ASSESSING THE BENEFITS OF A PASSIVE TREATMENT SYSTEM FOR MINE DRAINAGE IN NORTHEAST OKLAHOMA USING EMERGY ANALYSIS[1]

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Abstract: A ten-cell passive treatment system (PTS) in the Tar Creek Superfund Site in Ottawa County, Oklahoma treats approximately 605,000 L of net-alkaline, lead-zinc mine drainage daily using a single initial oxidation pond followed by two parallel treatment trains of aerobic surface flow wetlands, vertical flow bioreactors, re-aeration ponds and horizontal flow limestone beds, and a common final polishing cell. Re-aeration is achieved via renewable energy resources (solar and wind). Design and construction of the PTS cost $1.2 million and it has a design life of 30 years. Prior to treatment, water from boreholes flowed into a horse pasture, forming volunteer wetlands and discharged to an unnamed stream that eventually empties to Tar Creek, a tributary to the Neosho River. Emergy (spelled with an "m") analysis is a method used to quantitatively classify energy flows in systems with regard to the amount of embodied energy of a lesser quality (usually solar energy) used to form that flow. Because different forms of energy are not necessarily capable of doing the same amount of work (e.g., one joule of solar energy cannot do the same work as one joule of fossil fuel), emergy analysis is useful because it normalizes these differences for meaningful comparisons. Using emergy analysis, the emergy inputs of this PTS were compared to the amount of work required by the environment to achieve the same treatment performance with no PTS. When less work is done by the environment mitigating this mine drainage, more resources become available for other systems. In addition, the emergy costs of a modeled active treatment system (ATS) were considered. These three treatment scenarios (ATS, PTS, and No Treatment) were compared using the Treatment Sustainability Index for determining relative sustainability of treatment systems based on their emergy inputs. The TSI revealed that the PTS is 6 times more sustainable than the ATS.

Additional Key Words: arsenic, cadmium, lead, iron, zinc, constructed wetland, ecological engineering, systems ecology

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Introduction

Background

Nearly a century of intensive mining in northeast Oklahoma ended in the 1970s, resulting in millions of tons of lead-contaminated waste material and artesian-flowing mine drainage impacting Oklahoma surface water bodies for decades (WQS, 2000). Nearly 20,000 residents remain in the 11,000-ha Tar Creek Superfund Site after a targeted buyout of subsidence risk-prone properties by state and federal agencies (EPA, 2009). A passive treatment system (PTS) was constructed to treat three mine drainage discharges (seeps) in the North Miami/Commerce, OK area in late 2008. This PTS is designed for metal removal using a single initial oxidation pond followed by two parallel treatment trains of surface flow wetlands, vertical flow bioreactors, re-aeration ponds and horizontal flow limestone beds, and a common final polishing cell (Figure 1). Re-aeration is achieved using solar- and wind-powered aerators. The PTS design and construction cost $1.2 million and has a design life of 30 years (Nairn et al., 2009). In contrast to active treatment systems (ATS), this PTS has effectively removed contaminants of concern in its first year using renewable energy sources for operation, rather than fossil fuels. In order to evaluate the relative sustainability of this system, the PTS was compared to a modeled ATS using emergy (spelled with an “m”) analysis (Brown et al. 2009).

Emergy Analysis

Emergy analysis is a method used to quantify energy flows in systems normalized for their embodied energy (Odum, 1996). For instance, natural gas and wind can both be used to make electricity. They both waste energy due to second law of thermodynamics effects and thus have energy efficiencies. While a conventional energy analysis would focus on these inefficiencies to determine which energy source is ‘better’, an emergy analysis takes the energy accounting to the next level by creating an inventory of the energy embodied in the other resources (e.g., water, concrete, steel, human service) used to make the electricity. By accounting for these additional flows of energy, emergy analysis captures a larger analytical boundary and offers the ability to compare how much energy the environment contributed to a process compared to how much was used from fossil fuels. These energy flows are accounted for in the analysis based on the direction of flow in the Energy Systems Diagram. Inputs and outputs of energy to the system are calculated and multiplied by their solar transformities, which are estimates of how much total solar energy is embodied in the energy of resource. Solar transformities are expressed in solar emjoules (sej) per unit, the unit depending on the energy source (e.g., grams for steel, joules for oil, hours for labor, etc.).

Figure 1. Location map for mine drainage site. Mine water flows from seeps to Unnamed Tributary and to Tar Creek. Currently, PTS intercepts mine drainage from seeps before it reaches Unnamed Tributary. Key- Oxidation Pond: Ox. Pond, Surface Flow Wetland: SFW, Vertical Flow Bioreactor: VFB, Re-aeration Pond: ReAP, Horizontal Flow Limestone Bed: HFLB, Polishing Wetland: PWL.

Accounting methods are used to allocate emergy inputs to energy outputs from the system. Indices are constructed to compare systems' inputs and outputs of emergy based on the categorization of their source (i.e., purchased, renewable, non-renewable energy). The Emergy Yield Ratio (EYR) is the ratio of emergy yielded to the purchased inputs of the system (Ulgiati et al., 1995). This index compares a products' efficiency in using purchased emergy from the economy. With high amounts of local, renewable emergy inputs to the system and low purchased inputs, the EYR will increase, indicating high yield of utilizing local resources and using less purchased emergy. The Environmental Loading Ratio (ELR) is the ratio of the sum of renewable and non-renewable to the renewable emergy inputs to a system (Brown and Ulgiati, 2002). This index can be used to evaluate the environmental inputs to a system. The ELR will decrease when the EYR is high, indicating less stress on the environment. The Environmental Index of Sustainability is the ratio of the EYR to the ELR (Brown and Ulgiati, 2002). This index compiles the two previous indices to provide a measure of sustainability based on emergy inputs of a system. While these emergy-based indices are useful for comparing systems that have a product, or yield, they are less applicable to waste treatment systems, where the product is not something returned to the conventional economy.

This study uses experimental, field-collected data to evaluate two treatment systems- a modeled ATS and a recently installed PTS that treats mine drainage in the Tar Creek Superfund Site. Additionally, prior to the construction of the PTS, mine drainage flowed into Unnamed Tributary (UT) and subsequently to Tar Creek (Figure 1). The environmental impact of this scenario was evaluated using emergy analysis. Because typical emergy-based indicators are not applicable to these systems, a new index was developed in this study. Active and passive treatment systems for wastewater have been previously evaluated and compared using emergy analysis (Arias and Brown, 2009; Geber and Björklund, 2001; Nelson et al., 2001; Vassallo et al., 2009; Zhang et al., 2009; Zhou et al., 2009). Most of these studies evaluated secondary wastewater treatment systems and none of them investigated acid mine drainage treatment systems. However, Wójcik et al. (2000) found conventional treatment of mine wastewater required more emergy purchased from the economy than treatment by a modified natural wetland in Poland.

Methods

Data Collection and Site Information

Data from the Oklahoma Climatological Survey were collected from a weather station near the site in Miami, OK. Water quality samples were collected and analyzed from reference sites, seeps, and downstream on Tar Creek for the year preceding completion of construction of the PTS by the University of Oklahoma Center for Restoration of Ecosystems and Watersheds (CREW). Following construction, water quality samples were collected and analyzed for each cell outflow, in addition to the previously sampled locations. Analyses of Al, As, Ca, Cd, Co, Cr, Cu, Fe, K, Mg, Mn, Na, Ni, Pb, and Zn concentrations were completed using a Varian Vista-

Pro® simultaneous inductively coupled plasma-optical emission spectrometer (ICP-OES) following EPA methods 3050 and 6010. Using water quality data from sampling locations at the seeps, reference sites, and downstream on TC, the distance downstream at which metals concentrations were expected to reach reference site levels was approximated. These flow-weighted data were used to extrapolate an area of the river system needed to remove contaminants of concern (based on zero-order kinetics) from the seeps, henceforth referred to as 'receiving environment'. Seep and PTS cell outflow data were used in the emergy analyses to determine the extent of treatment of the PTS. CH2M_Hill, the design/build contractor, provided PTS as-built details (CH2M_Hill, 2009). Figure 2 shows a schematic of the PTS and its flow regime. Hypothetical ATS specifications were estimated using the software application AMDTreat (OSM et al., 2008) by using the water quality data of the seeps as the input data. Using the recommendations of the AMDTreat software, a $Ca(OH)_2$ system with a mechanical mixing tank and clarifier followed by a chemical oxidation treatment process containing thirty-three 9.5-m^3 $KMnO_4$ dosing tanks and a secondary clarifier was designed to have a lifespan of 25 years (Figure 3). The oxidizing agent KMnO4 was chosen because this treatment technique represents a less resource-intensive method compared to other oxidizing options in the software. Both clarifiers were 5.6 m in diameter and 1.2 m deep with a concrete wall thickness of 0.3 m. Two pumps were required for initial lime dosing and one pump operates the $KMnO_4$ dosing. The system was subsequently gravity-fed. For ease of analysis, treatment performance and flow capacity of the ATS was assumed to be identical to those of the PTS.

Emergy Analyses and Treatment Sustainability Index

Emergy Analyses. Energy Systems Diagrams were generated for each treatment scenario: (i) *No Treatment*, (ii) *Active Treatment System*, and (iii) *Passive Treatment System*. These diagrams were used to determine the flows of energy into and out of each system. Environmental data, water quality data, and treatment system specifications were used to develop the emergy analysis tables. For instance, using the mean annual precipitation in Miami, OK, the chemical potential energy of rain for each system was calculated based on the area of the system and the Gibbs free energy of rainwater (~4.94 J/g). The joules of precipitation per year are multiplied by the solar transformity of rain's chemical potential (3.06E4 sej/J) (Odum et al., 2000). This solar transformity was determined based on the amount of energy used in the global water cycle to form rain.

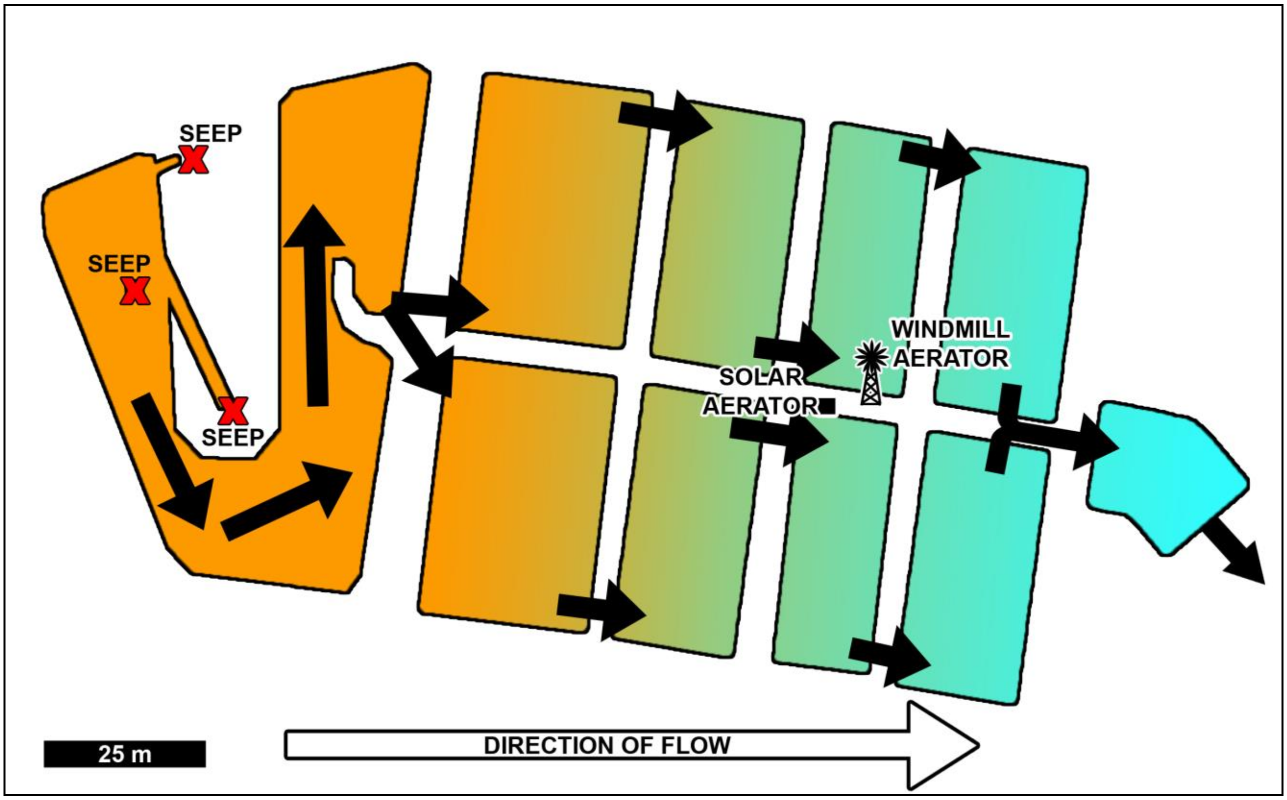

Figure 2. Schematic of PTS. Drawing not to scale, adapted from CH2M_Hill (2009).

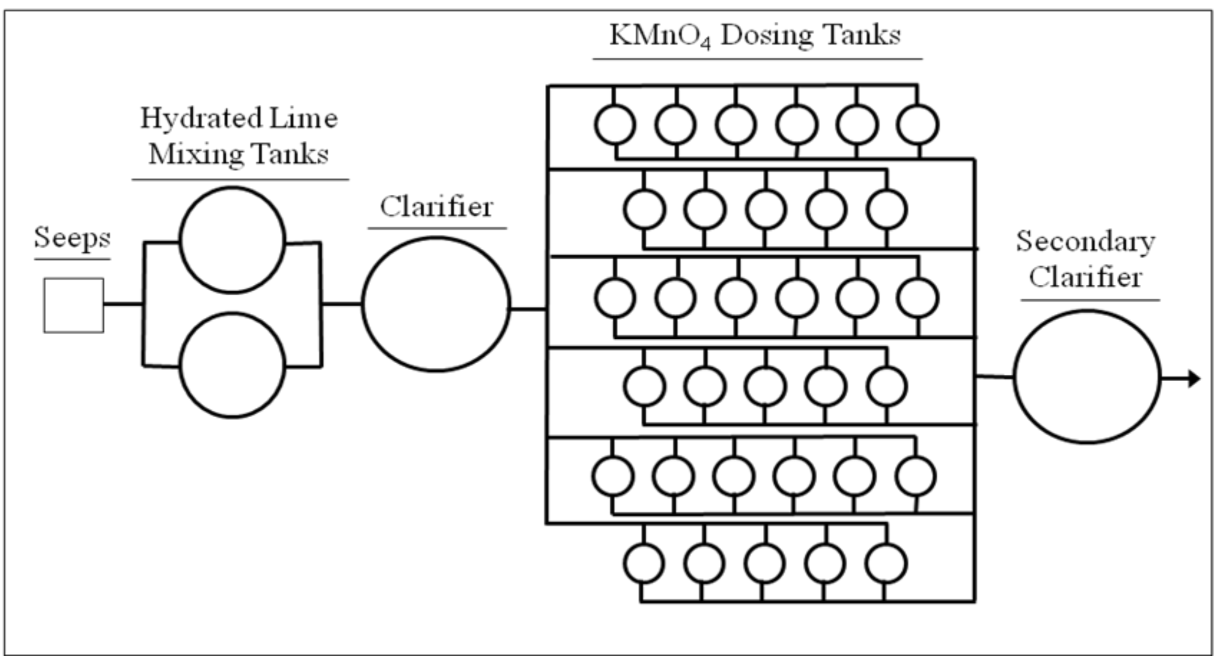

Figure 3. Active Treatment System diagram. Mine water enters mixing tanks on left, is pumped through the system and exits after the secondary clarifier on the right. Not to scale.

One-time energy flows (such as limestone used in the vertical flow bioreactors) were evaluated based on the embodied energy over the expected lifetime. Inputs from flow-through energy flows were determined by the difference of the emergy inputs and outputs of these flows. By accounting for the source of each emergy input and output, these flows were tabulated and classified based on their origin. Solar, wind, rain, and evapotranspiration are environmental sources (R) of energy. Non-renewable, purchased goods and services (F) included energy sources such as concrete, steel, seedlings, and electricity. Emergy values for these sources include services such as transportation to the site and fuels required making them in their transformities. In these systems, flow-through energy sources include mine drainage constituents, such as chemical potential and metals in the mine drainage (AMD_{in}) and treated effluent (AMD_{out}). Each line item in the emergy tables was calculated on a yearly basis from the specific energy, mass, labor time/area, or cost of a flow of energy into or out of the system and is multiplied by its transformity or unit emergy value to obtain the emergy of that flow.

A Treatment Sustainability Index. Waste is a byproduct of economic activities in society. Emergy evaluations are traditionally targeted at systems and products that drive the economy, not their byproducts. Consequently, existing emergy indices do not lend themselves to properly evaluating the sustainability of a waste treatment system. Therefore, a new emergy index was developed. The Treatment Sustainability Index (TSI) "punishes" a treatment system that requires more non-renewable inputs from the economy and puts a higher strain on the receiving environment than would otherwise be available for other systems to utilize. The new TSI "rewards" systems that use local, renewable resources and treats the waste effectively. By increasing the purchased emergy to operate a system or decreasing the treatment effectiveness, the TSI will decrease. Increasing the utilization of local, renewable energy or increasing the treatment effectiveness will increase the TSI. The TSI is the ratio of the sum of environmental resources used in treatment (R) and flow-through (AMD_{in}-AMD_{out}) emergy input to the treatment system to the sum of purchased, non-renewable (F) and environmental loading (ENV_{load}) emergy used in the receiving environment to reach background concentrations of metals (Equation 1).

$$TSI = \frac{1 + R + (AMD_{in} - AMD_{out})}{1 + F + ENV_{load}} \qquad (1)$$

This index can be used to indicate the relative use of emergy source categories and compare the sustainability of treatment systems with identical influent characteristics (higher TSI represents more sustainable treatment). The environmental loading was determined using the approximated area required to return metals concentrations to background levels from the outflows of each system, or in the case of *No Treatment*, from the seeps. Environmental inputs (solar, wind, rain, and evapotranspiration emergy) to the area receiving the mine drainage (effluent, in the case of *ATS* and *PTS*) are used to determine ENV_{load}. The TSI was used to compare these treatment scenarios for their relative sustainability in the Tar Creek Superfund Site.

Results and Discussion

Data Collection and Site Information

Influent mine drainage from the three seeps is net-alkaline, flowing at a combined average 7 L/s. Table 1 shows mean, flow-weighted metals concentrations from the seeps, treated PTS effluent, downstream Tar Creek, and reference sites. These reference sites were located in the general area of the Tar Creek Superfund Site, but have not shown evidence of being affected by mine drainage or overburden. The water quality at these sites represents the condition that affected streams should exhibit. Some metals of concern (Al, As, Cd, Cr, Cu, Fe, and Pb) at the outflow of the PTS were at or below reference site levels. Because the fraction of Mn removed in the PTS and between the outflow of the PTS and downstream were lower than other metals of concern, it was assumed Mn would return to background levels further downstream from the seeps than the rest of the metals. Using data from the year preceding completion of construction, Mn concentration at downstream Tar Creek similarly exhibited lesser concentration changes than other metals from the seeps. Using the decrease in Mn concentration from the treated PTS effluent (and seeps, for the *No Treatment* scenario) to the downstream Tar Creek site, and the distance along the river, an area of the river ecosystem required to return Mn concentration to reference levels was estimated. This area was used to evaluate the emergy inputs from the environment required to further treat the mine drainage from the outflow of the treatment system. In order to reach background concentrations, a constant decrease in concentration of Mn was assumed (i.e.: first-order kinetic modeling of Mn removal) continuing along Tar Creek for the *No Treatment*, *ATS*, and *PTS* scenarios. A fractional Mn removal rate of 0.13/ha was approximated for the *No Treatment* scenario. For the *ATS* and *PTS* scenarios, a fraction Mn removal rate of

0.27/ha was approximated. A higher removal rate was expected for the *ATS* and *PTS* scenarios, because some removal occurred in the treatment systems prior to release to the environment, decreasing the area required to reach reference levels. An environmental loading area of 5 ha was estimated for both treatment scenarios and 11 ha for the *No Treatment* scenario. This area was used to calculate ENV_{load}.

Table 1. Average metal concentrations at mine drainage seeps, PTS outflow, Tar Creek downstream of the seeps, and reference sites.

	Average Concentration (mg/L)				
	Seeps	**PTS Effluent**	**Downstream Tar Creek**	**Reference**	***Detection Limit***
Aluminum	0.097	0.076	0.301	0.308	*0.001*
Arsenic	0.063	BDL*	BDL	BDL	*0.0223*
Cadmium	0.018	BDL	0.003	0.001	*0.0006*
Calcium	735.50	733.75	389.03	53.98	*0.0005*
Chromium	0.002	0.002	0.004	0.002	*0.001*
Copper	0.003	0.003	0.003	0.004	*0.001*
Iron	178.19	0.632	2.782	0.527	*0.0007*
Magnesium	201.05	199.92	43.36	5.22	*0.0004*
Manganese	1.51	1.44	0.729	0.203	*0.0002*
Nickel	0.947	0.038	0.074	0.015	*0.004*
Lead	0.066	BDL	0.037	0.030	*0.0116*
Zinc	8.27	0.109	3.14	0.033	*0.0013*

*BDL- Below Detectable Limit

PTS design specifications were used to calculate the raw materials, machinery, and labor used in construction. Because the PTS has already been constructed, detailed specifications were available (Fig. 2). The ATS was designed as a chemical treatment plant with mixing. Treatment of mine drainage using hydrated lime ($Ca(OH)_2$) for alkalinity production and potassium permanganate ($KMnO_4$) is common (Skousen et al., 2009).

Emergy Analysis and Treatment Sustainability Index

Emergy Analyses. Energy systems diagrams were drawn for each system (*No Treatment*, *ATS*, and *PTS*), including the receiving environment and processes influencing the treatment of mine drainage (i.e., past mining, and groundwater flow) and the three treatment scenarios (Fig. 4-7). Figure 4 depicts all treatment scenarios as alternatives that occur simultaneously but were evaluated separately. Emergy inputs and outputs were classified and organized in a table for each treatment scenario (Tables 2-4). Each line item represents the sum of a given source of emergy in the system (e.g., line item “concrete” refers to the total amount of concrete used in construction of the clarifiers, treatment area, etc. for the ATS). These classifications were used to determine the type of emergy the system utilized to treat the mine drainage.

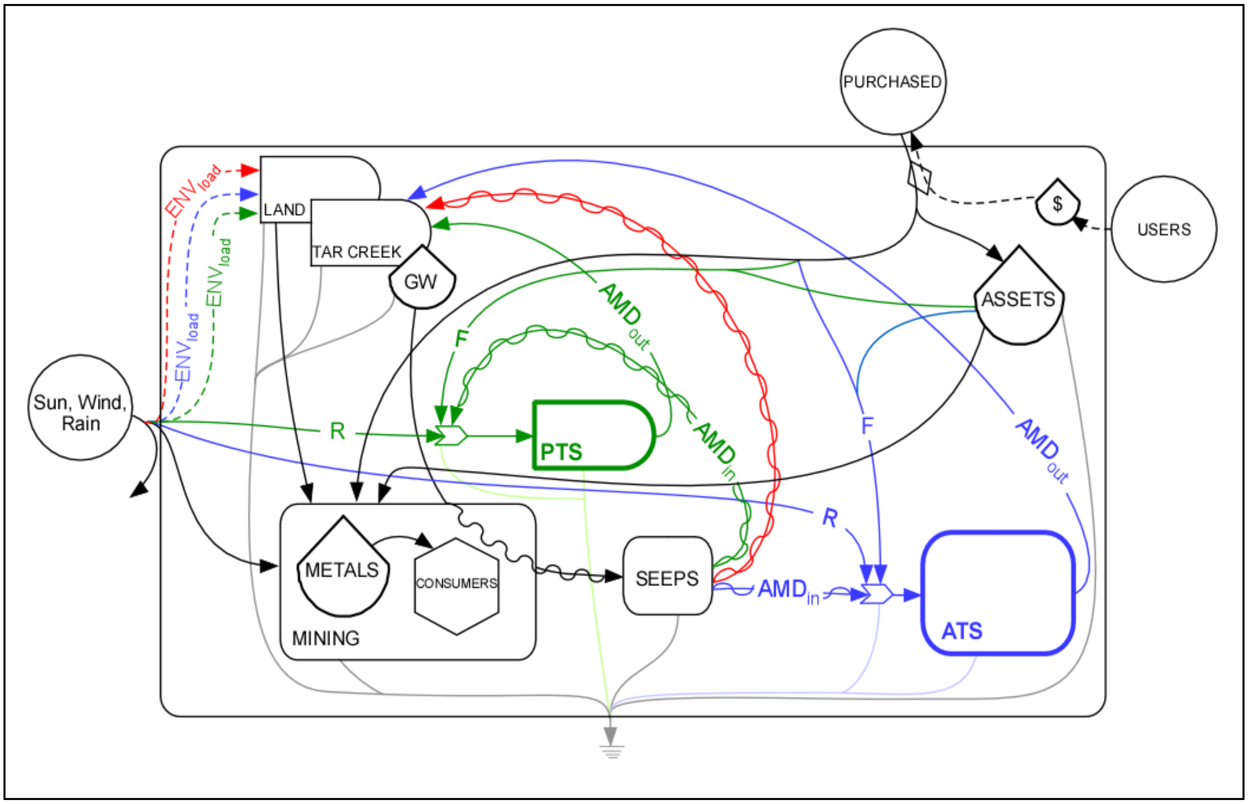

Figure 4. Energy systems diagram of the treatment process. Three treatment scenarios are shown- *No Treatment* (red), *PTS* (green), and *ATS* (blue), The wavy lines indicate the flow of energy is coupled to the mining waste. That is, the flow of energy from groundwater (GW) is coupled through the systems, as it eventually returns to the GW energy storage. Key- External Circle: source of energy, Rectangle with one rounded end: energy producer, Hexagon: energy consumer, Double-headed arrow: interaction of energy sources, Pointed polygon/semi-circle: storage of energy, Diamond: money exchange, Internal rectangle: process boundaries. Labels on flow lines correspond to energy flows used to calculate the emergy inputs in the TSI.

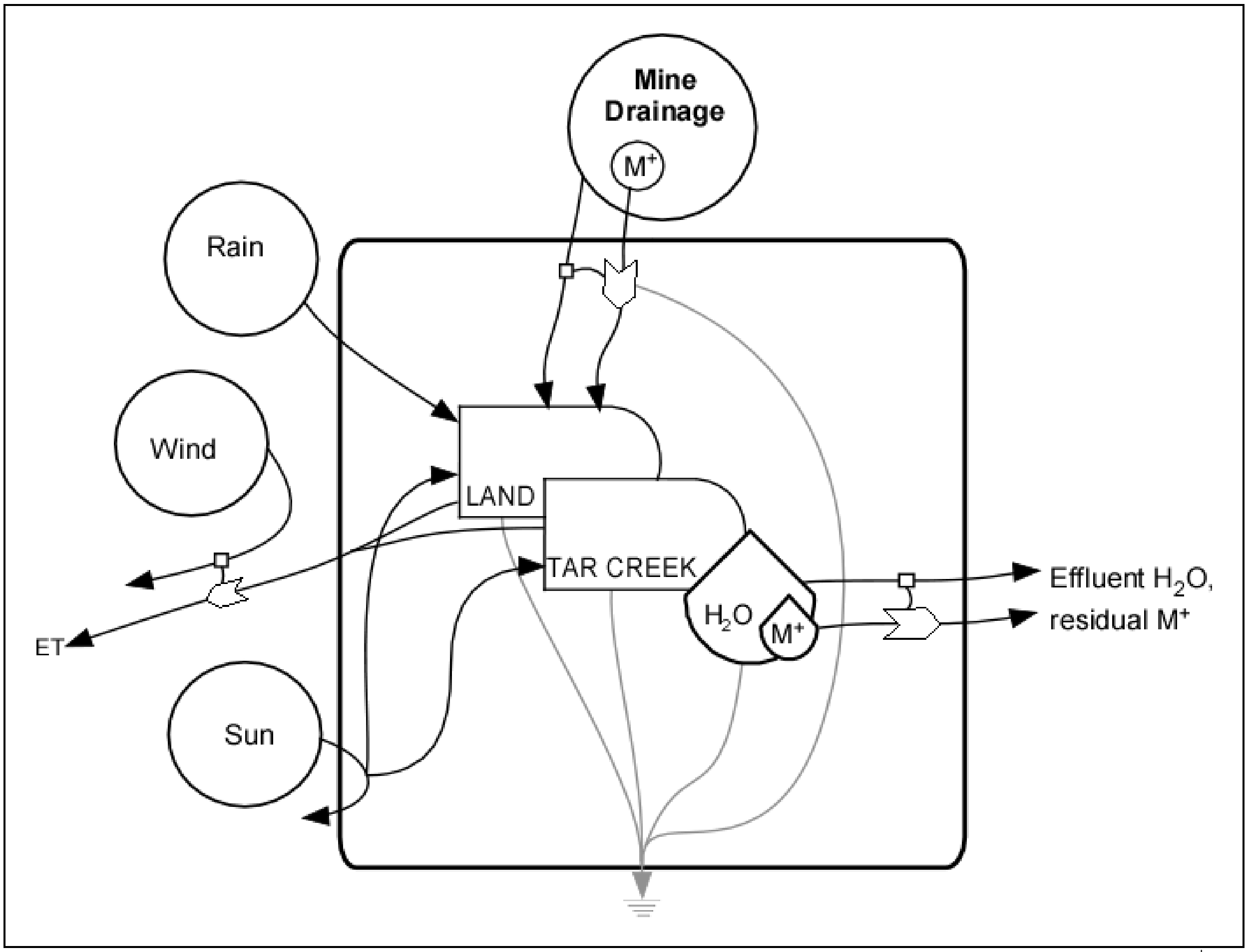

Figure 5. Energy systems diagram of *No Treatment* scenario. The energy from metals (M^+) is coupled to the mine drainage. Key- Metals: M^+

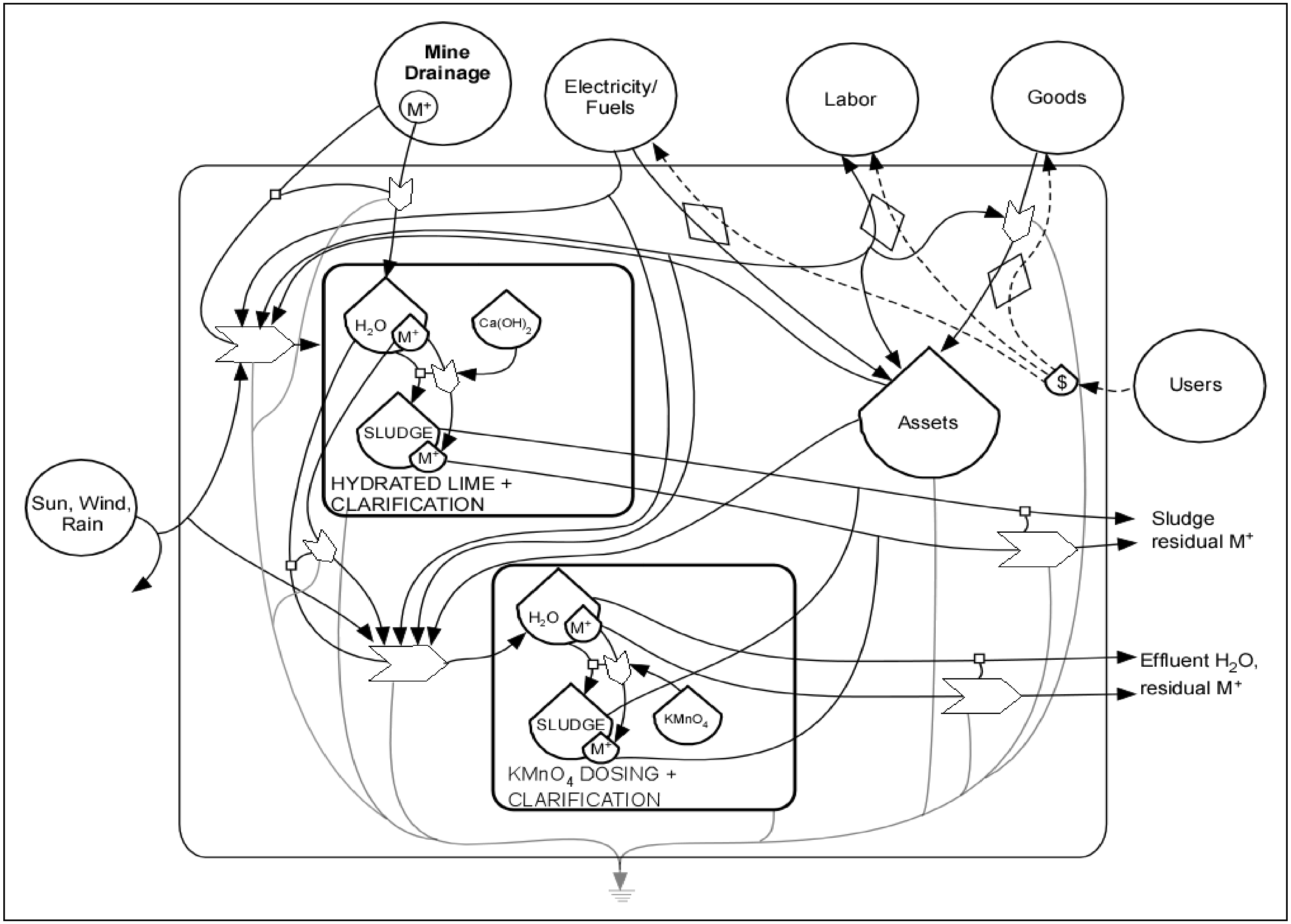

Figure 6. Energy systems diagram of Active Treatment System. Money is exchanged for goods and services, which drive most of the processes in this system. On the left, renewable sources of energy (Sun, Wind, Rain) minimally affect operations. Key- Metals: M^+, Hydrated Lime: $Ca(OH)_2$, Potassium Permanganate: $KMnO_4$.

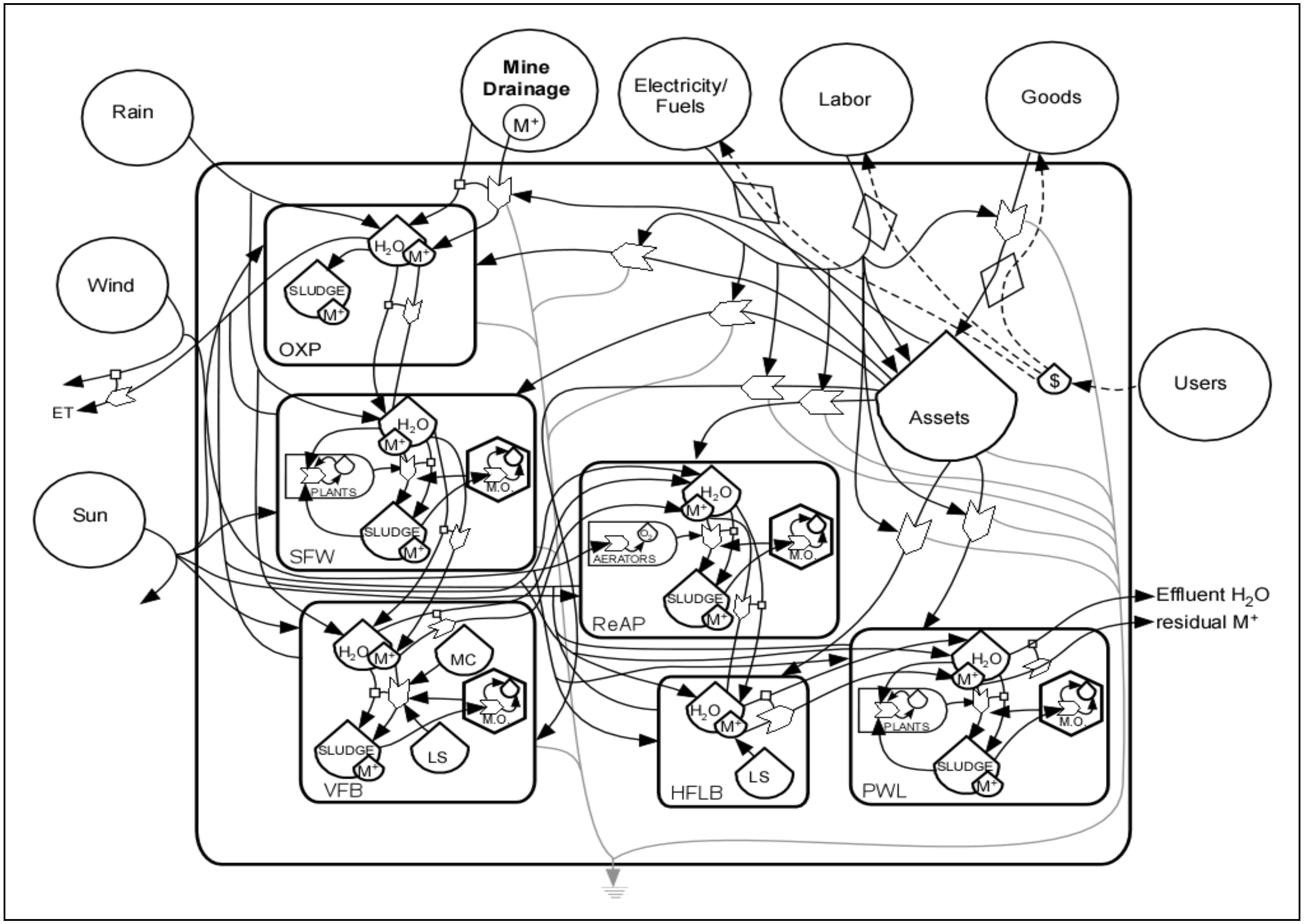

Figure 7. Energy systems diagram of PTS. Energy sources on left (Sun, Wind, Rain) drive much of the operation of this system. Each unit process operated on environmental inputs. One-time construction energy flows are present in the form of assets and labor. Key- Microorganisms: M.O., Metals: M^+, Limestone: LS.

Table 2. Emergy analysis table for *No Treatment* scenario. The 11 ha receiving environment was evaluated on a yearly basis with only local, renewable emergy inputs. Significant figures kept for accounting purposes.

#	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
1	Sunlight	J	6.20E+14	1.00E+00	By Definition	620
2	Wind	J	1.73E+11	1.50E+03	Odum 1996	259
3	Rain Chemical Potential	J	5.66E+11	3.06E+04	Odum 1996	17,333
4	Rain Nitrogen	g	2.00E+05	2.41E+10	Brandt-William 2002	4808
5	Rain Phosphorus	g	8.03E+03	2.20E+10	Brandt-Williams 2002	177
6	Rain OM	J	1.92E+09	3.19E+04	Brown and Bardi 2001	61
7	ET	J	5.83E+11	3.06E+04	Odum 1996	17,837
8	*Emergy of Env. Resources*					*17,837*
	MINE DRAINAGE INPUTS FROM SEEPS					
9	MD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
10	MDin Al	g	2.13E+04	1.44E+09	Odum et al. 1987a	31
11	MDin As	g	1.39E+04	1.54E+09	Odum et al. 1987a	21
12	MDin Cd	g	3.87E+03	1.54E+09	Odum et al. 1987a	6
13	MDin Ca	g	1.61E+08	1.68E+09	Odum 1996	270,568
14	MDin Cr	g	4.27E+02	1.54E+09	Odum et al. 1987a	1
15	MDin Cu	g	6.31E+02	3.36E+09	Brown and Ulgiati 2004	2
16	MDin Fe	g	3.90E+07	2.05E+09	Buranakarn 1998	79,989
17	MDin Mg	g	4.40E+07	1.68E+09	Odum 1996	73,959
18	MDin Mn	g	3.31E+05	1.14E+11	Odum 1996	37,755
19	MDin Ni	g	2.07E+05	1.54E+09	Odum et al. 1987a	319
20	MDin Pb	g	1.45E+04	1.54E+09	Odum et al. 1987a	22
21	MDin Zn	g	1.81E+06	7.56E+09	Odum 1996	13,694
22	*Emergy of AMD*					*528,831*
23	**Total Emergy Inputs**					**546,667**
	MINE DRAINAGE AT REFERENCE LEVELS					
24	MD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
25	Reference Al	g	6.73E+04	1.44E+09	Odum et al. 1987a	97
26	Reference As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
27	Reference Cd	g	2.50E+02	1.54E+09	Odum et al. 1987a	0
28	Reference Ca	g	1.18E+07	1.68E+09	Odum 1996	19,857
29	Reference Cr	g	3.90E+02	1.54E+09	Odum et al. 1987a	1
30	Reference Cu	g	9.64E+02	3.36E+09	Brown & Ulgiati 2004	3
31	Reference Fe	g	1.15E+05	2.05E+09	Buranakarn 1998	237
32	Reference Mg	g	1.14E+06	1.68E+09	Odum 1996	1,918
33	Reference Mn	g	4.46E+04	1.14E+11	Odum 1996	5,080
34	Reference Ni	g	3.18E+03	1.54E+09	Odum et al. 1987a	5
35	Reference Pb	g	6.65E+03	1.54E+09	Odum et al. 1987a	10
36	Reference Zn	g	7.29E+03	7.56E+09	Odum 1996	55
37	*Total Emergy of AMD at Reference Site Levels in Receiving Environment*					*79,726*

Table 3. Emergy analysis table for *ATS* Scenario. This 0.5 ha system was evaluated on a yearly basis with purchased and renewable inputs to the system and receiving environment. The receiving environment was approximately 5 ha. Significant figures kept for accounting purposes.

#	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12
	ENVIRONMENTAL INPUTS TO SYSTEM					
1	Sunlight	J	2.88E+13	1.00E+00	By Definition	29
2	Wind	J	8.06E+09	1.50E+03	Odum 1996	12
3	Rain Chemical Potential	J	2.63E+10	3.06E+04	Odum 1996	806
4	Rain Nitrogen	g	9.27E+03	2.41E+10	Brandt-William 2002	224
5	Rain Phosphorus	g	3.73E+02	2.20E+10	Brandt-Williams 2002	8
6	Rain OM	J	8.92E+07	3.19E+04	Brown & Bardi 2001	3
7	ET	J	2.71E+10	3.06E+04	Odum 1996	829
8	*Emergy of Env. Inputs to System*					*829*
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
9	Sunlight	J	2.87E+14	1.00E+00	By Definition	287
10	Wind	J	8.03E+10	1.50E+03	Odum 1996	120
11	Rain Chemical Potential	J	2.62E+11	3.06E+04	Odum 1996	8,030
12	Rain Nitrogen	g	9.24E+04	2.41E+10	Brandt-William 2002	2,227
13	Rain Phosphorus	g	3.72E+03	2.20E+10	Brandt-Williams 2002	82
14	Rain OM	J	8.89E+08	3.19E+04	Brown & Bardi 2001	28
15	ET	J	3.50E+11	3.06E+04	Odum 1996	10,711
16	*Emergy of Env. Inputs to Rec. Env.*					*10,711*
	INFLUENT MINE DRAINAGE FROM SEEPS					
17	MD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
18	MDin Al	g	2.13E+04	1.44E+09	Odum et al. 1987a	31
19	MDin As	g	1.39E+04	1.54E+09	Odum et al. 1987a	21
20	MDin Cd	g	3.87E+03	1.54E+09	Odum et al. 1987a	6
21	MDin Ca	g	1.61E+08	1.68E+09	Odum 1996	270,568
22	MDin Cr	g	4.27E+02	1.54E+09	Odum et al. 1987a	1
23	MDin Cu	g	6.31E+02	3.36E+09	Brown & Ulgiati 2004	2
24	MDin Fe	g	3.90E+07	2.05E+09	Buranakarn 1998	79,989
25	MDin Mg	g	4.40E+07	1.68E+09	Odum 1996	73,959
26	MDin Mn	g	3.31E+05	1.14E+11	Odum 1996	37,755
27	MDin Ni	g	2.07E+05	1.54E+09	Odum et al. 1987a	319
28	MDin Pb	g	1.45E+04	1.54E+09	Odum et al. 1987a	22
29	MDin Zn	g	1.81E+06	7.56E+09	Odum 1996	13,694
30	*Emergy of MD*					*528,831*
	GOODS					
31	Concrete	g	2.51E+08	1.15E+10	Odum 1996	2,889,395
32	PVC	g	1.05E+06	9.90E+09	Buranakarn 1998	10,347
33	Steel	g	1.20E+05	2.99E+09	Odum 1996	359
34	Machinery	g	1.60E+05	1.13E+10	Odum et al 1987b	1,808
35	Pumps	g	1.60E+04	1.10E+10	Arias & Brown 2009	176
36	Lime	g	1.78E+08	1.13E+07	Odum et al 1995	2,013
37	KMnO4	g	3.71E+07	4.97E+09	Brown & Arding 1991	184,529
	PURCHASED SERVICES					
38	Electricity	J	3.65E+10	2.92E+05	Odum 1996	10,670

39	Labor	hrs/ha	2.79E+03	1.06E+12	Odum 1996	2,957
40	*Total Emergy of Goods and Services*					*3,102,253*
41	**Total Emergy Inputs**					**3,641,795**
	EFFLUENT MD					
42	MDout Chemical Potential	J	1.07E+12	4.85E+04	Odum 1996	51,783
43	MDout Al	g	6.65E+04	1.44E+09	Odum et al. 1987a	95
44	MDout As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
45	MDout Cd	g	2.47E+02	1.54E+09	Odum et al. 1987a	0
46	MDout Ca	g	1.17E+07	1.68E+09	Odum 1996	19,599
47	MDout Cr	g	3.85E+02	1.54E+09	Odum et al. 1987a	1
48	MDout Cu	g	9.51E+02	3.36E+09	Brown & Ulgiati 2004	3
49	MDout Fe	g	1.14E+05	2.05E+09	Buranakarn 1998	234
50	MDout Mg	g	1.13E+06	1.68E+09	Odum 1996	1,894
51	MDout Mn	g	4.40E+04	1.14E+11	Odum 1996	5,014
52	MDout Ni	g	3.13E+03	1.54E+09	Odum et al. 1987a	5
53	MDout Pb	g	6.56E+03	1.54E+09	Odum et al. 1987a	10
54	MDout Zn	g	7.19E+03	7.56E+09	Odum 1996	54
55	*Emergy of MDout*					*78,692*
	MD AT REFERENCE LEVELS					
56	Reference Al	g	1.65E+04	1.44E+09	Odum et al. 1987a	24
57	Reference As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
58	Reference Cd	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
59	Reference Ca	g	1.59E+08	1.68E+09	Odum 1996	266,425
60	Reference Cr	g	3.86E+02	1.54E+09	Odum et al. 1987a	1
61	Reference Cu	g	5.53E+02	3.36E+09	Brown &Ulgiati 2004	2
62	Reference Fe	g	1.37E+05	2.05E+09	Buranakarn 1998	280
63	Reference Mg	g	4.32E+07	1.68E+09	Odum 1996	72,590
64	Reference Mn	g	3.10E+05	1.14E+11	Odum 1996	35,345
65	Reference Ni	g	8.30E+03	1.54E+09	Odum et al. 1987a	13
66	Reference Pb	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
67	Reference Zn	g	2.35E+04	7.56E+09	Odum 1996	177
68	*Emergy of MD at Reference Levels*					*374,856*

Table 4. Emergy analysis table for *PTS* Scenario. This 0.5 ha system was evaluated on a yearly basis with purchased and renewable inputs to the system and receiving environment. The receiving environment was approximately 5 ha. Significant figures kept for accounting purposes.

#	Item	Unit/yr	Amount Per year	Solar Transformity (sej/unit)	Ref. for Transf.	Solar Emergy (sej/yr) E12
	ENVIRONMENTAL INPUTS TO SYSTEM					
1	Sunlight	J	1.56E+14	1.00E+00	By Definition	156
2	Wind	J	4.35E+10	1.50E+03	Odum, 1996	65
3	Rain Chemical Potential	J	1.42E+11	3.06E+04	Odum 1996	4,351
4	Rain Nitrogen	g	5.01E+04	2.41E+10	Brandt-William 2002	1,207
5	Rain Phosphorus	g	2.01E+03	2.20E+10	Brandt-Williams 2002	44
6	Rain OM	J	4.82E+08	3.19E+04	Brown & Bardi 2001	15
7	ET	J	1.46E+11	3.06E+04	Odum 1996	4,477
8	*Emergy of Env. Inputs to System*					*4,477*
	ENVIRONMENTAL INPUTS TO RECEIVING ENVIRONMENT					
9	Sunlight	J	2.87E+14	1.00E+00	By Definition	287
10	Wind	J	8.03E+10	1.50E+03	Odum 1996	120
11	Rain Chemical Potential	J	2.62E+11	3.06E+04	Odum 1996	8,030
12	Rain Nitrogen	g	9.24E+04	2.41E+10	Brandt-William 2002	2,227
13	Rain Phosphorus	g	3.72E+03	2.20E+10	Brandt-Williams 2002	82
14	Rain OM	J	8.89E+08	3.19E+04	Brown & Bardi 2001	28
15	ET	J	3.50E+11	3.06E+04	Odum 1996	10,711
16	*Emergy of Env. Inputs to Receiving Env.*					*10,711*
	INFLUENT MINE DRAINAGE FROM SEEPS					
17	MD Chemical Potential	J	1.08E+12	4.85E+04	Odum 1996	52,463
18	MDin Al	g	2.13E+04	1.44E+09	Odum et al. 1987a	31
19	MDin As	g	1.39E+04	1.54E+09	Odum et al. 1987a	21
20	MDin Cd	g	3.87E+03	1.54E+09	Odum et al. 1987a	6
21	MDin Ca	g	1.61E+08	1.68E+09	Odum 1996	270,568
22	MDin Cr	g	4.27E+02	1.54E+09	Odum et al. 1987a	1
23	MDin Cu	g	6.31E+02	3.36E+09	Brown & Ulgiati 2004	2
24	MDin Fe	g	3.90E+07	2.05E+09	Buranakarn 1998	79,989
25	MDin Mg	g	4.40E+07	1.68E+09	Odum 1996	73,959
26	MDin Mn	g	3.31E+05	1.14E+11	Odum 1996	37,755
27	MDin Ni	g	2.07E+05	1.54E+09	Odum et al. 1987a	319
28	MDin Pb	g	1.45E+04	1.54E+09	Odum et al. 1987a	22
29	MDin Zn	g	1.81E+06	7.56E+09	Odum 1996	13,694
30	*Emergy of MD*					*528,831*
	GOODS					
31	Seedlings	J	4.82E+06	5.80E+04	Odum 1996	0
32	Limestone	g	1.27E+08	2.10E+09	Odum 1996	266,166
33	Geotextile Liner	g	1.57E+05	8.50E+09	Buranakarn 1998	1,335
34	Concrete	g	3.70E+04	1.15E+10	Odum 1996	426
35	PVC	g	2.24E+03	9.90E+09	Buranakarn 1998	22
36	Valves	g	1.36E+05	2.99E+09	Odum 1996	405
37	Agridrains	g	8.80E+04	1.13E+10	Odum et al. 1987b	991
38	Solar Aerator	g	2.75E+04	1.13E+10	Odum et al. 1987b	310
39	Windmill Aerator	g	2.61E+04	1.13E+10	Odum et al. 1987b	294
40	Lumber	g	2.55E+04	1.48E+09	Buranakarn 1998	38

41	Drain/Seep/Inflow Metal Pipes	g	1.52E+04	2.99E+09	Odum 1996	46
42	Compost	J	1.02E+11	3.02E+06	Ortega 1998	307,595
	<u>PURCHASED SERVICES</u>					
43	Construction Labor	hr	1.41E+02	1.06E+12	Odum 1996	149
44	*Total Emergy of Goods and Services*					*577,776*
45	**Total Emergy Inputs**					**1,117,317**
	<u>EFFLUENT MD</u>					
46	MDout Chemical Potential	J	1.07E+12	4.85E+04	Odum 1996	51,783
47	MDout Al	g	1.65E+04	1.44E+09	Odum et al. 1987a	24
48	MDout Al	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
49	MDout Al	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
50	MDout Al	g	1.59E+08	1.68E+09	Odum 1996	266,425
51	MDout Al	g	3.86E+02	1.54E+09	Odum et al. 1987a	1
52	MDout Al	g	5.53E+02	3.36E+09	Brown & Ulgiati 2004	2
53	MDout Al	g	1.37E+05	2.05E+09	Buranakarn 1998	280
54	MDout Al	g	4.32E+07	1.68E+09	Odum 1996	72,590
55	MDout Al	g	3.10E+05	1.14E+11	Odum 1996	35,345
56	MDout Al	g	8.30E+03	1.54E+09	Odum et al. 1987a	13
57	MDout Al	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
58	MDout Al	g	2.35E+04	7.56E+09	Odum 1996	177
59	*Emergy of MDout*					*426,639*
	<u>MD AT REFERENCE LEVELS</u>					
60	Reference Al	g	6.65E+04	1.44E+09	Odum et al. 1987a	95
61	Reference As	g	0.00E+00	1.54E+09	Odum et al. 1987a	0
62	Reference Cd	g	2.47E+02	1.54E+09	Odum et al. 1987a	0
63	Reference Ca	g	1.17E+07	1.68E+09	Odum 1996	19,599
64	Reference Cr	g	3.85E+02	1.54E+09	Odum et al. 1987a	1
65	Reference Cu	g	9.51E+02	3.36E+09	Brown & Ulgiati 2004	3
66	Reference Fe	g	1.14E+05	2.05E+09	Buranakarn 1998	234
67	Reference Mg	g	1.13E+06	1.68E+09	Odum 1996	1,894
68	Reference Mn	g	4.40E+04	1.14E+11	Odum 1996	5,014
69	Reference Ni	g	3.13E+03	1.54E+09	Odum et al. 1987a	5
70	Reference Pb	g	6.56E+03	1.54E+09	Odum et al. 1987a	10
71	Reference Zn	g	7.19E+03	7.56E+09	Odum 1996	54
72	*Emergy of MD at Reference Levels*					*26,909*

The *PTS* scenario relied upon free environmental inputs at a rate of 4 times that of the *ATS* scenario while the *ATS* scenario used 5 times as much purchased emergy (Table 5). However, 53% of the purchased emergy in the *PTS* scenario was from compost. This figure may be inflated, as the solar transformity for compost from Ortega (1996) was calculated using a larger agricultural system that interacted with the economy to a greater extent than the mushroom compost used in these bioreactors. Since the mushroom compost in these bioreactors was locally available and relatively inexpensive, the true transformity may be less. Consequently, the purchased emergy for the *PTS* scenario would decrease. Both treatment systems discharged the same amount of emergy to the environment, but both were less than the *No Treatment* system.

A Treatment Sustainability Index. Emergy classifications were compiled in Table 5, and the TSI was calculated for each treatment scenario. The *PTS* scenario utilized the most environmental inputs to the treatment system and had the highest TSI (Table 5). The environmental emergy that was required outside the treatment system (ENV_{load}) to reach background levels was much greater for the *No Treatment* scenario. Local, renewable emergy used in treatment (*R*) was greater in the *PTS* than other treatment scenarios, which increases the TSI for passive treatment.

Wójcik et al. (2000) found conventional treatment of mine wastewater in Poland required 270 times more purchased emergy than treatment with natural wetlands. However, this system adapted an existing wetland to treat the mine wastewater by building dikes around the wetland and planting specialized vegetation to better control the flow regime and uptake metals, respectively. Wójcik et al. (2000) did not account for direct emergy inputs. Rather, the cost of construction and operation of both treatment systems were multiplied by an emergy-to-money ratio that does not consider the specific type of emergy input to a system. The present study used specific emergy inputs gathered from real and simulated data and complementary transformities to find that the *ATS* scenario used 5 times more purchased, non-renewable emergy (*F*) than the *PTS*, decreasing the TSI for active treatment. A higher TSI suggests the *PTS* relies less on emergy inputs from outside sources that are non-renewable, utilizing more sustainable sources of energy that are locally available and renewable. Because treatment performances were assumed to be identical in these systems, the performance component (AMD_{in}-AMD_{out}) had no effect on the TSI. However, if a comparison between two real-world systems were made, treatment performance could affect the comparison of the TSI.

Additionally, if a system failed to compensate for highly variable flows, wherein its capacity was exceeded, the treatment performance component of the TSI would capture and reflect that failure. Unfortunately, because the treatment performance may change over time for some systems, this index may overestimate the relative sustainability when assessed based on performance of the first year of operation. However, a ten-fold decrease in the emergy associated with treatment performance would be required to decrease the TSI of the *PTS* to that of the *ATS*.

According to the Treatment Sustainability Index, the passive system was six times as sustainable as the active system (Table 5). The better sustainability of the passive system was due to its higher reliance on renewable energy and lower reliance on purchased (*F*) energy.

Table 5. Emergy inputs, by class, and TSI for each treatment scenario.

	Emergy (10^{16} sej)				TSI
	R	AMD_{in}-AMD_{out}	*F*	ENV_{load}	
No Treatment	0	0	0	1.78	5.3E-17
ATS	0.08	10.22	310.23	1.07	0.03
PTS	0.45	10.22	57.78	1.07	0.18

Conclusions

Further work needs to be done to better characterize the *No Treatment* and *ATS* scenarios. Prior to construction of the PTS, a volunteer wetland formed that provided some treatment. This situation could be viewed as a treatment option, requiring no purchased emergy. The removal of contaminants of concern could be evaluated from the seeps to the point of release to UT. The *ATS* scenario would benefit from a closer evaluation of the resources used in construction. Because this study used approximations from a software package that is intended to provide only cost estimates for coal mine drainage, the *ATS* scenario may not be closely representative of the appropriate treatment unit processes. One advantage of emergy analysis is that it evaluates the entire system, reducing all inflows and outflows to one currency, the solar emjoule. Consequently, this evaluation technique could be applied to an active system in operation. The TSI could be applied and compared to the *PTS* at Tar Creek. Additionally, the local availability of resources used in construction of the PTS was not accounted for in this evaluation. The build-up of sludge in the oxidation pond in the PTS may be an energy storage that could be utilized in the future. This energy storage could increase the TSI by decreasing the net F to the system. The largest purchased emergy (*F*) items were available in close proximity to the site. Finally, the total purchased emergy for the PTS was largely driven by two inputs; limestone and compost together made up 99% of purchased emergy (Table 5). A future study should perform a sensitivity analysis on the estimates of the solar transformity (or specific emergy) of these inputs and could start by considering the recent work of Campbell and Lu (2009).

Passive treatment of mine drainage is a viable alternative to active treatment not only because of the comparable treatment performance for similar (and many times less) initial capital cost but also for the increased dependence on renewable resources for treatment performance. Active treatment requires daily maintenance and use of fossil fuels for operation. Alternatively, unmitigated release of mine drainage to the environment requires a large amount of environmental inputs to reach background concentrations of contaminants that may compromise ecosystem and human health.

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