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EMERGY ANALYSIS OF WASTEWATER TREATMENT TECHNOLOGY

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Abstract

The article presents a brief description and criticism of the current state of the emergy analysis for wastewater treatment plants (WWTP) and a new index for the assessment of environmental facilities. As well as in the analysis of economic systems, the assessment of systems and plants for the protection of the environment, provided in the literature, is based on the calculation of basic emergy indices (the emergy yield ratio (EYR) is the ratio of the sum of renewable kinds of emergy, non-renewable ones and purchased or free resources to the emergy of purchased resources; the environmental loading ratio (ELR) is defined as the ratio of the sum of nonrenewable and imported (purchased) emergy to renewable emergy; the emergy sustainability index (ESI) equal to the ratio of economy (EYR) to depletion (ELR) determines the degree of viability of the facility), which does not take into consideration a fundamental difference of production facilities and facilities designed to protect the environment from pollution. The environmental performance of the facilities, calculated as the ratio of the difference between the emergy estimates of preventable damage and caused damage to the preventable damage, must serve as the main emergy index for the assessment of treatment facilities.

Keywords: Emergy analysis; sewage treatment plant; wastewater; environmental performance.

1. Introduction

Currently, economic development is unconceivable without advanced quantitative and qualitative growth of the facilities capacities intended for environmental protection from anthropogenic pollution. At that, the ecological imperative of the third quarter of the 20th century — "one ought not to be stingy with

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money to protect the natural resources" — is not interpreted literally today. In recent 30-40 years, increasingly wider circles of researchers and community have become aware of the fact that any further rise in the cost of products or services, including environmental ones, is directly or indirectly accompanied by an increase in the load on the environment in the biosphere scale. How do we determine the optimum level of concern for the environment that does not cause any further harm to it? What analysis tools will allow making the most appropriate choice of the best available treatment technology of production wastes and biowaste? As practice shows, these questions are far from being abstract. In Sakhalin, for example, the wastewater of one of the camps of gas industry workers is neutralized by means of its evaporation. It is quite possible that this decision is economically justified, but in terms of the biospheric effect, it raises many questions.

1.1. Problem statement

To evaluate production systems, the cost methods and life cycle analysis as well as energy methods (exergy and emergy ones) have been developed (Geber, 2001).

For almost twenty years, in the United States and Western Europe, the method of assessing the operation of wastewater treatment plants (WWTP) — emergy analysis — has been developed, which was based on the approach of Mr. U. Odum. In the last decade, Chinese researchers have made a significant contribution to the development of this analysis. In domestic science, unfortunately, this trend has not attracted deserved attention yet.

The research task is to examine existing emergy analysis and to determine the cause of the lack of interest in this analysis in the field of environmental protection. G. Odum recognizes wastewater as a valuable resource rather than waste one, which is not observed in the modern society. Thus, the objective of the work is the updating of existing emergy indices for assessment of the WWTP operation.

1.2. Research questions

The research problems to be discussed in this paper are as follows:

- exploration of classical emergy analysis;
- determination of the variants of improvement of emergy analysis;
- analysis of the reasons of little use of emergy analysis during assessment of environmental facilities functioning.

1.3. Objective of the study

The objective of the research is to offer an improved emergy index for analyzing the functioning of environmental protection enterprises.

2. Methods and Results

The results were obtained by analysing published studies.

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2.1. Emergy analysis

A wastewater treatment plant can be seen as a typical manufacturing enterprise, which has raw materials (water contaminated with organic and mineral substances and micro-organisms) at the input, and a commodity product - water purified to a level acceptable for its discharge into a water body — at the output. Ecocentrism is a part of the emergy analysis developed by H. Odum and his colleagues (Odum, 1988).

It is known that different types of energy (mechanical, thermal, electrical) are not equal to each other. Mr. Odum proposed to make an energy-wise evaluation of not only different kinds of energy (and offered a methodology for assessing non-equivalence of different kinds of energy) but also to assess substance, information, natural and anthropogenic processes in the same units.

For this purpose, the model, in which the objects and processes are distributed according to their energy content (all energy expenditures for the origination or creation of an object or process), has been developed. The model uses the concept of exergy that takes into account the degradation of energy in any processes according to the second law of thermodynamics. The basic concept of the model was represented by the notion "emergy" which is the value of exergy of one type that is directly or indirectly used to support the process or storage of different kinds of energy or a substance (Odum, 1988). A joule of solar radiation - emjoule - was adopted as a unit of measure in the model.

The conceptual basis of the model is the law of maximization of emergy capacity (Odum, & Odum, 1983), according to which all self-organizing systems (including the economy) in its development increase the flow of used emergy (emergy capacity) (Odum, 1988). In the course of complication of the system, the value of the energy comprised by an object (service) decreases and the degree of its conversion (transformation) increases. Thus, the consumers "comprise" more transformed energy than producers do, more electrical energy - than thermal energy, and more information – than labor etc. (Odum, 2002). The model is intended for assessment of the natural and industrial products and services from egocentric viewpoints (Hau, 2004).

Despite of the growing popularity and expansion of the scope of emergy analysis in the scientific literature, there are also quite a large number of publications with an approach of valid criticism.

The analysis of more serious critical works was made by Brown (Brown, 2004). He notes that a number of authors: Ayres, (1988), Cleveland, (2000), Mansson, (1993), Spreng, (1988) characterize the emergy analysis as simplistic, illogical, misleading and not accurate. Counterarguments to this criticism are presented in the works of Odum and M. Patterson (Patterson, 1993; Odum, 1995). The most debated element of the emergy analysis is the calculation of the transformation value, as the emergy method does not accept even a tiny amount of uncertainty. The generalized transformation of industrial and geological processes is used in specific cases without the knowledge of the degree of reliability of the obtained result. For example, the transformation of natural gas is the average efficiency of coal type and combustion in boilers (Odum, 1996), but this efficiency directly depends on the grade of coal and the type of natural gas as well as on the characteristics of the boiler itself. Calculation of the emergy of economic processes using emergy/cash flow index may be also incorrect and include double calculations.

Quantitative assessment of all energy flows and substance in a single dimension (emdjoule) allows their use in a variety of combinations and relationships to create rather informative indexes, ratios

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parameters. The most commonly used indexes discussed in the literature are EYR (emergy yield ratio), ELR (environmental loading ratio) and ESI (emergy sustainability index).

The emergy yield ratio (EYR) is the ratio of the sum of renewable kinds of emergy (R), non-renewable ones (N) and purchased or free (F) resources to the emergy of purchased resources (F):

$$EYR = \frac{R + N + F}{F}. \tag{1}$$

The index is a required parameter of the analysis of industrial and economic systems describing the emergy feasibility of the establishment and functioning of the considered system under certain conditions. The system which has higher values of the index is preferable.

The environmental loading ratio (ELR) is defined as the ratio of the sum of nonrenewable and imported (purchased) emergy to renewable emergy:

$$ELR = \frac{N + F}{R}. \tag{2}$$

This index describes resource depletion of the technology. The lower values of the index act as preferable.

The ESI index (emergy sustainability index) equal to the ratio of economy (EYR) to depletion (ELR) determines the degree of viability of the facility:

$$ESI = \frac{EYR}{ELR} = \frac{R^2 + NR + FR}{FN + F^2}. \tag{3}$$

On the whole, the three considered parameters yield the most common "sketch" characteristics of the production facility and are, as noted above, more objective indices compared with such similar cost parameters as profitability, total resource intensity, and a degree of independence from chargeable resources (market).

2.2. The attempts to improve emergy analysis

Sewage treatment plants are intended for protection of the environment from pollution by sewage. Currently, the efficiency of the vast majority of the sewage treatment plants is evaluated by the degree of achievement of standards of permissible discharge of pollutants and microorganisms from sewage into the receiving water body. This approach does not take into account that wastewater treatment plants, performing water treatment, are at the same time, direct or indirect sources of waste, emissions and discharges of pollutants into the environment as well as consumers of renewable and non-renewable natural resources. Therefore, to adequately assess the environmental efficiency of the wastewater treatment plants, it is necessary to take into account not only the quality of treated water, but also the damage to the nature caused by the establishing and functioning of these plants. This situation is more clearly understood by ecologists (Vassallo, 2009).

The most acute problem of eco-efficiency is faced by the traditional wastewater treatment plants intended for marginal sources, for instance, small towns, small business service sectors, food industry, etc. First of all, in comparison with similar systems used for treatment of sewage of large settlements, they require significantly higher specific capital and operating costs (Zhou, 2009; Nelson, & Odum, 2001). In addition, in most cases, they do not provide the quality of treated wastewater required by laws

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and regulations of the Russian Federation.

The application of the emergy analysis for assessment of environmental enterprises was initialized in the thesis of N. Flanagan (Flanagan, 1997) performed under the direction of William Mitch. At the moment, the results of three dozen research papers have been published in this area. To carry out the emergy analysis of the technologies of sewage sanitation in addition to the parameters listed above, the researchers suggested using more than a dozen of emergy indexes.

Simplified versions of the classic index of stability was offered in papers of Geber, (2001), Zhou, (2009), Nelson, & Odum, (2001), Brown, (2007), Zuo, (2004). Brown, (2007) and then Zuo, (2004) calculate the "investment ratio" (Ir) equal to the ratio of the emergy of purchased resources to the sum of the emergy content of renewable and non-renewable resources. Nelson, & Odum, (2001), Geber (2001) and Zhou (2009) use the ratio of flows of free and purchased resources to evaluate the stability, while Brown (Brown, 2007) and then Chen (Chen, 2009) characterize the stability of shares of the purchased resources in the total expenditures.

To assess the actual emergy efficiency of the environmental investment and operation of the wastewater treatment plants, Arias Arias,(2009) uses a mixed energy and cost indicators – the relation of the total emergy content of the plant to the capital expenditures, expressed in monetary units, and the relation of the total emergy content of the plant related to the annual maintenance costs, including depreciation charges.

To assess the profitability of the project realization of reconstruction of a wastewater treatment plant and a disposal system of purified water for irrigation, Sirscusa, (2006) calculates the ratio of profit to expenditures, expressed in units of emergy.

Specific emergy expenditures on sewage treatment are assessed by researchers using three types of parameters. Brown, (2007) and Arias, (2009) calculate the emergy expenditures on purification of a cubic meter of wastewater, which is necessary for comparison of treatment technologies when designing new or upgrading existing WWTP, in cases the contamination level of sewage and the effectiveness of purification of the plants being compared are identical. Vassallo P., (2009), Nelson et al., (2001), Arias M.E., (2009) use the indicator "emergy/ person", which makes sense only if to compare the plants with equal standards of water consumption for the population. Both considered indicator do not take into account the quality of wastewater purification. A more universal indicator of specific emergy inputs is offered by Zhou J.B., (2009). The ecological waste removal efficiency (EWRE), proposed by him, characterizes emergy costs for removal of a mass unit of pollutants, that is shows emergy economy of treatment technology.

In addition to the mentioned-above indices being emergy analogues of known cost parameters, the literature proposes new proper emergy factors and ratios. Zuo P., (2004) proposes the index of "base emergy change" as a measure of changes in environmental quality in the territory of the wastewater treatment plant. According to the author, this option can also be used to assess the stability of the plant, considered as an ecosystem. Unfortunately, Zuo does not give specific examples of ecosystem quality conversion by increasing the base emergy and a simultaneously increase of its stability. At the same time, it is known that the complexity of the system does not always lead to an increase in its stability (Hanfeng, 2011). However, the option "base emergy change" of the ecosystem, in our view, is one of the most

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important indicators of emergy analysis of the WWTP. Indeed, the result of appearance of biogeocoenosis with a high degree of biodiversity and productivity on the area of land, occupied by a low productivity ecosystem, in accordance with the modern ecological paradigm is usually regarded as a positive environmental effect, and the opposite effect – as a negative one.

The power density of the emergy flow fully characterizes the compactness of sewage treatment facilities, which is critical in case of the deficit of areas intended for accommodation of WWTP or in case of their high cost (Nelson et al., 2001; Arias, 2009). The most significant contribution to the methodology of the emergy analysis of the WWTP is awareness of the necessity of inclusion of the part of receiving water body of the WWTP, being under the influence of wastewater and providing the reduction of the concentration of pollutants to background, in the emergy diagram as an object of analysis beside the WWTP territory. Vassallo, (2009) proposes to evaluate not only the specific emergy cost on the territory of the WWTP, but also the ecosystem services required for the complete neutralization of wastewaters outside the territory. To illustrate the methodology, the volume of such natural services is calculated according to the amount of oxygen required to oxidize the residual concentrations of organic matter in the receiving reservoir.

The proposal of Vassallo was further developed in the article of Mu et al., (2011), where the emergy price of natural services, arriving from the environment to the dilution of effluent, and environmental charges of the enterprise for the discharge of pollutants are included in the formula of classical indices (EYR, ELR, ESI) and are calculated by the formulas:

$$EYR_{iw} = \frac{R + N + F_1 + F_2 + F_3}{F_1 + F_2 + F_3 + E_W}; \tag{4}$$

$$ELR_{iw} = \frac{N + F_1 + F_2 + E_w}{R + F_1 + F_3}, \tag{5}$$

where R - renewable resources; N - non-renewable resources; F_1 - investments in products (production); F_2 - investments in wastewater treatment; F_3 - additional investment in environmental protection; E_w - natural services, which arrive from the environment for waste water dilution.

2.3. Emergy ecological efficiency (EEE)

Classic indices were originally designed for enterprises aimed at making a profit, which is achieved by meeting direct human needs with goods or services. At that, all understand and accept as a necessary evil the fact that the establishment of such enterprises will inevitably increase the burden on the environment. The service of purifying wastewater satisfy human needs indirectly through the reduction of the environmental pollution degree; therefore the depletion of technologies used by WWTP and the load on the environment, in the above-stated sense (ELR) does not reflect the real impact of the WWTP on the biosphere. The purpose of the establishment and functioning of the WWTP is not production of emergy-intensive product, but the reduction of the load on the environment or the life support systems or production. Therefore, the main emergy characteristic of the WWTP should be their ecological (environmental) efficiency, i.e. the degree of gaining the object of establishing and operating WWTP. The degree of achievement of standards of permissible discharge of pollutants and microorganisms from

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sewage into the receiving water body, which assesses the work of WWTP today, is rather a sanitary index than an environmental one. A parameter characterizing the biosphere costs for neutralization of wastewater without treatment in comparison with the biosphere costs in case of its purifying at WWTP can be environment.

Ecological efficiency (EEE- emergy ecological efficiency), calculated as the ratio of the difference between the emergy assessment of the prevented damage and the actual damage to the prevented damage expressed in percentage, describes the reduction of the burden on the biosphere owing to establishing and operating WWTP. The EEE parameter is defined by the formula:

$$\text{EEE} = \frac{PD - AD}{PD} * 100\%, \tag{6}$$

where PD - prevented damage; AD - actual damage.

Prevented damage in its very rough approximation is natural services that come from the environment for the dilution of untreated sewage to the permissible limit of pollutant, according to which the highest dilution is required. For a more accurate calculation, it is necessary to take into account a self-purifying ability of the water body. The actual damage is calculated as the sum of depreciation of the WWTP, the annual expenditure on the operation expressed in emjoules and the emergy of clean water required for dilution of treated at WWTP wastewater up to background concentrations of pollutants in the receiving water body, or standards for water bodies of a certain category of water use. If the prevented damage is greater than the actual damage, the environmental performance is positive, and the construction of the WWTP using the proposed technology is expedient. In case of availability of alternatives, it is expedient to choose the technology that has the highest eco-efficiency.

3. Conclusions

Thus, for emergy assessment of the WWTP, a system of treatment with treated wastewater should be considered. During their disposal (for irrigation of agricultural fields, fish ponds, etc.), emergy analysis should be carried out using the emergy yield ratio (EYR) as the base index, and in case of the most mass practice today consisting in the discharge of effluents into natural water facilities – emergy ecological efficiency (EEE).

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