 Joules/year

Figure B1. Diagram of global hydrology for evaluating transformities. (a) Global emergy basis; (b) global water flows from L'vovich (1974); (c) energy flows.

Transformities of Migrant Birds

Preliminary transformities of migrant birds were estimated by estimating the emergy required to support the birds in a hectare of northern nesting area in summer (Hubbard Brook, New Hampshire) and a winter support area in Florida. Energy flows in the birds were estimated from respiration rates. See Appendix Table B1.

Transformities for Agricultural Commodities

Transformities for agricultural products rice, soybeans, wheat, sorghum, corn, and broiler chickens were evaluated in Appendix Tables B2-B7. The emergy signatures of these inputs to each of these production processes are shown in graphical form in Figures B2-B7.

Appendix Table B1
Emergy of a Migrant Bird

Note	Item	Emergy use sej	Energy use J	Transformity sej/J
1	Bird inWinter months	2.49 E13		
2	Bird in Summer months	2.60 E13		
3	Annual Support	5.09 E13	5.27 E7	9.7 E5

1. Chemical potential energy of rain transpiration per hectare in 6 months as approximation for ecosystem productivity in southern wintering area: Rainfall = 140 cm/yr; 35% in fall and winter
Transpiration = 75% of rainfall; Seasonal transpiration
= (140 cm/yr)(0.35/season)(0.75 transpired) = 0.37 m/season
Energy = (0.37 m/season)(1 E4 m^2/ha)(1 E6 g/m^3)(4.94J/g)
= 1.83 E10 J/6 months
Emergy support per bird the product of energy use and the solar transformity of rain over land, multiplied by 43% going into migrants, and divided by 5.75 birds/ha
(1.83 E10 J/yr)(1.82 E4 sej/J)(0.43)/5.75 = 2.49 E13 sej/6 mo/bird

2. As in note #1 except with data for summer months using data from Hubbard Brook, New Hampshire: Energy =
(130 cm rain/yr)(0.40 transp/season)(1 E8 cm^2/ha)(4.94 J/g)
= 2.57 E10 J/ha/season; Emergy =
(2.57 E10 J/6 mo)(1.82 E4 sej/J)(0.84 migrants)/(15 birds/ha)
= 2.6 E13 sej/6 months/bird

3. Annual emergy basis per migrant bird sum of winter and summer.
Bird energy used from annual respiration:
63% of annual consumption of bird 9.5 g
Energy = (annual respiration per bird)(5.6 kcal/dry wt)(4186 J/kcal)

Appendix Table B2
Emergy Evaluation of Rice Production
Annual Rates per Hectare

Note	Items	Data unit/yr	Emergy/Unit sej/J	Emergy E13 sej/yr
1	Sun, J	1.05 E13	1	1
2	Rain transpired, J	1.48 E10	1.82 E4	27
3	Soil used up, J	9.92 E8	6.30 E4	6
4	Groundwater	3.72 E10	1.60 E5	596
5	Fuel	1.35 E10	6.60 E4	89
6	Machinery, oil equiv.	2.87 E8	6.60 E4	2
7	Pesticide, oil equiv.	3.97 E9	6.60 E4	26
8	Nitrogen	2.92 E8	1.90 E6	55
9	Potassium	2.36 E7	3.00 E6	7
10	Seed, oil equiv.	2.63 E9	6.60 E4	17
11	Electricity	3.78 E9	1.70 E5	64
12	Service, US $ 1977	730	4.40 E12	321
13	Rice production	6.95 E10		1211
14	Transformity		1.76 E5 sej/J	

Footnotes
Data on rice plantation at Grand Prairie, AR, (Pimentel, 1980, p. 95)

1. Solar insolation = 1.00 E6 kcal/m^2/yr
Growing season = 3 months = 0.25 yr
(1 E6 kcal/m^2/yr)(1 E4 m^2/ha)(0.25 yr)(4186 kcal/J)
= 1.05 E13 J/yr

2. Transpiration Energy = (3000 m^3/yr)(1 E6 g/m^3)(4.94 J/g)
= 1.48 E10 J/yr

3. Soil used up assumed 10 ton/ha/yr (as in Odum, 1996)
Organic Fraction = 0.44% of dry matter
Energy = (weight)(0.0044 org)(5.4 kcal/J)(4186 J/kcal)
= 9.95 E8 J/yr

Footnotes for Appendix Table B2 (continued)

4. Groundwater irrigation = 0.76 m/ha = 7600 m^3/yr
Chemical potential energy
= (7600 m^3/yr)(1 E6 g/m^3)(4.90 J/g) = 3.72 E10 J/yr

5. Fuel (Pimentel, 1980): Gasoline 8.70 E5 + Diesel 2.34 E6 kcal/ha
Energy = (3.21 E6 kcal)(4186 J/kcal) = 1.35 +10 J/yr

6. Machinery (embodied fuel in the machinery, Pimentel 1980)
Energy = (6.86 E5 kcal)(4186 J/kcal) = 2.87 E8 J/yr

7. Pesticide
1.1 kg of 2,4,5-T =1.10 E5 kcal/ha
4.5 kg propanil = 4.50 E5 kcal/ha
3.4 kg molinate = 2.94 E5 kcal/ha
Total 9.50 E5 = kcal/ha
Energy = (9.5 E5)(4186 J/kcal) = 3.97 E9 J/yr

8. Nitrogen fertilizer = 134.5 kg/ha
Chemical potential = 2.17 E6 J/kg
Energy = (134.5 kg/yr)(2.17 E6 J/kg) = 2.92 E8 J/yr

9. Potassium fertilizer = 33.6 kg/ha
Chemical potential = 702 J/g
Energy = (33.6 E3 g/yr)(702 J/g) = 2.36 E7 J/yr

10. Seed 156.9 kg; embodied fuel 6.28 E5 kcal/ha
Energy equivalent: (6.28 E5 kcal/yr)(4186 J/kcal) = 2.63 E9 J/yr

11. Electricity in irrigation fuel 0.76 m/ha pumped up 38.1 m
Energy = (7600 m3)(38.1 m)(9.8 m/s^2)(1000 kg/m^3)/(0.75 eff.)
= 3.78 E9 J/yr

12. Service as price = 7.02 $/Cwt (CYB, 1978) = $ 0.154 $/kg
(4742 kg production)(0.154 $/kg) = $730

13. Production = 4742 kg/ha
Energy = (4.72 E6 g)(3.5 kcal/g)(4186 J/kcal) = 6.95 E10 J/yr

14. Transformity = (1.22 E16 sej/yr)/(6.95 E10 J/yr) = 1.76 E5 sej/J

Appendix Table B3
Emergy Evaluation of Soybean Production
Annual Rates per Hectare

Note	Items	Data unit/yr	Emergy/Unit sej/J	Emergy E13 sej/yr
1	Sun, J	1.05 E13	1	1
2	Rain transpired, J	1.48 E10	1.82 E4	27
3	Soil used up, J	9.92 E8	6.30 E4	6
4	Groundwater	1.47 E10	1.60 E5	235
5	Fuel	3.60 E9	6.60 E4	24
6	Machinery, oil equiv.	8.81 E8	6.60 E4	6
7	Pesticide, oil equiv.	1.29 E9	6.60 E4	9
8	Phosphate	1.56 E6	1.00 E7	2
9	Nitrogen	1.22 E7	1.90 E6	2
10	Seed, oil equiv.	2.45 E9	6.60 E4	16
11	Electricity	1.49 E9	1.70 E5	25
12	Service, US $ 1977	5.85 E2	4.40 E12	257
13	Soybean production	3.73 E10		609
14	Transformity		1.62 E5 sej/J	

Footnotes
Data on irrigated soybean plantation in Nebraska (Pimentel, 1980 p. 120)

1. Solar insolation = 1 E6 kcal/m^2/yr
Growing season = 3 months = 0.25 yr
(1 E6 kcal/m^2/yr)(1 E4 m^2/ha)(0.25 yr)(4186 kcal/J)
= 1.05 E13 J/yr

2. Transpiration Energy = (3000 m^3/yr)(1 E6 g/m^3)(4.94 J/g)
= 1.48 E10 J/yr

3. Soil used up assumed 10 ton/ha/yr (as in Odum, 1996)
Organic Fraction = 0.44% of dry matter
Energy = (weight)(0.0044 org)(5.4 kcal/J)(4186 J/kcal)
= 9.95 E8 J/yr

Footnotes for Appendix Table B3 (continued)

4. Groundwater irrigation = 3000 m^3/yr
   Chemical potential energy
   = (3000 m^3/yr)(1 E6 g/m^3)(4.90 J/g) =1.47 E10 J/yr

5. Fuel (Pimentel, 1980)
   Gasoline 2.43 E5 kcal + Diesel 6.16 E5 kcal
   Energy = (8.59 E5 kcal)(4186 J/kcal) = 3.6 E9 J/yr

6. Machinery (embodied fuel, Pimentel, 1980)
   11.7 kg/ha = 2.10 E5 kcal/ha
   Energy = (2.10 E5)(4186 J/kcal) = 8.81 E8 J/yr

7. Herbicide (embodied fuel, Pimentel, 1980)
   3.08 kg/ha = 3.08 E5 kcal/ha
   Energy = (3.07 E6)(4186 J/kcal) = 1.29 E9 J/yr

8. Phosphate application = 4490 g/ha
   Chemical Potential = 348 J/g
   Energy = (4490 g/yr)(348 J/g) = 1.56 E6 J/yr

9. Nitrogen Application = 5.61 kg/ha
   Chemical Potential = 2.17 E6 J/kg
   Energy = (5.61 kg/yr)(2.17 E6 J/kg) = 1.22 E7 J/yr

10. Seed Quantity = 73.2 kg; embodied fuel = 5.86 E5 kcal/ha
    Energy used (5.86 E5 kcal/yr)(4186 J/kcal) = 2.45 E9 J/yr

11. Irrigation electricity as fuel = 1.62 E6 kcal/ha
    Assumption: 0.30 m water/ha pumped 38.1 m; efficiency = 0.75
    Energy =
    (3000 m^3)(38.1m)(9.8 m/s^2)(1000 kg/m^3)/0.75 = 1.49 E9 J/yr

12. Service producing 2210 kg; price = 721 $/bushel (CYB, 1978)
    7.21 $/27.24 kg = 0.265 $/kg
    (2210 kg)(0.265 $/kg) = 585.65 $/ha

13. Production = 2210 kg
    Energy = (2.21 E6 g/yr)(4.03 kcal/g)(4186 J/kcal) = 3.73 E10 J/yr

14. Transformity = (6.09 E15 sej)/(3.73 E10) = 1.62 E5 sej/J

Appendix Table B4
Emergy Evaluation of Wheat Production
Annual Rates per Hectare

Note	Items	Data unit/yr	Emergy/Unit sej/J	Emergy E13 sej/yr
1	Sun, J	1.05 E13	1	1
2	Rain transpired, J	1.48 E10	1.82 E4	27
3	Soil used up, J	9.92 E8	6.30 E4	6
4	Groundwater	1.76 E10	1.60 E5	282
5	Fuel	4.98 E10	6.60 E4	329
6	Machinery, oil equiv.	1.32 E9	6.60 E4	9
7	Pesticide, oil equiv.	1.79 E8	6.60 E4	1
8	Phosphate	3.9 E5	1.00 E7	0.39
9	Nitrogen	1.95 E8	1.90 E6	37
10	Seed, oil equiv.	9.11 E8	6.60 E4	6
11	Electricity	1.79 E9	1.70 E5	30
12	Service, US $ 1977	2.60 E2	4.40 E12	115
13	Wheat production	3.81 E10		843
14	Transformity		2.21 E5	

Footnotes

Data on irrigated wheat in Kansas (Pimentel, 1980, p. 111)

1. Solar insolation = 1.00 E6 kcal/m^2/yr
   Growing season = 3 months = 0.25 yr
   (1 E6 kcal/m^2/yr)(1 E4 m^2/ha)(0.25 yr)(4186 kcal/J)
   = 1.05 E13 J/yr

2. Transpiration Energy = (3000 m^3/yr)(1 E6 g/m^3)(4.94 J/g)
   = 1.48 E10 J/yr

3. Soil used up assumed = 10 ton/ha/yr (as in Odum, 1996)
   Organic Fraction = 0.44% of dry matter
   Energy = (weight)(0.0044 org)(5.4 kcal/J)(4186 J/kcal)
   = 9.95 E8 J/yr

Footnotes for Appendix Table B4 (continued)

4. Groundwater irrigation = 0.36 m/ha = 3600 m^3/yr
Chemical potential energy
= (3600 m^3/yr)(1 E6 g/m^3)(4.90 J/g) = 1.76 E10 J/yr

5. Fuel (Pimentel, 1980)
Gasoline 3.52 E5 kcal/ha; Diesel 5.65 E5 kcal/ha;
Nat gas 1.10 E7 kcal/ha
Energy = (1.19 E7 kcal)(4186 J/kcal) = 4.98 E10 J/yr

6. Machinery (embodied energy in the machinery, Pimentel 1980)
17.5 kg/ha = 3.16 E5 kcal/ha
Energy = (3.16 E5 kcal/ha)(4186 J/kcal) = 1.32 E9 J/yr

7. Pesticide embodied fuel energy
0.22 kg herbicide 2.20 E4 kcal/ha; 0.24 kg insecticide 2.09 E4 kcal/ha
Energy = (4.28 E4 kcal/ha)(4186 J/kcal) = 1.79 E8 J/yr

8. Phosphate = 1.12 kg/ha; Chemical potential = 348 J/g
Energy = (1.12 E3 g/yr)(348 J/g) = 3.90 E5 J/yr

9. Nitrogen = 89.7 kg/ha; Chemical potential = 2.17 E6 J/kg
Energy = (89.7 kg/yr)(2.17 E6 J/kg) = 1.95 E8 J/yr

10. Seed embodied fuel energy
72.5 kg = 2.18 E5 kcal/ha
Energy used = (2.2 E5 kcal/yr)(4186 J/kcal) = 9.11 E8 J/yr

11. Irrigation electricity as fuel = 1.62 E6 kcal/ha
Assumption: 0.36 m water/ha pumped 38.1 m; efficiency = 0.75
Energy =
(3600 m^3)(38.1 m)(9.8 m/s^2)(1000 kg/m^3)/0.75 = 1.79 E9 J/yr

12. Services from production = 2600 kg; price = 2.73 $/bushel (CYB, 1978)
2.73 $/27.21 kg = 0.100 $/kg
(2600 kg/yr)(0.10 $/kg) = $260

13. Wheat Production
Energy = (2.6 E6 g)(3.5 kcal/g)(4186 J/kcal) = 3.81 E10 J/yr

14. Transformity = (8.43 E15 sej/yr)/(3.81 E10 J/yr) = 2.20 E5

Appendix Table B5
Emergy Evaluation of Sorghum Production
Annual Rates per Hectare

Note	Items	Data unit/yr	Emergy/Unit sej/J	Emergy E13 sej/yr
1	Sun, J	1.05 E13	1	1
2	Rain transpired, J	1.48 E10	1.82 E4	27
3	Soil used up, J	9.92 E8	6.30 E4	6
4	Fuel	2.99 E9	6.60 E4	20
5	Machinery, oil equiv.	5.27 E8	6.60 E4	3
6	Pesticide, oil equiv.	5.78 E8	6.60 E4	4
7	Phosphate	1.18 E6	1.00 E7	1
8	Nitrogen	8.20 E7	1.90 E6	16
9	Potassium	6.31 E5	3.0 E6	1
10	Seed, oil equiv.	1.97 E8	6.60 E4	1
11	Service, US $ 1977	1.47 E2	4.40 E12	65
12	Sorghum production	3.81 E10		145
13	Sorghum Transformity		3.81 E4 sej/J	

Footnotes
Nonirrigated sorghum production in Kansas, (Pimentel, 1980, p.104)

1. Solar insolation = 1 E6 kcal/m^2/yr
Growing season = 3 months = 0.25 yr
(1 E6 kcal/m^2/yr)(1 E4 m^2/ha)(0.25 yr)(4186 kcal/J)
= 1.05 E13 J/yr

2. Transpiration energy = (3000 m^3/yr)(1 E6 g/m^3)(4.94 J/g)
= 1.48 E10 J/yr

3. Soil used up assumed 10 ton/ha/yr (as in Odum, 1996)
Organic Fraction = 0.44% of dry matter
Energy = (weight)(0.0044 org)(5.4 kcal/J)(4186 J/kcal)
= 9.95 E8 J/yr

Footnotes for Appendix Table B5 (continued)

4. Fuel (Pimentel, 1980)
Gasoline 2.05 E5 kcal/ha
Diesel 4.90 E5 kcal/ha
Lp gas 2.00 E4 kcal/ha
Energy = (7.15 E5 kcal)(4186 J/kcal) = 2.99 E9 J/yr

5. Machinery embodied fuel energy (Pimentel, 1980)
(126,000 J/ha)(4186 J/kcal) = 5.27 E8 J/yr

6. Pesticide
1.0 kg herb. = 8.90 E4 kcal/ha
0.6 kg insect. = 4.90 E4 kcal/ha
Energy = (1.38 E5)(4186 J/kcal) = 5.78 E8 J/yr

7. Phosphate = 3.4 kg/ha; Chemical potential = 348 J/g
Energy = (3.4 E3 g/yr)(348 J/g)) = 1.18 E6 J/yr

8. Nitrogen = 37.8 kg/ha; Chemical potential = 2.17 E3 J/g
Energy = (37.8 kg/yr)(2.17 E6 J/kg) = 8.20 E7 J/yr

9. Potassium = 0.9 kg/ha; Chemical potential = 702 J/g
Energy = (900 g/yr)(702 J/g) = 6.31 E5 J/yr

10. Seed = 3.4 kg
Embodied fuel energy = 4.70 E4 kcal/ha
Energy = (4.7 E4 kcal/yr)(4186 J/kcal) = 1.97 E8 J/yr

11. Services from production = 1840 kg and
Price = 3.62 $/cwt (CYB, 1978)
3.62 $/45.36 kg = 7.98 E-02 $/kg
(1840 kg)(7.98 E-2 $/kg) = 147 $

12. Sorghum Production = 2600 kg/ha/yr
Energy = (2.6 E6 g)(3.5 kcal/g)(4186 J/kcal) = 3.81 E10 J/yr

13. Transformity = (1.45 E15 sej/yr)/(3.81 E10) = 3.81 E4

Appendix Table B6
Emergy Evaluation of Corn Production
Annual Rates per Hectare

Note	Items	Data unit/yr	Emergy/Unit sej/J	Emergy E13 sej/yr
1	Sun, J	1.05 E13	1	1
2	Rain transpired, J	1.48 E10	1.82 E4	27
3	Soil used up, J	9.92 E8	6.30 E4	6
4	Fuel	6.82 E9	6.60 E4	45
5	Machinery, oil equiv.	4.14 E9	6.60 E4	27
6	Pesticide, oil equiv.	9.28 E8	6.60 E4	6
7	Phosphate	1.81 E7	7.70 E6	14
8	Nitrogen	2.68 E8	1.69 E6	45
9	Potassium	4.0 E7	2.62 E6	11
10	Seed, oil equiv.	1.29 E9	6.60 E4	9
11	Electricity	6.85 E7	1.70 E5	1
12	Service, US $ 1977	3.53 E2	4.40 E12	15
13	Corn production	5.72 E10		313
14	Transformity		5.95 E4 sej/J	

Footnotes
Data from corn plantation in Alabama (Pimentel, 1980, p. 80)

1. Solar insolation = 1.00 E6 kcal/m^2/yr
Growing season = 3 months = 0.25 yr
(1 E6 kcal/m^2/yr)(1 E4 m^2/ha)(0.25 yr)(4186 kcal/J)
= 1.05 E13 J/yr

2. Transpiration energy = (3000 m^3/yr)(1 E6 g/m^3)(4.94 J/g)
= 1.48 E10 J/yr

3. Soil used up assumed 10 ton/ha/yr (as in Odum, 1996)
Organic Fraction = 0.44% of dry matter
Energy = (weight)(0.0044 org)(5.4 kcal/J)(4186 J/kcal)
= 9.95 E8 J/yr

Footnotes for Appendix Table B6 (continued)

4. Fuel (Pimentel, 1980)
   Gasoline 7.01 E5 kcal/ha
   Diesel 7.85 E5 kcal/ha
   LP gas 1.42 E5 kcal/ha
   Energy = (1.63 E6 kcal)(4186 J/kcal) = 6.82 E9 J/yr

5. Machinery embodied fuel (Pimentel 1980)
   35.3 kg/ha 9.90 E5 kcal/ha
   Energy = (9.9 E5 kcal/ha)(4186 J/kcal) = 4.14 E9 J/yr

6. Pesticide embodied fuel energy (Pimentel, 1980)
   1.21 kg/ha = 1.21 E5
   1.16 kg/ha = 1.01 E5
   Energy = (2.22 E5 kcal/ha)(4186 J/kcal) = 9.28 E8 J/yr

7. Phosphorus = 52.1 kg/ha; Chemical potential energy = 348 J/g
   Energy = (52.1 kg/yr)(348 J/g) = 1.81 E7 J/yr

8. Nitrogen = 123.35 kg/ha; Chemical potential = 2.17 E6 J/kg
   Energy = (123.35 kg/yr)(2.17 E6 J/kg) = 2.68 E8 J/yr

9. Potassium = 57.18 kg/ha; Chemical potential = 702 J/g
   Energy = (5.72 E4 g/yr)(702 J/g) = 4.0 E7 J/yr

10. Seed = 12.3 kg
    Embodied fuel = 3.08 E5 kcal/ha
    Energy = (3.08 E5 kcal/yr)(4186 J/kcal) = 1.29 E9 J/yr

11. Electricity = 19.02 kwh/yr
    Energy = (19.0 kwh)(3.60 E6 J/kwh) = 6.85 E7 J/yr

12. Service from production = 3902 kg/yr and
    Price = 2.30 $/bushel (CYB, 1978)
    2.3 $/25.42 kg = 0.0904 $/kg
    (3902 kg/ha)(0.09$/kg) = 353 $/ha

13. Corn production = 3902 kg/ha
    Energy = (3.9 E6 g)(3.5 kcal/g)(4186 J/kcal) = 5.72 E10 J/y

14. Transformity = (3.40 E15)/(5.72 E10) = 5.95 E4 sej/J

Appendix Table B7
Emergy Evaluation of Poultry Broiler Production
Rates for 50,000 Broilers on One Hectare Raised in 3 Months

Note	Items	Data unit/yr	Emergy/Unit sej/J	Emergy E13 sej/yr
1	Sun, J	1.05 E13	1	1
2	Rain transpired, J	1.48 E10	1.82 E4	27
3	Soil used up, J	9.95 E8	6.30 E4	6
4	Groundwater	1.79 E10	1.70 E5	304
5	Fuel	2.66 E11	6.60 E4	1756
6	Machinery, oil equiv.	1.64 E10	6.60 E4	108
7	Ration, corn	1.35 E12	6.00 E4	8123
8	Ration, soybean	5.82 E11	1.60 E5	9283
9	Electricity	2.7 E10	6.60 E4	178
10	Buildings, oil equiv.	2.98 E11	6.60 E4	1968
11	Service, US $ 1977	8.02 E4	4.40 E12	35288
12	Broiler production	8.02 E11		57042
13	Transformity		7.11 E5	

Footnotes

Data for 1000 broilers (Pimentel, 1980)
1.5 square feet/bird = 0.139 m^2/bird (Nesheim et al., 1979)
Birds/ha = ((10,000)/0.14)(0.75) = 53571.43 birds/ha
Assumed 50,000 broiler per ha

1. Solar insolation = 1.00 E6 kcal/m^2/yr
Growing season = 3 months = 0.25 yr
(1 E6 kcal/m^2/yr)(1 E4 m^2/ha)(0.25 yr)(4186 kcal/J)
= 1.05 E13 J/yr

2. Evapotranspiration = 1.2 m^3/m^2/yr = 12000 m^3/yr
3 months growth = 3000 m^3/3 months
Energy = (volume)(1 E6 g/m^3)(4.94 J/g) = 1.48 E10 J/yr

Footnotes for Appendix Table B7 (continued)

3. Soil used = 10 ton/ha/yr (as in Odum, 1996)
Organic Fraction = 0.44% of dry matter
Energy = (1 E7 tonne/ha/yr)(0.0044 org)(5.4 kcal/J)(4186 J/kcal)
= 9.95 E8 J/yr

4. Groundwater = 20-380 l/day/1000 broilers
(100 l/day/thsd broilers)(365 d/yr)(100 thsd broilers)/1000 l/m^3
= (3650 m^3/yr)
Chemical potential or water used
= (3650 m^3/yr)(1 E6 g/m^3)(4.90 J/g) = 1.79 E10 J/yr

5. Fuel (Pimentel, 1980)
Propane = 1.27 E6 kcal/1000 broilers
6.36 E7 kcal/50,000 broilers
Energy = (6.36 E7 kcal)(4186 J/kcal) = 2.66 E11 J/yr

6. Machinery
Embodied fuel energy (Pimentel, 1980)
3.78 kg 7.81 E4 kcal/1000 broilers
3.91 E6 kcal/50,000 broilers
Energy = (3.91 E6)(4186 J/kcal) = 1.64 E10 J/yr

7-8. Broiler rations
3182 kg 9.24 E6 kcal/1000 broilers
4.62 E8 kcal/50,000 broilers
Assumed 70% corn and 30% soybean
(3.23 E8 kcal corn)(4186 J/kcal) = 1.35 E12 J/yr
(1.39 E8 kcal soybeans)(4186 J/kcal) = 5.82 E11 J/yr

9. Electricity is fuel: 1.288 E5 kcal/1000 broilers (Pimentel, 1980)
6.44 E6 kcal/50,000 broilers
Energy = (6.44 E6 kcal/ha)(4186 J/kcal) 2.7 E10 J

10. Building area = 69.7 m^2/1000 broiler (Pimentel, 1980)
Used = 100 m^2/1000 broiler; 5000 m^2/50,000 broilers
Embodied oil in buildings = 1.425 E6 kcal/1000 broilers
Energy = (7.13 E7 kcal/50 thsd broil/yr)(4186 J/kcal) = 2.98 E11 J/yr

Footnotes for Appendix Table B7 (continued)

11. Service with production = 90,000 kg
    Price (1977) = 0.405 $/lb (Commodity Year Book, 1978)
    0.405 $/0.454 kg = 0.892 $/kg
    (9.0 E4 kg)(0.892 $/kg) = 8.02 E4 $/yr

12. Broiler production:
    (50,000 broiler)(average weight 1.8 kg ea) = 90,000 kg
    Energy = (9 E7 g)(2.13 kcal/g)(4186 J/kcal) = 8.02 E11 J/yr

13. Transformity = (5.71 E17 sej)/(8.02 E11) = 7.11 E5

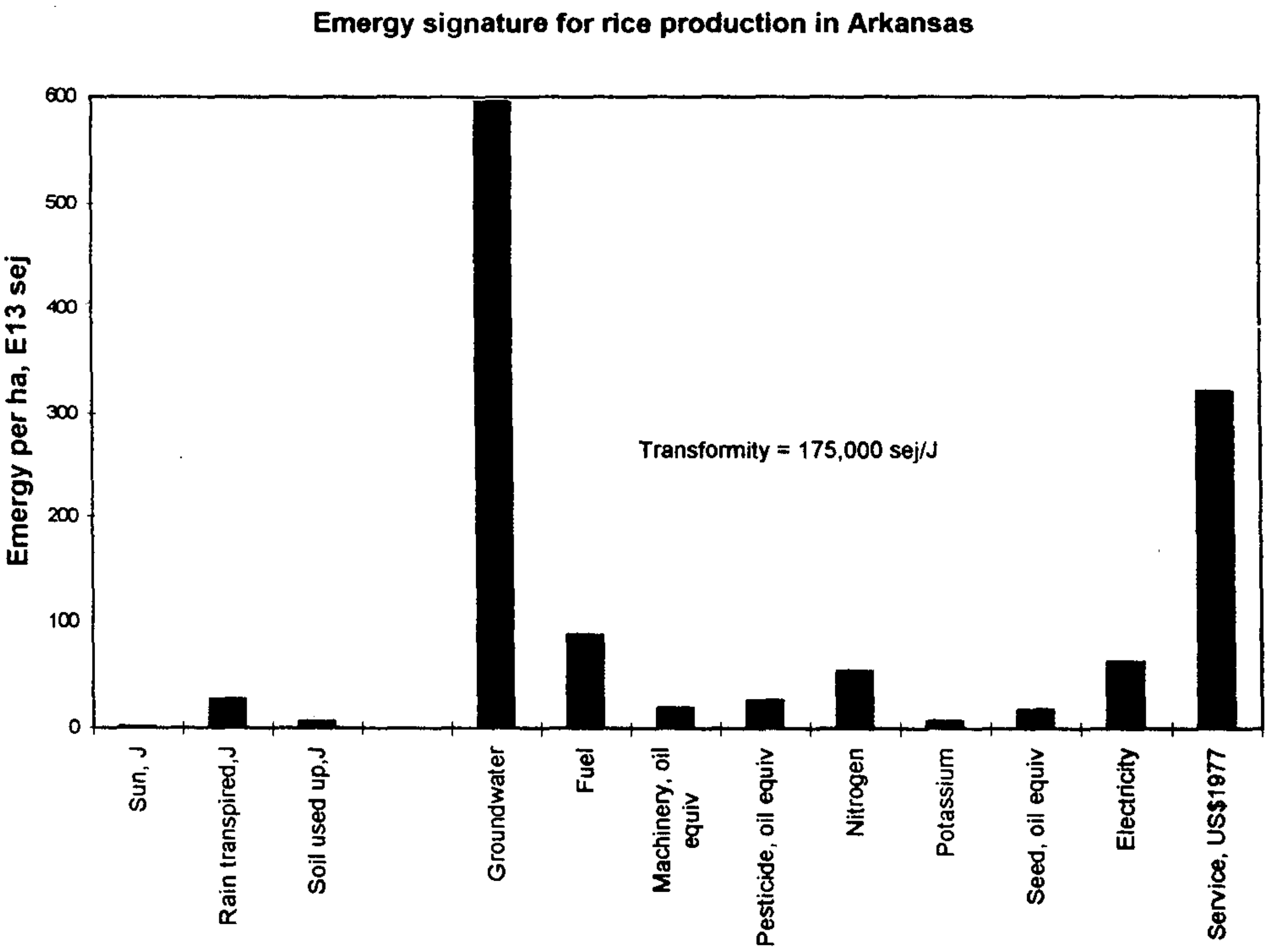


Figure B2. Emergy signature for rice production in Arkansas.

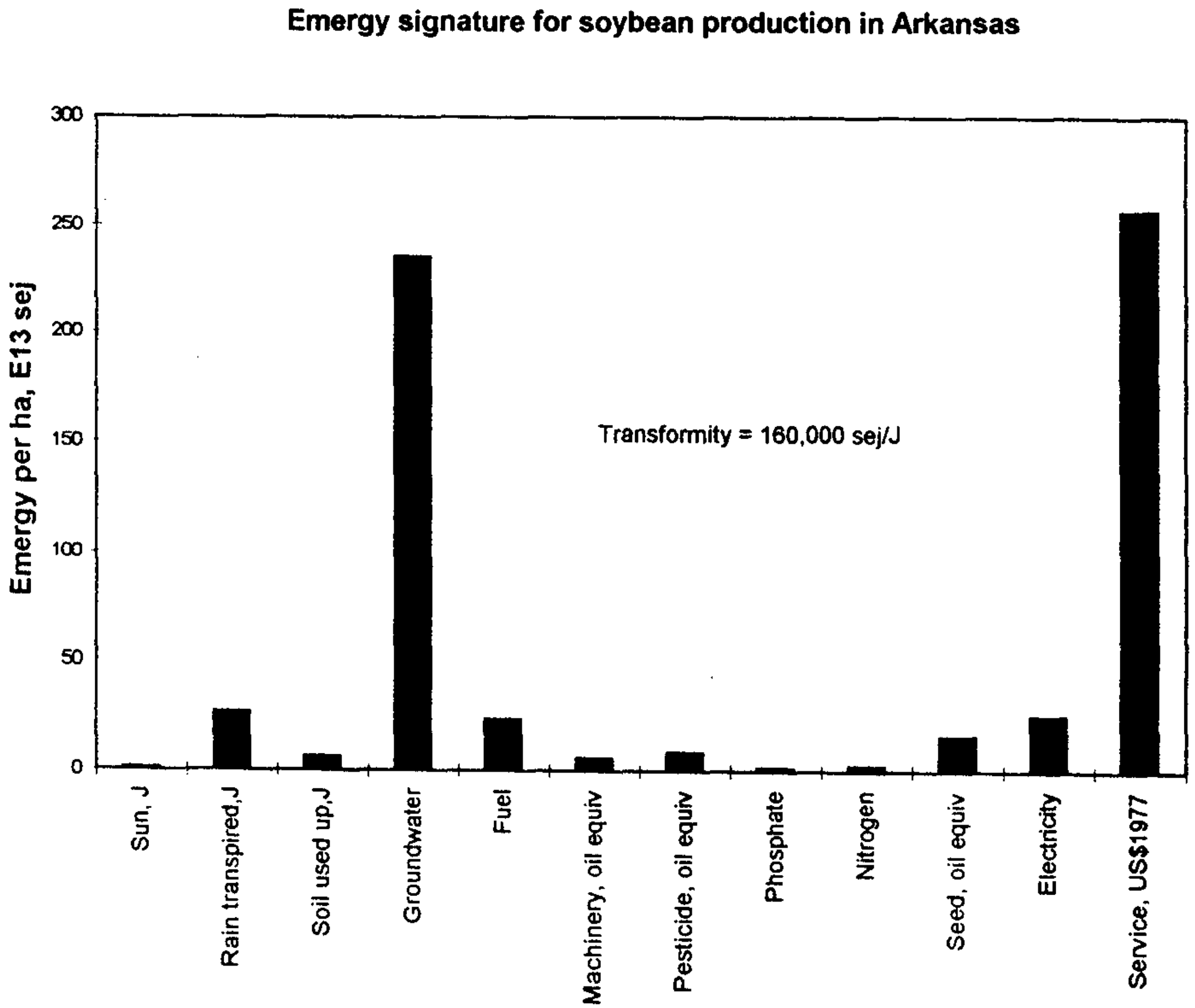


Figure B3. Emergy signature for soybean production in Arkansas.

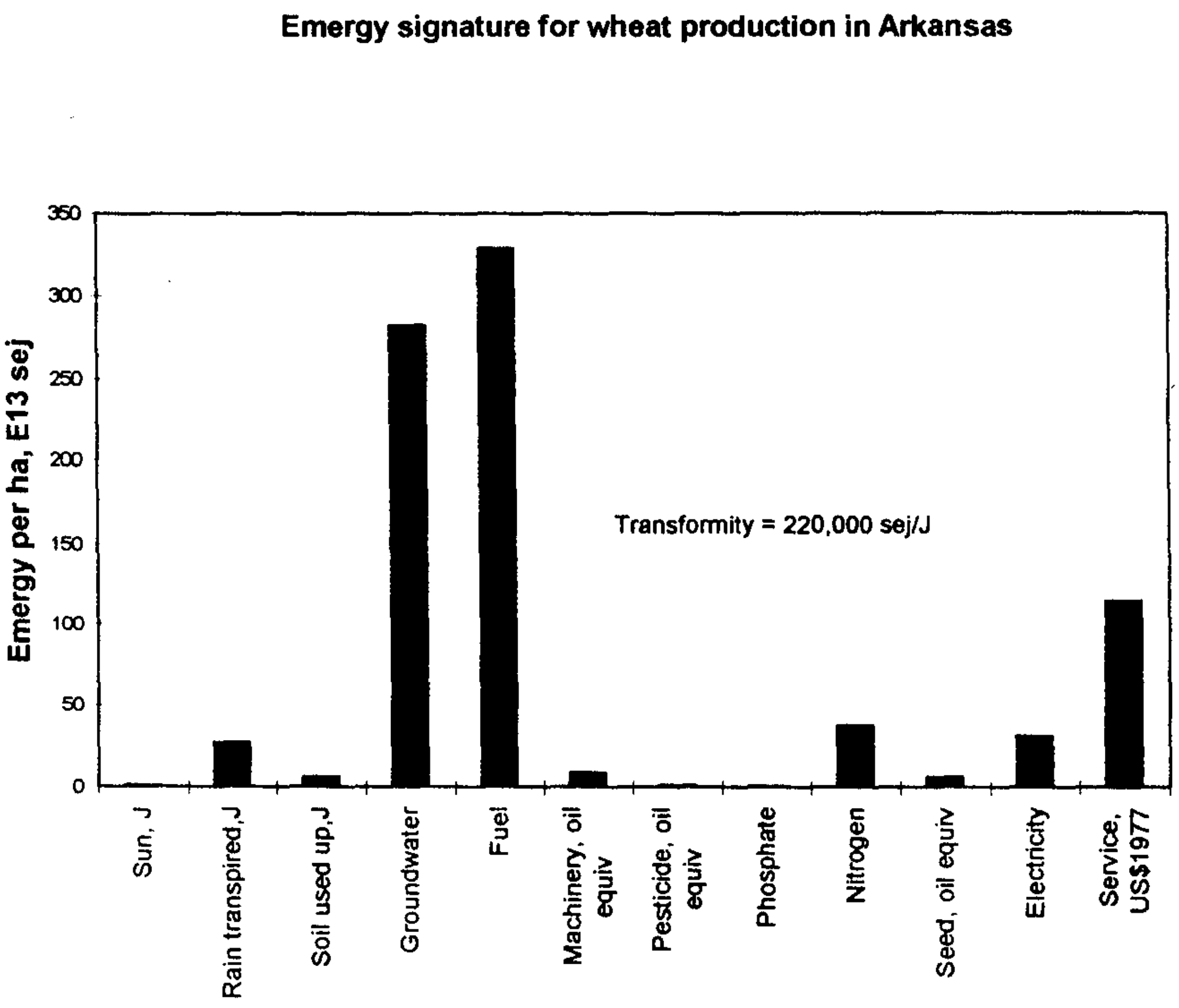


Figure B4. Emergy signature for wheat production in Arkansas.

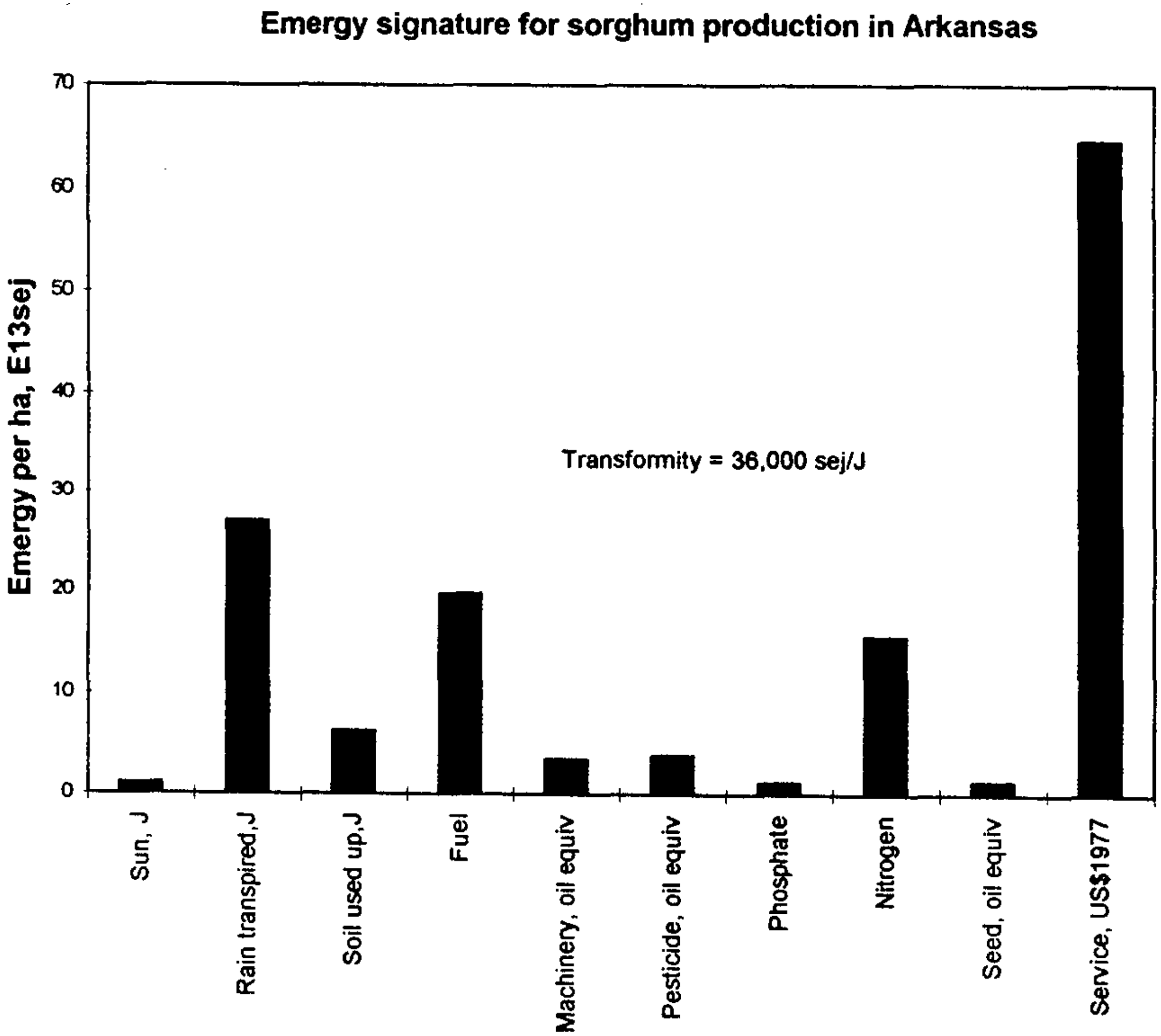


Figure B5. Emergy signature for sorghum production in Arkansas.

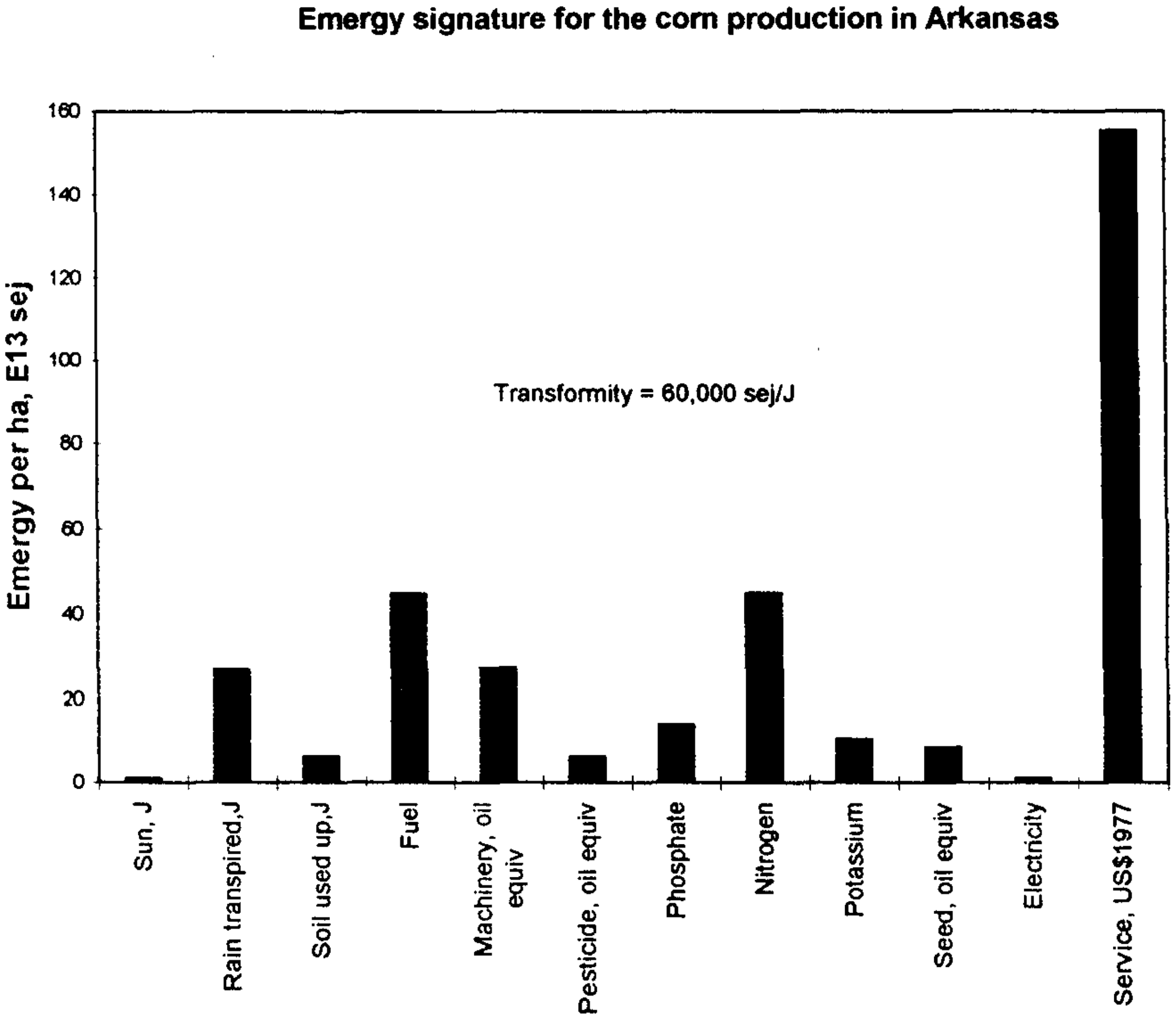


Figure B6. Emergy signature for corn production in Arkansas.

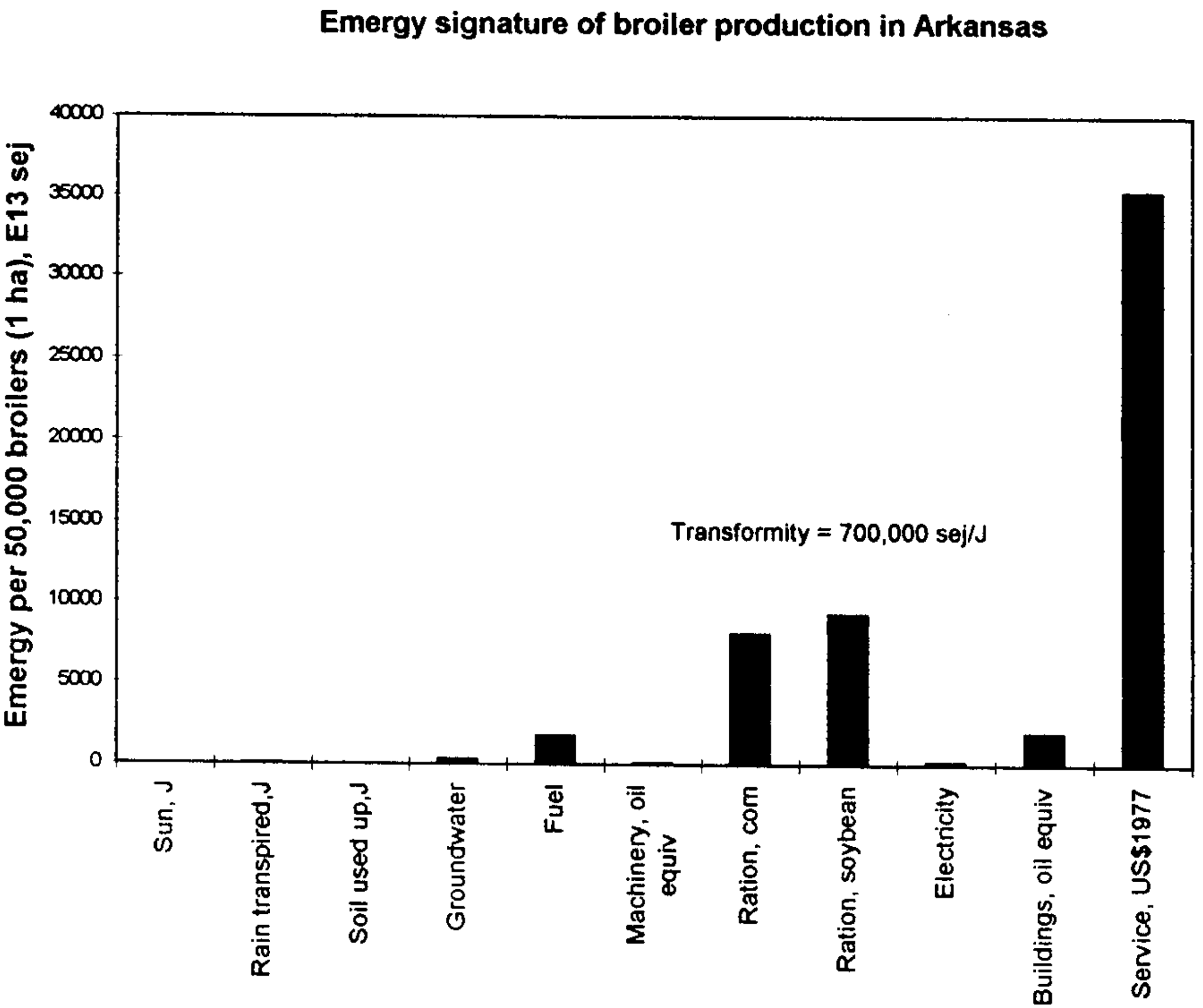


Figure B7. Emergy signature for broiler production in Arkansas.

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