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An emergy-based treatment sustainability index for evaluating waste treatment systems

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ABSTRACT

The treatment of wastes can be accomplished using various combinations of natural processes and human invented technologies that operate by using a variety of energy sources and natural resources. In many waste treatment systems, the waste itself is used as a main energy source to drive treatment (e.g., activated-sludge in advanced wastewater treatment). Understanding the sustainability of waste treatment systems thus requires the capability for quantitatively comparing the energy and resource inputs with the waste-derived energy inputs and effluent quality. This study applied concepts of emergy accounting to develop a treatment sustainability index (TSI). The theoretical basis of the TSI is explained and then applied to two wastewater treatment systems—an operating passive treatment system and a hypothetical active treatment system for treating mine drainage in NE Oklahoma. The TSI accounts for renewable and purchased emergy inputs, the input of emergy from the wastewater itself, and the amount of work required by the receiving environment to further treat the effluent. Unlike other emergy-based indices, the TSI explicitly accounts for the energy provided by wastes, the waste treatment efficiency and the downstream effect on the releasing pollutants into receiving environments. Since the emergy associated with the waste used during treatment was orders of magnitude larger than renewable, non-renewable or purchased inputs, the TSI clearly captured the importance of accounting for waste emergy, and was able to quantify their sustainability. The TSI offers a new way to assess the sustainability of all types of treatment systems.

1. Introduction

Waste is the result of society's consumption of agricultural and industrial products being decoupled from natural material cycling loops (Arias and Brown, 2009; Odum, 1994). In most industrialized societies, this waste is physically, biologically, and chemically transformed before becoming an environmental and public health liability. Valuable natural resources are required for these transformations to conform to the needs of society. As these resources become scarcer, there is an increased need to rely on energy derived from the environment. Using passive treatment systems to mitigate waste created in industrial and domestic activities utilizes natural energy sources for the benefit of both society and nature.

Emergy analysis, an environmental accounting technique, was used to evaluate the resource use of passive and active treatment of waste. In this paper, a passive treatment system operates on resources mostly from the environment, such as energy derived through solar and wind sources. Active treatment is defined here as operating on resources derived mostly from non-environmental, non-renewable sources, such as fossil fuels or minerals (e.g., through chemical treatment). The total available energy in a product or service is made up of previously transformed energy of various types. The total available energy previously used up directly and indirectly is the emergy. The total energy requirements for creating a product or service are normalized to solar energy equivalents, represented by the solar emjoule. The transformity is the ratio of the amount of solar emjoules used to create a product or service (emergy) to the total available energy (exergy, measured in Joules) in that product or service (Odum, 2007).

Since waste has exergy (e.g., chemical or gravitational potential energy), it causes mis-directed work in the environment in order to

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dissipate that available energy, which is a form of pollution. This available energy is called residual exergy since it is left over from a previous production process. Some have proposed that waste does not carry emergy because, by definition, it has no utility (Ulgiati et al., 2004). However, waste with residual exergy that is conveyed to the environment forces a reconfiguration of ecosystems and the dissipation of the residual exergy until all of the available energy has become waste heat and the residual exergy has reached background levels. Consequently, the emergy required by the environment to absorb the waste should be included as an input to the production system (Ulgiati et al., 2004; Vieira and Domingos, 2004). The emergy required to treat waste prior to disposal to the environment is an additional input to production processes that should be considered upstream of production (Ulgiati et al., 2004; Vieira and Domingos, 2004). Without treatment of waste products, the evaluation of the production process is not complete. Ideally, exergy in waste products would be used in the production process (recycling) or in another process (reuse), but many times waste is managed in treatment plants that require additional, purchased emergy and convey residual exergy into the environment at levels requiring emergy from the environment. By accounting for the dissipation of residual exergy in the environment, we are able to more accurately evaluate the impact of human activities on their surroundings. Attempts to quantify water quality pollution in ecosystems have been made using exergy alone as an indicator (Chen and Ji, 2007; Huang et al., 2007). These attempts provide further precedence to evaluate residual exergy disposed into a receiving environment.

Common emergy-based indicators do not address emergy associated with waste nor the effect of pollution on the environment. Nonetheless, active and passive treatment systems for wastewater have been previously evaluated and compared using emergy analysis (Arias and Brown, 2009; Geber and Björklund, 2002; 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.

This work introduces a new sustainability, emergy-based metric that can contrast linear and cycling treatment systems. In addition, the principles regarding environmental accounting of waste products, waste treatment, and the resulting environmental work required to absorb residual waste exergy were clarified. The index was applied to expanded case studies from Winfrey et al. (2014) that evaluated an existing passive treatment system and modeled active treatment system to contrast the sustainability of linear and cyclic treatment.

1.1. Impetus for new index

Because emergy is associated with utility, it seems counterintuitive to assign emergy to waste, which by definition has no utility. It can be argued that the portion of waste used to do work (e.g., anaerobic digestion of biosolids or solid waste with methane recovery and use, composting, or manure fertilizer) is no longer labeled waste. Regardless, when waste is conveyed to receiving environments, even after treatment, it has residual exergy, which can be quantified in emergy terms (Ulgiati and Brown, 2002). That is, some constituents in these wastes are above background concentrations. Consequently, the receiving environment must do work to return these constituents to the background concentrations (Fig. 1) because they still contain some emergy relative to the earth (Ulgiati and Brown, 2002). The emergy required by the receiving environment is not necessarily available for natural processes to occur if it is being invested in mitigating this residual emergy in waste. For instance, when a wastewater treatment plant discharges elevated nutrients into a river, algae that increase ecosystem metabolism may grow then die-off, depressing oxygen levels through decomposition. This interruption to the river ecosystem causes changes that should be considered in systems that create waste.

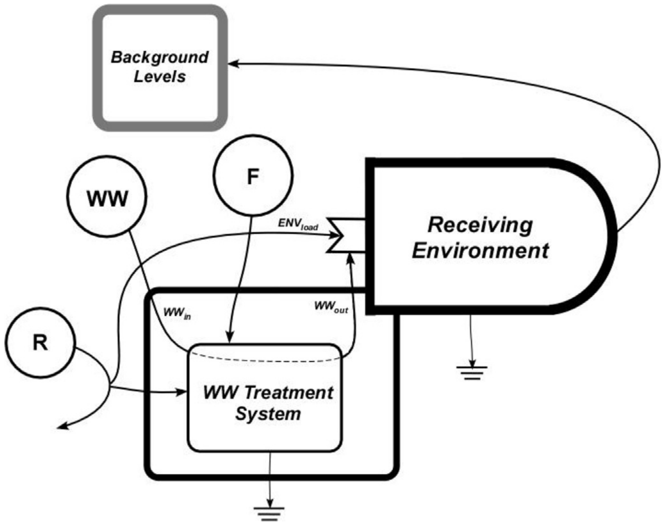

Fig. 1. Wastewater treatment process with eventual return to background concentrations (Dispersed Material) accounting for work done by receiving environment.

By evaluating the constituent of most concern (i.e., the constituent that will take the most emergy from the environment to mitigate), an emergy analysis can better reflect the true cost of discharging waste to the environment, even after treatment (Fig. 1). Certainly there are multiple constituents that require mitigation before reaching background levels, but by evaluating the constituent of most concern, double counting is prevented. Mitigation of residual exergy in the environment occurs in the same instance as natural processes (e.g., primary production, sedimentation, sorption, etc.), resulting in a co-product absorbing the residual exergy and ecological function. Consequently, it is appropriate to allocate to the residual exergy mitigation of the untreated waste all of the inputs to that receiving environment on an emergy basis. For this study, metals in the effluent of a mine drainage treatment system were diluted downstream to background levels.

1.2. Waste treatment case study- Miami, OK, USA

A passive treatment system (PTS) was constructed to treat three mine drainage discharges (seeps) in North Miami, Oklahoma (USA) and Commerce, Oklahoma (USA) in late 2008 at the 11,000-ha Tar Creek "Superfund" Site. Nearly a century of intensive mining in this region ended in the 1970's, which left behind millions of tons of lead-contaminated waste material and artesian-flowing mine drainage which has impacted surface water bodies ever since (WQS, 2000). 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 (Fig. 2). 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