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USE OF ENERGY DIAGRAMS FOR ENVIRONMENTAL IMPACT STATEMENTS

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In the new efforts in 1972 to understand the whole system of man and nature as man proposes to change it, demands a rise from many quarters for some way for individuals, committees, and public policy decision makers to visualize the whole system and the complex of cascading effects that may occur in response to change. Some laws have been passed which require studies of the systems to estimate expected changes. Those planning research and monitoring have wondered which data are needed for decisions. Under requirements of public pressure and new laws, many decision makers have pressed their technical associates for answers. Many call these studies of the anticipated effects "impact statements," but as more and more is learned of the complexities of interactions, more reference is made to systems methods which are evolving the means for visualizing or predicting complex systems.

One bulletin offered as a guideline for impact statements by Leopold (1971) uses large tabular matrices showing the interactions between various parts of the system and various treatments as the intersections of vertical and horizontal columns. One of our symposium sessions was on these matrices. Such diagrams have a very large number of items and often no distinction is made between the important items and those with small intersection interaction effects. Secondary effects of one action affecting the next in a chain are not shown. As used so far, these tables do not show whether the interaction effects are additive, integrative, multiplicative, subtractive, switching, or in another relationship. Such quantitative functions can be put at each intersection with coefficients of interaction but the relations of one such term to another are not readily visualized. The quantitative matrix is, thus, not easily read but it does serve as an easily understandable checklist that can be used to index suitable paragraphs and statements.

In efforts to anticipate changes in proposed resource uses in Florida, we have found in the energy circuit diagram another method which may have some advantages for organizing information, for aiding memories, improving presentations, and ultimately, in giving understanding and prediction.

The energy diagram uses a set of symbols (Figure 1) that shows the flows of all energies in a system, keeping track of the main compartments of the system such as the plants, animals, chemical processes, reservoirs of resource storage, the flows of information, and the outside actions that cause change. The energy diagrams show diagrammatically the pictures of structure and flows that the human mind tends to build for itself in understanding such patterns as the water pipes in a building, the flows of money in a town, or the cycles of elements in the sea. Since causal force is always accompanied by energy flow from storages, the pathways of energy flow are also the lines of impact of one part of the system on another or of the outside forces (called forcing functions) on those inside. An example of an energy diagram is given in Figure 2, where the impact of wastes on the Baltic Sea is considered. A general introduction to the symbol language and many examples of its use is given in a recent book (Odum, 1971). Note that some pathways lead to storages and accumulations and others lead to multiplicative actions on other flows or switching actions that turn flows on or off.

Figure 3 shows an impact energy circuit diagram for a marine meadows ecosystem which we offered to the Florida Coastal Coordinating Council in lieu of the matrix in a recent progress report of a project to develop concepts using the Fort Myers area as example (Wetterqvist et al, 1971). Figure 3 is a qualitative diagram showing the pathways of important effects that summarize our experience. For example, effects that add turbidity directly or indirectly lead to stresses on the main productive components of the ecosystem. Pathways believed to be unimportant are omitted so that the diagram has many less intersectional interactions than the full matrix table would have for this number of parts factors. The outside factors are shown as the energy sources on the sides of the diagrams. Lines from these sources show causal actions that pass through the main productive plant components to the consumers. Also shown are feedback loops for the recycle of chemicals and behaviorally programmed work services from the complex organisms at the end of the food chains back as controllers of the basic productive units in the same way that farmers control their crops.

An even more difficult problem than the impact summarization for a single ecosystem is that for a whole region in which there are many subsystems such as forests, lakes, highway strips, streams, urban developments, golf courses, etc. The choice of land use includes many subsystems such as vegetation and urban development. Figure 4 is a diagram of land management in which the effects of assigning land to agriculture, forestry, complex ecosystem, and human habitation is evaluated. Notice the total value indicator. As more land is developed, it passes through a maximum.

Any diagram must consider the driving functions such as power, money, the atmosphere, the waters, and many kinds of interactions with items in the system. Most man-made projects being considered at this time involve such wide variety of combinations of subsystems to consider, but few, if any, resource managers or technical

specialists are used to all these subsystems in the same consideration at the same time. Team discussions are sometimes useful in recognizing the properties believed important in developing a full diagram by pooling understanding. Before there are numerical quantities for the flows, the selections of pathways may involve artistic judgements that synthesize experiences with precious problems. One such effort at a regional impact model is given in Figure 4. Others are given in a report for the Department of Interior (Lugo et al, 1971) for freshwater marsh wetlands in Florida.

Quantitative Usages

The qualitative energy diagram can be made quantitative by adding energy flow and energy storage data so that the relative magnitudes of the flows can be seen. Some properties of the systems response can then be estimated. For example, the time constant (the full tank turnover time) can be read from the diagrams as the ratio of storage to a flow in or out of it. Figure 5 is a very simple impact statement to show how the diagram is used quantitatively. Figure 5a shows the equations used to program the system on an analog computer, and Figure 5b is an example of the graphs of vegetation and ground water with time starting with desert conditions and adding regular rain. The lower curves in both graphs result when the channelization switch is used.

In Figure 5 water flows on an area of vegetation. Some goes into the ground water, some passes into the air with evapotranspiration as is necessary for vegetation maintenance, and most joins the ground water being pumped to a nearby city for its use as a necessary multiplier on fossil fuel-based economy there. Shown also are two pathways (dashed lines) that are added when development changes the area from natural vegetation into a grassed, landscaped, pattern. These are channelization and increased runoff and a pumping of city water to irrigate the grass in dry weather up to the time that city shortages and regulations prevent this use.

The equations that the energy language contains are written in classifical form with one differential equation summing the flows in an out of each storage (Q's). The diagram is an impact statement since it shows the pathways to be considered before and after the proposed conversion of natural vegetation to managed grass. A complete quantitative impact statement has the coefficients for each pathway (k's) before and after. A computer simulation of the model shows consequences with time of the change.

A rough energy evaluation is given in Table 1. The diagram shows some outside energy sources including rain, the work of the city and the sun of which only a small percent is left after concentration to the higher energy states of the model and of the other energy values. For energy evaluation we use solar energy after conversion as the comparable potential energy. Comparing the system before and after channelization one finds energy values are greater before because the vegetational development is more effective and not interrupted to such a serious extent during the dry periods. The water that goes to the city is given *in the lower part of the table. As this is expressed as the kilocalorie value of the total city fuel metabolism that this water makes possible. Because water is a multiplier of rich fossil fuel, it has great energy and money circulation values. In this particular vegetation system, the development has negative effect on values of an outside system as well as a negative effect on the values inside.*

The energy diagram with the numerical values is thus a computer program since each modular symbol or a pathway has its mathematical statement. The diagram is really a system of differential equations. If the diagram has been made quantitative with storages and rates, then the diagram can be computer simulated, producing graphs of the stocks and flows with time with and without the proposed changes. In general, the simulations of smaller models of 10 to 20 units is now being done readily, whereas simulations of large models all at once like those in Fugures 2-4 is expensive, tedious to do in an error-free manner, and not yet routine. Thus, the state of the art makes it easier to show relationships and add quantitative estimates of the effects than to simulate and predict the whole system. However, progress has been rapid. Often the complex diagram that is done in the initial group enumerating procedure can be simplified if many of the properties and interactions can be regarded as changing little for the period of impact action. Such components, when constant, become simple pathways reducing the number of compartments. An example of simulation of a simplified energy diagram is given for a marine pond in a recent paper (Odum, 1972) in which the model was found to predict some, but not enough, of the seasonal cycles.

We find that energy derived language seems to have parallel equivalents with the empirically derived symbol of Forrester's diagrams (see Figure 1) (1963, 1970). Whereas Forrester's flows are considered as separate subsystems tied together with cross-system coefficients of interaction, we believe that all flows, whether of material, fuel, pure energy, or information, have an energy value measured as their effect in energy flow at their point of action. Forrester's diagrams are also impact statements and best known in urban sciences, whereas energy concepts as integrative means are best known in earth sciences and engineering.

The urban dynamics models tend to have large numbers of small components representing the details of human systems. The diagrams are often abbreviated and one has to scan computer statements to see the key functions. This fault, however, is readily remedied if diagrams are shown in full detail on submodel pages.

One of the properties of these network concepts that allows synthesis of many fields and problems is that there is combined in the same energy system those laws of flux (J) proportional to force (J=LX) and those where there is a population of collective parallel events with flow (J) proportional to population of forces (N) as in chemistry, population dynamics, economics, etc. (J=LN)

For those who think more readily in matrices, the energy diagram may also be tabulated in a matrix of forcing functions and components, the intersections each having the symbol's function and its coefficient. For most people, this is like an index card for location but not so useful for building mental values of the overall system.

Another use of the energy diagram is as a diagram of environmental design in the same sense as an electrical wiring diagram is used in electronics. It not only shows visible and invisible pathways of influence but by the form of the symbols, it shows the viewer what the part is and the mathematical response characteristics if responses of this class of parts have been determined.

In a procedure used by McHarg, maps that show magnitudes for properties are overlaid and added to estimate collective impacts, values, or difficulties. However, most interactions are not additive. The energy diagram is a unit model that shows how variables are to be treated, not only added but more often multiplied or integrated (summed with time). Thus, maps of variables may be processed with each grid point manipulated according to the unit model to produce energy value maps or other compound uses of the separate variables. The methodology is like the combining of the term for forces affecting motion in oceanographic computations which is done to produce maps of currents.

Another use proposed for the energy diagram is in the calculation of the component of overall values due to each flow, to a system component, or to each action by man. A sum of all the energy flows may be regarded as an overall summation of system value. As suggested earlier (Odum, 1971), perhaps the kilocalories of potential energy used or affected is the measure of any action. The energy diagrams include money flows as counter currents on sales and work pathways wherever money is involved; but total value is the total work generated towards effective system survival, not just those flows where one human activity pays money to another. The energy diagram allows one to consider economic and aesthetic values all in the same energy currency.

It may be useful to indicate the procedures in making an impact statement with an energy diagram. Such procedure is given in Table 1. Certainly the prerequisite for the process is that the readers will learn the meaning of the main symbols as given in Figure 1. Our experiences in general lectures and in school groups indicates that this is readily taught to the layman in a qualitative way.

One of our first symposium speakers, W. Fischer, in discussing scale of aerial mapping said there was rigor in the large scale overviews because there was the wholeness into which the result of the interaction of parts must fit, preventing cumulative errors where wholes are constructed from parts without overall functions to show the limits of effect on the parts. This is the point of the overall energy diagram if it is kept simple. The temptation to include all the small effects should be resisted. A good impact statement is by definition a good model. Perhaps the most important aspect in use of these models or any others is to keep the complexity of dissection small, using submodels when more detail is needed. We use the real world for accurate detail. The models are to help the human mind encompass what is important by simplification.

Impact statements can be made for large-scale systems, such as all of south Florida, with simplified macromodels in which only the main factors causing change are evaluated. In Figure 6, for example, growth in Florida is being accelerated by increased money from migrants, tourists, retirees, outside capital for investment related to land use, and the real bases of energy that money goes to purchase. The diagram shows that development takes lands formerly given to nature and that subsequently energy and money must be expended on environmental technology to replace displaced services of nature. Ultimately, prices of products and services are higher and economic viability is diminished. An analog simulation of a simplified version of this found total energy flows maximum when development had used about 40-60% of the land. Here managed grass, agriculture, golf courses, highway plantings and other land uses requiring high levels of management energies are regarded as part of development in contrast to the fully self-maintaining areas of energy value generation.

We are finding that impact statements for similar kinds of systems of land, water, swamps, cities, etc. are not so different. One may use the same general input network diagram as a starting place for many systems and problems.

The frustration with large volumes of testimony and citation is unnecessary. The single page or two of diagrams carries the same information and a few pages and documentations can be added to indicate the source of numbers, the simulation predictions, and efforts to draw value conclusions.

Since the methods for effective impact statements are now available, it will be a shame if there are legislative retreats from the new principles that man should not do anything large and drastic with nature until he knows what he is doing.

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Table 1

Steps in Making an Environmental Impact Statement Using Energy Diagrams

1. List the main properties of the system believed to be important in its operation and/or to man. These are the parts of the system sometimes called state variables. They are the tanks of the model or associated with tanks.

2. Make a list of the outside causal forces and energy sources including the proposed new ones associated with plans and actions of man. These are called forcing functions and are represented as circles.

3. Connect the symbols for forcing functions on the left to the components of the system with causal energy flows using appropriate intersection functions.

4. Each function has a different symbol as shown in Figure 1.
   The intersections are additive when two properties may be used interchangeably.
   The intersections are multiplicative when both are different and required.
   The intersections are switching when there are thresholds of action that are either on or off.
   The intersections are integrative and cumulative when there are storages that receive inflows and outflows developing balance between them.
   The intersections are autocatalytic, feeding storage back to act multiplicatively on the inflow, when the module represents some self-maintaining activity such as organisms, industries, and cities.
   One intersection type has the property of leveling itself due to a circular recycling of some material which is limited. This is called the Michaelis Menton property after its discoverers in biochemistry.

5. Having identified the pathways, try to put numbers on them to gain perspectives on importance and times involved for effects. Estimate the main effects believed to result in the system from the change through visual estimation of the effects of the change in stimulating or diminishing flows that converge and diverge within the diagram.

6. Having identified the pathways and compartments most likely to be involved in the proposed change, develop a simplified diagram that includes the main change and the essence of the system in few enough modules to make simulation feasible.

7. Run a simulation to test the simpler version to determine if there are unexpected patterns emerging from the network not previously recognized in the diagrams or in experiences. Whereas the simpler model cannot simulate the real complexity, it can identify effects and complications. For example, the system may show if there is a tendency to oscillate or if effects are counter intuitive (go up when you expect them to go down, etc.).

8. Sum the total energy values including those covered by money and those of nature not covered by money flows. Use these energy flow values in overall value calculations.

9. Write general English accounts to go with the diagrams to lead the reader to the points of main consideration in examining propositions for change.

Table 2

Annual Values of Water[1] Before and After Drainage-development of a Square Meter of Land with Water Relationships in Figure 5

Energy Value as Rates of Use of Potential Energy (Scal/m^2/yr)	Before	After
Rain head loss	30	20
Photosynthetic production[2]	18,000	5000
City pumping driven by city money[3]	330	240
TOTAL	18,360	5,260
Money value from converting energy values at one dollar per 10,000 kilocalories.	$1.84	$.53
Money valve to city machines as money equivalent of the energy flux of water which allows operation of the machines (industry).	$4,000	$1,000
Money flow in city payments to people for water works service	$.033	$0.24

Footnotes

[1]Water has several energy values since it is involved in several processes in the model. It has hydrostatic head that drives several pathways, is a reactant in photosynthetic production. Each process has a different calorie per gram energy value for water's participation.

[2]Solar energy is a dilute energy and not calculated as equivalent until after it is converted in net production of plants or other transformation.

[3]Energy export pathways are not regarded as value loses if they are a part of the model since work is done on the lands and atmospheres in the process as an inherent part of the surviving system of necessary exchanges with nearby systems. These systems may require these inputs to be a stable neighbor and not drain the system in question more than that shown.

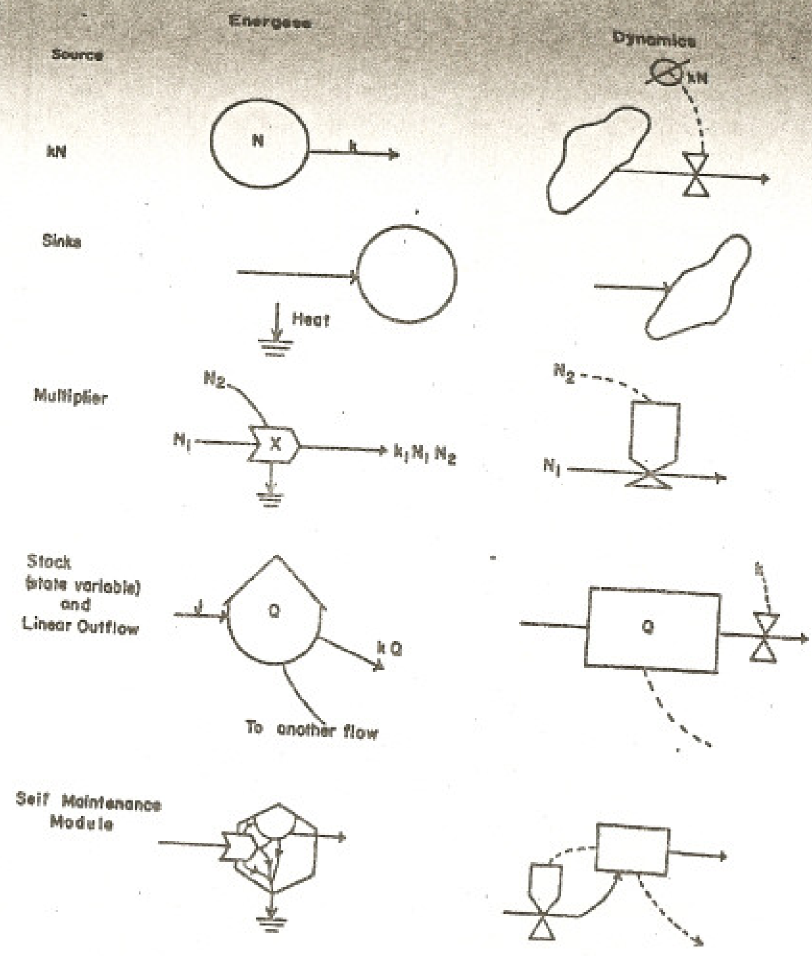


Figure 1 - Energy circuit symbols, their equations, and their equivalents in Forrester's symbols.

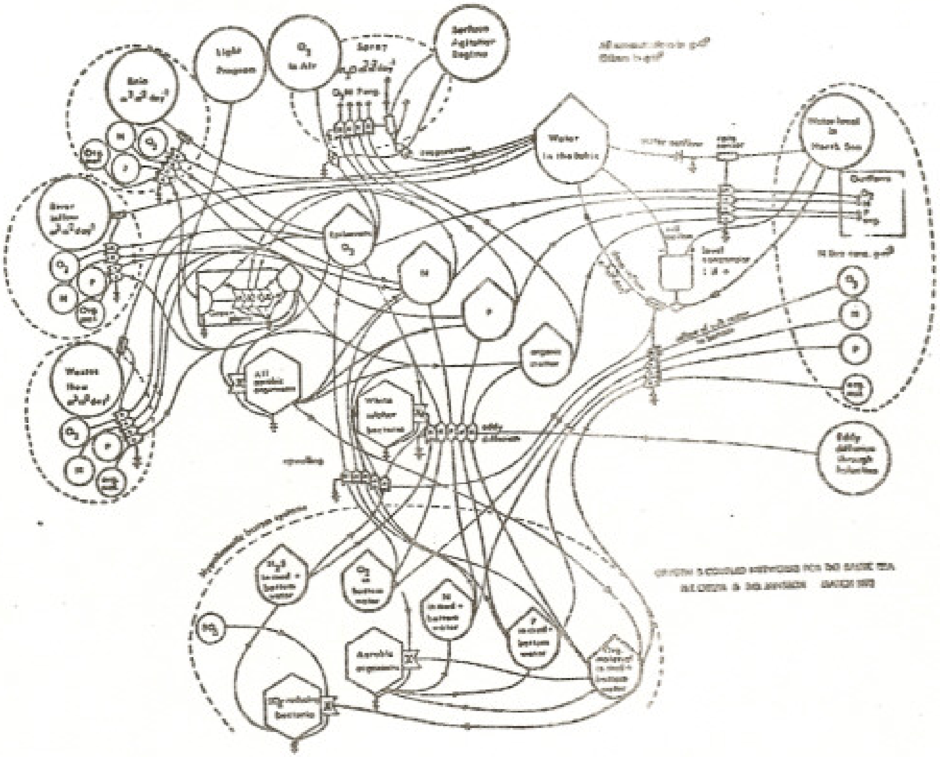


Figure 2 - An Example of an energy diagram that is an impact statement and is also a research planning model.

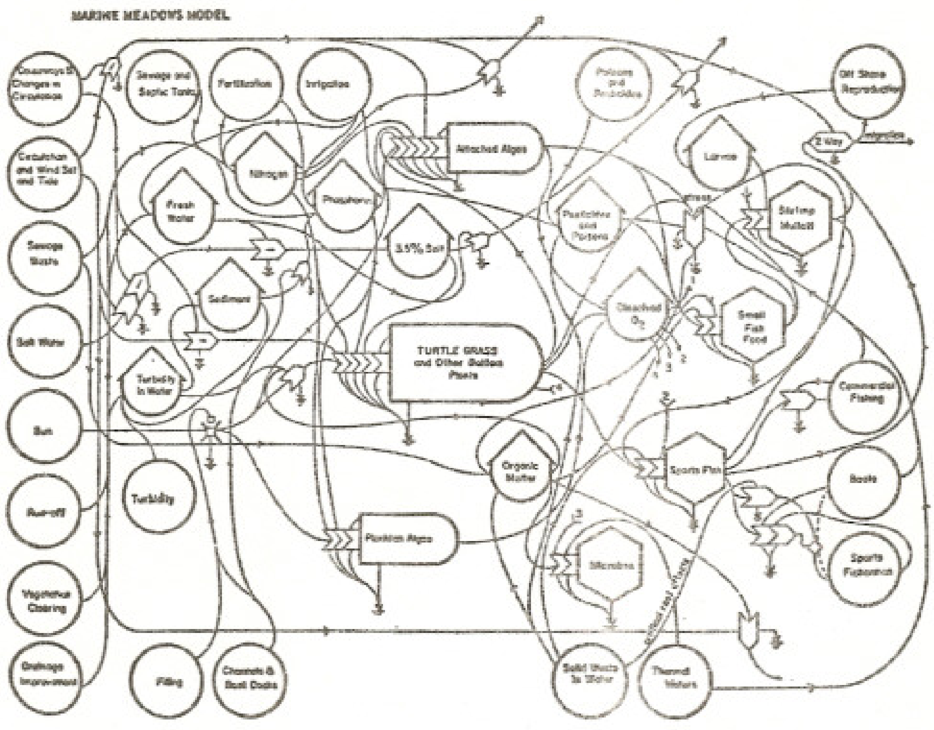


Figure 3 - Energy diagram of a marine meadows community with many kinds of disturbances imposed by estuarine development (from Wetterqvist, Peterson, Odum, Christiansen, Snedaker, Brown et al, 1972).

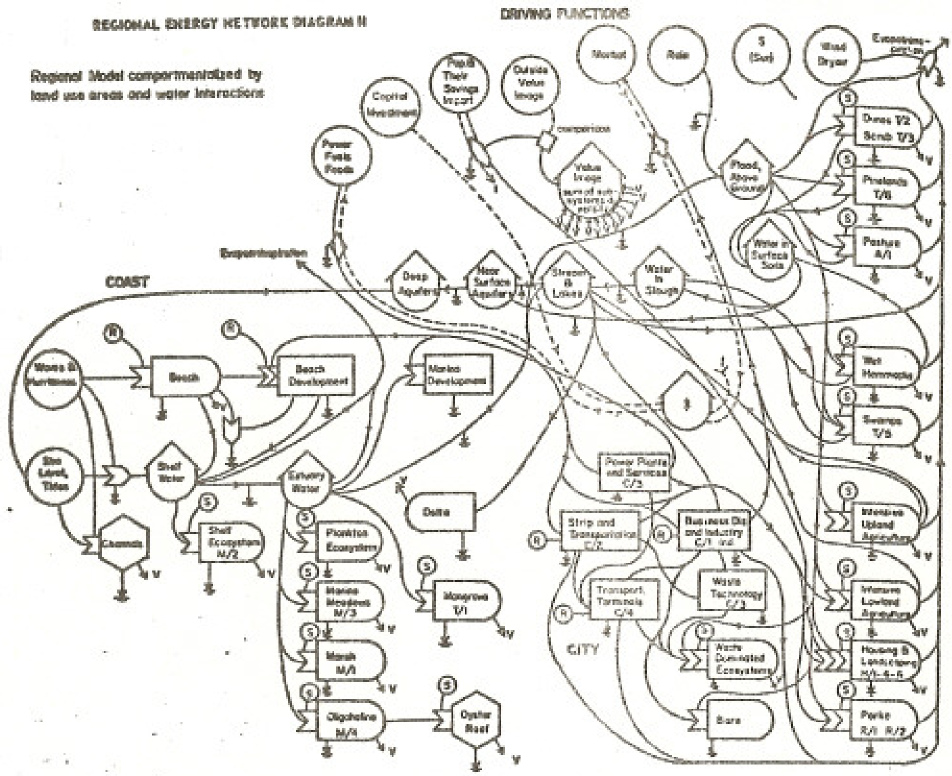
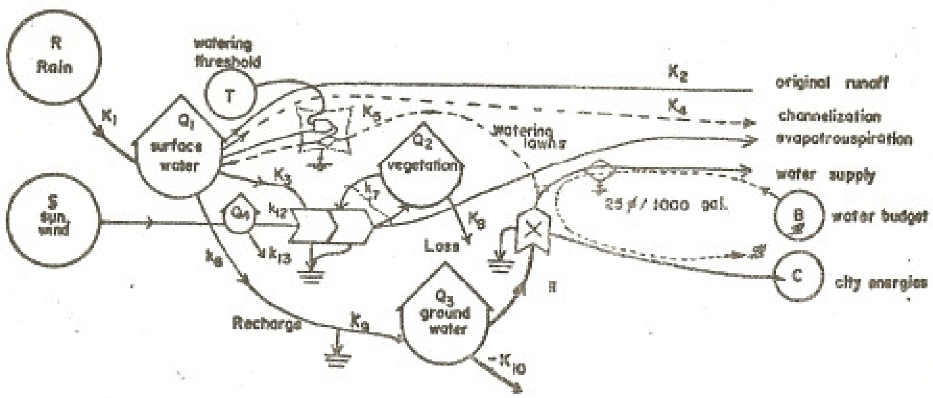


Figure 4 - Land Proportion diagram for a developing region and its combined values.



$$\dot{Q}_1 = K_1 R - K_2 Q_1 - K_3 Q_4 Q_1 Q_2 - K_6 Q_1 - \overbrace{K_4 Q_1 + K_5 B Q_3 C}^{\text{if developed}} \quad \text{when } Q_1 < T$$

$$\dot{Q}_2 = K_7 Q_4 Q_1 Q_2 - K_8 Q_2$$

$$\dot{Q}_3 = K_9 Q_1 - K_{10} Q_3 - K_{11} B Q_3 C$$

$$\dot{Q}_4 = S - K_{12} Q_4 Q_1 Q_2 - K_{13} Q_4$$

Figure 5 A - Simple impact statement to show the principles of energy circut exposition including equations for simulation and energy flows for value computation. A - Circut diagram; B (page 212) - Computer graph with and without channelization. V - Vegetation; G - Ground Water

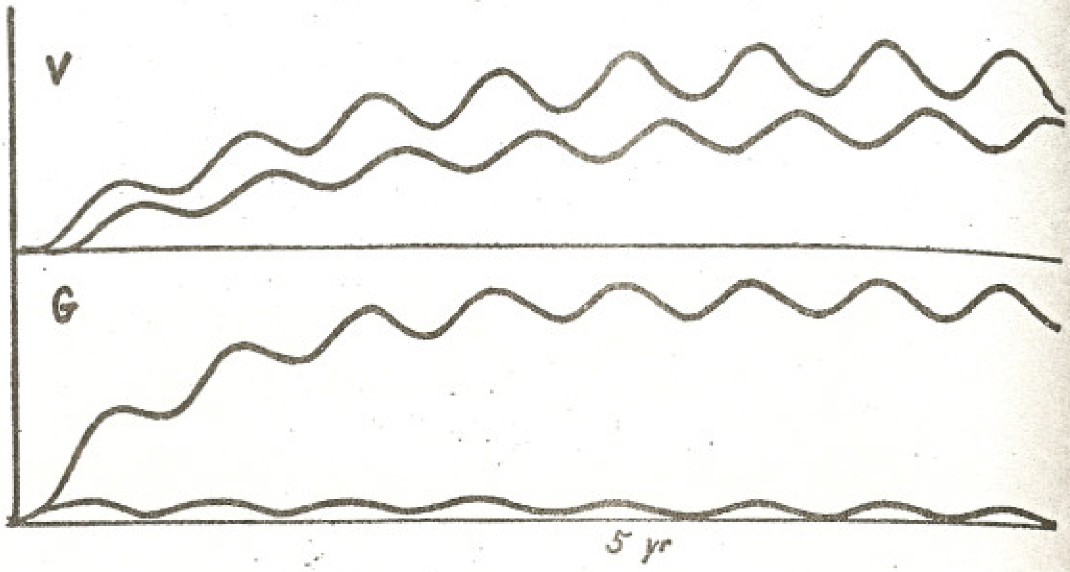


Figure 5 B - Simple impact statement to show the principles of energy circut exposition including equations for simulation and energy flows for value computation. A(page 211) - Circut diagram; B - Computer graph with and without channelization. V - Vegetation; G - Ground Water

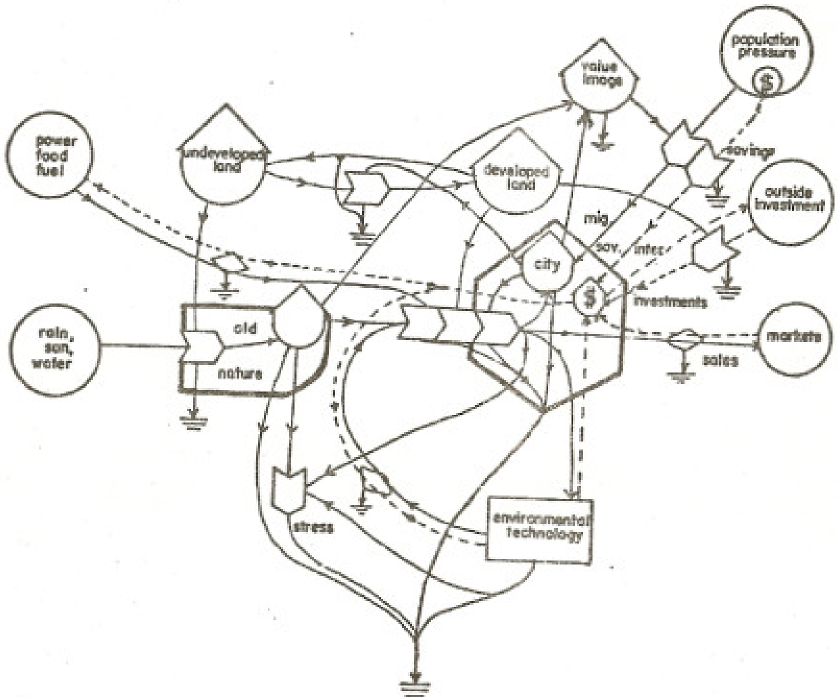


Figure 6 - Some impacts of money in Florida growth and the complex role of environmental technology in diverting energies and reducing output of goods and services that help balance of payments.