GARDNER 3

ENERGY VALUES OF WATER RESOURCES

by

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With a world sensitized on environmental issues, it is appropriate to respond to our Governor Robert Scott's call yesterday for a harmonious forward view for both economics and ecology and it becomes the business of a technical conference to provide means for this objective. By now it has been well established that simple ignoring of our life support system while draining mightily its services for us is generating damage to this essential part of the space ship earth. Man's decisions have usually been based on dollar calculations whereas the services of the natural members of our world have often been excluded from cost evaluation. We would not attempt to do business among corporations and leave out the most important member from the cost-benefit studies. Yet that is what we usually do when we ignore the services of our environmental systems. The natural sectors of our planet are silent corporations whose great services are first noticed when they have been lost.

People are now awakening to the problem and our leaders have called for quantitative solutions. How do we put the self operating natural members of the industry and the human operated members in the same calculations of value and pertinence? Can we use a currency that is common to both nature and man, which is energy flow. Let us calculate the contributions of each part of our overall economy of man and nature in calories and then convert back to dollars so as to compare the magnitudes with our previous experience. This approach applies to all the problems of man and environment, but consider here only some values of water.

A major part of the system of man and nature is a water cycle which starts with the action of sun's energy in distilling waters into the atmosphere, distributing it over the land where it serves as necessary raw material in many processes. It is a source of potential energy in many senses (Fig. 1). First, it has potential energy relative to gravity from sea level because of its height. Next, water serves as a fuel for chemical washing, solution, and reaction processes which are driven by concentration differences between water and its reactants. As a sink for absorbing, diluting, and metabolizing waste, the water's usefulness is proportional to the potential energy changes that go with the change of concentrations of substances dissolved. When waters are used to irrigate a desert where sunlight is in excess, water is the limiting factor and thus the main source in that process. Its value is the power flow that it facilitates.

On its circuitous road to the sea, water is re-used in many processes gradually losing its altitude and its purity, becoming at sea level ready for new energy from the sun. Whereas we are used to evaluations of hydroelectric potential, we have rarely evaluated the chemical energy values of water resources. In this communication let us compare some magnitudes. First it may be helpful for

Reprinted from *Proceedings Nineteenth Southern Water Resources and Pollution Control Conference—April 1970.*

exposition to diagram the water cycle and then the energy flows associated with the water.

Lotka Circle

In Figure 1 and 2 are shown water cycles and energy diagrams for the water cycle considering the stages of water as vapor, fresh rain, delta water with its solutes, and open sea water. At each step the rate is proportional to concentration according to conductivities that are inversely proportional to rate at steady state as shown in equation (1). The expression given is derived from Lotka (1925). Here transfer coefficients (k's) may be due to additional energy sources which are coupled so as to pump the flow of water from the sea into the atmosphere. Vapor formation is coupled to solar energy which drives the processes of evaporation, moving air, and rainfall.

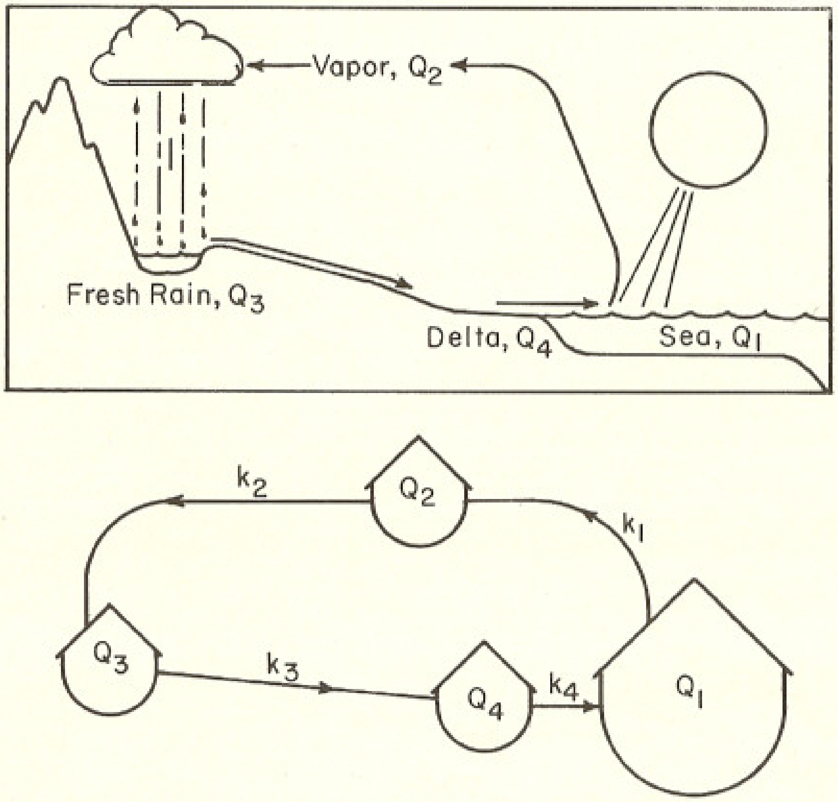

Figure 1

Fig. 1. Diagram of the water cycle showing four main compartments where Q's are the quantity of water storage and k's as the transfer coefficients relating upstream storage to downstream flow. A simple view is provided by compartmentalization of the cycle into 4 storages and 4 pathways.

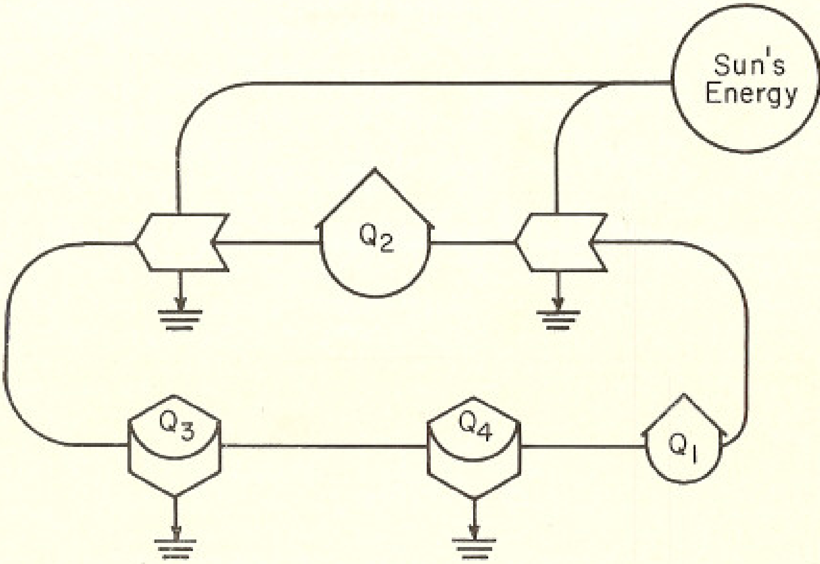

Figure 2

Fig. 2. Energy diagram for the same water circuit shown in Fig. 1. Potentia energy is injected from the sun in the first two stages. Energy is ultimately dispersed in heat as shown by the heat sink arrows as heat leaves the system. Q and Q_4 have feedbacks from their storage into maintenance of their own structura

flow systems. See details on energy symbols elsewhere (Odum, 1970).

A property of the cycle relationship in Fig. 1 and in equation (1) is th accumulation of stock (Q) upstream from bottlenecks in inverse relation to transfe coefficients. For example, steps requiring coupled energy from the sun may b limiting hence water accumulates in the stage preceding. The largest accumulatio is in the sea where it waits for the pumping energies of solar insolation.

$$Q_1 : Q_2 : Q_3 : Q_4 = \frac{1}{k_1} : \frac{1}{k_2} : \frac{1}{k_3} : \frac{1}{k_4} \qquad (1)$$

The energy diagram in Fig. 2 shows all of the energy inputs which ar coupled to drive the water cycle and to differentiate between those work flow which pump the water without changing the content of potential energy an other processes which increase the potential energy of the water as chemical fuel For example the distillation from the sea to the land raises the potential of th water as a cleaning fluid. When the rains run together in streams the potentia energy of gravity is converted into work of transport helping to concentrat chemical potential energies as the waters are concentrated in reservoirs. This i a form of power transformation in which potential energy over a broad area i concentrated into high density locally at the expense of dilution elsewhere. Simila processes are familiar in electrical power transmissions. The value of waters t us is in the cumulative energy costs in these natural processes in providing us our clean water resource.

Comparison of Some Magnitudes of Energy in Water Uses

Whereas we think of the potential energy values of elevated water as a valuable hydroelectric resource and input to our economy and to the economy of the natural life sector, how do these familiar values compare with some other energy values of the same water.

We may calculate the total hydroelectric potential energy per milliliter of water by multiplying height, density, and gravity as shown in equation (2). For example, if the average height of land were 300 meters and the density about 1 gram per milliliter the acceleration of gravity, 980 cm/sec², and the conversion factor for gram calories to ergs 2.39 x 10^{-8} then the potential energy per milliliter of water is about 0.7 gram calories per milliliter. This amount of potential energy is not very great per milliliter compared to the energy required to evaporate water which is of the order of 540 gram calories per milliliter even when done very slowly (reversibly).

$$
\begin{aligned}
\Delta G &= h\rho g \\
&= (300 \times 10^{2}\,\mathrm{cm})(1.0\,\mathrm{g/ml})(980\,\mathrm{cm/sec^{2}})(2.39 \times 10^{-8}\,\mathrm{gcal/erg}) \qquad (2)\\
&= 0.7\,\mathrm{gcal/ml}
\end{aligned}
$$

Next consider the chemical potential energy of 1 gram of clean water relative to its usual composition when that water reaches the sea. Livingston (1963) gives 120 parts per million as the content of dissolved substances in usual delta water. Rainwater however has 1.2 parts per million of dissolved substances such as nitrates. The chemical potential energy in the difference in concentration can be calculated from equation (3). If the predominant molecular species have molecular weights of about 35, if the gas constant used as 1.99 gram calories per degree-mole and if the absolute temperature is 300°, then the free energy is about 78 gram calories per gram of dissolved matter. The standard free energy in this example is the logarithm of 1 and thus is 0. Per gallon of water (3.8 liters) this is 37 gcal.

$$
\begin{aligned}
\Delta F &= \Delta F_0 + nRT \ln \frac{C_2}{C_1} \\
&= \left(\frac{1}{35}\,\mathrm{moles/g}\right)(1.99\,\mathrm{cal/deg\text{-}mole})(300^\circ)\left(\ln \frac{1.2}{120}\right) \qquad (3)\\
&= -78\,\mathrm{gcal/g\ of\ salts}
\end{aligned}
$$

Similarly one may calculate the potential energy in delta water relative to the high salinity water of the open sea. With about 120 parts per million in delta water and 35,000 parts per million in full strength sea water, the order of magnitude per gram of dissolved substance is similar to that between rain water and delta water but more per volume of water since there are more solutes. A rough calculation in expression (4) yields about 97 gram calories per gram of salt. The chemical potential energy is greater as seen from these calculations than the potential energy of elevation against gravity. This potential energy is available for various kinds of work: cleaning, chemical reactions; biological processes, and in the estuary, differences in salt content act through density differences to develop currents, causing mixing and other work for estuarine animals and plants. These same differences measure the value of water as a sink to accept wastes.

$$\Delta F = \left(\frac{1}{35}\right)(1.99)(300)\left(\ln \frac{120}{35,000}\right) = -97 \text{ gcal/g} \qquad (4)$$

Per gallon this is 12,920 gcal. Per gram of dissolved stuffs, the energy in solution of 2 orders of magnitude is similar for trace concentrations as for high concentrations. Per gallon of water however the values are much higher as solutes increase.

Another kind of energy value is in water's contribution to complex processes of living metabolism by supply of the limiting reactant to pathways capable of using the water with large amplification effect. The value of the water as a potential energy source to biological processes of forest or of agriculture are illustrated by the energy diagram in Fig. 3 for a desert agriculture. Here 5000 kilocalories per square meter per day of solar energy is in excess in the limiting factor to the system of photosynthetic production in fresh water. If about 1% of freshwater is incorporated into organic matter the other 99% being required for evapotranspiration, then the potential value of the water may be given in equation (5). For this particular example the chemical potential energy of water is about 68 gram calories per gram, a value of the same general magnitude of the other as in Table 1. To divert water from a forest or an agricultural system to an industry is to divert an important source of energy, and an adequate recognition of its value to the economic system is essential for any sensible management of an overall system of man and nature.

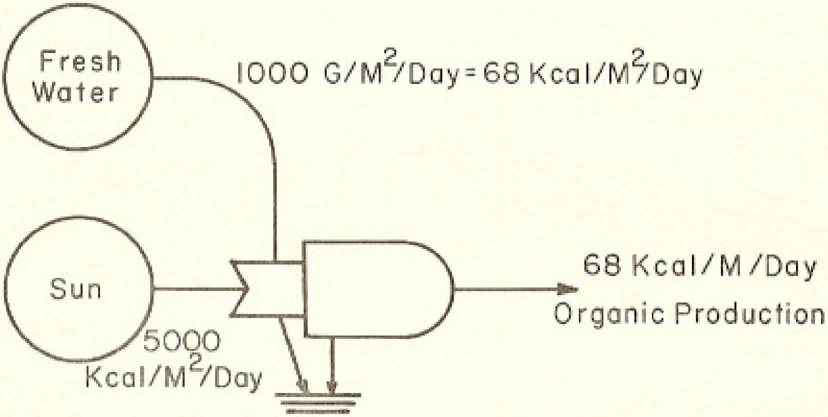

Figure 3

Fig. 3. Energy diagram for photosynthesis in desert agriculture where fresh water is a limiting factor and becomes a principle energy source.

TABLE 1.
POTENTIAL ENERGY VALUES OF WATER

	gcal/g H_2O	*Kcal/m²/day**
As weight, 333 m above the sea	0.7	2.4
As chemical reactant, rainwater relative to delta water	0.0094	0.038
As chemical reactant, delta water relative to sea water	3.4	12.7
As photosynthetic requirement where other requirements are in excess	68	236

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*50 inches of rainfall; 3760 g/m2/day.

Next compare these values on an area of land basis. Suppose a location receives an ordinary 50 inches of rain (127 cm per year) per day 0.348 cm per square meter is received there (3480 milliliters). Shown in Table 1 are these contributions of potential energy of water on an area basis with this rainfall.

$$\frac{(68\ \text{kcal/m}^2\text{/day food production})}{(1000\ \text{g}\ H_2O\ \text{used/m}^2\text{/day})} = 68\ \text{gcal/g photosynthesis} \qquad (5)$$

The potential energy values of water (Table 1) are high compared to potential energy values of photosynthetic production, which may have a magnitude in summertime of 68 kilocalories per square meter per day. These calculations show that water where used as a limiting factor in a high power process is a high grade energy fuel for chemical and biological processes with high values to our economic system in the same sense as our other chemical fuels such as oil or coal. The waters used to keep the forests, fields, lakes and estuaries ecological systems viable have similar values although we have formed a bad habit of thinking of these as free and outside our economic thinking.

As shown in previous papers (Odum, 1968, 1970) the recycling of money in an economy may be compared to the recycling of the work in that same economy. For the U. S. about 10,000 kilocalories of fuel energies are spent in work for each dollar in the U. S. economy, although the exact value changes. However, the inflow of potential energy and work services from the natural sector is not figured into the money and thus the very large values of nature's work in life support is not estimated on the same scale and becomes ignored and exploited inadvertently. The input to man's well-being in partnership with nature energetically is as great or greater than his works for himself, but he doesn't realize it because he takes it for granted and does not include dollar evaluation of the natural member of the economy. This is easily corrected by making the evaluations in energetic terms first and then converting energies to dollars with such ratios as the one above for purposes of presenting the data to audiences used to money magnitudes. The work of a forest or stream for the good of the system is just as valuable as if a corporation was doing it and expecting to be paid. Nature's works for us are as much a contribution to the energy of the system as the works which are transmitted through humans. Hence any effective consideration of the economics of both man and nature require that energies be used or that an energy equivalent to dollars be established for the contributions to the human system from the life supporting planet. If 10,000 kilocalories per dollar is used for figures in Table 1, the value of water in some uses in nature, agriculture or industry becomes about a dollar per twelve gallons. This is a much higher value than is now based on the human work necessary to take water from a reservoir situation and process it into the city. Processing costs, in humid regions, are of the magnitude of a dollar per 4,000 gallons.

The use of water for industry or cities constitutes a drain of value and energies from other systems which are part of our life support system which also does many services for our planet: maintaining wildlife, a compatible recreational matrix, purification of waters from poisons, and many others. As illustrated by comparing the second and last items in Table 1 the water may have much more energy (and thus dollar) value to one use pathway than to another. Calculation may help us therefore decide the best use for both natural and urban sectors. If water is diverted and thus energies are drained from a forest it loses some of its energy source and its output of values is diminished unless the using system puts back into that forest some critically needed services which have as much amplifying value to its energy budget as the water (Fig. 4 from Odum, 1968). Thus it is possible to drain water from a system and carry back some special management service, but if this repayment of positive feedback is not provided, one system is damaged at the expense of another. Rarely has this been understood or the importance of the planetary life support system to man's survival been measured in quantitative terms. Values in Table 1 indicate ways that some of the values of water may be calculated. When all the energy values of usages are no longer hidden we may decide by adequate public process the priorities. Since survival is the ultimate decision factor, there is a constitutional basic right to an adequate life support system, and this must be the first priority. The special-purpose industries, which increase industrial productivity and population must take second priority.

Another important concern in the energetics of a water cycling system is the rate of energy flow. Theorists are still groping with the laws that control the rate at which potential energy is dispersed into heat, being then unavailable for further use as an energy source. Lotka provided the theory of natural selection as a maximum power organizer; under competitive conditions systems are selected which use their energies in various structural-developing actions so as to maximize their use of available energies. By this theory systems of cycles which drain less energy lose out in comparative development. However, Leopold and Langbein have shown that streams in developing erosion profiles, meander systems, and tributary networks disperse their potential energies more slowly than if their channels were more direct. These two statements may be harmonized by an optimum efficiency maximum power principle (Odum and Pinkerton, 1955), which indicates that energies which are converted too rapidly into heat are not made available to the systems own use because they are not fed back through storages into useful pumping, but instead do random stirring of the environment. When back-force loadings are such that very little potential energy is drained, systems are too slow and are eliminated by competition. Thus there is an optimum rate of energy processing which is neither as fast or as slow as is possible with some different loading of a system of energy flows.

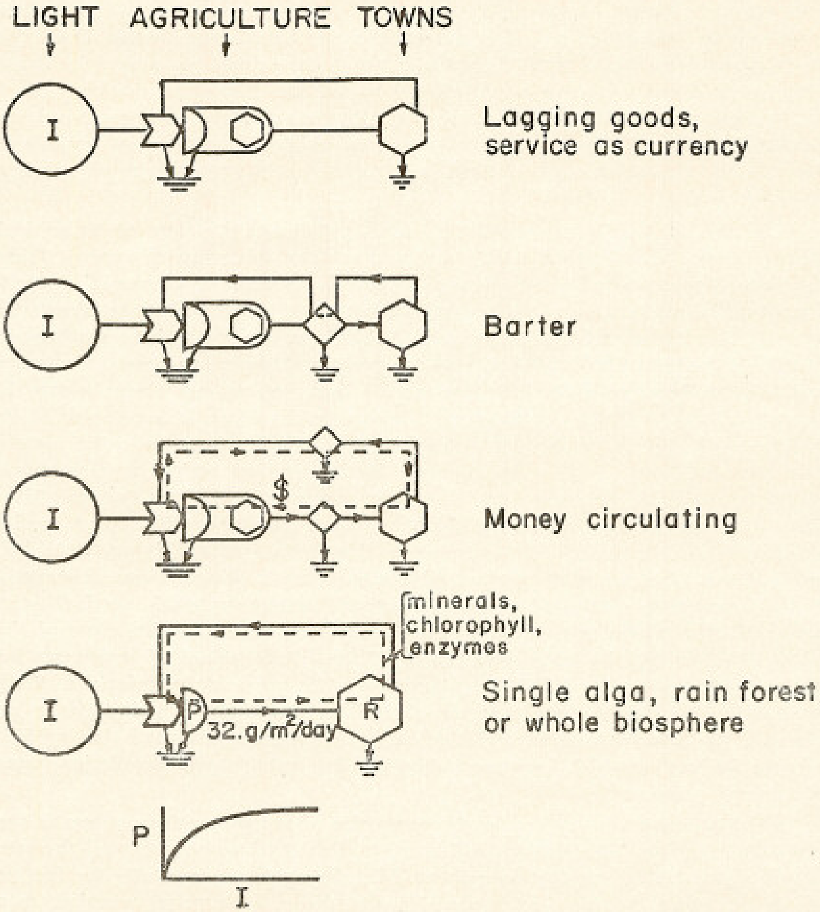

Figure 4

Fig. 4. Diagrams showing the self designing reward loop by which units in energy trains feed high quality services from downstream to an upstream process regaining through amplifier actions the energy value of their own drain. In the third diagram the cycling of money is shown for units where man in involved, the dollars running in countercurrent to the energy payment loop (Odum, 1968).

When a meandering stream in equilibrum with its landscape is channeled for navigational purposes, potential energies which were formally released slowly, maintaining stream beds, forest and flood plains are dumped dowstream, constituting a disruptive energy stress to the lower stream estuary or reservoir. These potential energies there become the source of competitive selection of such other natural systems as water eddies, whirlpools, and erosion systems, which may or may not be of value to that system. However, by diversion the well adapted, well evolved upstream landscape unit has lost its energy source and its ability to provide stability and self maintenance. The values of potential energy in Table 1 through dollar-calories conversions provide us a means for calculating the energies in dollar values of this energy diversion.

Another aspect of self-regulating systems are the storages provided by a system for its own stability. A flood plain has an interesting property of increasing its energy utilization for useful purposes in proportion to increases of the potential energy available. When their floods overflow the banks the flood plain forest derives some of the potential energies which go into forestry growth soil control and at the same time take the transient stress out of the flooding system as a whole. This is a very effective flood control mechanism and may turn out to be far cheaper than the reservoirs which are provided by various engineering plans to do the same jobs at greater expense and with less permanence. In electrical systems transients are controlled with both storages and with lag impedances, such as induction coils, that respond in proportion to input energy. In river basins we have attempted to control transients with storages, but nature has already been using an analogous system module to the inductance. The flow-dependent impedance is the flood-plain.

There are many students of water resources and many projects for system analysis of water which include the water budgets and the dollar interactions but the challenge before us now is to add the energy values and dollar values of the natural systems including the values of water inputs, their cleansing power and their roles in self-management of the natural systems. The environments have always been necessary to man but they are in danger of becoming in short supply and limiting to his survival. It is no longer satisfactory to calculate some cost benefit ratio leaving out all the energy budgets of the life support systems which are the basis for man's existence on the planet. What we need perhaps is conservation engineering which we can define as the guidance of self design to a workable partnership involving man and nature.

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