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# ECOLOGICAL AND SOCIOECONOMIC BENEFITS OF RESTORING AND-IMPAIRED STREAMS: EMERGY-BASED VALUATION

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## ABSTRACT

Sound environmental decisions require an integrated, systemic method of valuation that accurately accounts for environmental and social, as well as economic, costs and benefits. More inclusive methods are particularly needed for assessing ecological benefits because these are so poorly signaled by the market-derived or -modeled estimates of value, such as the standard willingness-to-pay and consumer-surplus measures of environmental economists that currently inform environmental decisions. We are currently assessing the potential of supplementing current economic analyses with emergy-based valuations to provide more realistic measures of ecological benefits from water quality restoration. We report here on our analysis of the emergy flows associated with four small streams (in West Virginia, USA) that are impaired by acid mine drainage. Preliminary results indicate that fishing and wildlife watching account for the greatest benefits of the stream systems to the socioeconomic system in terms of emergy contributions. Fish species diversity provides the greatest identified benefit from restoration in the form of an emergy accumulation within the streams. Ranking restoration options for these streams will require additional emergy analyses of costs and of less directly realized benefits.

## 1. INTRODUCTION

To achieve sustainability of economic and environmental systems, we must evaluate the benefits and costs of our environmental decisions and regulations. Economic valuation methods have been used during the past few decades by US EPA for the requisite benefit-cost analyses. However, the well-documented limitations of economic methods for quantifying ecological benefits [1,2,3,4], especially when derived from non-market goods and services, limit the usefulness of these analyses. Energy-based measures (such as emergy and exergy) might provide a more objective means for valuating many goods and services with benefits that are not limited to or defined by market transactions. Accordingly, the potential of supplementing current economic analyses with emergy-based valuations is being explored as part of EPA's effort to develop an integrated tool for environmental assessment based on more complete and objective valuations.

In this paper, we use emergy as an index of value for quantifying potential ecological and socioeconomic benefits of water quality restoration based on an analysis of the emergy flows associated with four small streams (in West Virginia, USA) that are impaired by acid mine drainage (AMD). The emergy costs of restoration alternatives (with respect to the methods of restoration used and the streams restored) will be estimated in a companion study that will then permit an emergy-based benefit-cost analysis and ranking of these restoration alternatives based on net emergy benefits. In this paper, however, only the estimated gross emergy benefits of restoration (which, being equal to the emergy costs of the AMD-impairment, do not differ with the restoration method selected) are reported. Ultimately, the rankings will be compared in a subsequent study with rankings derived from economic analyses of these alternatives. Strengths and weaknesses of the analyses will be explored and the possibility of their integration in light of detected complementarities and conflicts will be considered in this subsequent study.

West Virginia is not only rich in underground resources but is also home to a highly diverse biota including, in terms of species richness, 299 birds, 67 mammals, 46 amphibians, 42 reptiles, 180 fishes, 130 butterflies, thousands of other invertebrates, over 2800 plants, and 12 federally endangered species[5]. It contains approximately 9,000 streams and rivers with a total length of more than 45,000 km[6]. About 750 km of streams and rivers were identified as impaired by acid mine drainage in 1998 [7]. The impacts of AMD on the stream systems include reduction in growth and diversity of primary producers and change in species composition of the producer community. Benthic communities have also been greatly impaired by AMD, perhaps through reduction in available organic matter, shifts in food-type distributions, and toxicity of metal ions. Characterization of these potential effects on all the biotic groups cannot now be achieved directly due to the severe data inadequacies that most emergy analysts must confront when evaluating small and little-studied ecosystems. Reductions in fish diversity, biomass, and production, which can be estimated, might represent the best available integration of AMD's impact on entire stream systems when such fundamental data limitations cannot be remedied. Reductions in recreational fishing, wildlife watching, and kayaking provide a corresponding measure of AMD's effect on the ecosystem services provided by the streams to human society. These reductions represent a decrease in the emergy outflow from the systems. With respect to the integrated environmental-socioeconomic system, the emergy cost of AMD impairment, and consequently the potential benefits of restoration, must be quantified in terms of the emergy outputs, as well as inputs, of the stream ecosystems, given the contribution of these outputs to other productive processes in the integrated system.

## 2. METHODS

Four streams with water quality impaired by AMD—Pringle, Lick, Heather, and Morgan Runs (Table 1) each corresponding to a sub-basin of the Cheat River watershed—were selected for the valuation. An emergy analysis was conducted to determine the value of benefits from restoring stream water quality in each of the streams. Emergy inputs, outputs, and storages, including information (fish species richness), in the streams were estimated. The total empower of the emergy inputs to the streams represents the upper limit of each ecological and socioeconomic benefit (or sum of benefits in the case of emergy flow splits) that can be attained through the restoration of water quality. Benefits from outputs to the socioeconomic system include kayaking, fishing, and wildlife watching, with emergy values derived from stream flow, biotic productivity, and socioeconomic inputs. Ecological emergy benefits of restoration were based on the difference in emergy outflows between the impaired streams and averages for selected reference streams ($pH > 6$, fish IBI close to 70 or greater, watershed areas similar to those of the analyzed streams) or for the Cheat watershed or the state.

Table 1. Stream properties relevant to emergy benefit analysis

| | Pringle | Lick | Heather | Morgan |
|---|---|---|---|---|
| Stream area$^a$, $m^2$ | 19270 | 23040 | 15980 | 9101 |
| Watershed area, $m^2$ | 2.585E7 | 1.248E7 | 5.825E6 | 2.092E7 |
| Avg. watershed elevation, m | 587 | 591 | 581 | 701 |
| Avg. stream elevation, m | 547 | 536 | 518 | 561 |
| Elevation at mouth$^b$, m | 381 | 381 | 377 | 377 |
| Rainfall$^c$, m/yr | 1.354 | 1.338 | 1.309 | 1.305 |
| Water flow volume$^d$, $m^3$/yr | 2.029E7 | 9.679E6 | 4.416E6 | 1.583E7 |
| Specific conductance, $\mu$S/cm | 827 | 2180 | 1070 | 1420 |

$^a$stream and watershed area data from U.S. Geological Survey[8]
$^b$elevation data from U.S. Geological Survey[9]
$^c$1961–1990 average[10]
$^d$rainfall – evapotranspiration

The renewable resource inputs to the stream systems include rain, sun, wind, run-in, and organic matter (Figure 1). The energy/emergy effect of solutes from AMD was also included. Solutes from AMD cause absorption (i.e., reduction) of $H_2O$ concentration emergy in the stream water. (The emergy loss is the difference between the emergy of unimpaired stream water and the emergy of the AMD-impaired stream water). Emergy of purchased inputs to recreational services was analyzed based on monetary values due to the lack of emergy data for many of the inputs to each recreational activity, which include the direct and indirect energy flows necessary for the production of human preferences and for the realization of the effects of human choices. Even though the economic data used for these estimates was more complete than the ecological and environmental data available, many assumptions were required to carry out the analysis, specifically with respect to the use of state, county, or encompassing watershed averages when data for the smaller watersheds was unavailable.

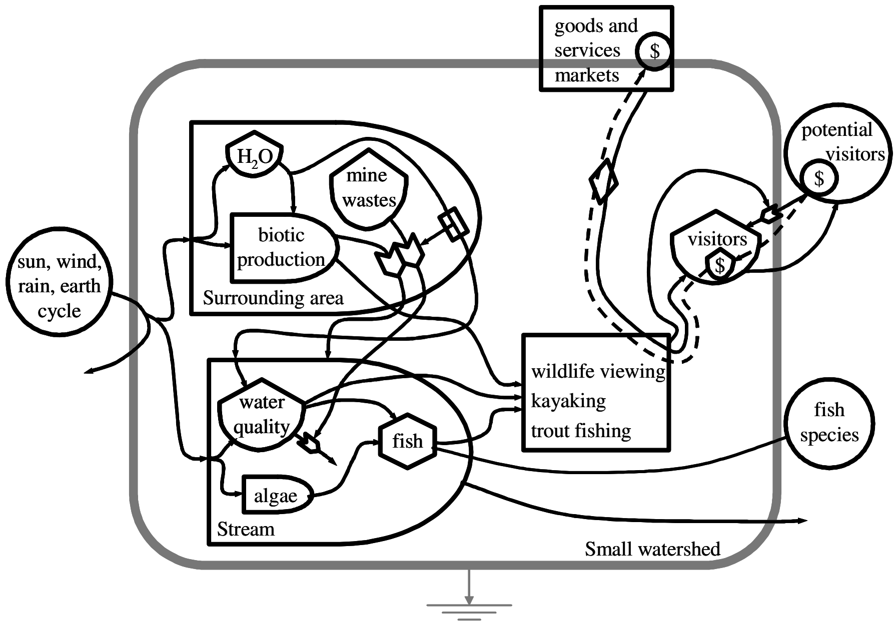

Figure 1. Energy flow network for major components of stream watersheds relevant to emergy analysis of potential benefits of restoration of streams impaired by acid mine drainage

## 3. RESULTS AND DISCUSSION

For each of these stream systems, the emergy abflux (i.e., the absorption flux, Table 2) derived within the area of the stream itself directly from the inputs and co-products of the global process (i.e., sun, wind, rain, and earth cycle) accounts for less than 0.5% of its total absorbed emergy. The rest of the emergy absorbed by these systems was received in inputs (run-in along with organic matter) from the surrounding areas (i.e., the watersheds, exclusive of the streams themselves). Similarly, the stream areas (Table 1) account for less than 0.3% of their complete watershed areas in all cases, with the ratios of these emergy absorption percentages to their corresponding area percentages ranging from 1.3 to 1.6. This close relation between emergy absorption and the area of the encompassing and supporting system is expected for streams, which are loci for the concentration of emergy acquisition, in areas with rather high uniformity among empower densities.

A number of uncertainties in the emergy abfluxes might be noted. First, the abflux of chemical potential emergy received in run-in and organic matter could not be estimated with the customarily expected precision because of the lack of concentration data for samples taken upstream from the mouth of the streams. The estimate used for the inorganic solute effect on the absorption of $H_2O$ concentration potential within the streams (of one tenth of total absorption occurring downstream, Table 2) is unlikely to be too low, however, given the gradients of the streams, their modest lengths relative to their distances via water to the sea, and the typical preponderance of such emergy absorption within estuarine systems. The run-in geopotential abflux, which is estimated with acceptable precision, is thus almost certainly greater than the corresponding chemical emergy abflux, which thus does not affect the total emergy abflux for the stream.

Table 2. Annual inputs to stream processes through emergy absorption

| | | Transformity | ---------------------- **Emergy (sej)** ---------------------- | | | |
|---|---|---|---|---|---|---|
| | Item | (sej/J) | Pringle | Lick | Heather | Morgan |
| 1 | Solar insolation | 1 | 7.95E+13 | 9.50E+13 | 6.59E+13 | 3.75E+13 |
| 2 | Wind | 2510 | 3.19E+14 | 3.82E+14 | 2.65E+14 | 1.51E+14 |
| 3 | Rain, chemical | 30900 | 5.82E+13 | 1.92E+14 | 6.16E+13 | 4.76E+13 |
| 4 | Rain, geopotential | 17600 | 7.46E+14 | 8.21E+14 | 5.08E+14 | 3.76E+14 |
| 5 | Earth cycle | 57600 | 1.75E+15 | 2.09E+15 | 1.45E+15 | 8.27E+14 |
| 6 | Organic matter | 124000 | 2.36E+17 | 1.75E+17 | 9.40E+16 | 3.50E+17 |
| 7 | Run-in, chemical | 85600 | 7.98E+17 | 3.70E+17 | 1.73E+17 | 6.15E+17 |
| 8 | AMD solute effect | 85600 | 5.37E+16 | 1.62E+17 | 1.53E+16 | 1.09E+17 |
| 9 | Run-in geopotential | 46600 | 1.27E+18 | 5.65E+17 | 2.35E+17 | 1.10E+18 |
| 10 | Total | | 1.51E+18 | 7.42E+17 | 3.30E+17 | 1.45E+18 |

**Notes:**

Emergy values were obtained by multiplying the items' calculated energy values by their transformities (from [11], except chemical potential transformities, from [12]), which were adjusted to a baseline value for global renewable empower acquisition of 1.583E25 sej/yr.

1) annually, insolation – albedo = 4.12E9 J/m$^2$[13]
energy = (stream area)*(insolation – albedo)

2) density of air = 1.23 kg/m$^3$; 10-yr average annual average wind velocity = 3.33 m/s[13]; geostrophic wind velocity = wind velocity/0.6 = 5.55 m/s; drag coefficient = 1E-3 [14]
energy = (stream area)(air density)(drag coefficient)(geostrophic wind velocity$^3$)(time)

3) average air temperature in the Cheat area = 10.7°C; Gibbs free energy/g rainwater ($H_2O$) with respect to seawater (at this temperature) = (8.3143 J/mol/K) * (283.85K)/(18 g/mol) * ln(999,983 ppm/965000 ppm); Gibbs free energy/g stream water ($H_2O$) at mouth = (8.3143 J/mol/K) * (283.85K)/(18 g/mol) * ln(stream-water $H_2O$ ppm/965000 ppm); solute concentrations at the stream mouths were estimated based on conductivity measurements; (mass of rain received) = (precipitation depth) * (stream area) * (water density)
energy = (mass of rain received) * ((Gibbs energy/g rainwater) – (Gibbs energy/g stream water))

4) energy = (mass of rain received) * (mean stream elevation – elevation at stream mouth) * (acceleration due to gravity)

5) heat flow (corresponding to earth cycle?) = 50.00 mW/m$^2$ [15]
energy = (area)(heat flow)(time)

6) Rates of topsoil loss associated with the major erosive land uses were multiplied by their respective areas in the streams' watersheds to estimate topsoil mass annually introduced to the streams.
energy = (topsoil mass) * (0.04 g OM/g topsoil) * (22600 J/g OM)

7) (run-in mass) = (watershed rain mass) – (watershed evapotranspiration mass); (Gibbs free energy ($H_2O$) absorbed in stream)/g run-in was estimated as one tenth of that remaining at the mouth
energy = 0.1 * (run-in mass) * (8.3143 J/mol/K) * (283.85K)/(18 g/mol) * ln(stream-water $H_2O$ ppm/965000 ppm)

8) The fraction of the absorption of H2O chemical potential (with respect to that in seawater) attributable to AMD solutes was estimated as the difference between the relevant Gibbs free energies of typical stream water (at 999850 ppm $H_2O$ [11]) and of the water at the mouths of the analyzed streams.
energy = (flow volume) * (density) * ((8.3143 J/mol/K)(283.85K)/(18 g/mol)) * ln((999850 ppm/(1e6 – stream solutes) ppm))

9) energy = (run-in mass)(mean stream elevation – elevation at mouth of stream)(acceleration due to gravity)

10) The total emergy absorbed annually is the sum of the maximum emergy value for items 1–5, the organic matter emergy, and the maximum emergy value for items 7 and 9. The solar input (i.e., emergy absorption) is treated—in accordance with standard emergy accounting practice[11]—in the same manner as a coproduct of the global process, based on the assumption that this input is completely accounted for in the reinforcement that such coproducts provide to the system.

The organic matter abflux could be an overestimate due to the potential for organic matter displaced by erosion to be deposited or utilized before reaching or after leaving the streams. The organic matter transformity applicable to these systems, however, is probably much higher than that of the standard value used in most emergy analyses. (The emergy of the organic matter inputs to the streams includes the geopotential emergy absorbed during runoff, which is not included in the standard calculation of organic matter transformity.) Thus, although this estimated abflux is less precise than we would like, especially given the substantial contribution it makes to the total abflux, it seems the most reasonable estimate currently available. Additional analysis of the emergetics of organic matter production and transport within the watersheds and data clarifying the fate of this organic matter when displaced by erosion could improve the precision of our estimate.

The second uncertainty that demands future clarification is associated with the total AMD solute effect, which we estimated solely on the basis of the effect of these solutes on the absorption of the chemical potential of $H_2O$ in the stream and rain with respect to seawater (Table 2). Such effects can be orders of magnitude smaller than the associated (co-product) effects of the absorption of the emergies associated with the concentration and chemical potentials of the solutes themselves. We were unable to estimate transformities for these solutes within the systems we studied, however, and the development of standard transformities for such substances is a project that has not yet been undertaken, despite its importance to the widespread application of emergy analysis[11]. Given the critical effect of these substances to system function and dynamics, a more adequate accounting of the associated emergy abfluxes is a principal research objective.

The other major uncertainties pertain to scientific questions that have yet to be resolved (as far as we know) by emergy practitioners. These questions range in scope from quite specific procedural concerns, with the use of generic drag coefficients to estimate frictional dissipation of wind energy in very diverse environments, for instance, to the more basic disputes concerning alternative methods of estimating the global fluxes, identifying and treating co-products, and including information flows in emergy analyses. We are unable to adequately address any of these questions here, but we note that, according to recent research[16,17], wind emergy might be found to contribute substantially to processes in the watersheds if a drag coefficient appropriate for forested, mountainous areas could be established (and if wind within each atmospheric layer represents a co-product of the global process). The current emergy contribution of the earth cycle to systems within residual mountain ranges is perhaps even more difficult to estimate, particularly within ranges formed by crustal shortening.

Following standard practice in accounting for the emergy abflux of solar insolation within a local area[11], the emergy abfluxes of solar insolation and deep earth heat to the analyzed systems have not been added to those of the largest co-product from the global process (which produces wind, rain, the earth cycle of uplift and erosion, etc.) in the calculation of total emergy abflux because solar insolation and deep earth heat are also primary inputs to the global process. The dependence of wind, rain, and earth-cycle abfluxes on solar abfluxes within this local area, however, is probably negligible; the dependence of such co-products of the global process on the deep earth heat absorption within this local area is also probably quite minor. Accounting for solar insolation and deep earth heat absorption on this more realistic basis might increase estimates of total emergy abflux in the watersheds (and thus ultimately our refined estimates of organic matter abfluxes in the streams) by about 10% and 20%, respectively. Finally, inclusion of information fluxes associated with species dispersion could alter our estimates substantially, as indicated by our estimates for fish species richness emergy (Table 3). Net fluxes of this emergy might eventually achieve a persistent, long-term average balance.

Table 3. Estimated annual benefit of outflows and increased ecological capital achieved by restoring streams to pH 7

| Notes | Item | -------------------- **Emergy (sej)** | | | ------------------- |
|---|---|---|---|---|---|
| **Outflows** | | Pringle | Lick | Heather | Morgan |
| 1 | Fish productivity | 1.51E+18 | 7.42E+17 | 3.30E+17 | 1.45E+18 |
| 2 | Trout fishing | 1.91E+18 | 9.04E+17 | 4.51E+17 | 1.66E+18 |
| 3 | Kayaking | 1.51E+18 | 7.46E+17 | 0.00E+00 | 1.45E+18 |
| 4 | Wildlife watching | 1.81E+18 | 8.63E+17 | 4.21E+17 | 1.77E+18 |
| 5 | Total outflows | 2.21E+18 | 1.02E+18 | 5.39E+17 | 1.98E+18 |
| **Storages** (ecological capital) | | | | | |
| 6 | Fish biomass | 1.87E+18 | 7.10E+17 | 5.32E+17 | 2.12E+18 |
| 7 | Fish diversity | 2.44E+19 | 1.01E+19 | 7.91E+18 | 3.35E+19 |

**Notes:**

Monetary values given below are in US$; emdollar ratios are West Virginia's 2000 emergy-to-US$ ratio (derived in [18]).

1) Increased fish productivity will harness the total emergy influx absorbed within the impaired reaches of the streams. See Table 1 for calculations.
2) For fishing in WV streams during 2001, the average expenditure per angler per day was $16 and the total number of days fishing was 4,152,000[19]. Trout fishing accounted for 37% of the fishing days in WV during 1996[20]. There are approximately 2000 mi. native brook trout streams in addition to 750 mi. stocked with brown and rainbow trout and 500–700 mi. stocked with fingerlings[21]. The fraction of each stream's impaired length that would be suitable trout habitat (strFrc) was estimated based on its maximum temperature and the maximum temperature tolerance thresholds for the above trout species[22]. Thus the emergy benefit from trout fishing on a restored stream length is the sum of the renewable emergy absorbed in that length (upon which trout fishing depends) and the emergy of the purchased inputs, estimated as strFrc*$16/trout angler–d*0.37 trout anglers/angler*4.152E6 angler–d/yr*5.79E12 sej/$.
3) 6903 visitors rafted the Cheat in 2001, spending an estimated $720673[23]; kayakers and canoeists in West Virginia added 5–15% to the number of whitewater rafters in 1995, half of whom we assumed would kayak the Cheat's small streams; 45% of the expenditure of Cheat rafters was associated with the commercial rafting experience itself[24] and would generally not be applicable for kayakers; thus we estimated expenditure by independent kayakers using the Cheat's small streams to be 10%*0.5*.55*$720673/yr, or $19819/yr; assumed preference relationships of stream use with stream class, length, and run quality were used to apportion use among the small streams in the Cheat with documented whitewater runs, thereby assigning to each stream an estimated fraction (useFrc) of total kayaking use; rafting on West Virginia's three most popular rivers for rafting approximately doubled from the 1980s to 1995 while rafting on the Cheat declined by more than 75%[25], so we estimated that use of the Cheat might increase by 50% following restoration; the emergy benefit from a stream with a whitewater run is thus the sum of the renewable emergy absorbed in the restored stream length, upon which the (improved) kayaking skill depends, and the emergy of the purchased inputs, estimated as 50%*useFrc*$19819/yr*5.79E12 sej/$.
4) In West Virginia, total recreational spending in 2000 was $2.947E9, and 5.29% of recreational spending in 2001 was attributed to wildlife watching. A watershed's

capacity for attracting wildlife watchers was assumed to be determined (in equal measure) by unimpaired stream length (strLngth) and by other unrelated factors. Thus the emergy benefit of restoration due to increased wildlife watching is the sum of the renewable emergy absorbed in a restored stream length and the emergy of the purchased inputs, estimated as impaired strLngth/WV strLngth*\$1.559E8*0.5* 5.79E12 sej/\$.

5) The total annual emergy benefit from restoration for each system as analyzed is equal to the sum of the benefits from items 2–4 minus either the benefit from item 1 (for Heather) or twice the benefit from item 1 (for Pringle, Lick, and Morgan).
6) The emergy benefit of the fish biomass in a restored stream length is obtained by multiplying the fish biomass transformities in these systems (as derived from the estimated emergy benefits of fish productivity) by our estimate for fish biomass energy in these lengths, which is the product of the restored stream length, the fish biomass in reference streams (13.35 g/m) and energy content of the fish biomass (4312 J/g [18]). The transformities were obtained similarly as the ratios of the estimated emergy requirements for fish productivity in the analyzed streams (in sej/m/yr) to the products of the fish biomass productivity in reference streams (8.31 g/m/yr) and the energy content of the fish biomass.
7) The estimated time required for reestablishment of the fish community, including its more sensitive species, in restored streams is 3 to 5 years (based on timeframe given in [26]). Fish species richness in the reference streams ranges from 3 to 20 species and is related with the Shannon diversity of major land use (LUD) such that estimated fish species richness (N) is equal to 15.907*LUD + 1.5338, with r = 0.96. If reestablishment requires 5 years at the upper value for the species-richness range and 3 years at the lower value, reestablishment time can be estimated as 3 + 2*(N – 3)/17. Emergy required to reestablish the pre-impaired species richness is then estimated as the renewable empower of the next larger, encompassing watershed (from which the species migrate into the restored streams) divided by the fraction of that empower received in fish species dispersion by each recovering stream length and multiplied by the estimated reestablishment time. The empower fraction so received by each recovering stream length was estimated as that length divided by the total stream length in the encompassing watershed, and the renewable empower of the encompassing watershed was estimated as its area multiplied by the empower density of West Virginia (1.09E11 sej/m2/yr [18]).

Our benefit analysis indicates that total annual emergy benefits (and thus empower acquisition increases by the systems of interest) are greatest for restoration of Pringle Run, while the greatest ecological capital benefits result from the restoration of Morgan Run (Table 3). The ranking of restoration efforts with respect to these streams will depend on the importance rankings for these goals (as well as the estimated restoration costs). The differences in benefits between Pringle and Morgan Runs in terms of total outflows and fish biomass are only 12% and 13%, respectively, however, while the fish diversity benefit estimated for Morgan Run is 37% higher than that for Pringle Run. Thus although affording priority to the goal of empower maximization might suggest, in the absence of cost considerations, that Pringle Run should be restored first, the emergy efflux associated with fish species dispersion and consequent effects on the larger, encompassing system were not included in our analysis. Morgan Run's substantially higher estimated emergy of fish species richness might support a higher efflux as well, and thus higher empower acquisition at this larger scale.

Our estimated transformity of fish biomass (productivity) is about 500 times that given by Odum[11] as a generic standard. Fish biomass transformities vary widely among systems, however, given the much lower biomass produced and supported in systems with relatively high empower densities that are allocated to other processes, especially when such empower densities are accompanied by environments that are challenging for fish production. Such high biomass transformities will often prevail in mountain stream systems. Thus the use of local transformity estimates is necessary for the accurate analysis of the AMD-restoration alternatives.

The resulting estimates for ecosystem productivity benefits dominate the benefits assessment as a result of these high transformities, with little distinction afforded by the differing economic emergy inputs to the three recreation outflows we considered. Among these outflows, trout fishing provides the highest benefits in all the systems other than Morgan Run, for which wildlife watching provides highest benefits. This conclusion depends on the close association assumed between restored stream length and increased wildlife watching (Table 3 notes), however, and is thus quite tentative. Including a recreation-specific fraction of the empower of ecosystem productivity in the recreation effluxes, rather than including the entire empower productivity in all recreation effluxes as we did (Table 3 notes), could also alter these results and thus should also be considered as more detailed analyses are performed. This alternative approach would not affect the ranking of the systems in terms of total emergy benefits, however.

More detailed analyses are also warranted, if relevant data can be obtained, to replace assumed relations among purchased inputs and the emergy effluxes (as described in Table 3 notes) with empirically determined relations. Differences in value among the recreation effluxes as calculated herein result solely from their respective differences in monetary value (i.e., in human willingness to pay for the respective recreational experiences), and increased accuracy of the estimated monetary values depends on studies providing improved willingness-to-pay estimates.

A higher priority for the purposes of the present study, however, given the dependence of the total estimated values of all fluxes and storages on environmental services, is to better quantify river flow volume and thus the run-in geopotential abflux, which accounts for 43-58% of the total efflux value (i.e., of total annual emergy benefit). Our current formula for estimating this abflux depends directly on watershed area and the mean elevation of the streams above their mouths (Table 3); correlations of total efflux with these stream system attributes reflect this dependence (with $r = 0.99$ and 0.86, respectively). Improved quantification of organic matter fate follows in importance, with the estimated organic matter abflux accounting for 11-18% of the total efflux value. Additional research priorities include a more realistic incorporation within our analysis of AMD effects, diversity benefits, and downstream consequences of impairment and restoration.

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