EMERGY SYNTHESIS:
Theory and Applications of the Emergy Methodology

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ABSTRACT

The transformity for riverine sediments specific to the Mississippi delta was determined to be $6.28 \times 10^8$ sej/g. The calculation accounted for the accumulated solar em joules (sej) that were required to weather the rock and deliver the sediments from the Mississippi river basin to the delta. This amount was then divided by the annual mass of sediments reaching the delta to calculate the transformity of the sediments in units of solar em joules per gram. An emergy signature diagram identified riverine sediments as the largest natural input of emergy to river diversions. Determining the transformity of riverine sediments is a critical step in completing a thorough emergy analysis of river diversions to determine if the benefits from these projects merit the required economic investments.

INTRODUCTION

By transforming flows of energy and material into the amount of emergy required for their production, emergy analysis provides a basis to compare dissimilar flows, such as natural resources and economic inputs. This ability makes emergy analysis a valuable tool to evaluate management plans operating at the interface between natural and economic systems. River diversions, which rely on economic investments and flows of riverine natural resources, have been used in deltas and river basins to create and sustain marsh habitats (Lane et al. 1999, Templet and Meyer-Arendt 1988), remove nutrients (Lane et al. 1999, Reilly et al. 1999), and to ensure navigation (Mirza 1998). The overall goal of this project is to perform emergy analyses of river diversions within the Mississippi delta to determine if the benefits of sustaining and creating marshes merit the economic investments required for their construction and maintenance. Before performing an emergy analysis the transformity, the emergy per unit energy or mass, must be known for each flow entering and exiting the system, including riverine sediments. The focus of this paper will be to quantify the transformity of riverine sediments in the Mississippi delta.

The calculation of a transformity of riverine sediments specific to the Mississippi delta was necessitated because of the integral role of the sediments in the functioning of river diversions and the sensitivity of the results to the transformity of riverine sediments. Previously, Odum (1996) calculated the transformity of the sediments in the global sedimentary cycle to be $1 \times 10^9$ sej/g. In this calculation the total annual emergy input to the geobiosphere was divided by the average mass of sediment uplifted annually across the continental areas of the earth. This spatially averaged transformity has been utilized for riverine sediments in previous emergy analyses of deltas (Day et al. 1997) and river basins (Brown and McClanahan 1996). Because the emergy input, rate of geologic uplift, and rock density vary across river basins the transformity of riverine sediments specific to an individual delta depends upon the characteristics of the river basin. One of the main goals of river diversions in the Mississippi delta is to capture and direct riverine sediment to hydraulically isolated marshes. The increased supply of sediment will build elevation, sustaining and creating marsh habitat and reducing the conversion of these areas to open water (Martin et al. 2000, Day et al. 1997). Land loss is a pervasive problem within the Louisiana coastal zone where 4000 km$^2$ of marsh habitat have been converted to open water areas over the past 60 years.
years (Britsch and Dunbar 1993). Preliminary emergy analysis results revealed that riverine sediments are the largest emergy input to river diversions and, therefore, that the results would be highly dependent upon the transformity of these sediments.

Transformity is defined as the ratio obtained by dividing the total emergy that was used in a process by either the energy, mass, or cost of the product yielded (Odum 1988). For example, the transformity of corn is 8.3E4 sej/l (Odum 1996). Energy necessary for the production of corn on a contemporary U.S. farm includes the environmental energies of sun, rain, wind and soil and the human inputs of fertilizers, pesticides, machinery, labor, and management. The transformity value means that 8.3E4 solar joules are necessary to create these inputs and, therefore, required to produce each joule of energy in corn. Transformities are used to convert different energies and products to emergy of the same type and, therefore occupy a central role when performing emergy analyses.

Viewed holistically, sediments, as with all cycled materials, are characterized by a gain of energy quality, or transformity, as they are concentrated or processed. As they become more diffuse in another phase of the cycle, energy availability and emergy are lost, resulting in a decrease of transformity (Odum 1996). Mineral sediments reach a minimum transformity and concentration just prior to entering a stream (Figures 1 and 2). The geopotential energy of the riverine system works on the sediments, concentrating them and increasing their emergy and transformity as they flow downstream. The recycling of aluminum cans offers an opportunity to demonstrate these concepts with familiar material and energy flows. The aluminum of a can is at a minimal transformity just after being utilized as a beverage container. Just as the transformity of sediments begins to increase when they enter a stream, the transformity of aluminum cans increases when the consumer invest energy to increase their concentration by collecting the cans for recycling. As the geopotential energy of the river basin increases the concentration of the sediments, the energy of labor and fuels are utilized to collect the cans, eventually delivering them to a processing plant where they are again rendered into usable aluminum. Sediments reach a maximum transformity when

![Figure 1](image)

**Figure 1.** The system diagram of the sediment cycle illustrates the increase in transformity and concentration of sediments prior to stream capture of eroded mountain sediments. Sun energy evaporates ocean water to form rain that erodes mountain sediments and creates river geopotential. The geopotential concentrates the sediments following stream capture and delivers them to the delta. Over long time periods geological energies reform and elevate the sediments. During the cycle the transformity and concentration of sediments reaches a maximum in mountain sediments and minimum in sediments prior to stream capture.
Chapter 3. The Transformity of Riverine Sediments

**Figure 2.** During the sediment cycle both transformity and concentration increase as the sediments are captured by streams and transported to the delta and over long periods of time reworked, buried and elevated to form rock in mountains (solid line). As the sediments are eroded from mountains both the transformity and concentration decline (dashed line).

they are highly concentrated and reworked by earth energies and uplifted to form mountains. The investment of labor and fuel energies necessary to render usable aluminum into final products such as cans, results in the maximum transformity for the cycled aluminum. Similar to the erosion of sediments the aluminum loses transformity as spatial concentration is lost through distribution and during the use of the product.

**METHODS**

After using the system diagram (Figure 1) to identify geopotential energy as responsible for increasing the emergy and transformity of the sediments, the next step was to quantify the energy flows producing the geopotential energy of the Mississippi basin. Following the work of Romitelli (1997), the sources of energy contributing to the geopotential of river water are rain and geological uplift. Rainfall produces river flow and stimulates erosion of sediments. Tectonic uplift caused by earth energies is needed to create a slope to direct and concentrate riverine flow.

The total weight of rainfall across the basin was calculated as the product of the basin area, the average rainfall across the basin, and the density of rain water (Table I). The average annual rainfall across the basin, 0.799 m, was calculated in a previous study of the Mississippi basin (Odum et al. 1987) and is in agreement with the United States national average of 0.890, considering the low rainfall that characterizes the western portion of the basin. The annual mass of rainfall, 2.67 E18 g/yr, was then multiplied by the emergy per mass for rainfall, 8.99 E4 sej/g (Romitelli 1997), to quantify the equivalent amount of solar energy required to produce this amount of rainfall, 2.40 E23 sej/yr (Table I). The emergy per mass for rainfall quantifies the amount of embodied solar energy used to create rainfall, by transforming energies in radiative heating and wind into solar emjoules.

The annual mass of sediments uplifted each year was determined by multiplying the annual rate of uplift, the rock density, and the basin area experiencing active uplift. The area of active geologic uplift was determined as all areas with an elevation greater than 1000 m above sea level and amounted to 21% of the basin area (Table 1). With the exception of a small portion of eastern Tennessee (5500 km²), this included the portion of the basin westward of the north-south line dividing the states of Kansas and
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Table 1. The annual contribution of solar emjoules from rainfall and geologic energies was calculated by multiplying their respective transformities by the grams of each component. The sediment transformity was arrived at by summing the rainfall and geologic contributions and dividing by the annual flow of sediments.

<table>
<thead>
<tr>
<th></th>
<th>Annual Flow (g)</th>
<th>Transformity (sej/g)</th>
<th>Annual solar emjoules (sej/yr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Rainfall</td>
<td>2.67E+18</td>
<td>8.99E+04</td>
<td>2.40E+23</td>
</tr>
<tr>
<td>2. Uplift</td>
<td>1.83E+14</td>
<td>1.00E+09</td>
<td>1.83E+23</td>
</tr>
<tr>
<td>3. Total annual solar emjoules</td>
<td></td>
<td></td>
<td>4.23E+23</td>
</tr>
<tr>
<td>4. Annual flow of sediments to delta(g)</td>
<td>6.20E+14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>5. Mississippi delta sediment transformity</td>
<td></td>
<td>6.82E+08</td>
<td></td>
</tr>
</tbody>
</table>

1. Annual rainfall=annual ht. rain 0.799m(Odum et al. 1987)*rain density 1.00E6 g/m3* basin area 3.34E12m2
2. Annual rock uplifted=Uplift rate 10cm/1000yr (Ruddiman and Kutzback 1991)* rock density 2.61E6 g/m3*basin area experiencing uplift 7.01E11 m2 (Ruddiman et al. 1991)
3. sum of row 1 and row 2
4. Roberts 1997
5. Row 3 divided by row 4

Colorado. This agrees with geological studies (Ruddiman et al. 1989) finding rapid uplift in the Rocky Mountains and negligible uplift in the Great Plains. The annual uplift experienced by this area has been estimated as 10 cm/1000yr (Ruddiman and Kutzback 1991). Similar to the rain calculation the annual mass of uplifted sediments, 1.83 E14 g/yr, was multiplied by an emergy per mass for the global sedimentary cycle, 1 E9 sej/g (Odum 1996). The total annual energy contributed by geologic uplift was 1.83 E23 sej/yr (Table 1).

The last step to calculating the transformity of the sediments was to sum the total energy contributed to the sediments and divide by the total mass of sediments reaching the delta (6.20 E14g/yr Roberts 1997). The sum of rain and geologic emergy was 4.23 E23 sej. The resulting sediment transformity after dividing by the mass of sediments was 6.82E8 sej/g (Table 1).

DISCUSSION

Because of variations between the characteristics of the Mississippi basin and global averages the transformity for riverine sediments in the Mississippi delta was lower than the previously calculated global sediment value of 1 E9 sej/g. The emergy per year per area, empower density, used to create and deliver the sediments from the basin to the Mississippi delta was 1.27 E11 sej/m2/yr. This value is twice that of the global average employed by Odum (1996). However, the Mississippi basin contributes three times more sediment mass per area (185.6 g/m2) than the global average. Although the Mississippi basin has greater empower than the global average, the greater amount of sediment per area results in a transformity that is 68 percent of the global average sediment transformity.

After determining the transformity of Mississippi delta sediments it was possible to calculate the total embodied solar emjoules input to river diversions via sediments. Emergy signature diagrams were then constructed to compare emergy contributed by sediments with other natural inputs to river diversions and other coastal systems. These calculations were carried out for the Caemervon river diversion (Lane et al. 1999) located along the Mississippi river 20 km downstream of New Orleans. The annual...
Figure 3. Emergy signature diagrams comparing the emergy inputs to the Caernervon river diversion and Texas coastal zone. Riverine water use is nearly an order of magnitude greater and the sediments are nearly two orders of magnitude greater in the river diversion compared to the Texas coast. The protected and more inland location of the diversion resulted in reduced tidal and wave inputs. Data for the Texas coastal zone obtained from Energy Systems in Texas and United States Policy Research Project (1987).

The amount of sediments entering the diversion (1.57 E12 g) was multiplied by the transformity to calculate the total embodied solar emjoules input to the project via sediments (9.85 E20 sej/yr). Dividing by the area of the diversion (195 km²) resulted in an empower density of 5.05 E12 sej/m²/yr due to sediment input (Figure 3). Riverine sediments captured by the Caernervon diversion represent the largest emergy input to the system by almost an order of magnitude. Figure 3 also contains an emergy signature diagram for the Texas coastal zone. Standardized for area, the inputs to the river diversion in the Mississippi delta (riverine sediments and riverine water use) are nearly an order of magnitude greater compared to the Texas coastal setting. This difference reflects the much greater area of the Mississippi river basin that contributes water and sediment to the delta. The larger area leads to greater amounts of embodied energy and a higher concentration of resources in the Mississippi delta.

CONCLUSION

Using data from the Mississippi river basin the transformity for riverine sediments specific to the Mississippi delta was determined to be 6.28 E8 sej/g. With this value the amount of emergy contributed by sediments to a river diversion could be calculated and compared with other natural inputs. The sediments contributed the greatest amount of emergy and are a dominant energy input to river diversions. The next research priority will be to quantify the economic inputs required to construct and maintain river diversions and to compare these costs to the renewable energies captured by the diversions and the exports from the diversions. This will determine if the benefits derived from river diversions, including sustaining and creating coastal marshes, and augmenting the production of coastal fisheries, merit the economic investments required for construction and maintenance. Determining the transformity of riverine sediments in the Mississippi delta was an integral component of this research.
ACKNOWLEDGEMENTS

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REFERENCES


