

Handbook of Emergy Evaluation

**A Compendium of Data for Emergy Computation
Issued in a Series of Folios**

**Folio #5
Emergy of Landforms
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Preface, Handbook of Emergy Evaluation

Emergy, spelled with an "m," is a universal measure of real wealth of the work of nature and society made on a common basis. Calculations of emergy production and storage provide a basis for making choices about environment and economy following the general public policy to maximize real wealth, production and use (maximum empower). To aid evaluations, this handbook provides data on emergy contents and the computations on which they were based. A series of Folios are to be issued. Folio #1 introduces concepts and evaluates the empower of the geobiosphere.

There may be Folios by many authors, who take the initiative to make new calculations or assemble results from the extensive but dispersed literature. Data on emergy content are in published papers, books, reports, theses, dissertations, and unpublished manuscripts. Tabulating unit emergy values and their basis is the main purpose of this handbook. Presentations document the sources of data and calculations. As received, Folios will go to reviewers, back to authors for revision and back for publication. Each will have an index to indicate the page where emergy is evaluated. Each Folio should be usable without reference to other folios.

Most landforms involve inflows of materials with emergy and their storage. Anyone evaluating land formation will need to consider these using trans-formities from previous papers such as those by students of Mark Brown. These may soon be assembled in a folio on emergy in materials. However, in this folio on landforms, the emphasis is on the construction of form. Materials emergy was not included.

Policy on Literature Review and Consistency

This handbook is based on emergy evaluations assembled from various reports and published literature plus new tables prepared by folio authors. Our policy is to present previous calculations with due credit and without change except those requested by original authors. This means that unit emergy values in some tables may be different from those in other tables. Some tables may be more complete than others. No attempt is made to make all the tables consistent. Explanatory footnotes are retained. The diversity of efforts and authors enriches the information available to users, who can make changes and recalculate as they deem desirable to be more complete, update, or otherwise revise for their purposes.

Folios #1 and #2 in year 2000 revised the global emergy base of reference with a larger estimate of tide. The 1996 global emergy base of reference ($9.44 E^{24}$ sej/yr) was increased to $15.83 E^{24}$ sej/y. Using a different base changes all the unit emergy values which directly and indirectly are derived from the value of global annual empower. Two alternatives are suggested when using the values from the 1996 base and from the 2000 base. Either increase the 1996 base values by multiplying each by 1.68 or decrease those from the 2000 base by multiplying each by 0.60. Some of the folios of this handbook, including this Folio #5, use the older 1996 base.

-- Howard T. Odum and Mark T. Brown

Introduction To Folio #5

Folio #5 presents energy evaluations of 9 landforms chosen for analysis to portray a range of geomorphologic settings. Eight are natural landforms; the spoil mound from phosphate strip mining in Florida was human-made. Calculations are made with data available from the literature to construct a case study for each landform type. Tables 1-9 evaluate physical characteristics of these landforms and their energy flows and storages. Physical characteristics of the landform and the sources of estimates are given in part a of each table (Table 1a, Table 2a, etc.). The energy inputs contributing to the land forming processes are given in part b of each table (Table 1b, Table 2b, Table 3b). These inputs are the energy signature of the landform given per area of supporting territory. Transformities used in evaluations are given in Appendix Table A1 at the end of the folio. Table 10 compares and summarizes the empower, energy stored, emergy stored, and transformities (emergy/energy). Storages are given on a unit area basis (per square meter), which makes comparisons and applications to other situations easy. For each kind of landform, a literature review and discussion of characteristics was given previously (Kangas, 1983). Appendix A2 is included to illustrate the emergy value of landform by comparing it with other associated storages, in this case for a stream case study.

1. Concepts and Methods

A landscape model showing main energy storages and pathways is given in Figure 1. Using land as a platform, local energies such as sun, wind, rain, uplift, and others create form and ecosystems on any given area. These are long-term storages of landscape. Because these storages secure and amplify their own energy inputs, they feed back and have value. As noted by Odum (1975), geological structures of landforms “served as quality upgraded potential energy, information, and material storages that feed back control actions on the energy input processes.”

At one scale, landform is a consumer, causing a convergence of energies collected by surrounding land area. In return, the landform performs services such as organizing vegetation patterns, the flow of water and nutrients, etc. Many individual land units such as shown in Figure 1 are combined into landscape by exchange with the surrounding systems, mainly through flows of water, sediments, wind, seed, and animal movements. These flows integrate and organize the larger surface,

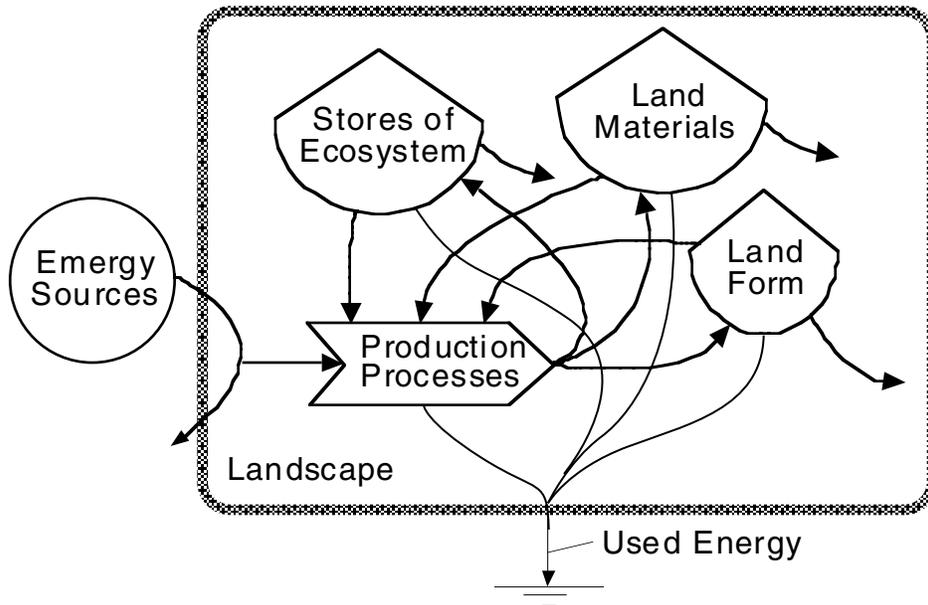


Figure 1. Energy systems diagram summarizing the way landscapes produce landforms.

generating properties of hierarchy in spatial dimension and feedback mechanisms that support self-maintaining stability.

Some of the actual stored energy in landform is elevated potential against gravity, either to fill in for depression forms or to erode away for accumulation forms. Emergy in landform is the energy that was used to develop the form, even though most of the actual energy used is no longer stored in the structure. Emergy stored in landforms was calculated as the product of energy use rate, its transformity, and development time.

Though not often considered as such, the form of land is a long-term storage. Odum (1975) states, “geomorphological form and information as measured by capital energy investment becomes as much a state variable as biomass in biology or water in hydrology.” The actual storage value of landform is its potential energy (exergy). Geomorphic forms are either depressions, like lakes and wetlands, or elevations, like mounds and hills. Their exergy content can be estimated as potential energy stored against gravity, either to fill in for depression forms or to erode away for elevated forms. In this folio landforms are considered to be characteristic and recurring forms shaped by similar energy inputs. Small scale forms are evaluated here as opposed to large scale forms of mountain ranges, coastal plains, ocean basins, polar ice caps, etc.

As stated above, emergy of a landform is the energy used, in equivalents of one type, multiplied by the development time. This approach to quantifying emergy assumes that a production process is competitive, so that for any given landform development time has been minimized through the interaction of the ecosystem with the energy sources. In this sense, natural selection may operate on the non-living landform directly through the living ecosystem. This approach assumes that the current morphology is in dynamic equilibrium with energy sources.

Emergy inputs (empower) of the energy signature of each system were summed to calculate total inputs. Since sun, wind and rain are generated as co-products by the earth weather system at the same time, only the largest of these components was included to avoid double counting. The last line item in each of the evaluation Tables 1-9 explain which inflows are added to obtain total annual empower per area (empower density).

Areas of Landform and Contributing Territory

Like other centers of earth hierarchy, landforms involve two areas. One is the smaller area of their structure; the other is the larger territory of support which contributes its emergy. In this folio, the ratio of these two areas is

called "landform concentration area." A first attempt is made here to estimate the concentration area of landforms using various literature citations.

Calculation of Transformity and Emergy Stored in Landform

Emergy contributed from supporting territory accumulates as the landform is constructed. Emergy stored in a landform was calculated with the following equation:

$$\text{Landform energy} = (E)(C)(D)$$

where: E = Total emergy input in solar emjoules/m²/yr; also called empower density

C = Landform concentration area in m²/m²

D = landform development time in years

Transformities

Energy quality and position in the earth hierarchy is measured by the transformity, which was calculated as the quotient of emergy stored / energy stored.

2. Result of Landform Evaluations

Physical characteristics, concentration areas, development times, signature of input emergy flows, and values of the empower density in the supporting territory, E, are given in Tables 1–9 for each landform.

Table 10 summarizes the emergy evaluations of landforms. Transformities range from 1 E9 to 1 E15 sej/J. Overall, this order of magnitude is similar with other earth products and processes (Odum 1996, 2000). The coral reef had the highest transformity at 1.2 E15 sej/J, which was two orders of magnitude greater than any of the other landforms. This result was due to the high wave energy used to develop the form. The high transformity of coral reef form is consistent with the general theory that coral reefs are the most complex ecosystems in the biosphere. Perhaps the high emergy of this landform contributes directly to the high complexity of the ecosystem by providing a complex habitat structure to which biological populations adapt to through natural selection.

The next highest transformities were for the floodplain and oyster reef forms at about $1 \text{ E}13 \text{ sej/J}$. These are both productive systems known for high accumulation patterns due to riverine flood flow and tidal currents, respectively. The rest of the landforms had transformities on the order of $1 \text{ E}10 \text{ sej/J}$. The man-made form of the spoil mound had a transformity of $2.3 \text{ E}10 \text{ sej/J}$, which was similar to the natural forms. This result suggests that the spoil mound is not unusual and may be able to be incorporated into reclamation plans after strip mining, since the landform scale may match the scale of the colonizing vegetation (Kangas, 1983).

Table 1a
Floodplain

Parameter	Value	Reference
Landform Density	1.36 g/cm ³	Miller and Wendorf, 1958
Landform Volume	6.96 E7 m ³	a
Landform Area	6.96 E7 m ²	Corps of Engineers, 1976
Concentration Area	23 m ² /m ²	b
Development Time	10,000 yrs	Time since last glaciation in southeast Michigan, assumed
Landform Energy	6.7 E3 J/m ²	c

a Volume (rectangle) = area x depth. Area = 6.96 E7 m² (Corps of Engineers, 1976). Depth = 1 m (assumed).

b Floodplain concentration area using Huron River data from Table 5:
Concentration area = (watershed area)/(floodplain area)
= (2.3 E9 m²)/(1 E8 m²) = 23 m²/m².

c Landform energy = ((6.96 E7m³)(10E6 cm³/m³)(1.36 g/cm³)(50 cm)
(980 cm/sec²)(2.39 E-11 Cal/erg)(4186 J/Cal))/ 6.96 E7m²
= 6.7 E3 J/m².

Table 1b
Emergy Flows to Floodplain

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	4.2 E9	1	4.2
2	Wind	4.2 E6	1496	6.3
3	Rain, Chemical Potential	1.0 E4	18199	0.2
4	Runoff, Geopotential	2.5 E3	10488	0.3
5	Rain Impact	2.3 E4	238000	5.4
6	Organic Inflow	6.3 E6	74000	466.2
7	Flood Head	2.0 E4	400000	8.0
8	Total of Items 2, 4, 6, 7	—	—	480.8

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 1b

1 Sunlight = 1.0 E6 solar Cal/m²/yr (Odum et al., 1978)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E-3 g/cm³

V = wind velocity = 478.3 cm/sec (NOAA, 1974)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(478.3 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 1.0 E3 Cal/m²/yr

Footnotes for Table 1b (continued)

3 Rain (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 281^\circ\text{K}$

$C_2 = \text{water content of rain}$

$= 1,000,000 \text{ ppm} - 14 \text{ ppm (Odum et al., 1978)}$

$= 999,986 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 100 \text{ ppm}$

$= 999,900 \text{ ppm}$

$M = \text{mass of rain per year}$

$\text{Rain} = 78 \text{ cm/yr (NOAA, 1974)}$

$\text{Mass of rain} = (78 \text{ cm/yr})(1 \text{ g/cm}^3)(1 \text{ E4 cm}^2/\text{m}^2)$

$= 7.8 \text{ E5 g/m}^2/\text{yr}$

$\text{Rain (chemical potential)} = (1 \text{ mole}/18\text{g})(1.99 \text{ cal/}^\circ\text{mole})(281^\circ)$

$\ln ((999,986 \text{ ppm})/(999,900 \text{ ppm}))(7.8 \text{ E5 g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 2.4 \text{ Cal/m}^2/\text{yr}$

4 Runoff (elevated potential) = MGH

$M = \text{mass of runoff per yr}$

$G = \text{gravity} = 980 \text{ cm/sec}^2$

$H = \text{elevation drop or head}$

$\text{Runoff} = 25.4 \text{ cm/yr (Odum et al., 1978)}$

$\text{Mass} = (25.4 \text{ cm/yr})(1 \text{ E4 cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 2.5 \text{ E5 g/m}^2/\text{yr}$

$H = 100 \text{ cm (assumed)}$

$\text{Runoff (elevated potential)} = (2.5 \text{ E5 g/m}^2/\text{yr})(980 \text{ cm/sec}^2)(100 \text{ cm})$

$(2.38 \text{ E-11 Cal/erg}) = 0.6 \text{ Cal/m}^2/\text{yr}$

5 Rain (kinetic impact) = $1/2 M V^2$

$M = \text{mass of rain per yr}$

$V = \text{velocity of raindrops}$

$= 762 \text{ cm/sec for an average drop diameter (Odum et al., 1978)}$

$\text{Rain} = 78 \text{ cm/yr (NOAA, 1974)}$

$\text{Mass} = (78 \text{ cm/yr})(1 \text{ E4 cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 7.8 \text{ E5 g/m}^2/\text{yr}$

$\text{Rain (kinetic impact)} = (0.5)(7.8 \text{ E5 g/m}^2/\text{yr})(762 \text{ cm/sec})^2$

$(2.38 \text{ E-11 Cal/erg}) = 5.4 \text{ Cal/m}^2/\text{yr}$

Footnotes for Table 1b (continued)

6 Organic Inflows in Floodwaters

Wolman and Leopold (1970) give an average deposition rate in major floods of about 0.1 foot (3.1 cm). Assuming a recurrence interval of 20 years, the annual rate of deposition is

$$(3.1 \text{ cm})/(20 \text{ yrs}) = 0.16 \text{ cm/yr}$$

Assume a bulk density of 1.4 g/cm³, mass of sediments is

$$(0.16 \text{ cm/yr})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)(1.4 \text{ g/cm}^3) = 2.2 \text{ E}3 \text{ g/m}^2/\text{yr}$$

Assume an organic content of 15% (Brown et al., 1979) and a heat content of 4.5 Cal/g (E.P. Odum, 1971), energy in organic input is

$$(2.2 \text{ E}3 \text{ g/m}^2/\text{yr})(0.15)(4.5 \text{ Cal/g}) = 1.5 \text{ E}3 \text{ Cal/m}^2/\text{yr}$$

7 Flood head = $r D G H F (1/A)$

r = density of water = 1 g/cm³

D = flood discharge = 3000 cfs or 8.5 E7 cm³/sec (Corps of Engineers, 1976), for a 20 yr flood.

G = gravity = 980 cm/sec²

H = elevation drop or head = 7625 cm (Say and Jansson, 1976)

F = duration of flood per yr (5 days/flood)(flood/20 yr)(8.64 E4 sec/day)
= 2.16 E4 sec/yr

A = area of floodplain = 6.96 E7 m² (Corps of Engineers, 1976)

Flood energy = (1 g/cm³)(8.5 E7 cm³/sec)(980 cm/sec²)(7625 cm)

$$(2.16 \text{ E}4 \text{ sec/yr})(2.38 \text{ E-}11 \text{ Cal/erg})(1/6.96 \text{ E}7 \text{ m}^2) = 4.68 \text{ Cal/m}^2/\text{yr}$$

Table 2a
Coral Reef

Parameter	Value	Reference
Landform Density	3.17 g/m ³	Statham, 1977
Landform Volume	1.6 E6 m ³	a
Landform Area	87569 m ²	b
Concentration Area	588 m ² /m ²	c
Development Time	700 yrs	d
Landform Energy	2.0 E6 J/m ²	e

a Volume (1/2 ellipsoid) = $.5(4/3 \pi abc)$; a = length = 2400 ft = 731.5 m, b = width = 500 ft = 152.4 m, c = height = 23 ft = 7.0 m (all from Shinn, 1963).

b Area = $3.1416(\text{length}/2)(\text{width}/2) = 3.1416(365.8 \text{ m})(76.2 \text{ m}) = 87569 \text{ m}^2$.

c Coral reef concentration area is given by Smith (1978) at 0.17% of global ocean or 588 m²/m².

d Development time for the 7m thick reef considered, using a growth rate of 1 cm/yr (Adey, 1978; Odum and Odum, 1955; Hoffmeister and Multer, 1964) is: Development time = (700 cm)/(1 cm/yr) = 700 yrs.

e Landform energy = $((1.6 \text{ E6 m}^3)(10 \text{ E6 cm}^3/\text{m}^3)(3.17 \text{ g/cm}^3)(350 \text{ cm})(980 \text{ cm/sec}^2)(2.39 \text{ E-11 Cal/erg})(4186 \text{ J/Cal}))/87569 \text{ m}^2 = 2.0 \text{ E6 J/m}^2$.

Table 2b
Energy Flows to Coral Reef

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	6.3 E9	1	6.3
2	Wind	2.7 E6	1496	4.0
3	Tide	5.9 E5	16842	9.9
4	Waves	1.92 E11	30550	5865600.0
5	Organic Inflows	1.38 E7	150000	2070.0
6	Total of Items 1, 3-5	—	—	5867686.2

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 2b

1 Sunlight = 1.5 E6 solar Cal/m²/yr (Ruttenber, 1979)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E-3 g/cm³

V = wind velocity = 378.3 cm/sec (Ruttenber, 1979)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(378.3 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 6.5 E2 Cal/m²/yr

3 Tide = 1/2 r G H² n

r = density of seawater = 1.025 g/cm³

G = gravity = 980 cm/sec²

H = tidal head = 40 cm (Ruttenber, 1979)

n = number of tides per year = 717 (Ruttenber, 1979)

Tide = (0.5)(1.025 g/cm³)(980 cm/sec²)(40 cm)²(717 tides/yr)

(1 E4 cm²/m²)(2.38 E-11 Cal/erg) = 1.4 E2 Cal/m²/yr

Footnotes for Table 2b (continued)

4 Wave energy = $1/8 r G^{3/2} H^{5/2} W$

r = density of seawater = 1.025 g/cm^3

G = gravity = 980 cm/sec^2

H = wave height = 30.5 cm (Ruttenber, 1979)

W = width of area affected = $100 \text{ ft} = 30.5 \text{ m}$ (assumed)

Wave energy = $1/8 (1.025 \text{ g/cm}^3)(980 \text{ cm/sec}^2)^{3/2}(30.5 \text{ cm})^{5/2}$
 $(2.38 \text{ E-11 Cal/erg})(3.15 \text{ E7 sec/yr})(100 \text{ cm/m})(30.5 \text{ m})$

= $4.6 \text{ E7 Cal/m}^2/\text{yr}$

5 Organic inflows = ME

M = mass of organic matter input per year

= $730 \text{ g/m}^2/\text{yr}$ (Odum and Odum, 1955)

E = heat content of organic matter

= 4.5 Cal/g (E.P. Odum, 1971)

Organic inflow = $(730 \text{ g/m}^2/\text{yr})(4.5 \text{ Cal/g}) = 3.3 \text{ E3 Cal/m}^2/\text{yr}$

Table 3a
Salt Marsh

Parameter	Value	Reference
Landform Density	0.2 g/cm ³	McCaffrey and Thompson, 1980
Landform Volume	2.28 E7 m ³	a
Landform Area	1.14 E7 m ²	Bahr, 1976
Concentration Area	2 m ² /m ²	b
Development Time	300 yrs	c
Landform Energy	4.2 E3 J/m ²	d

a Volume (rectangle) = area x depth. Area = 11.4 km² = 1.14 E7 m² (Bahr, 1976); Depth = 2 m (Teal, 1962).

b Concentration area of Sapelo Island salt marsh was assumed to be 2 m²/m², see map in Bahr (1976).

c Development time taken from Ranwell (1972) and Steers (1977).

d Landform energy = ((2.28 E7 m³)(10 E6 cm³/m³)(0.2 g/cm³)(100 cm) (980 cm/sec²)(2.39 E-11 Cal/erg)(4186 J/Cal))/1.14 E7 m² = 4.2 E3 J/m².

Table 3b
Emergy Flows to Salt Marsh

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	5.4 E9	1	5.4
2	Wind	2.6 E6	1496	3.9
3	Chemical Potential of Rain	4.6 E6	18199	83.7
4	Elevated Potential of Runoff	2.1 E3	10488	0.02
5	Kinetic Impact of Rain	3.4 E4	238000	8.1
6	Tide	1.67 E7	16842	281.3
7	Total of items 3, 4, 6	—	—	365.0

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 3b

1 Sunlight = 1.3 E6 solar Cal/m²/yr (Odum et al., 1978)

2 Wind = $1/2 r V^2 C (1/d)$

r = density of air = 1.2 E⁻³ g/cm³

V = wind velocity = 375.5 cm/sec (NOAA, 1974)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = $(0.5)(1.2 E^{-3} \text{ g/cm}^3)(375.5 \text{ cm/sec})^2(1 E4 \text{ cm}^2/\text{sec})$

$(1/1 E4 \text{ cm})(2.38 E^{-11} \text{ Cal/erg})(3.15 E7 \text{ sec/yr})(1 E4 \text{ cm}^2/\text{m}^2)$

= 6.3 E2 Cal/m²/yr

Footnotes for Table 3b (continued)

3 Rain (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 292^\circ\text{K}$

$C_2 = \text{water content of rain}$

$= 1,000,000 \text{ ppm} - 8 \text{ ppm (Odum et al., 1978)}$

$= 999,992 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 28,000 \text{ ppm}$

$= 972,000 \text{ ppm}$

$M = \text{mass of rain per year}$

$\text{Rain} = 124 \text{ cm/yr (NOAA, 1974)}$

$\text{Mass of rain} = (124 \text{ cm/yr})(1 \text{ g/cm}^3)(1 \text{ E}4 \text{ cm}^2/\text{m}^2)$

$= 1.2 \text{ E}6 \text{ g/m}^2/\text{yr}$

$\text{Rain (chemical potential)} = (1 \text{ mole}/18 \text{ g})(1.99 \text{ cal/}^\circ\text{mole})(292^\circ)$

$\ln ((999,992 \text{ ppm})/(972,000 \text{ ppm}))(1.2 \text{ E}6 \text{ g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 1.1 \text{ E}3 \text{ Cal/m}^2/\text{yr}$

4 Runoff (elevated potential) = MGH

$M = \text{mass of runoff per yr}$

$G = \text{gravity} = 980 \text{ cm/sec}^2$

$H = \text{elevation drop or head}$

$\text{Runoff} = 20.3 \text{ cm/yr (Odum et al., 1978)}$

$\text{Mass} = (20.3 \text{ cm/yr})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 2.0 \text{ E}5 \text{ g/m}^2/\text{yr}$

$H = 100 \text{ cm (Teal, 1962)}$

$\text{Runoff (elevated potential)} = (2.0 \text{ E}5 \text{ g/m}^2/\text{yr})(980 \text{ cm/sec}^2)(100 \text{ cm})$

$(2.38 \text{ E-}11 \text{ Cal/erg}) = 0.5 \text{ Cal/m}^2/\text{yr}$

5 Rain (kinetic impact) = $1/2 M V^2$

$M = \text{mass of rain per yr}$

$V = \text{velocity of raindrops}$

$= 762 \text{ cm/sec for an average drop diameter (Odum et al., 1978)}$

$\text{Rain} = 124.2 \text{ cm/yr (NOAA, 1974)}$

$\text{Mass} = (124.2 \text{ cm/yr})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 1.2 \text{ E}6 \text{ g/m}^2/\text{yr}$

$\text{Rain (kinetic impact)} = (0.5)(1.2 \text{ E}6 \text{ g/m}^2/\text{yr})(762 \text{ cm/sec})^2$

$(2.38 \text{ E-}11 \text{ Cal/erg}) = 8.2 \text{ Cal/m}^2/\text{yr}$

Footnotes for Table 3b (continued)

$$6 \quad \text{Tide} = 1/2 r G H^2 n$$

r = density of seawater = 1.025 g/cm³

G = gravity = 980 cm/sec²

H = tidal head = 220 cm (Odum et al., 1978)

n = number of tides per year = 700 (Ruttenber, 1979)

$$\begin{aligned} \text{Tide} &= (0.5)(1.025 \text{ g/cm}^3)(980 \text{ cm/sec}^2)(220 \text{ cm})^2(700 \text{ tides/yr}) \\ &= (1 \text{ E4 cm}^2/\text{m}^2)(2.38 \text{ E-11 Cal/erg}) = 4.0 \text{ E3 Cal/m}^2/\text{yr} \end{aligned}$$

Table 4a
Glacier

Parameter	Value	Reference
Landform Density	0.88 g/cm ³	Lachapelle, 1965
Landform Volume	5.7 E8 m ³	Lachapelle, 1965
Landform Area	4.3 E6 m ²	Lachapelle, 1965
Concentration Area	34 m ² /m ²	a
Development Time	3 E4 yrs	Porter, 1971
Landform Energy	7.4 E6 J/m ²	b

a Glacier concentration area is given by Flint (1957) at about 10% of world land area in glaciers, which divided into total area of the earth is (5.1 E14 m²)/(1.5 E13 m²) = 34 m²/m².

b Landform energy = ((5.7 E8 m³)(10 E6 cm³/m³)(0.88 g/cm³)(660 cm)(980 cm/sec²)(2.39 E-11 Cal/erg)(4186 J/Cal))/4.3 E6 m² = 7.4 E6 J/m².

Table 4b
Energy Flows to Glaciers

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	2.5 E9	1	2.5
2	Wind	5.4 E6	1496	8.1
3	Chemical Potential of Precipitation	2.6 E4	18199	0.5
4	Land Uplift	0.24	1.5 E12	360.0
5	Total of items 2, 4	—	—	368.1

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 4b

1 Sunlight = 0.6 E6 solar Cal/m²/yr (Odum et al., 1978)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E⁻³ g/cm³

V = wind velocity = 536.4 cm/sec (NOAA, 1974)

c = eddy diffusion coefficient = 1 E4 cm² /sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(536.4 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 1.3 E3 Cal/m²/yr

Footnotes for Table 4b (continued)

3 Rain (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 277^\circ\text{K}$

$C_2 = \text{water content of rain}$

$= 1,000,000 \text{ ppm} - 10 \text{ ppm (assumed)}$

$= 999,990 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 100 \text{ ppm}$

$= 999,900 \text{ ppm}$

$M = \text{mass of rain per year}$

$\text{Rain} = 203 \text{ cm/yr (NOAA, 1974)}$

$\text{Mass of rain} = (203 \text{ cm/yr})(1 \text{ g/cm}^3)(1 \text{ E}4 \text{ cm}^2/\text{m}^2)$

$= 2.0 \text{ E}6 \text{ g/m}^2/\text{yr}$

$\text{Rain (chemical potential)} = (1 \text{ mole}/18\text{g})(1.99 \text{ cal/}^\circ\text{mole})(277^\circ)$

$\ln ((999,990 \text{ ppm})/(999,900 \text{ ppm}))(2.0 \text{ E}6 \text{ g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 6.1 \text{ Cal/m}^2/\text{yr}$

4 Uplift = $r V G H$

$r = \text{density of rock} = 2 \text{ g/cm}^3$

$V = \text{volume uplift per yr} = (\text{uplift rate})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)$

$= 5 \text{ E}3 \text{ cm}^3/\text{yr}$

$G = \text{gravity} = 980 \text{ cm/sec}^2$

$H = \text{average elevation developed in uplift}$

$= 0.25 \text{ cm}$

$\text{Uplift rate} = 500 \text{ cm}/1000 \text{ yr or } 0.5 \text{ cm/yr (Schumm, 1963)}$

$\text{Uplift} = (2 \text{ g/cm}^3)(5 \text{ E}3 \text{ cm}^3/\text{m}^2/\text{yr})(980 \text{ cm/sec}^2)(0.25 \text{ cm})$

$(2.38 \text{ E-}11 \text{ Cal/erg}) = 5.8 \text{ E-}5 \text{ Cal/m}^2/\text{yr}$

Table 5a
Palsa Mound

Parameter	Value	Reference
Landform Density	0.1 g/cm ³	Zoltai and Tarnocai, 1971
Landform Volume	5 E3 m ³	a
Landform Area	471.2 m ²	b
Concentration Area	1 m ² /m ²	c
Development Time	4000 yrs	d
Landform Energy	3.3 E4 J/m ²	e

a Volume (1/2 ellipsoid) = $.5(4/3 \pi abc)$; a = length = 40 m, b = width = 15 m, c = height = 4 m, (all from Kershaw and Gill, 1979).

b Area = $3.1416(\text{length}/2)(\text{width}/2) = 3.1416(20 \text{ m})(7.5 \text{ m}) = 471.2 \text{ m}^2$.

c Palsa concentration area is their surface area only, since most water for the ice core comes from below.

d Average from Kershaw and Gill (1979), Brown (1973), Salmi (1970) and Ruuhijarv (1970).

e Landform energy = $((5 \text{ E3 m}^3)(10 \text{ E6 cm}^3/\text{m}^3)(1.58 \text{ g/cm}^3)(200 \text{ cm})(980 \text{ cm/sec}^2)(2.39 \text{ E-11 Cal/erg})(4186 \text{ J/Cal}))/471.2 \text{ m}^2 = 3.3 \text{ E4 J/m}^2$.

Table 5b
Energy Flows to Palsa (Arctic Freeze-thaw) Mounds

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	8.4 E8	1	0.8
2	Wind	8.4 E5	1496	1.2
3	Chemical Potential of Rain	3.3 E3	18199	0.1
4	Elevated Potential of Runoff	2.1 E3	10488	0.02
5	Heat Flux in Freeze-thaw cycle	1.0 E9	12.9	12.9
6	Total of items 2, 4, 5	—	—	14.1

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 5b

1 Sunlight = 0.2 E6 solar Cal/m²/yr (Bliss, 1975)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E⁻³ g/cm³

V = wind velocity = 210 cm/sec (Bliss, 1975)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(210 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 2.0 E2 Cal/m²/yr

Footnotes for Table 5b (continued)

3 Rain (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 279^\circ\text{K}$

$C_2 = \text{water content of rain}$

$= 1,000,000 \text{ ppm} - 10 \text{ ppm (assumed)}$

$= 999,990 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 100 \text{ ppm}$

$= 999,900 \text{ ppm}$

$M = \text{mass of rain per year}$

$\text{Rain} = 28.4 \text{ cm/yr (Bliss, 1975)}$

$\text{Mass of rain} = (28.4 \text{ cm/yr})(1 \text{ g/cm}^3)(1 \text{ E4 cm}^2/\text{m}^2)$

$= 2.8 \text{ E5 g/m}^2/\text{yr}$

$\text{Rain (chemical potential)} = (1 \text{ mole}/18\text{g})(1.99 \text{ cal/}^\circ\text{mole})(279^\circ)$

$\ln ((999,990 \text{ ppm})/(999,900 \text{ ppm}))(2.8 \text{ E5 g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 0.8 \text{ Cal/m}^2/\text{yr}$

4 Runoff (elevated potential) = MGH

$M = \text{mass of runoff per yr}$

$G = \text{gravity} = 980 \text{ cm/sec}^2$

$H = \text{elevation drop or head}$

$\text{Runoff} = 10 \text{ cm/yr (assumed)}$

$\text{Mass} = (10 \text{ cm/yr})(1 \text{ E4 cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 1 \text{ E5 g/m}^2/\text{yr}$

$H = 200 \text{ cm}$

$\text{Runoff (elevated potential)} = (1 \text{ E5 g/m}^2/\text{yr})(980 \text{ cm/sec}^2)(200 \text{ cm})$

$(2.38 \text{ E-11 Cal/erg}) = 0.5 \text{ Cal/m}^2/\text{yr}$

Footnotes for Table 5b (continued)

5 Freeze-thaw energy = (heat energy per freeze-thaw cycle)(number of cycles per yr). Assume typical freeze-thaw cycle of 15°C/day. Heat energy flux over the cycle is

$$\text{Heat energy} = ((DT)(\text{volume})(\text{heat capacity}) + (\text{heat of melting})(\text{volume})) (DT/T) / T$$

$$DT = \text{change in temperature} = 15^\circ\text{C}$$

Volume = assume depth of freeze and thaw is 100 cm, and 30% water content.

$$\text{Thus } V = (100 \text{ cm})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)$$

$$= 1 \text{ E}6 \text{ cm}^3/\text{m}^2$$

$$\text{Heat capacity} = 4.4 \text{ E-}4 \text{ Cal/cm}^3/\text{C}^\circ \text{ (Kelley and Weaver, 1969)}$$

$$\text{Heat of melting} = 8.0 \text{ E-}2 \text{ Cal/cm}^3$$

$$DT/T = \text{Carnot ratio} = 15^\circ/279^\circ = 0.054$$

$$DT = \text{length of cycle} = 1 \text{ day}$$

Heat energy =

$$((15^\circ\text{C})(1 \text{ E}6 \text{ cm}^3/\text{m}^2)(4.4 \text{ E-}4 \text{ Cal/cm}^3/\text{C}^\circ) + (8 \text{ E-}2 \text{ Cal/cm}^3)(0.30)(1 \text{ E}6 \text{ cm}^3/\text{m}^2))(0.054)/\text{day}$$

$$= 1.6 \text{ E}3 \text{ Cal/m}^2/\text{day}$$

Using 150 daily cycles per year, total freeze-thaw energy is

$$\text{Freeze-thaw energy} = (1.6 \text{ E}3 \text{ Cal/m}^2/\text{day})(150 \text{ days/yr})$$

$$= 2.4 \text{ E}5 \text{ Cal/m}^2/\text{yr}$$

Table 6a
Arroyo

Parameter	Value	Reference
Landform Density	1.36 g/cm ³	Miller and Wendorf, 1958
Landform Volume	1.77 E8 m ³	a
Landform Area	2.1 E7 m ²	b
Concentration Area	35.7 m ² /m ²	c
Development Time	43 yrs	Leopold et al., 1964
Landform Energy	4.8 E5 J/m ²	d

a Volume (rectangle) = abc; a = length = 150 miles = 2.4 E5 m, b = width = 285 ft = 86.9 m, c = depth = 28 ft = 8.5 m (all from Leopold et al., 1964).

b Area = (length)(width) = (2.4 E5 m)(86.9 m) = 2.1 E7 m².

c Arroyo concentration area = (watershed area)/(arroyo area) = 7.5 E8 m²/(2.1 E7 m²)(calculated from Leopold et al., 1964) = 35.7 m²/m².

d Landform energy = ((1.77 E8 m³)(10 E6 cm³/m³)(1.36 g/cm³)(425 cm)(980 cm/sec²)(2.39 E-11 Cal/erg)(4186 J/Cal))/2.1 E7 m² = 4.8 E5 J/m².

Table 6b
Energy Flows to Arroyo

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	5.0 E9	1	5.0
2	Wind	2.97 E6	1496	4.4
3	Chemical Potential of Rain	2.9 E3	18199	0.05
4	Kinetic Impact of Rain	5.9 E3	238000	1.4
5	Storm	1.25 E8	4600000	575000
6	Total of items 2, 5	—	—	575004.4

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 6b

1 Sunlight = 1.2 E6 solar Cal/m²/yr (Odum et al., 1978)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E-3 g/cm³

V = wind velocity = 397.8 cm/sec (NOAA, 1974)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(397.8 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 7.1 E2 Cal/m²/yr

Footnotes for Table 6b (continued)

3 Rain (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 295^\circ\text{K}$

$C_2 = \text{water content of rain}$

$= 1,000,000 \text{ ppm} - 12 \text{ ppm (Odum et al., 1978)}$

$= 999,988 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 100 \text{ ppm}$

$= 999,900 \text{ ppm}$

$M = \text{mass of rain per year}$

$\text{Rain} = 20.65 \text{ cm/yr (can't read)}$

$\text{Mass of rain} = (20.65 \text{ cm/yr})(1 \text{ g/cm}^3)(1 \text{ E4 cm}^2/\text{m}^2)$

$= 2.1 \text{ E5 g/m}^2/\text{yr}$

$\text{Rain (chemical potential)} = (1 \text{ mole}/18 \text{ g})(1.99 \text{ cal/}^\circ\text{mole})(295^\circ)$

$\ln ((999,988 \text{ ppm})/(999,900 \text{ ppm}))(2.1 \text{ E5 g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 0.7 \text{ Cal/m}^2/\text{yr}$

4 Rain (kinetic impact) = $1/2 M V^2$

$M = \text{mass of rain per yr}$

$V = \text{velocity of raindrops}$

$= 762 \text{ cm/sec for an average drop diameter (Odum et al., 1978)}$

$\text{Rain} = 20.65 \text{ cm/yr (NOAA, 1974)}$

$\text{Mass} = (20.65 \text{ cm/yr})(1 \text{ E4 cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 2.1 \text{ E5 g/m}^2/\text{yr}$

$\text{Rain (kinetic impact)} = (0.5)(2.1 \text{ E5 g/m}^2/\text{yr})(762 \text{ cm/sec})^2$

$(2.38 \text{ E-11 Cal/erg}) = 1.4 \text{ Cal/m}^2/\text{yr}$

Footnotes for Table 6b (continued)

5 Storm energy = $1 \text{ E4 Cal/m}^2/\text{storm}$ (average from Odum et al., 1978 and Odum, 1978)

Assume 3 storms per year

$$\begin{aligned} \text{Total storm energy} &= (1 \text{ E4 Cal/m}^2/\text{storm})(3 \text{ storms /yr}) \\ &= 3 \text{ E4 Cal/m}^2/\text{yr} \end{aligned}$$

Storm Transformity: Assume an average thunderstorm diameter of 5 km (Blair and Fite, 1965) and a 10:1 concentration area over which the storm draws its energy.

The area of the storm is

$$\begin{aligned} A &= \pi r^2 = (3.1416)(2500 \text{ m})^2(10 \text{ m}^2/\text{m}^2) \\ &= 2 \text{ E8 m}^2 \end{aligned}$$

Bennett and Chorley (1978) give the life span of a storm at about one hour with a kinetic energy of about 1 E11 joules or 2.5 E7 Cal . Using the sunlight value from above, the energy of the storm is

$$\begin{aligned} \text{Storm energy} &= (1.2 \text{ E6 solar Cal/m}^2/\text{yr})(2 \text{ E8 m}^2)(1 \text{ hr/storm})/(8760 \text{ hrs/yr}) \\ &= 2.7 \text{ E10 solar Cal.} \end{aligned}$$

The storm transformity is then

$$\begin{aligned} \text{Transformity} &= (2.7 \text{ E10 solar Cal})/(2.5 \text{ E7 Cal}) \\ &= 1.1 \text{ E3 solar Cal/Cal} \end{aligned}$$

Table 7a
Oyster Reef

Parameter	Value	Reference
Landform Density	0.89 g/cm ³	May, 1971
Landform Volume	1.05 E5 m ³	a
Landform Area	19635 m ²	b
Concentration Area	33 m ² /m ²	c
Development Time	766 yrs	d
Landform Energy	4.6 E4 J/m ²	e

a Volume (1/2 ellipsoid) = $.5(4/3 \pi abc)$; a = length = 500 m, b = width = 50 m, c = height = 2 m (assumed)(a and b from Lehman, 1974).

b Area = $3.1416(\text{length}/2)(\text{width}/2) = 3.1416(250 \text{ m})(25 \text{ m}) = 19635 \text{ m}^2$.

c Oyster reef concentration area is given by Lehman (1974) at 3% of total by area or $33 \text{ m}^2/\text{m}^2$.

d Development time is calculated below with data from May (1971) using the 2 m thickness of Crystal River reef. Development time = $((920 \text{ yr})(2 \text{ m})/((8 \text{ ft})(0.3 \text{ m/ft})) = 766 \text{ years}$.

e Landform energy = $((1.05 \text{ E}5 \text{ m}^3)(10 \text{ E}6 \text{ cm}^3/\text{m}^3)(0.89 \text{ g/cm}^3)(100 \text{ cm})(980 \text{ cm/sec}^2)(2.39 \text{ E-}11 \text{ Cal/erg})(4186 \text{ J/Cal}))/19635 \text{ m}^2 = 4.6 \text{ E}4 \text{ J/m}^2$.

Table 7b
Energy Flows to Oyster Reef

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	6.3 E9	1	6.3
2	Wind	3.5 E6	1496	5.2
3	Chemical Geopotential of Runoff	2.0 E8	18199	3639.8
4	Tide	1.7 E6	16842	28.6
5	Organic Inflows	4.6 E8	74000	34040.0
6	Total of items 1, 3, 4, 5	—	—	37714.7

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 8b

1 Sunlight = 1.5 E6 solar Cal/m²/yr (Kemp, 1977)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E⁻³ g/cm³

V = wind velocity = 433 cm/sec (Kemp, 1977)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E⁻³ g/cm³)(433 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E⁻¹¹ Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 8.4 E2 Cal/m²/yr

Footnotes for Table 7b (continued)

3 Runoff (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 293^\circ\text{K}$

$C_2 = \text{water content of runoff}$

$= 1,000,000 \text{ ppm} - 120 \text{ ppm (Kemp, 1977)}$

$= 999,880 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 24,000 \text{ ppm (Kemp, 1977)}$

$= 976,000 \text{ ppm}$

$M = \text{mass of runoff per year}$

Total runoff = $48.5 \text{ E}9 \text{ m}^3/\text{yr}$ (Kemp, 1977)

Area of bay = $7.98 \text{ E}8 \text{ m}^2$

Runoff = $(48.5 \text{ E}9 \text{ m}^3/\text{yr})/(7.98 \text{ E}8 \text{ m}^2)$

$= 60.7 \text{ m}^3/\text{m}^2/\text{yr}$ or $6.1 \text{ E}7 \text{ cm}^3/\text{m}^2/\text{yr}$

Runoff (chemical potential) = $(1 \text{ mole}/18 \text{ g})(1.99 \text{ cal/}^\circ\text{mole})(293^\circ)$

$\ln ((999,880 \text{ ppm})/(976,000 \text{ ppm}))(6.1 \text{ E}7 \text{ g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 4.8 \text{ E}4 \text{ Cal/m}^2/\text{yr}$

4 Tide = $1/2 r G H^2 n$

$r = \text{density of seawater} = 1.025 \text{ g/cm}^3$

$G = \text{gravity} = 980 \text{ cm/sec}^2$

$H = \text{tidal head} = 70.1 \text{ cm (Kemp, 1977)}$

$n = \text{number of tides per year} = 705 \text{ (Kemp, 1977)}$

Tide = $(0.5)(1.025 \text{ g/cm}^3)(980 \text{ cm/sec}^2)(70.1 \text{ cm})^2(705 \text{ tides/yr})$

$(1 \text{ E}4 \text{ cm}^2/\text{m}^2)(2.38 \text{ E-}11 \text{ Cal/erg})$

$= 4.1 \text{ E}2 \text{ Cal/m}^2/\text{yr}$

5 Organic inflows = ME

$M = \text{mass of organic matter input per yr}$

$= 2.5 \text{ E}4 \text{ g/m}^2/\text{yr}$ (Lehman, 1974)

$E = \text{heat content of organic matter}$

$= 4.5 \text{ Cal/g}$ (E.P. Odum, 1971)

Organic inflow = $(2.5 \text{ E}4 \text{ g/m}^2/\text{yr})(4.5 \text{ Cal/g})$

$= 1.1 \text{ E}5 \text{ Cal/m}^2/\text{yr}$

Table 8a
Marine Mud Mound

Parameter	Value	Reference
Landform Density	1.58 g/cm ³	Scholl, 1966
Landform Volume	9.25 E6 m ³	a
Landform Area	3.46 E6 m ²	b
Concentration Area	4.4 m ² /m ²	c
Development Time	2000 yrs	Enos and Perkins, 1979
Landform Energy	2.1 E4 J/m ²	d

a Volume (1/2 ellipsoid) = $.5(4/3 \pi abc)$; a = length = 7000 m, b = width = 630 m, c = height = 1 m (all from Enos and Perkins, 1979).

b Area = $3.1416(\text{length}/2)(\text{width}/2) = 3.1416(315 \text{ m})(3500 \text{ m}) = 3.46 \text{ E6 m}^2$.

c Marine mud mound concentration area is given by Scholl (1966) at 23% of area of Florida Bay, or $4.4 \text{ m}^2/\text{m}^2$.

d Landform energy = $((9.25 \text{ E6 m}^3)(10 \text{ E6 cm}^3/\text{m}^3)(1.58 \text{ g/cm}^3)(50 \text{ cm})(980 \text{ cm/sec}^2)(2.39 \text{ E-11 Cal/erg})(4186 \text{ J/Cal}))/3.46 \text{ E6 m}^2 = 2.1 \text{ E4 J/m}^2$.

Table 8b
Energy Flows to Marine Mud Mound

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	6.3 E9	1	6.3
2	Wind	2.7 E6	1496	4.0
3	Chemical Geopotential of Runoff	9.6 E6	18199	174.7
4	Tide	2.1 E5	16842	3.5
5	Total of items 1, 3, 4	—	—	184.5

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 9b

1 Sunlight = 1.5 E6 solar Cal/m²/yr (Ruttenber, 1979)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E⁻³ g/cm³

V = wind velocity = 378.8 cm/sec (Ruttenber, 1979)

c = eddy diffusion coefficient = 1 E4 cm² /sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(378.8 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 6.5 E2 Cal/m²/yr

Footnotes for Table 8b (continued)

$$3 \quad \text{Runoff (chemical potential)} = nRT \ln (C_2/C_1) M$$

$$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$$

$$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$$

$$T = \text{absolute temperature} = 295^\circ\text{K}$$

$$C_2 = \text{water content of runoff}$$

$$= 1,000,000 \text{ ppm} - 120 \text{ ppm (Ruttenber, 1979)}$$

$$= 999,880 \text{ ppm}$$

$$C_1 = \text{water content of receiving water}$$

$$= 1,000,000 \text{ ppm} - 3500 \text{ ppm (Scholl, 1966)}$$

$$= 965,000 \text{ ppm}$$

Assume 1/4 of the runoff from the Everglades watershed enters Florida Bay.

Average annual runoff over the 9000 square mile area of the Everglades is 7.5 inches (Parker, 1974). On a volume basis this is

$$\text{Total runoff} = (9000 \text{ miles}^2)(2.59 \text{ E6 m}^2/\text{mile}^2)(1 \text{ E4 cm}^2/\text{m}^2) \\ (7.5 \text{ inches/yr})(2.54 \text{ cm/inch})$$

$$= 4.4 \text{ E15 cm}^3/\text{yr}$$

This runoff volume mixes over the area of Florida Bay making

$$12.18 \text{ E9 m}^2 \text{ (from Scholl, 1966)}$$

Runoff on area basis

$$\text{Runoff per m}^2 = (4.4 \text{ E15 cm}^3/\text{yr})/(2.2 \text{ E9 m}^2)$$

$$= 2 \text{ E6 cm}^3/\text{m}^2/\text{yr}$$

$$\text{Mass of runoff} = (2 \text{ E6 cm}^3/\text{m}^2/\text{yr})(1 \text{ g/cm}^3)$$

$$= 2 \text{ E6 g/m}^2/\text{yr}$$

$$\text{Runoff (chemical potential)} = (1 \text{ mole}/18 \text{ g})(1.99 \text{ cal/}^\circ\text{mole})(295^\circ)$$

$$\ln ((999,880 \text{ ppm})/(965,000 \text{ ppm}))(2 \text{ E6 g/m}^2/\text{yr})(\text{Cal}/1000 \text{ cal})$$

$$= 2.3 \text{ E3 Cal/m}^2/\text{yr}$$

$$4 \quad \text{Tide} = 1/2 r G H^2 n$$

$$r = \text{density of seawater} = 1.025 \text{ g/cm}^3$$

$$G = \text{gravity} = 980 \text{ cm/sec}^2$$

$$H = \text{tidal head} = 24 \text{ cm (Scholl, 1966)}$$

$$n = \text{number of tides per year} = 717 \text{ (Ruttenber, 1979)}$$

$$\text{Tide} = (0.5)(1.025 \text{ g/cm}^3)(980 \text{ cm/sec}^2)(24 \text{ cm})^2(717 \text{ tides/yr})$$

$$(1 \text{ E4 cm}^2/\text{m}^2)(2.38 \text{ E-11 Cal/erg})$$

$$= 49.4 \text{ Cal/m}^2/\text{yr}$$

Table 9a
Spoil Mound

Parameter	Value	Reference
Landform Density	1.4 g/cm ³	Assumed
Landform Volume	3000 m ³	a
Landform Area	1200 m ²	b
Concentration Area	1 m ² /m ²	Assumed
Development Time	1 yr	Assumed
Landform Energy	8.7 E4 J/m ²	c

The form of a prism = .5(abc); a = length = 60 m, b = width = 20 m, c = height = 5 m (assumed).

b Area = (length)(width) = (60 m)(20 m) = 1200 m².

c Landform energy = ((3000 m³)(10 E6 cm³/m³)(1.4 g/cm³)(250 cm)(980 cm/sec²)(2.39 E-11 Cal/erg)(4186 J/Cal))/1200 m² = 8.7 E4 J/m².

Table 9b
Emergy Flows to Spoil Mound

Note	Source	Energy* J/m ² /yr	Transformity sej/J	Emergy E9 sej/m ² /yr
1	Sun	6.3 E9	1	6.3
2	Wind	2.5 E6	1496	37.4
3	Chemical Potential of Rain	1.6 E4	18199	0.3
4	Elevated Potential of runoff	6.3 E3	10488	0.1
5	Kinetic Impact of Rain	3.7 E4	238000	8.8
6	Dragline	—	—	1950000.0
7	Total of items 2, 4, 6	—	—	1950037.5

* Footnote calculations in kilocalories multiplied by 4186 joules per kilocalorie.

Abbreviations: Cal = kilocalorie; J = joule; sej = solar emjoules

Footnotes for Table 10b

1 Sunlight = 1.5 E6 solar Cal/m²/yr (McCuller, 1975)

2 Wind = 1/2 r V² C (1/d)

r = density of air = 1.2 E⁻³ g/cm³

V = wind velocity = 366.5 cm/sec (McCuller, 1975)

c = eddy diffusion coefficient = 1 E4 cm²/sec (Kemp, 1977)

d = height of boundary layer = 1 E4 cm

Wind = (0.5)(1.2 E-3 g/cm³)(366.5 cm/sec)²(1 E4 cm²/sec)

(1/1 E4 cm)(2.38 E-11 Cal/erg)(3.15 E7 sec/yr)(1 E4 cm²/m²)

= 6 E2 Cal/m²/yr

Footnotes for Table 9b (continued)

3 Rain (chemical potential) = $nRT \ln (C_2/C_1) M$

$n = 1 \text{ mole}/18 \text{ g of H}_2\text{O}$

$R = \text{gas constant} = 1.99 \text{ cal/}^\circ\text{mole}$

$T = \text{absolute temperature} = 293^\circ\text{K}$

$C_2 = \text{water content of rain}$

$= 1,000,000 \text{ ppm} - 8 \text{ ppm}$

$= 999,992 \text{ ppm}$

$C_1 = \text{water content of receiving water}$

$= 1,000,000 \text{ ppm} - 100 \text{ ppm (Odum et al., 1978)}$

$= 999,900 \text{ ppm}$

$M = \text{mass of rain per year}$

$\text{Rain} = 127 \text{ cm/yr}$

$\text{Mass or rain} = (127 \text{ cm/yr})(1 \text{ g/cm}^3)(1 \text{ E}4 \text{ cm}^2/\text{m}^2)$

$= 1.3 \text{ E}6 \text{ g/m}^2/\text{yr}$

$\text{Runoff (chemical potential)} = (1 \text{ mole}/18 \text{ g})(1.99 \text{ cal/}^\circ\text{mole})(293^\circ)$

$\ln ((999,992 \text{ ppm})/(999,900 \text{ ppm}))(1.3 \text{ E}6 \text{ g/m}^2/\text{yr})(1 \text{ Cal}/1000 \text{ cal})$

$= 3.9 \text{ Cal/m}^2/\text{yr}$

4 Runoff (elevated potential) = MGH

$M = \text{mass of runoff per yr}$

$G = \text{gravity} = 980 \text{ cm/sec}^2$

$H = \text{elevation drop of head}$

$\text{Runoff} = 25.4 \text{ cm/yr (Odum et al., 1978)}$

$\text{Mass} = (25.4 \text{ cm/yr})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)(1 \text{ g/cm}^3)$

$= 2.5 \text{ E}5 \text{ g/m}^2/\text{yr}$

$H = 250 \text{ cm}$

$\text{Runoff (elevated potential)} = (2.5 \text{ E}5 \text{ g/m}^2/\text{yr})(980 \text{ cm/sec}^2)(250 \text{ cm})$

$(2.38 \text{ E-}11 \text{ Cal/erg})$

$= 1.5 \text{ Cal/m}^2/\text{yr}$

5 Rain (kinetic impact) = $1/2 M V^2$

$M = \text{mass of rain per yr}$

$V = \text{velocity of raindrops}$

$= 762 \text{ cm/sec for an average drop diameter (Odum et al., 1978)}$

$\text{Rain} = 127 \text{ cm/yr (McCuller, 1975)}$

$\text{Mass} = (127 \text{ cm/yr})(1 \text{ E}4 \text{ cm}^2/\text{m}^2)(1 \text{ g/cm}^3) = 1.3 \text{ E}6 \text{ g/m}^2/\text{yr}$

$\text{Rain (kinetic impact)} = (0.5)(1.3 \text{ E}6 \text{ g/m}^2/\text{yr})(762 \text{ cm/sec})^2$

$(2.38 \text{ E-}11 \text{ Cal/erg}) = 9.0 \text{ Cal/m}^2/\text{yr}$

Footnotes for Table 9b (continued)

6 Inputs to Dragline to Build a Spoil Mound

Inputs to a 35 yard³ capacity dragline are given below (from Zeindler, 1964) on a yard³ basis:

Labor = 2.6 E-3 man-hours (at 3.17 \$/hr) or 8.2 E-3 \$

Electricity = 0.6 KWH

Maintenance = 0.02 \$

Amortized capital cost = 9.4 E-3 \$ (2 E6 \$ over 20 yrs)

Dragline inputs are about 0.04 \$/yd³ for dollar costs and 0.6 KWH/yd³ for electrical energy input.

Converting these to solar energy equivalents and summing gives

Solar energy = (0.04 \$/yd³)(1.37 E12 sej/\$ from Odum 1996, Table D.1) + (0.6 KWH/yd³)

(860.5 Cal/KWH)(4186 joules/Cal)(2 E5 sej/j from Odum 1996, Table C.5)

$$= 5.5 \text{ E}10 \text{ sej/yd}^3 + 43.2 \text{ E}10 \text{ sej/yd}^3$$

$$= 48.7 \text{ E}10 \text{ sej/yd}^3$$

Using the average dimensions of a spoil mound:

Height = 5 m

Width = 20 m

Length = 60 m

The volume of the mound can be found by assuming prism shape

Volume = (1/2) height x width x length

$$= (0.5)(5 \text{ m})(20 \text{ m})(60 \text{ m})$$

$$= 3000 \text{ m}^3 \text{ or about } 4000 \text{ yd}^3$$

Total input to dragline in building a spoil mound is then

Total input to dragline = (48.7 E10 sej/yd³)(4000 yd³/mound)

$$= 1.95 \text{ E}15 \text{ sej/mound}$$

Table 10
Transformity of Landforms^a

Table	Land Form Units	Time ^b yr	Empower ^c sej/m ² /yr	Emergy ^d sej/m ²	Energy ^e J/m ²	Transformity ^f sej/J
1	Floodplain	10,000	480.8 E9	1.1 E17	6.7 E3	1.6 E13
2	Coral Reef	700	5.87 E15	2.4 E21	2.0 E6	1.2 E15
3	Salt Marsh	300	365.0 E9	2.2 E14	4.2 E3	5.2 E10
4	Glacier	30,000	368.1 E9	3.8 E17	7.4 E6	5.1 E10
5	Palsa Mound	4,000	14.1 E9	5.6 E13	3.3 E4	1.7 E9
6	Arroyo	43	5.8 E14	8.9 E17	4.8 E5	1.8 E12
7	Oyster Reef	766	3.8 E13	9.6 E17	4.6 E4	2.1 E13
8	Marine Mud Mound	2000	184.5 E9	1.6 E15	2.1 E4	7.6 E10
9	Spoil Mound	1	2.0 E15	2.0 E15	8.7 E4	2.3 E10

a Elevated potential expressed on an area basis

b Time required to develop the landform

c Sum of annual emergy inflows (empower use); see Tables 1b-9b

d Product of the development time in column #3 (see Tables 1a-9a), Empower in column #4 and the landform concentration ratio (see Tables 1a-9a)

e Accumulated storage of energy in the landform; see notes to Tables 1a - 9a

f Emergy in column #5 divided by energy in column #6

Appendix Table A1
Transformities Used for Landform Evaluation

Energy Type	Transformity sej/J	Reference
Sun	1	Odum, 1996 (Table C.3)
Heat Flux	12.9	Odum et al., 1983 (Table 1a)
Wind	1496	Odum, 1996 (Table C.3)
Geopotential of Runoff	10488	Odum, 1996 (Table C.3)
Tide	16842	Odum, 1996 (Table C.3)
Chemical Potential of Rain	18199	Odum, 1996 (Table C.3)
Wave Impact on a Shoreline	30550	Odum, 1996 (Table C.3)
Soil Organic Matter	74000	Odum, 1996 (Table C.4)
Zooplankton	150000	Odum, 1996 (Table C.5)
Physical Impact of Rain	238000	Odum et al., 1983 (Table 1a)
Hydraulic Head of a Flood	400000	Odum et al., 1983 (Table 1a)
Thunderstorm	4600000	See Footnote to Table 7
Geologic Uplift	1.5 E12	Odum et al., 1983 (Table 1a)

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APPENDIX B

EMERGY ANALYSIS OF STORAGES IN A STREAM ECOSYSTEM

Modified from a Paper Presented at the SREL Symposium on Dynamics of Lotic Ecosystems, October, 1980, Augusta, Georgia

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Abstract

The emergy analysis approach is used to evaluate aggregated storages in a stream ecosystem. Storages considered were stream channel form, substrate rocks, and animal community biomass. Using the concept of transformity, emergy values are calculated for each storage in equivalent units of solar kcal/m². Emergies in channel form and substrate were found to be similar (about 1 E9 solar kcal/m²), while animal biomass was five orders of magnitude less. Differences in storage energy values are due largely to the transformities used, and problems with their calculation are mentioned. Implications of the results are discussed in terms of the use of emergy values for environmental impact assessment.

Introduction

A stream ecosystem is a complex combination of flowing waters, rocks, detritus and living organisms contained within a channel landform. The separate parts are often studied by scientists from diverse disciplines: hydrology, geomorphology, ecology, etc. The ecosystem operates as a more or less integrated whole unit however, and for certain purposes the properties of the larger system are of interest. Emergy analysis is one method for investigating systems. The purpose of this paper is to apply the emergy analysis approach to a problem in stream ecology. Specifically, the relative importance of aggregated storages of a riffle ecosystem are compared through calculation of their emergy value.

Data were taken from a heterotrophic riffle ecosystem of the Huron River near Ypsilanti in southeastern Michigan. The Huron River is a fourth order stream, approximately 125 miles in length. Its origin is in glacial outwash of Oakland County, Michigan. Flow is in a general southeastern direction with the mouth of the river in western Lake Erie. The river is characterized by a number of impoundments formed by hydroelectric dams which were constructed along the lower portion of the river during the 1920s. The

study site was located about one mile downstream from one of these impoundments.

Emergy Analysis

Emergy analysis is a quantitative method for evaluating systems (Gilliland, 1978; Odum, 1971, 1978, 1981; Odum and Odum, 1976). It is based on the use of energy as a common denominator so that flows and storages of different types can be expressed and compared in the same units. Three main operations or steps are involved. First a diagram of the system of interest is drawn using the energy circuit language or other suitable language. The energy circuit language is a modeling language composed of a set of symbols, each representing an aggregated class of objects or processes (Odum, 1972, 1974, 1981). Diagrams are built by connecting symbols into configurations which represent the main features of the system being studied. Each symbol or configuration has a mathematical translation allowing equations to be drawn directly from the diagram.

Given a diagram the next step is to quantify the flows and storages and to express them in equivalent energy units. The basis for this expression is the concept of transformity, which states that different kinds of energy have the ability to provide different amounts of useful work. The transformation into equivalent units is done by multiplying actual energy values by transformities which relate different kinds of energy to a standard unit type. This is a crucial step and is highly dependent on the values of the transformities. Unfortunately, these factors are difficult to calculate and must be viewed as somewhat tentative and subject to improvement.

The final step is analysis of the model. This can involve either simulation to test the dynamics of the model in response to alternative manipulations such as management scenarios or calculation of summary indices for the model, usually ratios of various flows which characterize the energetics of the system.

To illustrate the emergy analysis method calculations are given for energy value of aggregated storages in the stream ecosystem. For each storage the calculation of emergy is outlined. Emergy is a measure of value in equivalent energy units. It is (or attempts to be) the total amount of energy needed to produce a flow or storage, similar to a replacement cost. Each calculation will include

- 1) derivation of the actual energy content of the storages,
- 2) statement of storage transformity, and

3) calculation of energy of the storage by multiplying actual energy by the transformity. The energy values are then compared, and implications of their distribution are discussed

Energy in Stream Ecosystem Storages

A model of a stream ecosystem is given in Figure 1. Other stream models using the energy circuit language are given by Hall (1972), Mitsch et al. (1978) and Odum (1981). Energy sources are shown on the right flowing into the system. Conventional energy sources of sunlight and organic matter are shown along with auxiliary sources of current, drift, rocks and land as a platform for the stream channel. Inorganic nutrients as sources for primary producers could also be added, however since this is a model for a primarily heterotrophic stream they are left off. The energy sources are shown supporting three aggregated storages. Channel form is potential energy in channel volume available to be filled in. Just as an elevated landform has potential energy in the elevation to erode, so also a depression landform has potential to be filled. Channel form is related to flooding in the simple way that if water volume exceeds channel volume a flood occurs. The other stream storages, substrate and biomass, are chemical potential energies. Substrate rocks and sediments have potential energy in the inorganic molecules which are chemically weathered or eroded into simpler molecules. Biomass has potential energy in the organic molecules which are oxidized into simpler molecules through metabolism of plants, animals and microbes.

Energy in channel form is derived in Table 1. Actual energy is calculated from the standard potential energy equation using the physical dimensions of the stream channel and gravitational acceleration. The transformity for channel form is calculated in Footnote 1. This calculation attempts to estimate the amount of energy input to the watershed that developed the actual energy of the river channel. Emergy of channel form was found to be $3.1 \text{ E}10 \text{ solar kcal/m}^2$.

Energy in substrate rocks is given in Table 2. Mass of rocks in the stream was 6500 g/m^2 . Chemical potential energy content and the transformity are from Gilliland et al. (1978). Emergy of the substrate was calculated at $8.0 \text{ E}9 \text{ solar kcal/m}^2$.

Energy in stream animals is shown in Table 3. Average biomass was 1 g/m^2 . Actual energy was found using a standard chemical potential energy content of 5 kcal/g (E.P. Odum, 1971). A transformity was calculated from

data given by Mitsch et al., (1978) and Kemp (1977). This is an average for animals in all trophic levels of the stream ecosystem.

The transformity represents the amount of detritus energy (in equivalent units of solar kcal) required to produce a unit kcal of actual energy of animal tissue. Emergy of animals was found to be 1.5×10^4 solar kcal/m².

Discussion

Stream storage values are summarized in Table 4. These data are a ranking of storage value from a systems point of view. Specific numerical values are less significant than orders of magnitude.

The distribution of energy value is different for actual energy as compared with emergy, due to the magnitudes of the transformities. The most important column is the emergy value, since this quantifies the relative importance of storages in equivalent energy units. The storage with the largest value is implied as the most important to the system in the sense that this storage would take more energy to replace if it was degraded. This is based on the hypothesis that a system would not invest a large amount of energy in a storage if it did not feed back to bring more energy into the system. It is also related to the idea of cost being proportional to effect.

Immediately obvious is the great range of emergy values, more than six orders of magnitude between animal emergy and channel emergy. The explanation for the large range lies in the transformities whose calculation cuts across scales of time and space. For example turnover time of stream animals is on the order of months or years while turnover of the river channel for most instances is on the order of tens of thousands of years. Also in terms of spatial scale, transformity of stream animals is evaluated for local areas of a stream whereas the stream channel must be evaluated at the scale of the watershed.

Substrate rock emergy is nearly of the same magnitude as channel emergy. This large value for substrate compared with animals goes along with the often made observation that substrate determines the animal community living on or among the rocks. The small relative value for stream animals stands out. The implication is that the relative role of animals in relation to the geologic storages considered here is small. This is not unexpected, however a system dominated by beavers whose dams can greatly alter stream character might give a different result.

The practical application of this kind of analysis might come in the assessment of stream impacts by human actions or natural catastrophes. Impacts could be evaluated in terms of the change inflicted on total storage values. Based on the data in Table 4 as an example, impacts to channel form would be potentially more damaging to the system than an impact which affects only the animal community within the stream ecosystem. Thus, an impact such as channelization is suggested as potentially more serious than organic pollution, in terms of the entire system as conceptualized in Figure 1. The emergy values then allow prioritization and quantitative evaluation of different kinds of stresses or impacts to stream ecosystems.

Table A2.1. Energy in Channel Form

Potential Energy = MGH

$$M = (\text{density})(\text{volume}) = (1.4 \text{ g/cm}^2)(4 \text{ E}5 \text{ cm}^3/\text{m}^2) = 5.6 \text{ E}5 \text{ g/m}^2$$

$$G = 980 \text{ cm/sec}^2$$

$$H = (1/2 \text{ stream depth}) = 20 \text{ cm}$$

Actual Energy in Channel Form

$$= (5.6 \text{ E}5 \text{ g/m}^2)(980 \text{ cm/sec}^2)(20 \text{ cm})$$

$$= 1.1 \text{ E}10 \text{ g cm}^2/\text{sec}^2/\text{m}^2 \text{ or ergs/m}^2$$

$$= (1.1 \text{ E}10 \text{ ergs/m}^2)(2.39 \text{ E-}11 \text{ kcal/erg})$$

$$= 0.26 \text{ kcal/m}^2$$

Transformity of River Channel

$$= 1.2 \text{ E}11 \text{ solar kcal/kcal (see footnote 1)}$$

Emergy in Channel Form

$$= (0.26 \text{ kcal/m}^2)(1.2 \text{ E}11 \text{ solar kcal/kcal})$$

$$= 3.1 \text{ E}10 \text{ solar kcal/m}^2$$

Table A2.2. Energy in Substrate Rocks

$$\text{Mass of Rocks (greater than 10 mm in diameter)} = 6500 \text{ g/m}^2$$

Chemical Potential Energy Content of Rocks (assume granite)

$$= 0.012 \text{ kcal/g (Gilliland et al., 1978)}$$

Actual Energy in Rocks

$$= (6500 \text{ g/m}^2)(0.012 \text{ kcal/g}) = 78 \text{ kcal/m}^2$$

Transformity of Rocks

$$= 1 \text{ E}8 \text{ solar kcal/kcal (Gilliland et al., 1978)}$$

Emergy in Rocks

$$= (78 \text{ kcal/m}^2)(1 \text{ E}8 \text{ solar kcal/kcal}) = 8 \text{ E}9 \text{ solar kcal/m}^2$$

Table A2.3. Energy in the Animals

Biomass = 1 g/m^2

Chemical Potential Energy Content of Biomass
 = 5 kcal/g (E.P. Odum, 1971)

Actual Energy in River Animals
 = $(1 \text{ g/m}^2)(5 \text{ kcal/g}) = 5 \text{ kcal/m}^2$

Transformity of Animals
 = $3000 \text{ solar kcal/kcal}$ (calculated from data in Mitsch et al., 1978 and Kemp, 1977)

Emergy in River Animals
 = $(5 \text{ kcal/m}^2)(3000 \text{ solar kcal/kcal}) = 1.5 \text{ E}4 \text{ solar kcal/m}^2$

Table A2.4. Embodied Energy in Storages of a Riffle Ecosystem

	Actual Energy kcal/m^2	Transformity solar kcal/kcal	Emergy solar kcal/m^2
Animals	5.0	3000	1.5 E4
Rocks	78.0	1 E8	8.0 E9
Channel Form	0.3	1.2 E11	3.1 E10

Footnote 1. Calculation of Transformity for Channel Form

$$\text{Channel Form Transformity} = \frac{\text{Total Solar Input to Watershed over Development Time of River, solar kcal}}{\text{Actual Potential Energy of River, kcal}}$$

Total Solar Input = solar input, solar kcal/m²/yr x watershed area, m² x development time, yrs

Solar Input = 1.42 E6 solar kcal/m²/yr (E.P. Odum, 1971)

Watershed area = 2.3 E9 m² (Say and Janssen, 1976)

Development time = Assume 10,000 years, length of time since recession of last glaciation

Total Solar Input
 = (1.42 E6 solar kcal/m²/yr) x (2.3 E9 m²) x (10,000 yrs)
 = 3.3 E19 solar kcal

Actual Potential Energy of River
 = depth, cm x volume, cm³ x density of sediments, g/cm³ x gravity, cm/sec²

Depth = 457 cm (estimated from Say and Janssen, 1976)

Volume = 1.9 E13 cm³ (estimated from Say and Janssen, 1976)

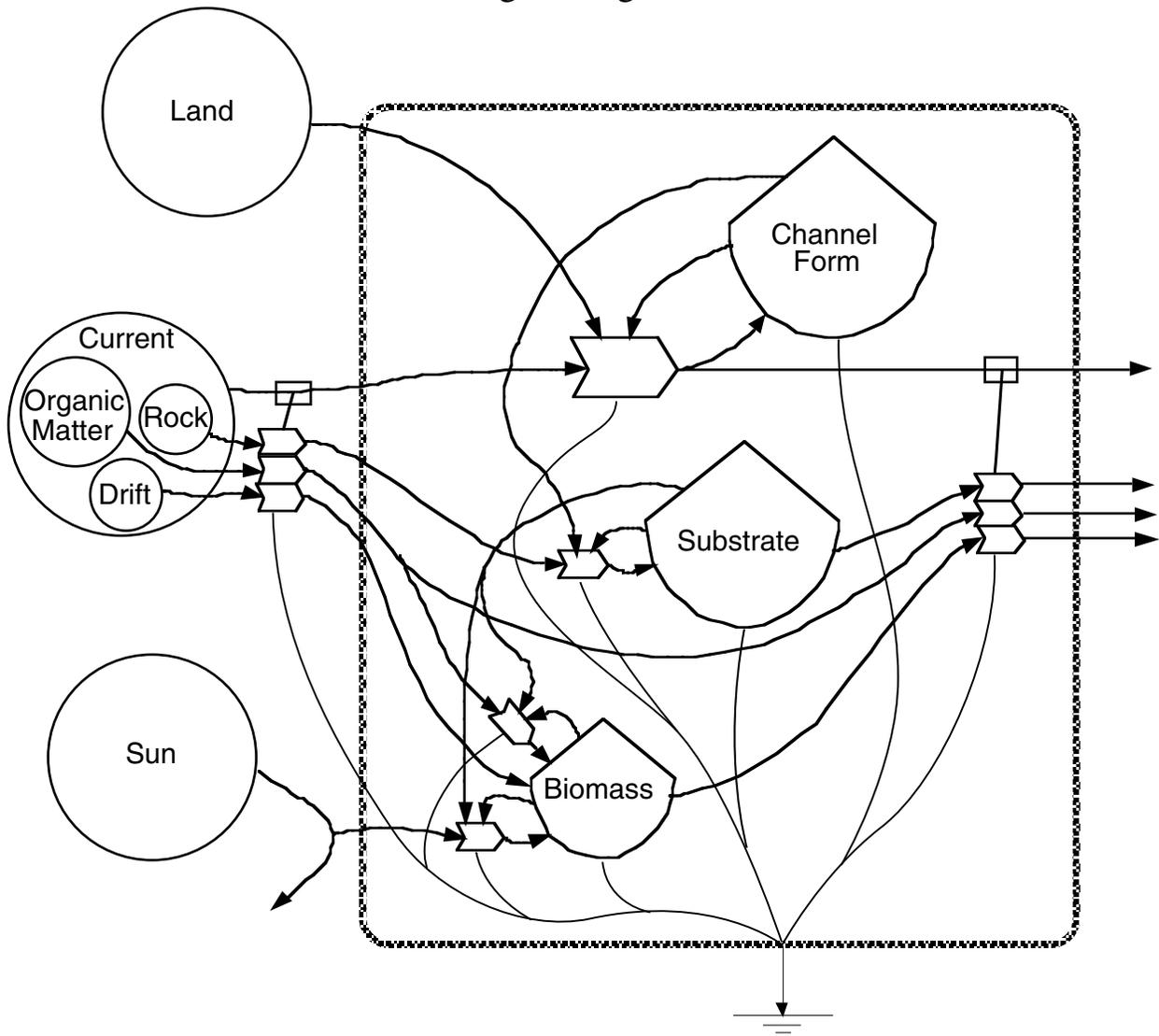
Density of sediments = Assume 1.4 g/cm³

Gravity = 980 cm/sec²

Actual Potential Energy of River
 = (457 cm) x (1.9 E13 cm³) x (1.4 g/cm³) x (980 cm/sec²)
 = (1.2 E19 ergs) x (2.4 E-11 kcal/erg)
 = 2.8 E8 kcal

$$\text{Channel Form Transformity} = \frac{3.3 \text{ E19 solar kcal}}{2.8 \text{ E8 kcal}} = 1.2 \text{ E11 solar kcal/kcal}$$

Figure Legend:



Appendix Figure B1. Energy model of a stream riffle ecosystem.

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