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from Nobel Symposium 20

Chemical Cycles with Energy Circuit Models

By Howard T. Odum

Introduction. Modelling Symbols

In the expanding quest to understand the large and complex systems of cycles of the earth, the seas, and man, comprehension requires the simplification that comes with making models. Each type of model may bring new concepts into existence in men's minds, condensing complexity of the real world within the capacity of the simpler human comprehension. Among the modelling and modular languages being developed for synthesis of macrosystems is an energy language that we have used to study and simulate some contrasting systems of ecology, anthropology, and other sciences. In this essay this energy circuit language is used to consider the chemical cycles that sustain the sea.

The modelling of material fluxes and budgets is now a standard part of any consideration of chemistry of the lands, seas, and atmospheres. What we now need is modelling of the total system of all the total energies including those of man's system including information and cultural programs of control. The energy language is a way of visualizing and synthesizing all types of components.

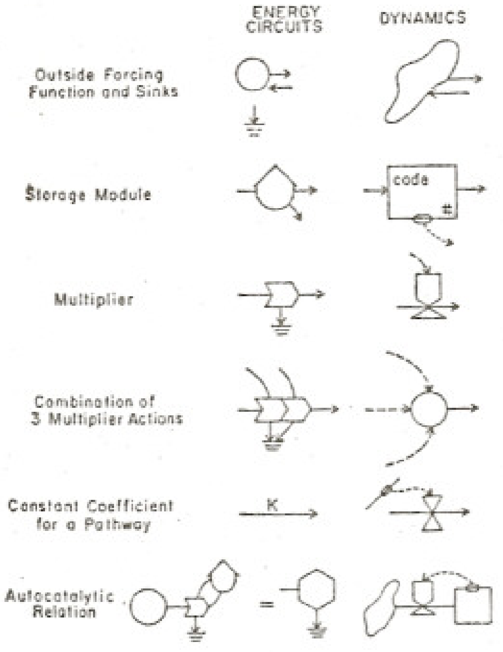

Fig. 1. Comparison of symbols of the energy circuit language (left) with "Dynamics" symbols of Forrester (1963).

The energy circuit language has been described in several previous papers (Odum, 1967, 1968; Odum and Pigeon, 1970; Odum, Nixon, and DiSalvo, 1971) and applied to a wide variety of systems in a book (Odum, 1971 *a*). Some of the main symbols are given in Fig. 1. The language is a formalization of concepts of energy flow in which pathways represent either the energy flow driven by single forces or those driven by populations of forces. Each driven flow has opposing forces of frictional, inertial, or static nature, the latter derived from downstream storages of potential energy. Details about the language in relation to concepts of physics and chemistry were given previously (Odum, 1971 *a*). As defined, the language is supposed to use the constraints from basic laws of physics and chemistry and the principles of larger systems at the same time. Since the pathways represent all energy flows, and since theorems of the language allow all flows of matter and information to have their energy values at their points of action in the system, a common denominator is provided for all parts of all kinds of systems.

Comparison of Energy Language with Forrester's Language

One of the characteristics of the energy language is its simple representation of network phenomena that are often represented as a system of differential equations, a more difficult language but one familiar to scientists and engineers. Whereas the energy language was developed first from consideration of energy laws, ecological data on food chains and some physical and chemical laws about forces, fluxes, and reactions, it was discovered later that it was also a form of visual mathematics, each modular symbol having an algebraic term for the system of differential or difference equations used in translations for computer simulation.

This year Larry Peterson and I (Odum and Peterson, 1971) found that an older language of symbols first developed by Forrester (1963, 1970) to summarize digital programs based on empirical coefficients had symbols that seem to match the ones derived from energy considerations. Notice the comparison in Fig. 1. We would judge that Forrester was modelling energies and true forces without knowing it just as we were writing a symbolic language that automatically translates into his Dynamo digital program without our knowing it. Forrester calls his language and its simulation "Dynamics". Among biologists who have used it for ecological systems are King (Paulik, 1967) and McRoy (1971). That two entirely different processes of thinking should develop similar languages suggests that basic concepts are involved. In the dynamics language, the use of a different kind of line for each class of matter, energy, or information is quite unnecessary since there is an energy value for all flows, not just for flows of fuels and sunlight. Both languages are being used in parallel efforts to

consider large scale world processes. The translation in Fig. 1 may be hel to readers used to a single language. Both languages serve similar role giving the human mind concepts which can be easily held and readily transla into other languages for other purposes such as simulation.

There is an intellectual's tendency to seek an explanation in that spe language that is familiar to him before he accepts a phenomenon. If a r language turns out to be simpler in expression of the particular phenomer than older ways of thinking about the same relationship, the custodian of old may only accept it as a teaching device or popularization because he can easily accept a loss of status of the more difficult ways of expression for wh he takes pride in mastery. It is an instinctive reaction to regard the simp way of doing something as less valuable. One's language carries one's though If one has complex mental procedures, they are not necessarily more use than simpler ones even if they did take more training to learn. These symbo languages by uniting concepts may have the simplicity to displace some mc cumbersome mathematics for general modelling, at least for some kinds minds.

Notes on the Use of the Energy Language with Chemical Systems

The following points about the energy language are offered to clarify its u in chemical systems as illustrated by the diagrams in Fig. 2.

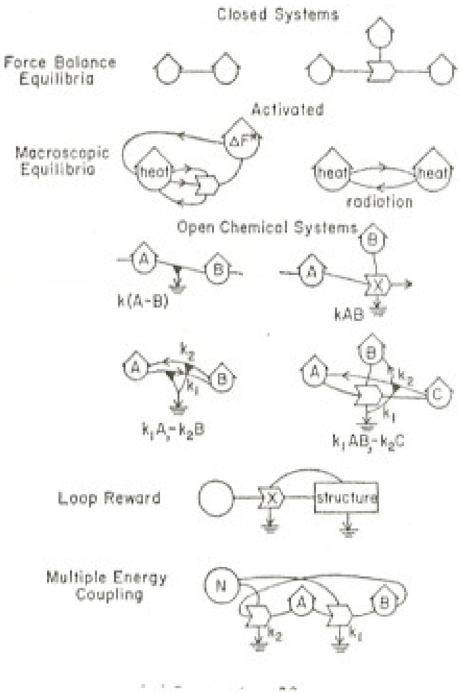

Fig. 2. Some configurations of f balance and energy flow commo chemical systems expressed energy circuit language.

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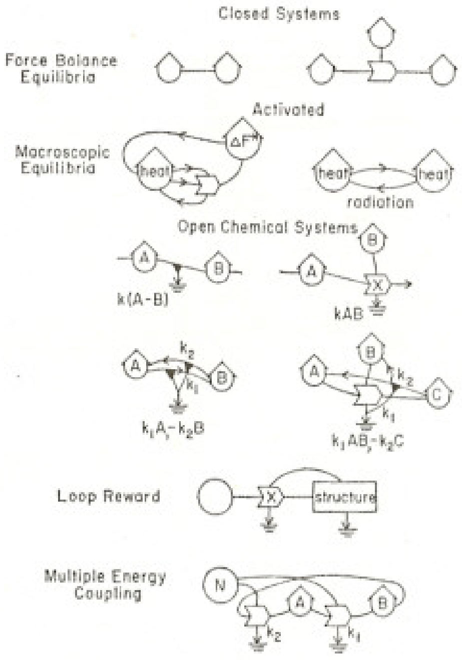


Fig. 2. Some configurations of force balance and energy flow common in chemical systems expressed in energy circuit language.

Equilibrium. At the top are two systems at equilibria in the sense of simple physical balance of static forces from energy storages. The pathway lines are lines of force action. There are no heat sinks and no energy flow. The exact relationship between the energy stored and the force delivered depends on the type of energy stored (tank symbols).

Chemical equilibria. Illustrated in the two systems of the second row in Fig. 2 are chemical equilibria which are microscopically and locally not in true force balance. Accumulations of energy at random produce some momentary storages of higher potential energy that are subsequently dispersed back into the base evel of average molecular momentum that we call heat.

Open chemical systems. Shown next are four familiar, open, chemical systems vith heat sinks representing heat dispersion and entropy increase. On the left he flow between energy storage A and B is in proportion to the difference in he forward and backforce on the single pathway as in flow in an electrical ield. The other three systems have no backforce but have separate pathways or return flows. These can establish steady states; two have multiplier actions n one direction. In a multiplier action, one of the two converging flows may e a tiny but required item such as a trace element or even a unit of information. ts energy value becomes that of the reaction as much as that from the apparently larger flow.

election for structural feedback facilitation. Inherent in the language is the rovision that any energy flow generates randomness and choices from which atural selection continually selects according to the principle of maximum ower toward maintaining the flow. Even at constant temperature, the thermal andomness that generates local energy concentrations gives natural selection e means for developing feedbacks that facilitate flow in the pathway. These edbacks constitute pathway structure that may take the form of storages, ldies, gradients, membranes, catalysts, or more complex means for using ergy storages for maximizing energy flows. Such feedbacks are illustrated in e loop reward diagram in Fig. 2. Because of these mechanisms, flows do beme a function of the potential energies available as soon as choice, selection, d loop rewards develop. Natural selection is nature's Maxwell demon and main basis for introducing new information.

rce-flux conventions. A chemical audience may be used to the problem in dy-state thermodynamics of flux not being proportional to thermodynamic e when the force is chosen as the chemical potential. Rather than make selection for force and the necessary accompanying assumptions about ll distance from reversibility, we define a second force-flux law that includes mass action concepts. A pathway may represent a flow of energy under impetus of a population of similar forces acting so that the flux is proportional to the number of unit forces. The number of forces (n) is related to population force (N) to which flux (J) is proportional. The energy circuit networks may have some pathways which have single driving forces and others which are the action of population force. We, thus, combine chemical kinetics and steady-state thermodynamics in the one more general language in which every pathway without acceleration fits one of the two linear laws ($J=LX$ or $J=LN$). For more discussion of these definitions see Odum (1971).

Energy coupling to a cycle. Illustrated in the last diagram of Fig. 2 is the outside energy source coupled to a circular chemical cycle with each step the result of a multiplier action of an outside and a cyclic storage developed force. There is no upstream or downstream in the circular loop although there is an upstream-downstream sense in the flow of outside potential energies into dispersed heat (sinks).

Energy value of a reactant. A storage may have as many energy values as it has reaction pathways. If the reactant from a storage is a tiny quantity with a large energy release of another power flow, it serves as an amplifier. When energies are fed from downstream back upstream, the flux may leave its storage with one value as related to its storage input process but after upstream coupling, it may develop the new value of the power flow facilitated there. For example, a cycling chemical substance develops new values of potential energy in each reaction step coupled to outside components.

Storage distribution as a facilitating structure. Illustrated by the last diagram in Fig. 2 is Lotka's principle that in a closed steady-state cycle, the storages develop in inverse magnitude to the pathway conductivities that follow. In such cases greatest energy storage develops in a different part of the cycle from the site of maximum outside energy application. The lesser outside energy has the lesser multiplier action. The distribution of energy storage within the cycle becomes self adjusted to maximize the flow and, thus, is another case of feedback of information and structure towards power maximization, competition, and system survival. For example, if energy of (N) with k_1 is smaller than with k_2, storage A becomeslarger than B.

The physical systems of the sea such as eddies and gyres are also examples of the distribution of energy storages in non-random pattern. Such maximization is the basic explanation for development of turbulent eddies with the energy storage that is feasible depending on the size of the outside energies available for maximization (Odum, 1968); in the discussion one participant indicated that similar applications have been made by J. Malkus). The energy diagrams such as those in Fig. 2 help us generalize about organic evolution, chemical reaction development, social change, and geophysical systems as variants on one basic plan. Consider next overall geochemical processes with energy language

Compartmental Models in Geology

In a recent book, Harbaugh and Bonham-Carter (1970) review the use of compartmental and other models in geology including applications to sedimentary depositions, deltas, salt domes, reef developments, and many others. Much of the book concerns the simulation of a field of unit models each feeding its shared inputs and outputs into each other, thus, producing the geographical mapping of variables characteristic of much geological data. One may simulate a whole system by such joining together of unit models or make a unit model apply to the whole of the system. In this paper the latter class of models is considered.

Harbaugh and Bonham-Carter include an overall two-compartment model for the earth sedimentary and igneous cycle citing a manuscript by Garrels and Mackenzie. They simulated the model considering the shape of growth curves with a case of steady input and one with constant mass constraint. These models are drawn in energy language (which automatically expresses the differential equations of the model) in Fig. 3. Note that the energy sources and pumping actions are dashed since they were not explicitly covered by these

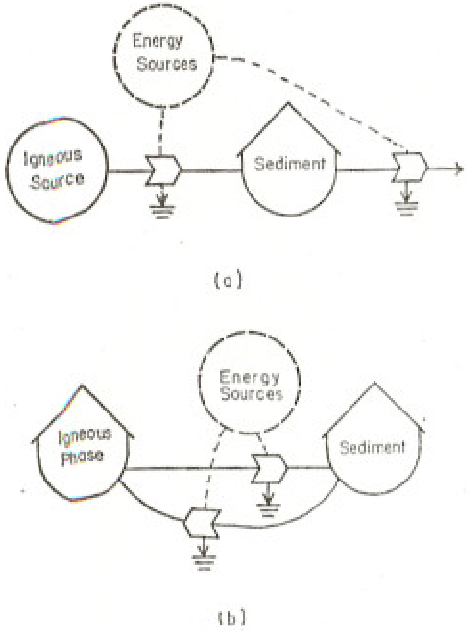


Fig. 3. Energy circuit diagram of earth model simulated by Harbaugh and Bonham-Carter (1970): (*a*) with constant addition of new mass from igneous source; (*b*) with constant mass constraint.

authors who, in effect, assumed them constant by using constant tran coefficients.

The Harbaugh and Bonham-Carter book helps express an optimism a felt by this author in an emerging subject of systems geology and geochemis as its hydrological and mass models are generalized to include all of energies and forces of a system. Hopefully, the energy language may be help in these kinds of synthesis. The discussion of unsettled issues and two anal simulations that follow show the methodology.

Those not used to the approaches of compartmentalizing for concept and simulating simplicity may be disturbed when known processes are lump or seem to be omitted. A process that one is holding constant as in a controll experiment becomes a constant coefficient and a property of the pathway, a thus, seems to disappear in these models. Where these methods have be much used in ecology, experience has gradually given empirical guidance o which processes are important and dominant in these systems. At present, w have less experience with whole earth models, but we must get on with effort of these cycles and check them by comparison of the simulations with the rea data which are still very approximate in these fields.

World Geochemical Processes Simplified with Energy Circuit Language

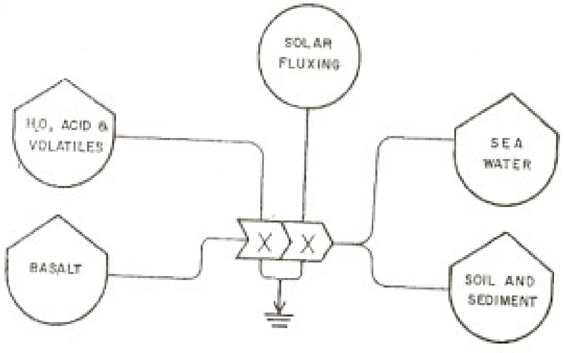
As a unit of the world's geochemical cycles, the ocean's processes and man' effect on constitution of the sea can be understood only in perspective of th main cycles of the lithopshere, atmosphere, and hydrosphere. The energy circuit language may be helpful in organizing our understanding and hypothese about which flows are linear, which are multiplicative actions, which are important, and which receive outside forcing energies. By diagramming subsystem and subcycles, it is possible next to focus on various ideas about the origin stability, and changes in the sea as related to man and other changing patterns

Goldschmidt Reaction

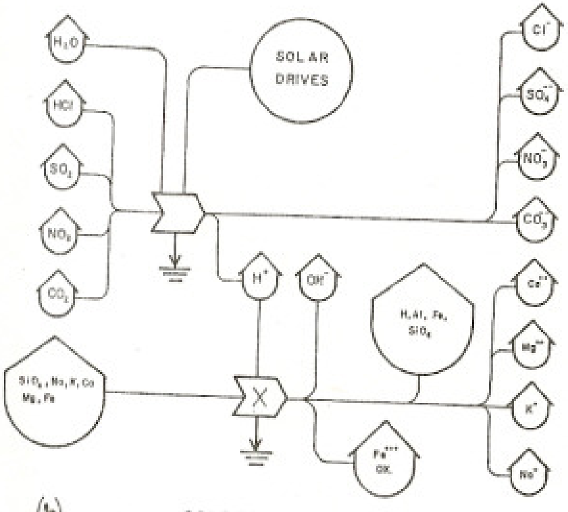
To illustrate energy diagramming of geochemical models, consider the reactio in Fig. 4*a* that may be called conveniently the Goldschmidt reaction after th originator of the calculations of the stoichiometry of the overall proces (Goldschmidt, 1933; Goldberg and Arrhenius, 1958). In an overall way, th reaction of acid volatiles on igneous rock can produce a medium like sea wate plus residual soils and sediments. According to some ideas, this class of reactions describes early events in our world starting with initial igneous condition In our current world, the reaction may be only a smaller part of the system cycles now operating. In Fig. 4*b* more of the details of the input and output flows are shown. Note that a source of energy directly or indirectly from the sun is involved for the stirring and mixing of the reactants. As drawn, such a model implies much simpler kinetics than the millions of tiny component processes that we know to be involved in such a world-dimensioned process. Yet, considering accuracy of our data and the crudeness of our questions, simple models may be an adequate summarization, but one has to check performance against the real world, a difficult kind of test to make with huge world systems.

Goldschmidt Microcosms

In Fig. 4*c* is an apparatus in which we refluxed acids on rock with four replications in 1957 to simulate the Goldschmidt reaction. Data are given in Table 1.



(a) OVERALL MODEL



(b) GOLDSCHMIDT REACTION

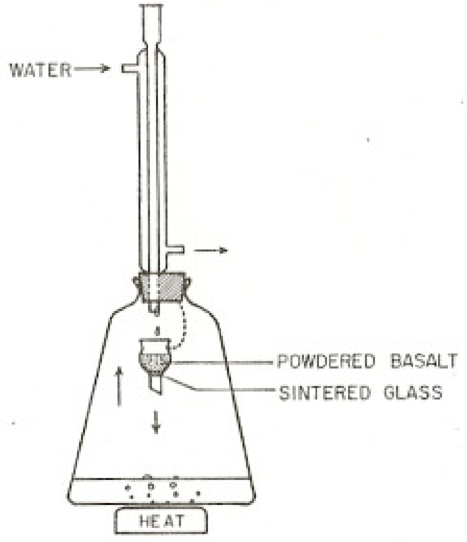
Fig. 4. Goldschmidt Reaction: (*a*) overall process; (*b*) separate elemental flows shown; (*c*) Goldschmidt microcosm.

Table 1. *Ionic concentrations after refluxing 10 g of Basalt in Goldschmidt Microcosms*[1]. *See Fig. 4c*

Trial	Initial Conditions, %		Volume ml	Months refluxed	pH	Final Concentrations, ppm				
	HCl	H_2SO_4				Na	K	Ca	Mg	Fe
1	1.9	0.50	150	6	3.5	177	15 000	180	101	0.0055
2	1.1	0.04	100	2	1.0	69	31	14	2	0.0035
3	0.3	0.10	400	2	0.4	36	6	1	0.4	0.0011
4	0.3	0.10	50	2	2.5	53	150	2888	123	0.0059
sea					8.2	10 561	400	400	1272	

[1] Work by Walter Abbott and H. T. Odum supported by National Science Foundation grant in 1957 on ecological microcosms.

In the period of 2 to 6 months that these systems were cooking, it was clear that something like sea water was evolving. The pH was rising and it became doubtful that the earth should need millions of years for neutralizing any accumulation of acid volatiles to form sea water if this was the history. The appearance of substantial iron which would precipitate as the pH neutralized suggested some precambrian iron deposits of the sedimentary and metamorphosed rock record. Whether operating on an igneous earth or on a small scale, the reaction may be relatively fast whenever there are igneous rock surfaces. This part of the igneous cycle may have a relatively fast reaction rate.



(c)

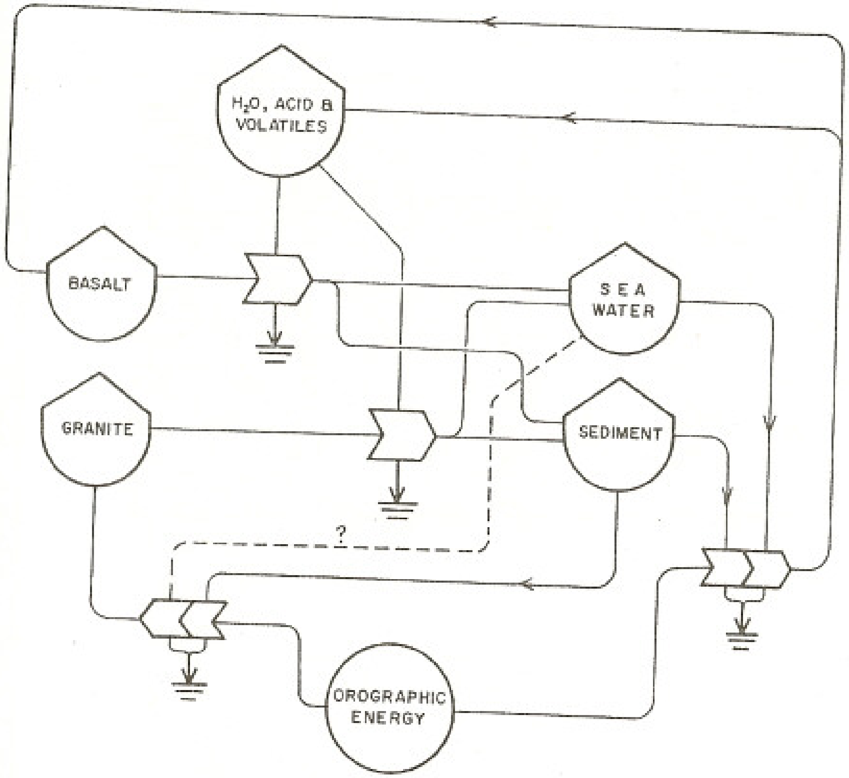


Fig. 5. The earth's igneous cycle simplified into two competing pathways, the volcanic and plutonic-granitization flows.

The Igneous Cycle

The Goldschmidt reaction (Fig. 3) is only a part of the main igneous cycles since volcanoes and plutonic uplifts continue drawing their input materials and end energies from some recycled materials. Other processes only somewhat known transform sediments into igneous rock with uplift. Compartmentalizing for simplicity the overall igneous cycle is given in Fig. 5. Like some ecological systems this network has two competing multiplicative pathways with shared common reactants which are regenerated by common recycle reactions. Although the substances are different, the energy circuit language helps us recognize a system similar to the photosynthesis and respiration model of world biosphere that cycles nutrient elements with competing production pathways.

The Equilibrium Model

The Goldschmidt reaction has sometimes been visualized as producing an ocean by a running down process from initial potential energies with elements distributed ultimately according to stable equilibria without requiring any roles for recycling. The equilibrium model for the ocean developed by Sillén (1961) seemed to resemble the modern ocean as if the world were dead without incoming energies, without new volcanoes, without cycling, without spreading sea floors, or without a sedimentary cycle. It was an astonishing fact requiring explanation that the real steady-state ocean should have some similarity with an equilibrium model. Consider the nature of cycles and their self-regulated storage structures under selection for survival by maximizing power.

Adaptive Value of Pseudo-Equilibrium States in an Open System

Consider the open cyclic steady state given in Fig. 6, which has outside energy drive in two parts of the cycle, but derives potential energy from its own storages in the other two pathways. Suppose the storages are self adjusting to maximize power flow by means of natural selection from among random variations generated in any power flow. Which distribution of storages so maximizes incorporation of inflow energies? With the help of the energy circuit diagram we see that energy incorporation is a multiplicative action at the intersection of the outside source and the flow from an inside storage just upstream. Energy is maximized when the upstream storage is maximized. In this instance, the cycling matter is a reactant and, thus, a part of the energy reaction by which outside energy sources are incorporated. In Fig. 6 if outside energy sources were stopped, the system would run downhill with storages ending up in the compartments (E) that were interacting with outside energies. Regular equilibrium would result. Calculations such as those by Sillén of an equilibrium model for the sea are computations of the final concentrations in the run down compartments. Thus, the distribution of mass that is self regulated to maximize power is only slightly different from the distribution at equilibrium. Some storage is required in non-equilibrium compartments to maintain steady recycle.

There is a second feature of storage in systems that favors near-equilibrium mass distributions. Maintaining storages is expensive in energy either because of the losses in adventitious lateral pathways or in the energy costs that the system must spend to prevent that loss if they are so organized. In either case, the losses are proportional to the surface to volume ratio as described in the

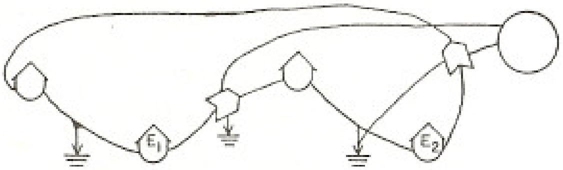


Fig. 6. Energy circuit diagram of a geochemical cycle with 4 compartments driven by external energy coupling through two of the pathways. Power is maximized by a pseudo-equilibrium mass distribution.

theory of population force discussed elsewhere (Odum, 1971*a*, 1971*b*). However, storage of matter in run-down equilibrium states has no energy costs or losses and, thus, is economical. Systems that distribute their cyclic masses in near equilibrium distributions minimize losses and maximize capture of input energy pumping, thus, competing with alternative pathways for these energies.

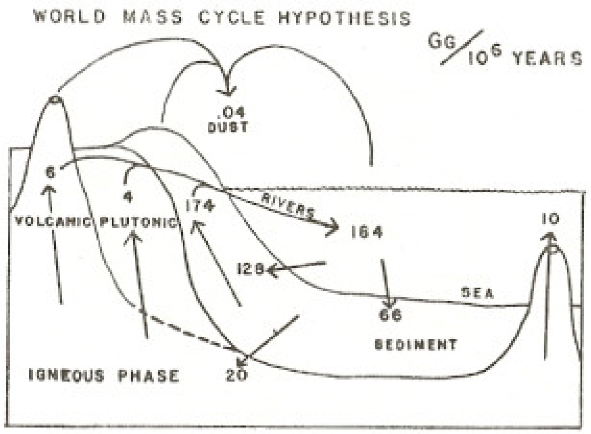
Another way of thinking of the equilibrium state storage distributions is one of high energy relative to outside energy sources. Having a low energy state relative to the cycle maximizes high energy relative to the source. As described in relation to the development of information in human affairs, the expenditure of potential energy into heat actually increases the energy multiplier value of the cycling system.

Steady State Ocean

In 1950 and 1951 along with details on the strontium cycle, I presented calculations for time constants of main elements in a steady-state lithosphere, ocean, and atmosphere driving the cycles of the common elements. The overall mass movements suggested were those in Fig. 7 (Odum, 1950). Probably improved were the calculations made later by Barth (1952), Goldberg (1961) and others.

The steady-state ocean may be conceptualized into four main component cycles. The first was the igneous cycle subsystem, already sketched in Fig. 5. Sedimentary matter incorporated into igneous and granitization-like processes constituted the upward returning part of the simplified cartoon in Fig. 7.

Another subsystem is the salt and water cycles by which materials move from the sea through the atmosphere to the land as diagrammed in Fig. 8 and discussed in this symposium by Chatellet. The sun clearly drives these pathways directly and indirectly through the atmospheric engines. Potential energy of the water drives the return flow of water and also does the work of moving the salts.



Odum (1950)

Fig. 7. Summary diagram of the hypothesis of a steady state earth surface from Odum (1950).

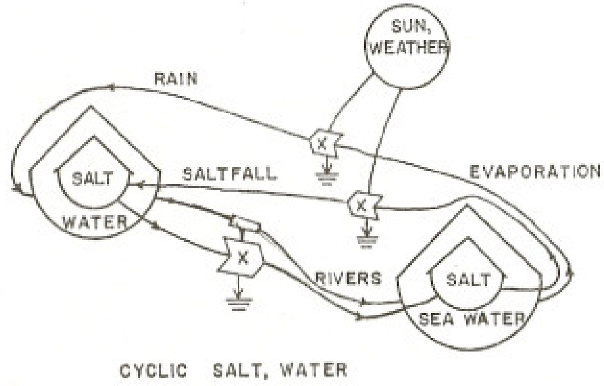


Fig. 8. Overall subsystem for hydrologic cycle and its coupling drives to the cyclic salt system.

A third subsystem is the cycling of solids into marine sediments with elevation again by orographic uplift shown in Fig. 9. This system involves the carbon-dioxide cycle, solution of the alkaline earth elements and others and reprecipitation in biogenic pathways. Parts of this system seem identical with the system presented at our symposium by Pytkowicz. An overall abbreviation of the main features is given in Fig. 9*b*.

The fourth subsystem contributing to the steady-state ocean is the oxidation and reduction system of the living biosphere, which is given in a simple 3-compartment form in Fig. 10 and more complex form in Fig. 25. Fig. 10 includes explicitly the algebraic terms for the pathways as implied by the conventions of the energy circuit language. Scientists and engineers usually recognize concepts of the energy language when we add the algebraic terms with which they are familiar. Simulation of models of this class has been done. For example, John Day did an analog simulation of Fig. 10 finding its charge-up and discharge curves like the ones published for the simpler 2-compartment P–R model (Odum, Beyers and Armstrong, 1963; Odum, Lugo and Burns, 1970).

One of the features of the energy language is its utility for presenting the functions by which one energy flow is coupled to pump another. In the model the return of sediments by uplift is derived in part from the sun-driven hydrological transfers of mass from continent to the sea with isostatic adjustments and deep return flows matter to denuded areas. More controversial are the energy sources for the conversions of sediment into igneous phases and their relation to the observed sea floor spreading. If the continents are still spreading and, thus, not in some kind of overall steady state, then the ocean might not be either. However, perhaps the sea floor spreading is being misinterpreted as a transient rather than a part of a steady recycling steady state.

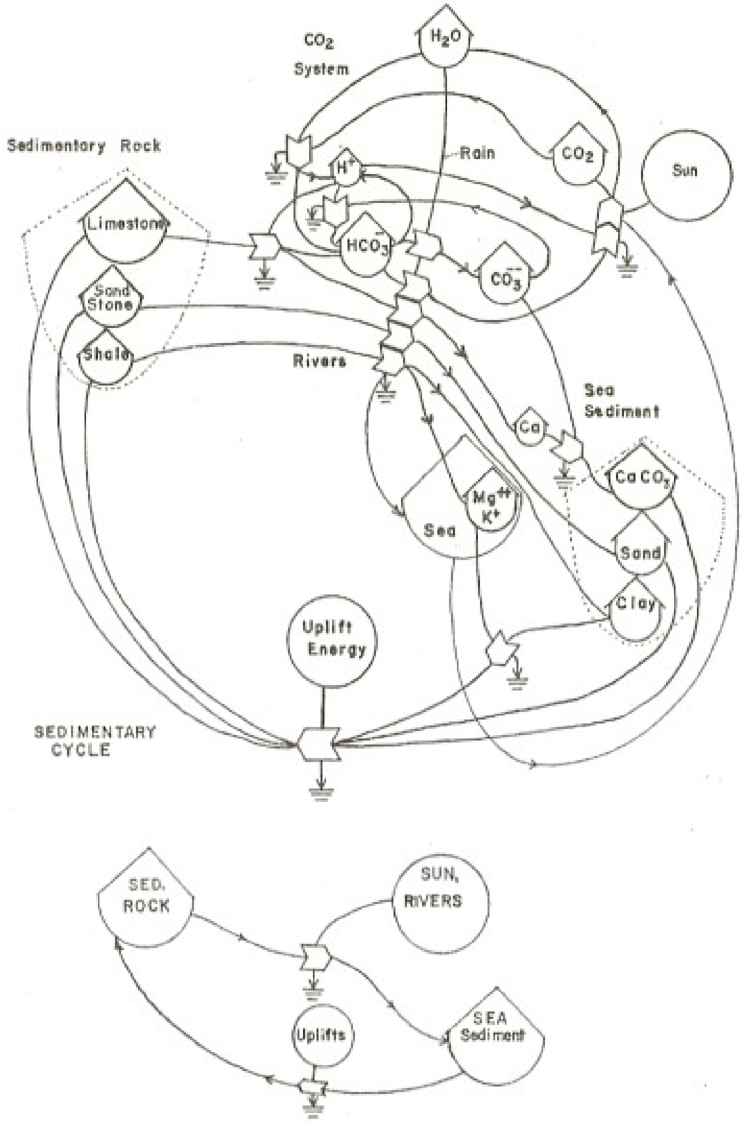
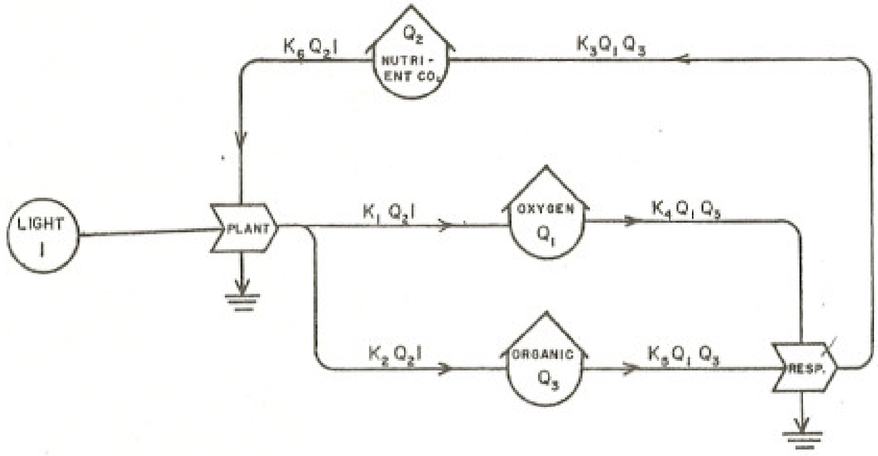


Fig. 9. Overall subsystem of the sedimentary cycle: (*a*) with details of limestone, sandstone, and shale circuits separated; (*b*) overall summary.

Continental Drift or Convection Spacing?

When there are convection vortices in a fluid, these are self-spacing forces, separating their centers of upcurrent while sharing downcurrents. What real evidence is there that mid-ocean ridges do not adjust similarly so as to maintain themselves halfway between the continental sedimentary cycles with asymetries for oceans where thrusts from the sea are different. Examination of a recent review written by Dickinson (1971) does not show facts which distinguish these interpretations.



$$Q_1 = K_1Q_2I - K_4Q_1Q_3$$
$$Q_2 = K_3Q_1Q_3 - K_6Q_2I$$
$$Q_3 = K_2Q_2I - K_5Q_1Q_3$$

Fig. 10. A three compartment model for the main oxidation and reduction system of the biosphere, the photosynthetic production, and recycling respiratory consumption.

Whereas continents may have been shifting some from time to time, they may have been kept spaced by near steady-state cycles. Continents may have congruent marginal shapes because the two counter-turning rotations are formed similarly by their mid-ocean sea floor circulations and vice versa. Is

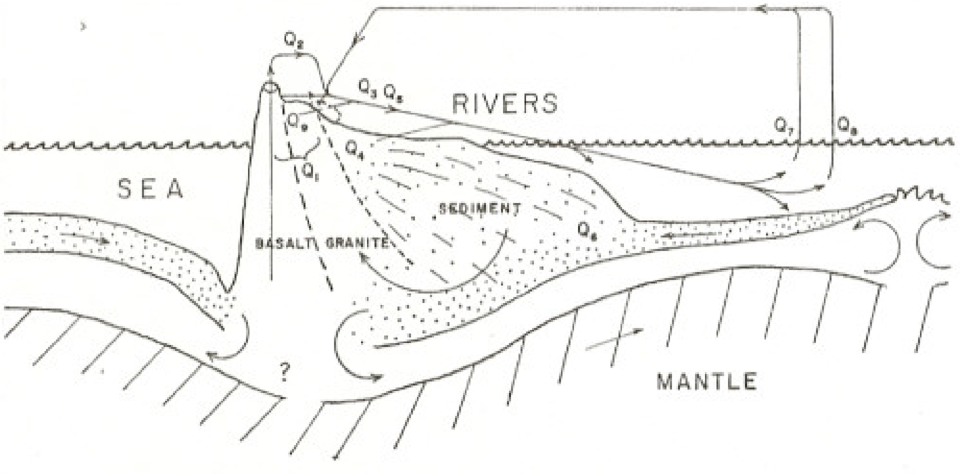


Fig. 11. Phases of earth cycles with compartmental designations used in the simulations in Fig. 14.

there need to postulate that the continents were part of one larger mass? Can we return to uniformitarianism, which was really an older way of describing faith in the steady states? It can be said that all transients are parts of a longer steady state and all steady states are made up of successional transients. For example, the Pacific with less sedimentation may require more area but develop more direct lateral thrust on North and South America equal to the under thrust of the sedimentary Atlantic. Such reasoning relates some of the lateral thrusts to the action of the weight of sedimentation.

Fig. 11 illustrates the familiar difference between the west coast of North America without much sedimentary cycle and the east coast in which the sedimentary cycle in its turning presses plate thrusts down and under the continental masses. The lateral thrust may be, thus, diverted more on the side with more sedimentation. As is well known, the relative role of the sedimentary cycle subsystem and the volcanic cycle subsystem vary, the former being large in the Atlantic and the latter in the Pacific. The higher concentrations of some photosynthetic nutrients, the size of the Pacific, and the atoll depositions are among the oceanic differences that the subsystem ratios may explain.

Where are the Input Energies?

In the world's cycles, one is not certain what the run-down state is or where the main energy inputs are in the cycles. As discussed in relation to Figs. 2 and 6 the coupling of energy input may be at the low energy states relative to the cycle. However, it is not clear whether elevated parts of the continents and the mid-Atlantic ridges are the high or the low energy parts of the cycles. The delivery of input energies to the cycle may be far removed from the orographic and volcanic regions. There may be heat release in crystallization and chemical reactions of transported "fuels" far removed from the energy sources. Or perhaps the motions draw on forces developed from energies elsewhere.

Possible Solar Chemical Drive to Earth Cycles

The energy for the sedimentary and volcanic cycles is often said to be from residual heat gradients, from heat released by radioactivity, and from the lateral weight transport by the atmosphere and oceans under solar drive. Another energy source of possible importance in sediments is the chemical potential energy in the combination of oxidized and reduced substances laid down together which can interact releasing heat when they are transported to sites of higher temperature and pressure. The overall sun's action in photosynthesis is neither oxidative nor reducing but a separation of the two that starts when photons separate electrons from plus charge sites in chloroplast semiconductor elements. As shown in the model in Fig. 10, the production system develops the oxidative and reducing materials that are then recombined in the work of life with a small part of both deposited in the sediments with particles of oxidized and reduced materials together. What is the chemical potential energy in bulk sediment?

Evidence that the deposition of organic and other chemical potential energies in sediments may be of adequate magnitude comes from the rates of heat diffusion from the lithosphere and the sea floor.

A heat diffusion of about 0.4 kcal/m^2/day would require a photosynthetic net deposition of about 0.05 g c/m^2/day, a figure of the right order of magnitude as compared with estimates of world photosynthetic production.

Even if it is not the sole energy source, the living system may be feeding back control action on the earth systems. Similarly, the carbon-dioxide content of the earth depends on the relative transfer coefficients of the consumer and producer parts of the "P and R" system as we sometimes call the model in Fig. 10.

We showed earlier in terrestrial microcosm measurements that the steady-state carbon-dioxide content in such systems could vary from 300 to 2 000 ppm depending on the ratios of producers to consumers (Odum, Lugo and Burns, 1970). In effect evolution controls the atmosphere and climate.

The Nonliving Feedback of Geochemical Structure to Pumping

Discussed at length in a recent book is the basic model for any surviving system by which there is a feedback from downstream rewarding the upstream pathway with some flow, augmenting service and giving the system competitive advantage over alternative circuits. The models already given in Figs. 5, 6, 8, 9, and 10 have this property. The means for this feedback is the processing of special energy from downstream into structure, storages, and high quality information that serve high degrees of amplification in their effect back upstream. This property may be most complex in living and economic systems, but it occurs in simple non-living systems as well. Weather systems build cumulonimbus clouds and cyclones as the structural means for feeding back services to augment further input energy flow. Turbulent eddies develop when the energy cost of eddies serves to accelerate energy flow over non-turbulent flow competition. The older geochemical systems developed a structure of storage distributions that was in inverse proportion to unit outflow rate as described by Lotka, thus, maintaining maximum flow. In earlier times before man, some of our concentrated types of mineral deposits developed until their outflows equalled their inflow rates. Pockets of free energy were maintained because they were necessary to the self-adjusting survival of the whole cyclic system in competition with alternatives competing for the same energies. These concentrations were the system's self developed structure.

In addition to the mineral concentrations, there were the continents which also served as flow augmenting feedback structures. By emerging above the water, continents harness the solar driven atmospheric systems more effectively, thus, promoting the lateral thrust plate and other processes developing and maintaining the continents. The distribution of the sedimentary cycle between continental circuits and the circuit under the ocean (including sea floor spreading) may keep the continents organized and serve as an energy separation division capable of sensitive self-correcting regulation, a boundary something like biological territories, tribal war systems, or ecological edges. When continents contain too much of the energies, the sedimentary cycle may run faster towards the sea; when the seas contain too much of the energy, landward pressures may increase.

One may regard other geological structural development as contributing to maximizing the earth's energy flow systems in similar reward loop mechanisms. There are the volcanic structures, the reef systems, the beach, the geosyncline sequences and other self developing means for storage of energy and information.

Competition from Life

In an overall sense, the evolution of life with a production and respiration system gradually becoming more and more efficient and detailed, stored the information and structure and began to drain flows of the earth's geochemistry away from purely inorganic cycles. Illustrated in Fig. 12 is the similarity of the role of life and the igneous cycle both taking in oxidized and reduced mixtures, putting out water, carbon-dioxide, and mineral substances important to the recycle. Culminating this evolution is the emergence of man, his culture, and finally his machines, some kind of ultimate in the pumping of these cycles.

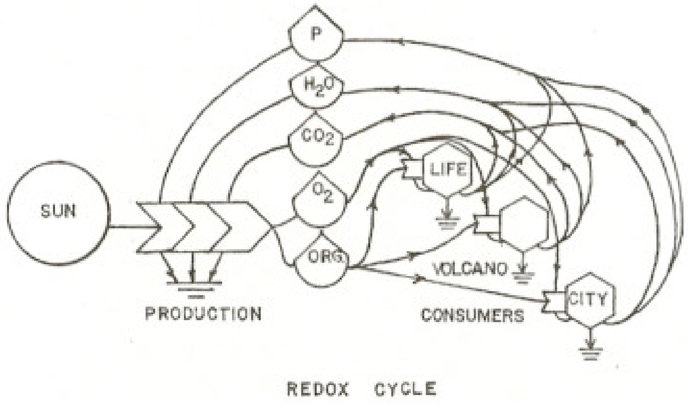


Fig. 12. A diagram of the cycle of production and regeneration compartmentalized to suggest the parallel and competing roles of the biosphere, the volcanic system and the urban system of man.

Man's System as a Volcanic Preemptor

The history of man's increasing capture of energies of the earth show him first a minor consumer, next the main consumer, then the main photosynthetic net producer, and then the main geochemical mining diverter, going deeper and deeper into diversion of the energies of the earth's system. Bertine and Goldberg (1971) and Goldberg in this symposium stress and measure the geochemical alterations by man's total system. Let us make the comparison that man is a fine tuned volcano just as life is a fine tuned fuel fire. Man's main consumptions of fossil fuels, mined raw materials, and water cause the smoke stacks and exhausts to put out acid volatiles such as hydrogen chloride, nitric and sulfuric acid, precursors just like the volcanoes leaving the alkaline elements in ash, solid wastes, and ground wastes. The overall model is given in Fig. 12. How much of the energy of future earth processes are, thus, diverted?

The Temporary Surge in Circuit Substitution

To understand the temporary surge of man's take-over of the geochemical cycle, refer to Fig. 13 where an old pathway below with large storages is replaced with a miniaturized system of man that does not keep large storages. As man begins to divert the fossil fuels, the concentrations of other chemical substances which served as free energy for control of the sedimentary, cycle serve as a surge when diverted to man's noösphere from the geochemical cycle. In principle, at least, the present accelerating civilization of man may be running on energies stolen from the mountain building cycle. Whether the magnitudes are or will become major is an open question. Even some of the nuclear energy that contributes heat to the earth system is being withdrawn now by man with his mining of nuclear fuels. As the diagram shows, the system that ultimately develops with the new pathway will not have the subsidy of using up the old system and will settle into a different steady state. When agricultural man

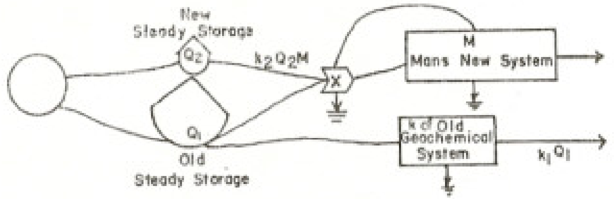


Fig. 13. A new system of man supplies miniaturized means for pumping flux in a geochemical pathway replacing an older system which used a large storage as means for facilitating flux. The old capital storage is available to accelerate the new system until it is exhausted.

displaced hunting man, something like this occurred in depleting the capital base of the hunting economy which was the great game animals and the forest soil. The capital of a discarded system helps to establish the new systems in its early stages, which survive only to the extent that they can stabilize when the subsidy is gone.

These aspects may be described by some generalizations from ecology that concern succession. When the starting state for succession has some large storages initially, the early development of a new system accelerates due to these energy sources, but later settles into a less energetic pattern because the costs of cycling utilize energies whereas in the initial condition the concentrations were already available as a resource. In other words, starting energies were higher than those inflowing at steady state. Thus, fertilized fish ponds return to a lesser metabolism when the inputs of fertilizer are stopped.

Simulation of a Simplified Model of the World Earth Geochemical System

The four intercoupled cycles that were drawn separately in Figs. 5, 8, 9, and 12 can be combined into one large model and simulated for various coefficients and initial conditions, a fairly tedious task with one coefficient to the pathway even for these simplified models. An international team with a lot of computer resources may be required for a larger model of many elements and subsystems. In the meantime, simpler ones can be considered. In Fig. 14 is a simplified model for a world cycle that has some of the sedimentary cycle, the igneous cycles, and hydrologic-cyclic salt flows that help us with ideas about the origin of the ocean. For aid to the reader, the algebraic terms of the system of differential equations are given on the diagram although the energy circuit language already means these. The analog computer diagram was drawn using this system of terms.

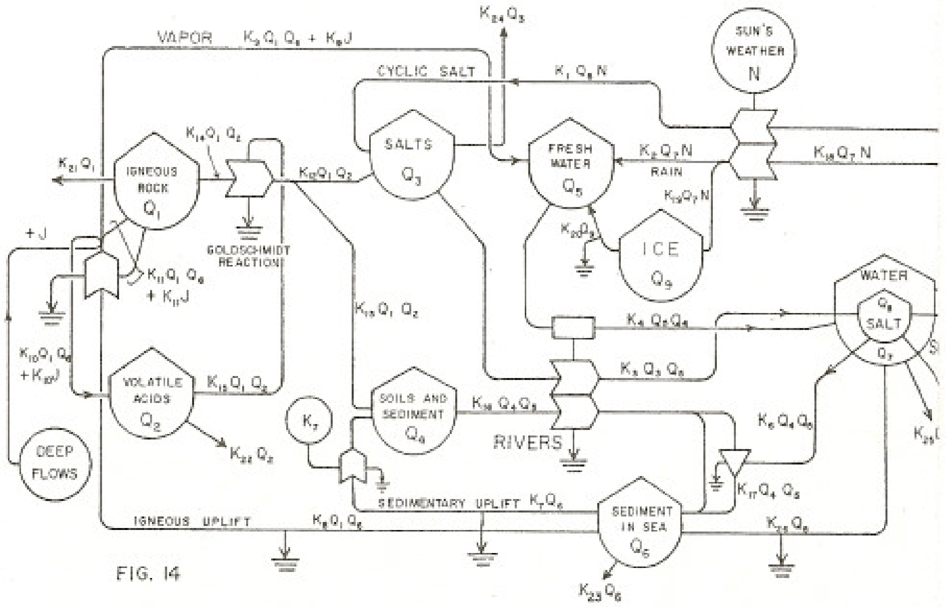


FIG. 14

Fig. 14. A simplified model for the early development of the ocean and its controlling cycles: igneous uplift and water release is an autocatalytic process like that of living units in feeding back structure as a pumping multiplier. Salts and soils develop from the Goldschmidt reaction. Sun drives the water cycle to which is coupled the movement of sediments and salts to the sea. The outside energy for uplift in this model is not specified and is held constant on both sedimentary and igneous uplift processes. There is a small flow from the deep earth and some return flow when there are high storage levels.

For estimating coefficients values of flux and stock that may have the correct order of magnitude were estimated and entered in the energy network diagram (Fig. 15). Given these at one time, one may calculate the transfer coefficient as the unknown. For example, if a multiplicative junction has known output flux (J) when input storages (A and B) originating the forces are known, then the output is calculated by solving for k.

$$J = kAB$$

The units used become those of the coefficient so that one may work with heterogeneous units.

After scaling the differential equations with the coefficients, the final analog computer diagram was generated as given in Fig. 16. The system was then

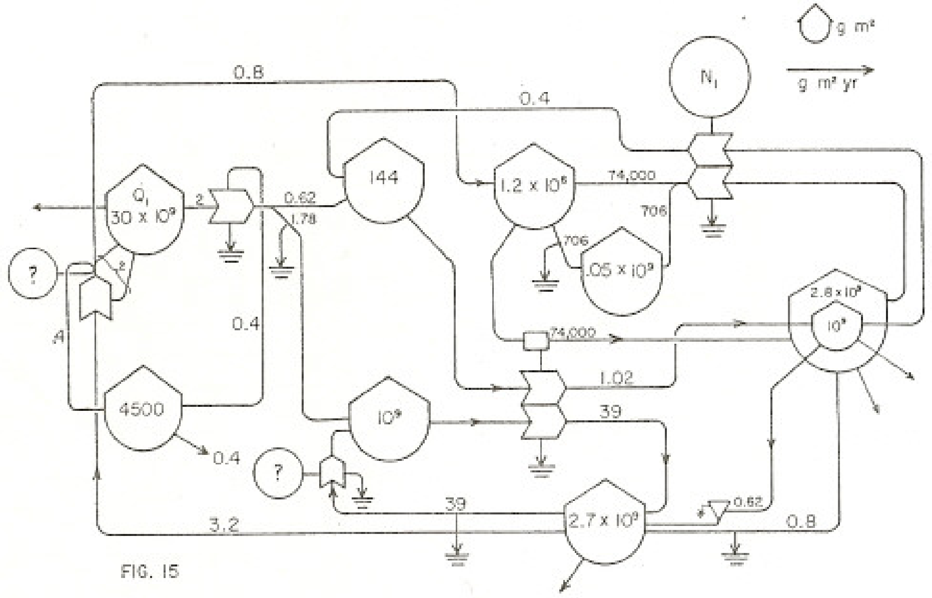
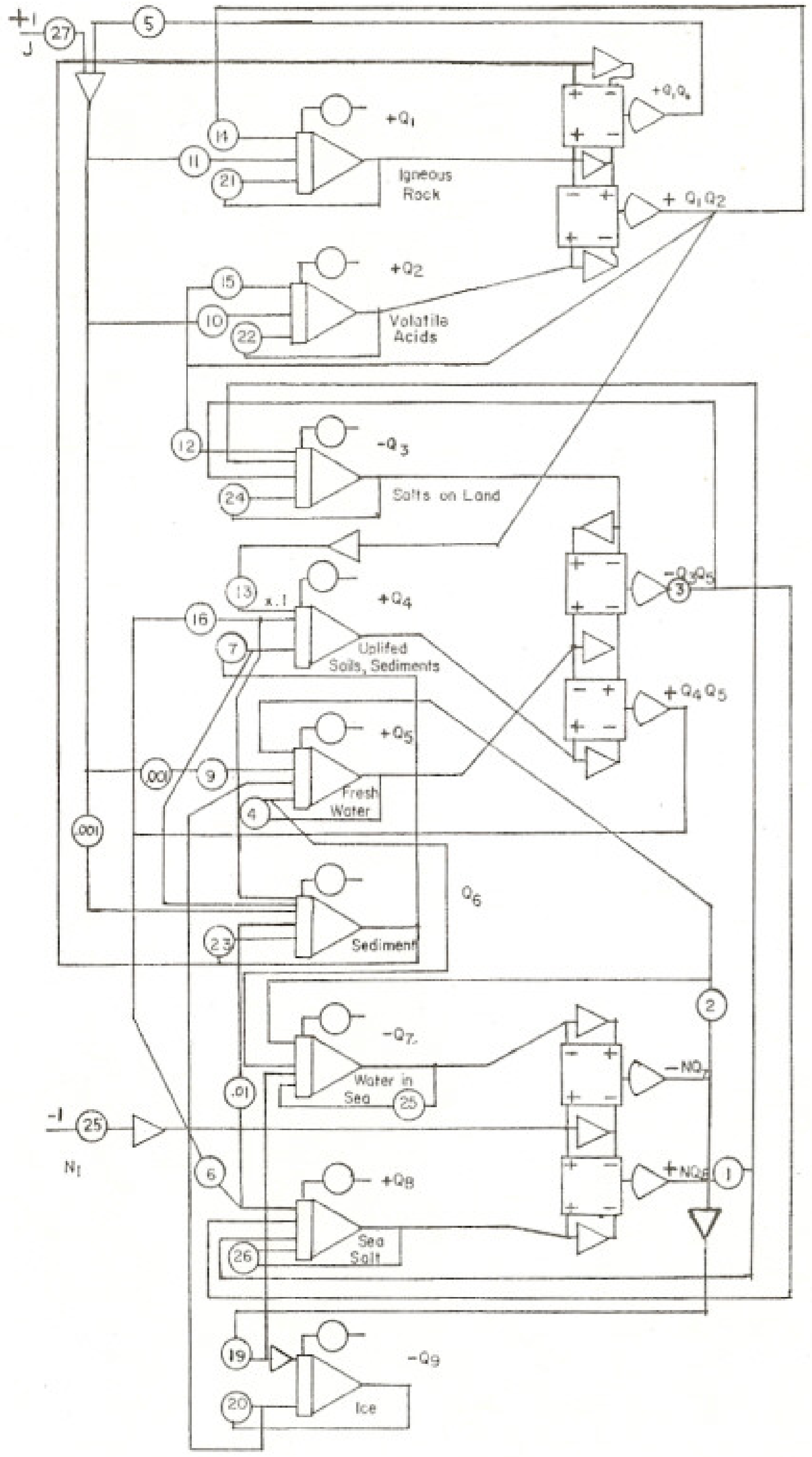


FIG. 15

Fig. 15. Estimates of stock and flux used in preliminary scaling of the earth mod diagrammed in Fig. 14.



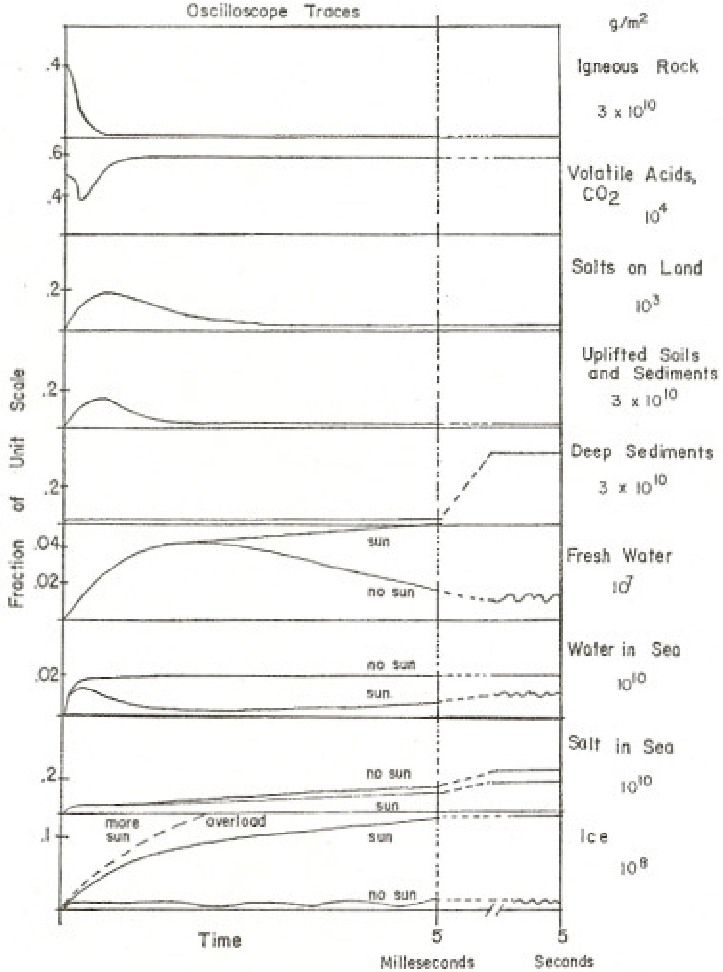


Fig. 17. Preliminary simulation of model in Fig. 14–16.

studied with oscilloscope output traces for various settings of initial conditions and coefficients. There are a very large number of possible combinations even with this simple system and it was useful to have the facility with which an analog computer allows one to vary coefficients at fingertip, turn pathways on and off, vary time scales, and study the system continuously on repeat operation mode. The temporal graphs of the storages are given for one particular setting in Fig. 17 with and without the solar drive forcing function on. The graphs in Fig. 17 represent 50 000 years to one million years. With the sun's action, the model builds a higher level of fresh water and the ice in the glaciers tends to overload beyond the scaling that we provide from our present ideas about possible extents of ice. This model has the property of Simpson's theory of increasing ice ages with the sun pumping more weather. Temperature and heat balance were held constant in this model. Only the water system develops oscillations and noise. For the starting condition of extensive igneous rock, the early part of the system shows a fast reaction with volatile acids, development of an ocean and a cycling salt system. In this model, the initial conditions regarding the amount of igneous rock and volatile acid was not important to the steady state that developed.

In the Harbaugh and Bonham-Carter simulation of sedimentary growth (Fig. 3), steady state was not reached although the model is of the exponential asymptotic first order type whereas the graphs in Fig. 17 did develop a steady-state ocean in a relatively short time. The ultimate differences depend on the rate of reincorporation of sediments into magma and the unknown rate of exchange with the deep phases of the earth.

How real such models are remains to be seen, but the ability of the simple system to produce some of the events of geologic history suggests the possibilities of this approach as it is refined.

Eutrophication of the Sea

One aspect of man's increasing role in the geochemistry of the sea is eutrophication, the acceleration of chemical inputs favoring photosynthesis. Much of the sea is oligotrophic, with dilute life, dilute organic matter concentrations, low concentrations of photosynthetic reactants, and an ecosystem that has developed very complex structure per unit energy available in the form of highly adapted animals such as the larger fishes that carry much of the critical storages and perform important programs of ecosystem management including chemical cycling. Oligotrophic systems can exist in steady state with organisms that cycle matter, process energies, and maintain similar patterns on the average year after year without any net storage gains and without any actions that progressively change structure. With energies scarce there may be evolution but at a slow rate since the energies in alternative choices are less than in more fertile systems. Parenthetically, it should be emphasized that steady state (the ecologist's climax) is possible in either eutrophic or oligotrophic states depending on the inputs as high or low. Also, it should be stated parenthetically that the oligotrophic sea may be processing sunlight with a much greater efficiency of gross photosynthesis than can be determined from metabolic exchange measures if one defines energy flows for only the first step, since the small nanoplankton may be cycling internally rapidly many times faster in the oligotrophic system.

A characteristic of low energy systems is the lack of energies of development of interactions and organization on larger scale. The oligotrophic open sea systems are tied together mainly through a few fish migrations and the physical current systems. Fig. 18*a* summarizes the essence of oligotrophy compared with eutrophy in Fig. 18*b*.

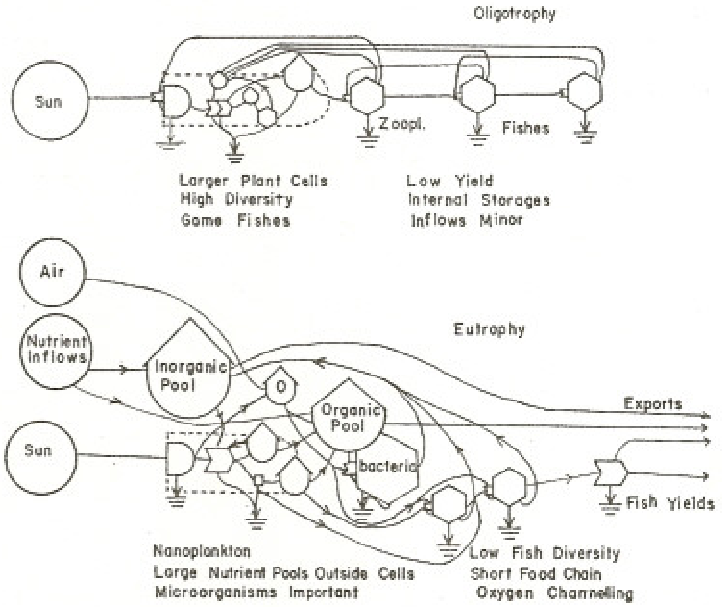


Fig. 18. Energy circuit diagrams comparing principal features of oligotrophic and eutrophic seas where the latter are induced by nutrient inflow.

Now the pattern changes as fossil fuel usages by man accelerate the geochemical cycles many of which bypass the older cycles. As long as there are high and accelerating energies of the urban system, the cyclic injections of the raw materials of photosynthesis into the sea increase the eutrophic zones, replacing the oligotrophic, internally-closed cycling system with one which is complete only as part of the larger cycle of land and water. The eutrophic waters do deposit organic chemical potential energy, shortcut many of the larger animals that are neither needed nor competitive with their programs for covering large areas with organizing functions. The rising organic matter concentrations permit foodchain pathways without so large a proportion of the systems work for concentrating actions. The role of direct micro-organism consumers increases, less work of microbial management by the animals being required. In shallow waters, plankton may replace bottom plant systems such as marine meadows, kelps, or coral reefs, the latter being natural eutrophic systems that derive auxiliary energies from current and wave energy pumping but require clear oligotrophic water.

Our land experience with agriculture suggests that the systems which can give high yields to other systems and to man are the ones that are eutrophic and also coupled to channeling mechanisms that remove yields and storages before they develop structure for their own consumption. The contrasting nature of such systems is given in Fig. 18.

Recent efforts to discuss the potential fish yields from the sea have been more realistic than some claims for feeding the world offered in an earlier decade. Present estimates, however, concern the fish yields possible with the present distribution of primary photosynthetic production (Ricker, 1969). Theoretically, as the runoffs of nutrients of the land accelerate with continuing urbanization, intensive agriculture, and increased energy budgets, the resulting eutrophication may be harnessed with much higher yields than now unless accompanying toxic wastes are offsetting.

Channeling the food of eutrophic systems is customary in agriculture and occurs naturally in some marine systems that have sharp pulses or in those with a separation of production and consumption that occurs in the streaming of upwelling zones. More general harnessing of eutrophic production into yield seems possible as coastal eutrophication increases.

Pond Microcosms for the New Coastal Eutrophic Systems

Something of the behavior of an oligotrophic marine system under eutrophication from the treated sewage wastes of man can be seen from our pond microcosms at Morehead City, N.C., where a U.S. Sea Grant Progam has completed a 3-year study of the ecosystems that develop by self design where seeding of species has been added similarly to ponds receiving waste and control ponds (Fig. 19). General summaries are given in project reports (Odum and Chestnut, 1970; Kuenzler and Chestnut, 1971).

Small in size and averaging 0.5 m in depth, these ponds were readily monitored for their total photosynthetic production and respiratory consumption of oxygen. Because diffusion exchange rates with the atmosphere in this situation are small compared to the large changes in concentration due to metabolism, it was possible to use the oxygen change from dawn minimum to late afternoon maximum as a measure of the days production and the change from afternoon to the next dawn as a measure of the nighttime consumption. Representative data from control and waste ponds are available from thesis work by Martha Smith and others included in Fig. 20–23. Figure 20 shows the rise and fall of the oxygen during August 1970 in one of the control ponds (C-3) compared with one of the P ponds. Figure 21 shows the calculated P (production) and R (respiration) values that resulted. Monthly means for a year are given in Fig. 22 and 23 for two of the same ponds.

Clearly the waste receiving microcosms have much higher basic production and respiration and the two are closely correlated as shown in the mirror image pattern in Fig. 21 as well as in other graphs of M. Smith's thesis. As long ago shown in freshwater fish pond studies, such increases are only partly transmitted to edible products.

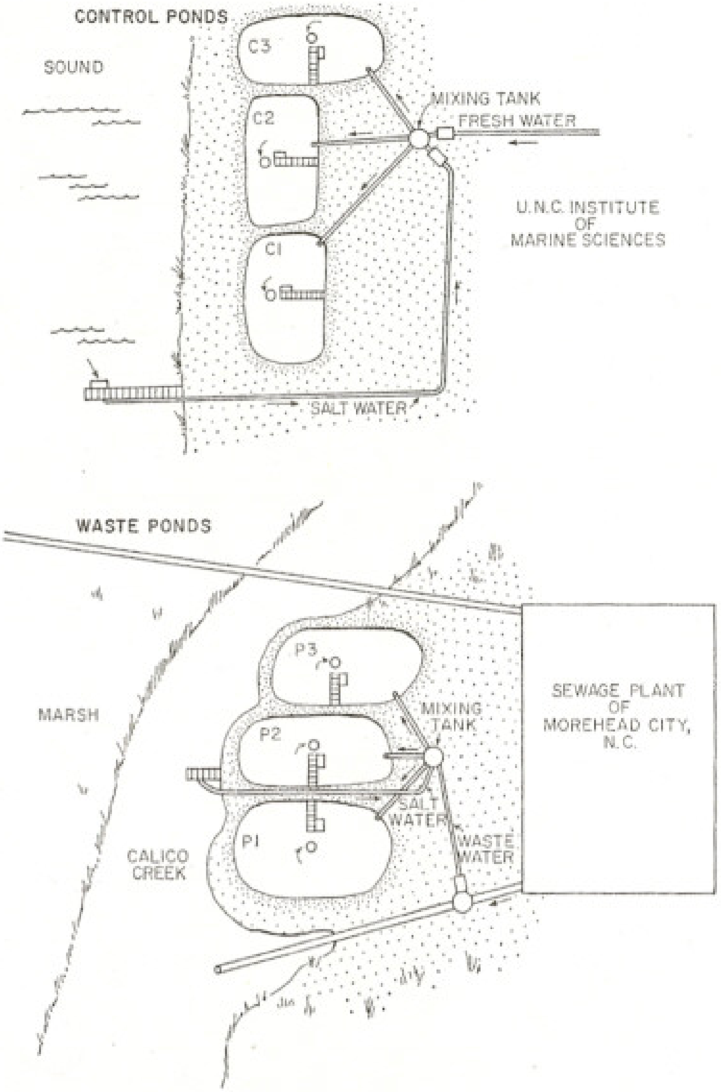


Fig. 19. Experimental marine ponds for study of self design of ecosystems developing with treated sewage: (*a*) control ponds receiving tap water and marine water; (*b*) experiment ponds receiving treated sewage mixed with sea water. Ponds are operated by Institute of Marine Sciences, University of North Carolina at Morehead City, North Carolina.

The waste ponds by maintaining intense blooms in winter and summer shaded out the bottom plants (*Ruppia*) that were covering two of the control ponds in the third year. The storage of nutrients and chlorophyll in algal blooms was heaviest in the winter although metabolism was much less then. The plankton was dominated by copepod *Oithona* and the bottoms by the

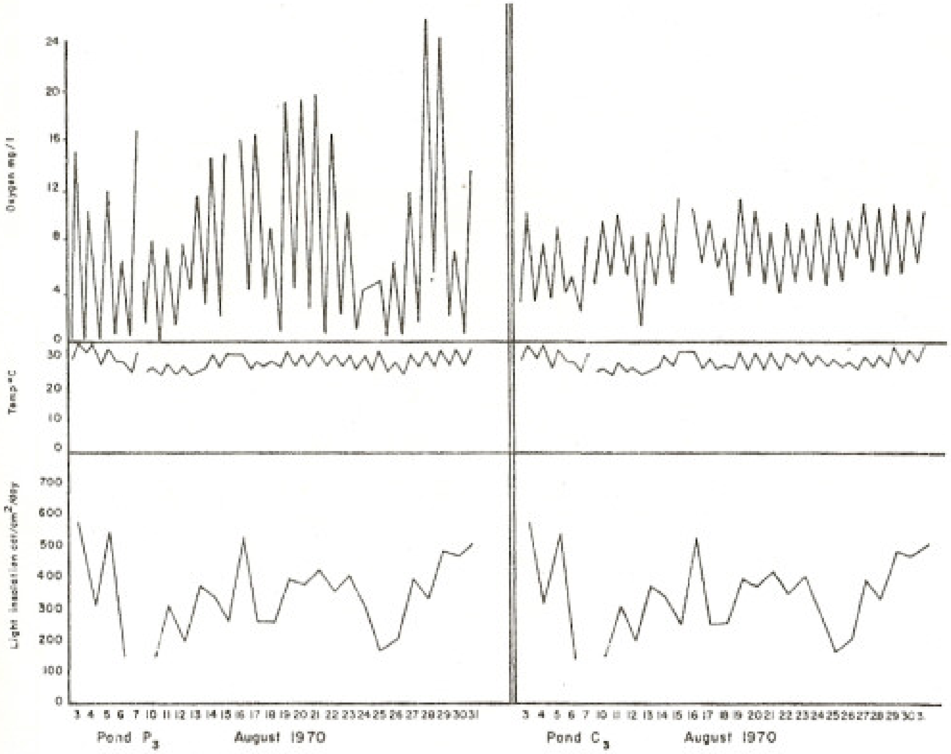


Fig. 20. Records of oxygen temperature and insolation for Waste Pond P-3 and Control Pond C-3 during August, 1070 from Smith (1971). Oxygen and temperature were measured at dawn and at 1630.

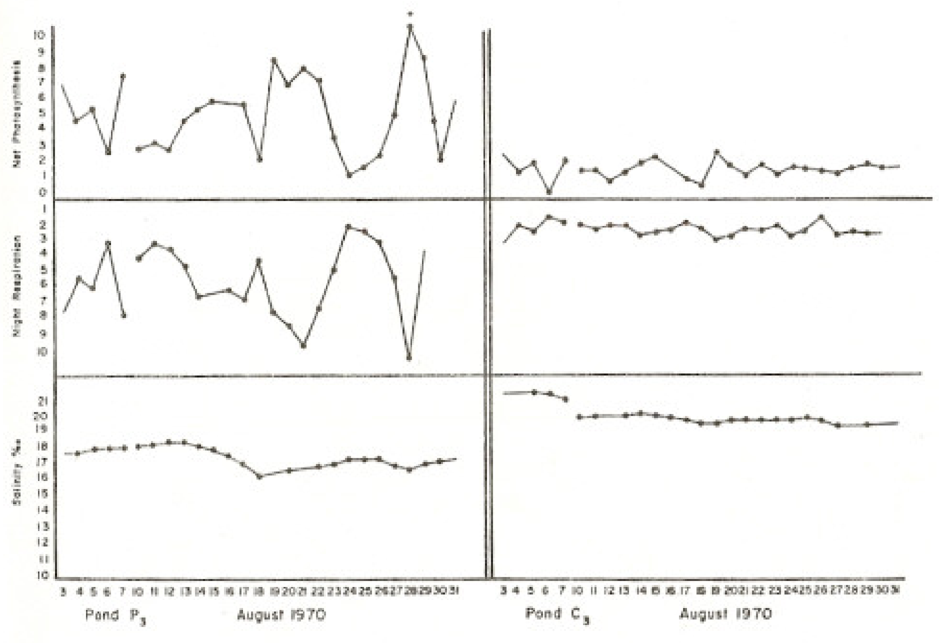


Fig. 21. Daytime net production and night respiration calculated for Waste Pond P-3 and Control Pond C-3 based on oxygen data in Fig. 20 from Smith (1971).

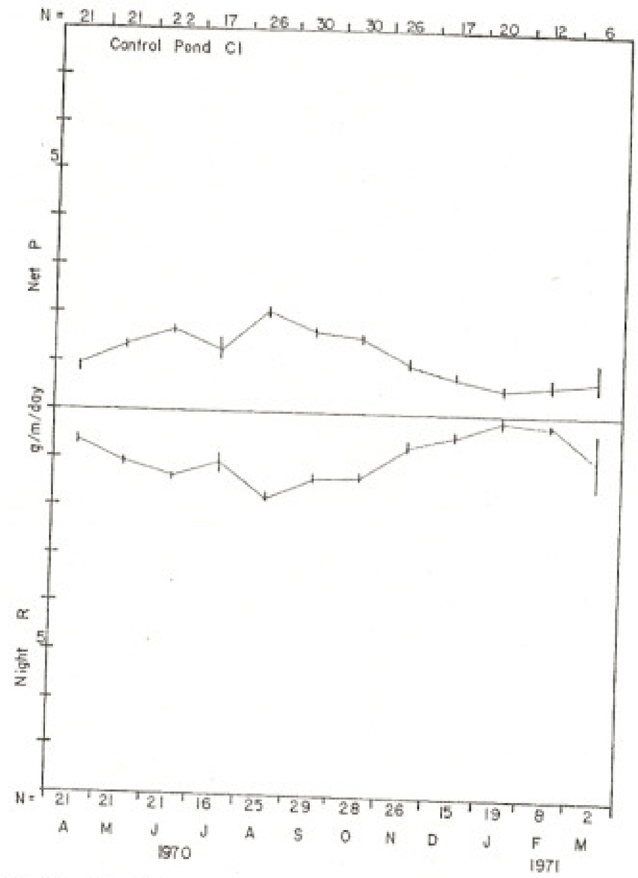


Fig. 22. Monthly mean records of daytime net production and nighttime respiration for Control Pond C-1.

annelid *Capitella.* Larger moving consumers were dominated by grass shrimp, *Paleomonetes*; small air breathing fishes, *Cyprinodon, Fundulus, Gambusia*; and blue crabs, (*Callinectes*). The ponds were apparently exporting substantial protein yields to water fowl also. Many properties found in the third year were like those in the second year; the ponds were beginning to approach steady state in some aspects.

Diurnal Simulation Models

The rise and fall of the oxygen in these ponds like that in many others studied in our previous work in shallow estuaries has established the shape of the daily curves as that predicted by simulations of the P and R model in Fig. 10 (Odum,

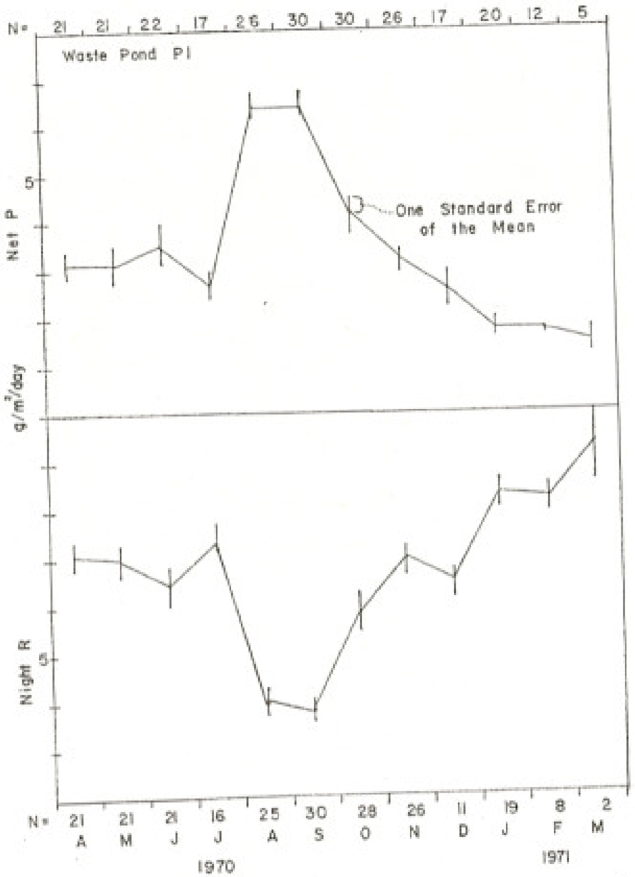


Fig. 23. Monthly mean records of net daytime oxygen production and nighttime respiration for Sewage Waste Pond P-1.

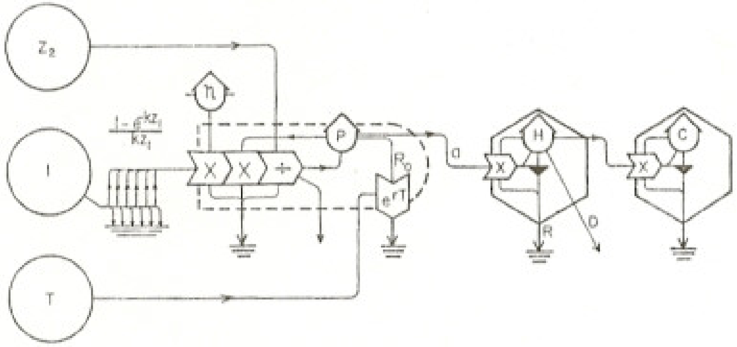
Armstrong and Beyers, 1963; see general discussion, Odum, 1971). The correlation of diurnal day production and night respiration of the simple model is like that of the real world systems.

Among other studies done in our group project was a study of the carbon cycle in these ponds including analog simulation of the diurnal pattern in doctoral dissertation by John Day (1971) with C. Weiss and the phosphorus cycle by H. McKellar (1971) with E. J. Kuenzler including an analog computer simulation for diurnal phosphorus movements. These chemical cycle studies follow the same general methodology of six steps as follows: (1) draw a materials or an energy circuit diagram, (2) write the differential equations, (3) diagram the equations in analog computer language, (4) do the simulation, (5) compare the simulation graphs with observed curves, and (6) readjust the model to improve fit.

Seasonal Simulations of an Estuarine Model with Recycling

One of the first seasonal simulations of a marine ecosystem was done by G. Riley for north Atlantic Waters in 1945, doing the calculations by hand in the pre-computer period. If we take his models given in differential equation form (Riley, 1945, 1946) and translate into the energy circuit language, we obtain the diagram in Fig. 24 which has multiplicative limiting factor actions for nutrients and phytoplankton stock and logistic structure for herbivores (H) and carnivores (C), Riley's model appropriately has turbulent dilution action (Z) and a non-linear temperature action on respiratory drains on the plants. However, there is no feature of recycled nutrients included of the type already given in Fig. 10. Later models such as one by J. Steele at this symposium do have the recycling feature. Recent models for the Peru current by Walsh and Dugdale (1970) simulate the nutrient actions in upwelling stream with similar features.

In Fig. 25 is a simplified model for our sewage waste ponds prepared by W. Smith, J. Day and H. T. Odum which includes inflow and outflows, and recycling of nutrients by consumers, storages for organic and inorganic nutrients, a parallel competing subsystem of bottom plants favored by current but sensitive to shading out by phytoplankton when nutrients are high. Values for storage and flux of the order of magnitude measured in the ponds were used to estimate coefficients. As in the previously discussed example in Fig. 14–16, the energy circuit diagram is a way of writing the differential equations and is a computer program when the coefficients are added. To help the reader not used to the language, the algebraic terms were added although this is unnecessary re-



$$\dot{P} = P\left[p\left(\frac{I_0[1 - e^{-kz_1}]}{kz_1}\right)\frac{n}{K}\,\frac{Z_1}{Z_2} - R_0 e^{rT} - gH\right]$$

$$\dot{H} = H\left[a - R - C - D\right]$$

Fig. 24. Energy circuit translation of models simulated by Riley (1946, 1947). Light, *I*; temperature, *T*; turbulence, *Z*; depth, *z*; herbivores, *H*; carnivores, *C*; *D*, mortality losses; *n*, nutrient concentration.

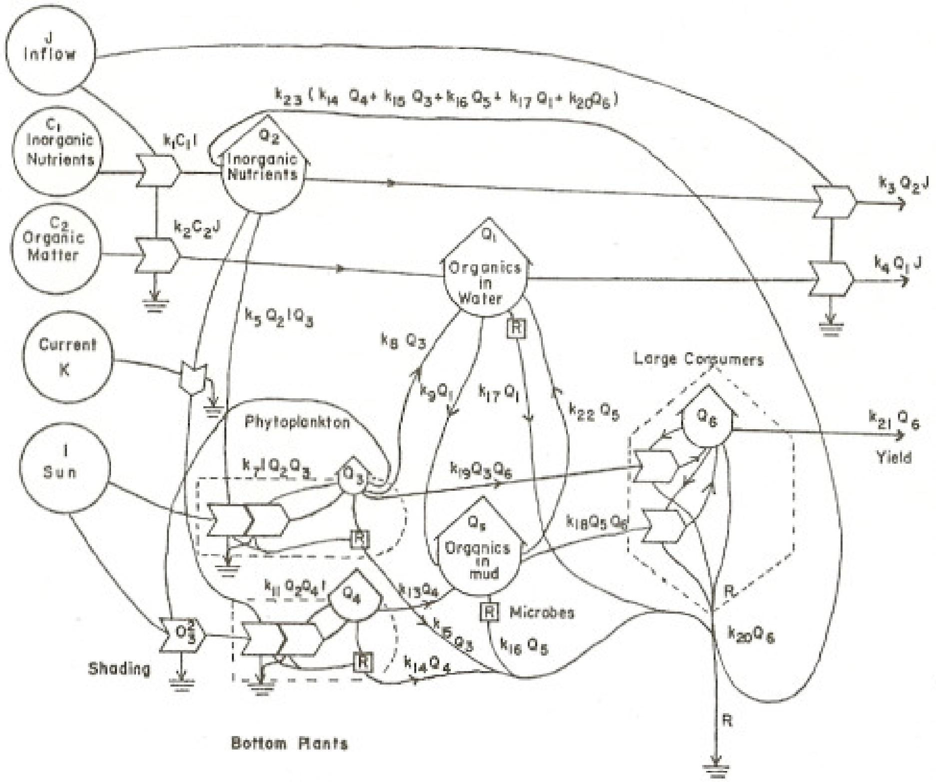


Fig. 25. Simplified model of waste pond estuarine microcosms used for simulation in Fig. 26 (H. T. Odum, J. Day, and W. Smith).

dundancy. This model was patched on analog computer with the usual steps of translating into a diagram of hardware like that in Fig. 16. Then the model was simulated (Fig. 26) with an annual sine wave as input forcing function for light like that with season in the real world. Fig. 16 is the simulation with one setting. The input forcing curve is at the top representing light. Short term oscillations were observed in the phytoplankton as in blooms in nature, and the maximum phytoplankton was in the winter as in the real ponds. Apparently, even this simple one cycle model accounted for some of the main features of these ecosystems.

Maximization of Power by Self Adjusting Storages that Pulse Recycling Pathways

Many of the simulations of ecological systems have involved linear pathways transferring energy downstream from solar sources without multiplicative feedback pathways. However, the property of a multiplicative feedback which rewards the upstream system for its contribution to the downstream unit may be associated with survival and, thus, with all real ecological and geochemical

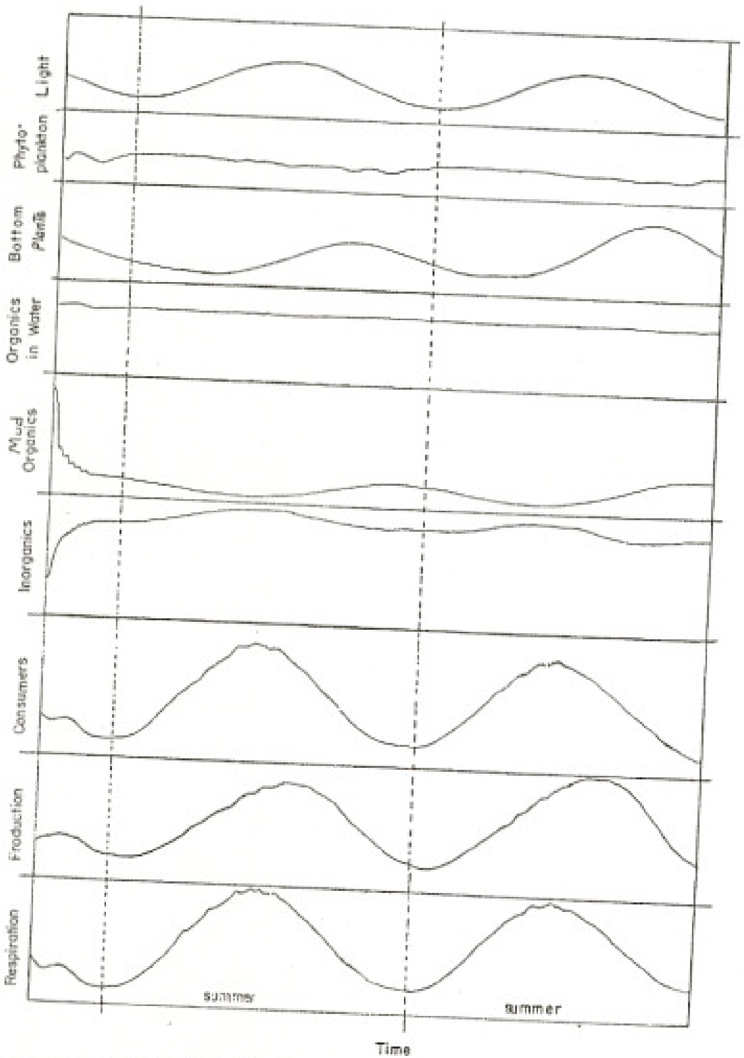


Fig. 26. A simulation of stabilization (succession) and seasonal pattern of the model in Fig. 25 with an input sine wave for light intensity.

systems. Loop reward pathways allows the downstream unit to develop timing relationships that maximize the systems effectiveness in gaining input energy.

For example, Williams (1971) in simulating Lindeman's system of food webs for Cedar Bog Lake, Minnesota, without such multiplicative feedback finds the seasonal pulse of production preceding that of the next level of consumers (the herbivores) and this preceding the pulse of the higher consumers. Yet, as we found in Texas bays (Odum, 1967), the real systems have inherent in their structure of pathways the means for adjusting the pulse of consumption to be simultaneous or earlier than the photosynthesis, thus, providing nutrient

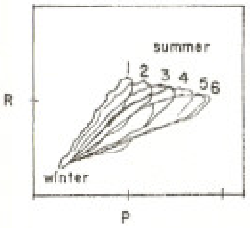


Fig. 27. X – Y recording of P and R in the model of Fig. 25 during the 6 sine wave undulations (years) required to achieve steady state. During succession input production was increased. This simulation started with an initial condition of high organic content in Q_5 because ponds were built with organic mud.

recycling and other work services such as reproduction necessary for maximizing the ability of the system to use the increasing sunlight in the annual cycle. The sewage waste ponds also show P and R processes staying together seasonally as well as diurnally (Fig. 22–23). Is this a property of models of the type which we used to discuss the nature of eutrophication in Fig. 18?

When the model in Fig. 25 was simulated to learn its behavior in succession and in response to a sinusoidal annual variation of light, the model developed adjustments of its nutrients and organic matter storages so that consumption was pulsed in advance of production during the annual cycle, in effect, insuring high concentrations of those recycled items needed for maximization. The model was self-maximizing in respect to the adjustment of storage quantities available to it. Fig. 27 shows the graph of P and R during one simulation of the first 12 cycles, steady state being developed in the 6th year.

Interface Regulation and Yield Possibilities

The microcosms for eutrophication done in this project and the models that help us understand them suggest that increasing eutrophication of the coastal seas may see self stabilizing adjustments in which the chemical cycles are principle control mechanisms. The chemical cycles quite apart from more complex biological succession and evolution may have relatively short-time periods for chemical cycle stabilization. With P and R similar, the eutrophic systems without management may be neither waste disposing nor waste generating, but rather systems for self regulating, power rich interface between man and his more dilute open seas.

Our ponds were inventoried by the group in 1971 after 3 years of self design processes that followed much seeding of miscellaneous organisms. Under the conditions of oxygen extremes, the fertile waste ponds were found with fewer species of higher edible animals than in the control ponds which had a rather normal estuarine composition. Mainly animals capable of air breathing were left in the waste ponds. Because of low oxygen conditions on many predawn mornings, the fishes and crabs surviving were often observed at dawn in the shore shallows washing their gills with surface film waters, making them prime targets for waterfowl that were much attracted to these ponds.

It was a fascinating realization that the oxygen extremes were channeling the food flows into relatively few species with oxygen adaptations. The channeling service was not free since special energies were diverted in the work of adaptation by these species, but the system was much like terrestrial agricultural systems where channeling is done with weeding agents. If such areas can be provided oxygen refuges into which fishes and crabs can move during low oxygen periods, a means is provided for aquaculture harvest, for culling, and for use of species that need more oxygen.

Summary. Value

The systems of chemical cycle pathways are being captured by man's accelerating control of the earth's energy sources with such symptoms as coastal eutrophication and the substitution of his pathways for many of those of the volcano and sedimentary cycle. The energy circuit language helps us recognize principles of energy of chemical cycles that apply to man's new cycles as well as to the simpler old ones. These abstractions may help us attain the simplicity and synthesis for whole earth simulations and perceptions.

In previous discussion (Odum, 1971) we found the state of competitive survival at maximum power attainable by a system of man and nature when it uses both its solar based resources and its energy flows from fossil fuels, not allowing one to interfere with the other. If value is also identifiable with maximum power flows, then maximum value also follows the dual uses of the geochemical cycle inputs and those of the sun directly. Ultimately, there may develop the possibility of man directing too much away from geochemical cycles so that the optimum utilization of sun and sea diminishes. Is man a better volcano and better at aiding the sedimentary cycle than the older geochemical systems in the sense of developing stable steady states which maximize power and, thus, value towards useful purposes related to total system survival?

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