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Emergy assessment for depollution of the Charles de Gaulle stream in Brazil

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Authors' notes

The authors have no conflicts of interest to declare.

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Abstract

Objective: This study aimed to conduct an emergy assessment for the depollution of the Charles de Gaulle stream in Brazil.
Methodology: A case study approach was employed, utilizing interviews and participant observation for data collection. The emergy assessment was applied to the gathered data, yielding significant results.
Originality: This study addresses a critical research gap, as no literature specifically applies emergy assessment to urban stream depollution. It provides a comprehensive evaluation of the stream's revitalization and monitoring impacts, contributing to the United Nations Sustainable Development Goal 6 (SDG 6) on clean water and sanitation.
Results: Emergy indicators, analyzed through sensitivity analysis, reveal improvements in ecosystem services, resource optimization, and water quality. A decrease in the stream's total emergy indicates clear environmental restoration and societal reintegration into the ecosystem.
Contributions: This research demonstrates the feasibility of applying emergy assessment in urban water revitalization. The reduction in total emergy signifies environmental restoration and supports practical actions toward achieving SDG 6 focused on clean water and sanitation.

Keywords: emergy, ecosystem services, urban rivers, sensitivity analysis.

Avaliação emergética para a despoluição do córrego Charles de Gaulle no Brasil

Resumo

Objetivo: Este estudo teve como objetivo realizar uma avaliação de emergia para a despoluição do riacho Charles de Gaulle no Brasil.
Metodologia: Foi adotada uma abordagem de estudo de caso, utilizando entrevistas e observação participante para a coleta de dados. A avaliação de emergia foi aplicada aos dados coletados, gerando resultados significativos.
Originalidade: Este estudo aborda uma lacuna crítica na pesquisa, uma vez que nenhuma literatura aplica especificamente a avaliação de emergia à despoluição de riachos urbanos. Ele fornece uma avaliação abrangente da revitalização do riacho e do monitoramento dos impactos, contribuindo para o Objetivo de Desenvolvimento Sustentável 6 (ODS 6) das Nações Unidas, relacionado a água limpa e saneamento.
Resultados: Indicadores de emergia, analisados por meio de análise de sensibilidade, revelam melhorias nos serviços ecossistêmicos, na otimização de recursos e na qualidade da água. A redução na emergia total do riacho indica uma clara restauração ambiental e reintegração da sociedade ao ecossistema.
Contribuições: Esta pesquisa demonstra a viabilidade da aplicação da avaliação de emergia em processos de revitalização de água urbana. A redução na emergia total sinaliza a restauração ambiental e apoia ações práticas para alcançar o ODS 6, focado em água limpa e saneamento.

Palavras-chave: emergia, serviços ecossistêmicos, rios urbanos, análise de sensibilidade.

Evaluación emergética para la descontaminación del arroyo Charles de Gaulle en Brasil

Resumen

Objetivo: Este estudio tuvo como objetivo realizar una evaluación de emergía para la despolución del arroyo Charles de Gaulle en Brasil.
Metodología: Se utilizó un enfoque de estudio de caso, aplicando la evaluación de emergía al arroyo Charles de Gaulle. La recolección de datos involucró entrevistas y observación participante. La evaluación de emergía se aplicó a los datos recopilados, generando resultados significativos.
Originalidad: No hay estudios en la literatura que hayan aplicado específicamente la evaluación de emergía a la despolución de arroyos urbanos, revelando una brecha crítica en la investigación. Este estudio ofrece una evaluación integral para la revitalización del arroyo y el monitoreo continuo de los impactos observados en la despolución, contribuyendo al Objetivo de Desarrollo Sostenible 6 (ODS 6) de las Naciones Unidas, relacionado con agua limpia y saneamiento.
Resultados: Los indicadores de emergía, calculados y analizados a través de análisis de sensibilidad, muestran mejoras en los servicios ecosistémicos, optimización de recursos y calidad del agua. A medida que la emergía total del arroyo (transformidad) disminuye, hay evidencia clara de restauración ambiental, junto con la reintegración de la sociedad en el ecosistema.
Contribuciones: Esta investigación ilustra la viabilidad de aplicar la evaluación de emergía en procesos de revitalización del agua urbana. Además, la reducción en la emergía total del arroyo indica restauración ambiental y promueve la reintegración social en el ecosistema revitalizado. También contribuye a acciones prácticas para lograr el ODS 6, enfocado en agua limpia y saneamiento.

Palabras clave: emergia, servicios ecosistémicos, ríos urbanos, análisis de sensibilidad.

Introduction

The ongoing absence of urban planning results in a decline of essential ecosystem services in urban areas, highlighting the impact of revitalization processes on local environments (Anin and Banahene, 2021). A significant challenge in addressing urban river depollution is identifying and evaluating factors influencing water resources through sustainability indicators, which is vital for stakeholders like citizens, policymakers, and researchers (Nahiduzzaman and Sadiq, 2023).

The emergy approach has been extensively used in quantitative research to analyze social and environmental system interactions. It evaluates complex urban hydrological systems by integrating economic, technical, and social indicators, capturing the contributions of both natural and human resources in restoration efforts (Brown and Ulgiati, 2002).

Odum (1996) defines emergy as "the available energy previously used, directly or indirectly, to produce a product or service." Emergy theory consolidates various contributing factors into a common unit, solar equivalent joules (sej), allowing for a holistic evaluation of complex systems. This standardized measurement facilitates the comparison of different energy inputs, providing a comprehensive framework for assessing system interactions (Liu et al., 2019; Song et al., 2019).

According to the Millennium Ecosystem Assessment (MEA, 2005), a systematic review identified five key articles on the impact of climate and environmental changes, highlighting the need for ecological compensation to improve ecosystem service provision (Li et al., 2021). The studies emphasize factors such as the relationship between urban densification and local economic dynamics (Song et al., 2021), the declining economic value of soil conservation (Wang et al., 2021), and the economic benefits of environmental revitalization (Liu et al., 2019). Furthermore, increasing economic development pressures are associated with higher emergy inflows (Zeng et al., 2010).

Emergy has been used in environmental revitalization studies. Sun et al. (2021) analyzed emergy to enhance restored ecological zones, while Song et al. (2019) explored renewable energy's impact on ecological sustainability. Sun et al. (2019) emphasized the need to preserve natural resources, and Zhan et al. (2018) examined industrialization's effects on ecosystem services.

Emergy assessment is highlighted in three articles analyzing water resources' costs and value, focusing on river basin impacts. Chen et al. (2009) noted its promotion of efficient water use and ecological stability, Di et al. (2019) emphasized ecological balance, and Lv et al. (2018) demonstrated its effectiveness in revealing water resource benefits.

Two key articles address the challenges of revitalization and ecosystem preservation in urban river basins, emphasizing societal actions for sustainability. Su et al. (2013) highlighted the need for population control, waste disposal, and recycling. Pan et al. (2020) used emergy analysis in China's Simon River basin to show how ecosystem services benefit local communities.

Additionally, Zhang et al. (2017) applied emergy analysis to assess water body health and suggest restoration actions, while Pulselli et al. (2011) showed that infrastructure investments are affected by water losses, influencing emergy values. Lv et al. (2020) emphasized the need to include urban land costs in planning to enhance sustainability.

Emergy analysis also evaluates environmental conditions and economic performance in river basin restoration, with Wu et al. (2019) demonstrating its effectiveness in highlighting the environmental benefits of unpolluted water. Emergy calculations of ecosystem services have informed local public policies for river conservation (Zhong et al., 2018). However, no studies have specifically applied emergy assessment to the depollution of urban streams, indicating a significant research gap. To address this, the evaluation procedure developed by Flausino et al. (2023) was implemented to assess contributions and improvements in urban river depollution, focusing on economic gains and ecosystem service enhancements.

In this context, the following research question is identified: “Is it feasible to apply the emergy assessment procedure in an urban stream?”, being the objective of this study was to conduct an emergy assessment for the depollution of the Charles de Gaulle stream in Brazil, thereby contributing to both economic and environmental evaluations. The theoretical motivation behind this research is to illustrate the feasibility of applying emergy assessment procedures in urban water revitalization processes. Furthermore, this study aims to demonstrate that emergy theory facilitates the adoption of novel sustainability indicators.

The application of emergy indicators in the revitalization of urban streams contributes significantly to the development of more sustainable public policies, presenting a new method of measuring the various aspects involved in a decontamination process, assisting decision-makers in identifying and asserting the practical actions to be taken, such as in determining the allocation of economic investments, while increasing the population's awareness and understanding of the ecosystem services provided by the watershed. By integrating emergy indicators, policy-makers can effectively assess the ecological and economic benefits of restoration efforts, promoting a more sustainable relationship between urban communities and their surrounding environments.

Materials and Methods

This section outlines the emergy assessment procedure for urban stream depollution, developed through a systematic literature review. Following this, we will detail the methodology employed in the case study of the Charles de Gaulle stream in Brazil.

A systematic review was conducted using the databases Scopus, Science Direct, Google Scholar, Springer, Emerald, and Taylor & Francis, with the following keyword groups: (i) "emergy" and "ecosystem services"; (ii) "emergy" and "sustainability indicators"; (iii) "emergy" and "urban river revitalization"; (iv) "emergy" and "watershed restoration"; (v) "emergy" and "urban rivers." The content analysis identified 40 relevant articles, of which only 19 specifically addressed emergy assessment in watershed revitalization, wetlands, or water-related issues (see Appendix A). The remaining 21 articles focused on topics not directly related to water. The articles were categorized into eight groups based on their emergy applications, with the concept of ecosystem services emphasizing the dependence and integration of humans with the environment and the services it provides (see Appendix A).

Procedure for the application of emergy assessment in the depollution of urban rivers

The emergy assessment begins with a systemic diagram illustrating relevant energy inputs that influence the system. This diagram is a foundational tool for understanding how these energies interact and impact the calculated indicators (see Figure 1).

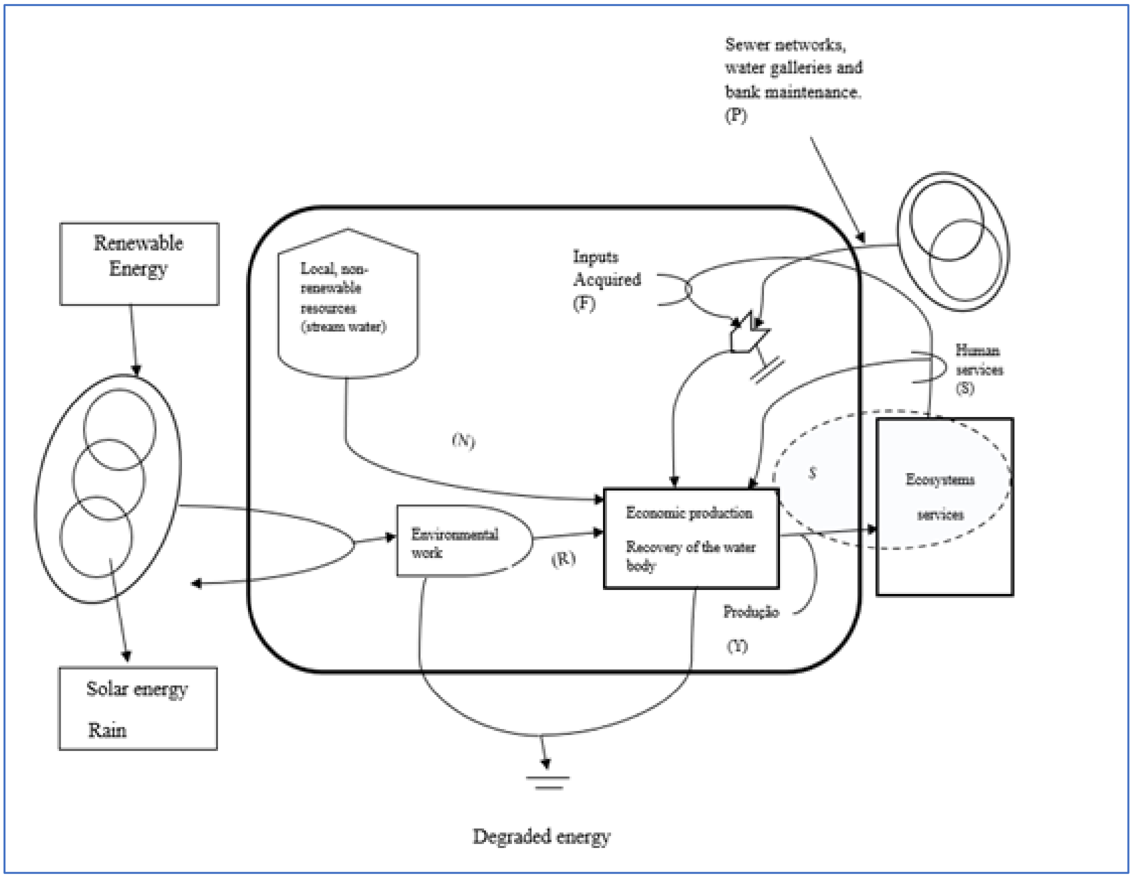
Emergy calculations are performed by multiplying transformities by their respective specific energies. Transformity classifies global resources used to produce a unit of a specific service. Resources are categorized into three types: non-renewable resources (N), economic resources (F), and renewable resources (R). Non-renewable resources (N) are those consumed faster than they regenerate, while economic resources (F) are generated through anthropogenic activities reliant on non-renewable inputs (Odum, 1996). This classification is crucial for accurately assessing emergy contributions from various resource types.

The procedural steps, adapted from Flausino et al. (2023), are illustrated in Figure 2 and based on emergy studies in river basins. The emergy values and transformities used in this study were identified based on their contributions to the river system (Odum, 1996), ensuring a comprehensive understanding of emergy dynamics.

Relevant inputs and works incorporated into the river depollution process are integrated into the equations alongside water quality data (Di et al., 2019). The generated indicators enable analysis of the process before and after revitalization, providing stakeholders with information necessary for implementing sustainable development policies effectively. (Sun et al., 2019). This approach not only assesses the outcomes of the revitalization efforts but also informs future decision-making for improved ecosystem management.).

Figure 1

Systemic diagram of the emergy flow in the depollution of the Charles de Gaulle stream. (Adapted from Flausino, et.al., 2023)



The parameters depicted in Figure 2 outline the emergy calculations conducted in this study. The incorporation of natural elements, such as solar energy and precipitation, is directly linked to the emergy assessment. Specifically, solar energy is essential for the transformation of components within an emergy system and is a key factor influencing the functioning of a river basin. These natural inputs play a crucial role in the ecological dynamics and overall health of the river ecosystem.

The emergy values identified before and after the depollution process—comparing river water with sewage to river water without sewage—help delineate the configurations of non-renewable resources. This assessment incorporates elements of biochemical oxygen demand (BOD), which is utilized to evaluate the quality of river water. In this study, the verification of BOD measurements is crucial for accurately determining the emergy indicators calculated (Flausino & Gallardo, 2021). This analysis provides insight into the effectiveness of the depollution efforts and their impact on water quality.

The natural resources adopted in the presented model determine fundamental parameters incorporated in the calculation of transformities and emergy in a process for the decontamination of an urban river (Tables 01 and 02). Solar energy, rainfall index, and water quality (BOD) are part of the natural contribution in the emergy assessment for human economic and social development (LV, et al., 2018).

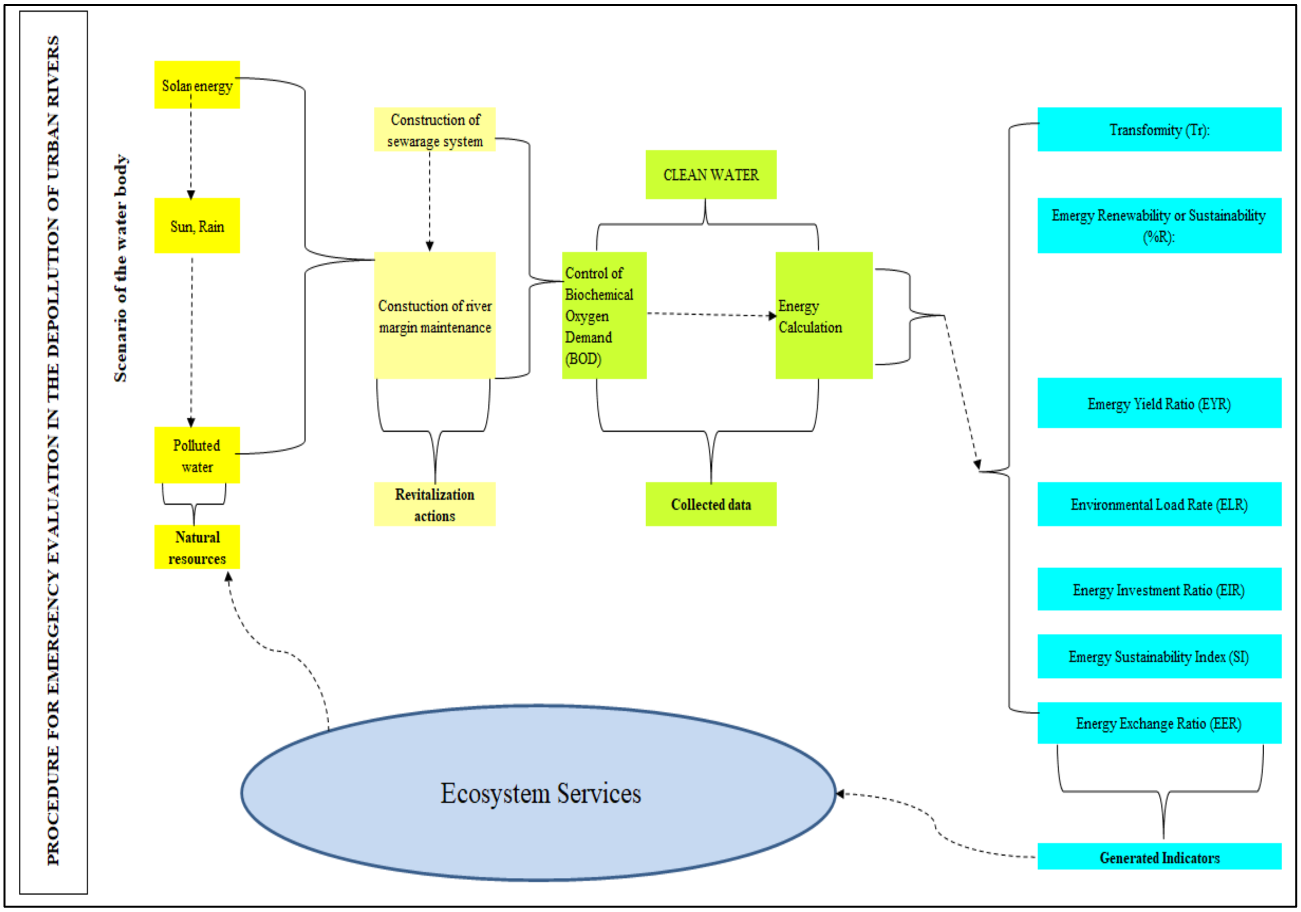
ZENG, et al. (2010) demonstrated the contributions of natural resources within the context of watersheds through emergy assessment, such as river flow and water quality directly related to ecosystem health, essential for the preservation and provision of ecosystem services (provisioning, regulation, support, and cultural) that are crucial for sustaining life.

Emergy assessments conducted in the Yellow River Basin in China demonstrated that the volume and quality of the water body (BOD) after sediment removal directly affect the emergy and transformity indicators used to measure eco-economic resources utilized in the Yellow River Basin region in China (DI, et al., 2019).

The costs associated with sewage networks and the maintenance of the stream banks identified in this study represent the expenses incurred for the depollution efforts. As emergy calculations are conducted in the analysis of complex systems, incorporating these costs related to infrastructure and maintenance is essential for developing the analytical framework presented in this article. This comprehensive approach ensures that all relevant financial inputs are considered, enhancing the robustness of the emergy assessment and its implications for sustainable management practices (Flausino, et.al., 2023).

Figure 2

Procedure for emergy assessment in urban rivers. (Adapted from Flausino, et.al., 2023)



The parameters illustrated in Figure 2, which constitute the emergy evaluation proposed in this study, focus on the key aspects that influence the depollution of an urban river. The incorporation of natural elements, such as solar energy and rainfall, is directly aligned with the principles of emergy theory. Specifically, solar energy is essential for transforming system components into emergy, while rainfall serves as a critical element within a watershed. Together, these factors play a significant role in shaping the ecological dynamics and overall health of the river system.

The emergies identified before and after the revitalization process—comparing sewage-laden river water to clean river water—are crucial for establishing non-renewable resource parameters. This assessment includes biochemical oxygen demand (BOD) elements, vital for measuring water quality. Verifying BOD measurements is essential for accurately calculating emergy indicators and assessing the effectiveness of revitalization efforts.

Additionally, including costs associated with sewage networks and stream bank maintenance is necessary to capture expenses involved in revitalizing the water body. By incorporating these costs, the emergy assessment provides a comprehensive analysis aimed at enhancing sustainability and improving understanding of the economic implications of river revitalization efforts.

Equations for calculation of emergy indicators in the depollution of stream

The natural resource identification step of the procedure (Figure 2) includes equations that convert natural energies into emergy, enabling the measurement of the contribution rate of water to energy, as well as the economic contributions derived from the natural resources embedded in the water system. Equations 1, 2, 3, 4, 5, and 6 have been adapted from emergy assessment studies conducted in hydrological environments by Lv et al. (2018), Chen et al. (2009), and Pulselli et al. (2011). They form the foundation for quantifying the various inputs and their impacts on the overall emergy assessment.

$$Se = rad * S * (1-alb) \qquad (1)$$

where Se is solar energy (Joules/year); rad is radiation (Megajoules/square me-ters/day); alb is albedo.

$$Re = P * G * S \qquad (2)$$

where Re is Rain emergy (Joules/year); P is Precipitation (millimeter/year); G is Gibbs free energy (Joules/gram); S is total area of the watershed (square meters)

$$Epw = BODp * q * Eom \qquad (3)$$

where Epw is Energy from polluted water (Joules/year); BODp is Biochemical oxygen demand in polluted stream (milligram/liters); q is the maximum flow rate (liters/second); Eom is emergy organic material (Joules/kilocal).

The parameters for economic resources (F) and services (S) in the revitalization actions (Figure 2) include costs related to maintaining and implementing sewage systems around the studied stream. The conversion of these energies into emergy was based on analyses of water body revitalization projects, as noted in studies by Pulselli et al. (2011) and Lv et al. (2018). The relevant equations for these calculations are as follows:

$$F1 = Ti / Slf \quad (4)$$

where F1 is energy from actions taken monetary unit defined in dollar (U$/year); Ti is total investment (U$); Slf is Service life of sewage networks (years).

$$F2 = oc * pop \quad (5)$$

where F2 is energy from operating actions monetary unit defined in dollar (U$/year); oc is operation cost (U$/population/year); pop is total of population from stream area.

The total emergy (Y) used in the assessment equations for enhancing the depollution process of urban streams and rivers includes the sum of renewable and non-renewable natural resources, along with the calculated river emergy before and after revitalization. Data from water quality analyses is integrated into Equation 6 to facilitate the data collection step (see Figure 2). This data is then converted into emergy to evaluate the effectiveness of the revitalization process, as illustrated in studies by Sun et al. (2019) and Di et al. (2019).

$$Ecw = BODc * q * Eom \quad (6)$$

where Ecw is Energy from clean water (Joules/year); BODc is Biochemical oxygen demand in clean stream; q is the maximum flow rate (liters/second); Eom is emergy organic material (Joules/kilocal).

The values calculated from equations 1 to 6 are used to determine the emergy indicators in the application of emergy assessment in urban river depollution.

Equations 7, 8, 9, 10, 11, 12, and 13 calculate the emergetic indicators developed by Odum (1996) and are developed in studies that use emergy assessment as a method.

Tranformity (Tr) evaluates the quality of energy flow and allows to make comparisons with other forms of energy and with other systems, solar transformity is the ratio of the energy embodied by the system (Y) to the energy of the resource produced (Odum, 1996 and Li, et.al. 2021).

$$Tr = Y/Ep \qquad (7)$$

where Tr is transformity (Sej/J); Y is energy from the resource produced (Sej/year); Ep is energy from the resource produced (Joule/year).

The percentage of Renewability is the ratio of the emergy from renewable resources to the total emergy used and identifies that systems with higher sustainability ratings have a greater chance of survival (Odum, 1996).

$$\%R = R/Y \qquad (8)$$

where %R is renewability (% percentage); R is natural resources (sej/year); Y is en-ergy from the resource produced (sej/year).

The Energetic Yield Ratio (EYR) indicates the emergy yield of the system, or the gain in primary energy made available to the economy that will consume the product. If its value is close to one, the system consumes as much energy as it makes available to the economy. It is the ratio of the emergy embodied in the product to the emergy of the inputs that come from the economy (Odum, 1996 and Lv, et.al. 2018).

$$EYR=Y/F \qquad (9)$$

where EYR is emergy yield ratio; Y is energy from the resource produced (Sej/year); F is sum of energy from actions taken (F1) and energy from operating actions (F2).

The environmental load ratio (ELR) is the ratio between non-renewable and renewable resources. It is an important index because it evaluates the pressure that the produc-tion system causes on the ecosystem. High ELR indices indicate greater pressure of the economic system on the ecosystem (Li, et.al. 2021).

$$ELR = (N+F)/R \qquad (10)$$

where ELR is environmental charge rate; N is natural resources; F is sum of energy from actions taken (F1) and energy from operating actions (F2).

The emergy investment ratio (EIR), assesses whether one of the resources of the economy (monetary investment) in a project has a good natural resource counterpart and measures the proportion of recycled emergy from the economic sector in relation to the emergy inputs from the environment. This ratio indicates the degree of savings when using the investments of the economy compared to another alternative. To be economical, the process must have an emergy investment ratio value like the average value of activities in the region. If it demands more from the economy than other alternatives, it will have less chance of survival. Otherwise, its costs will be lower, which offers a chance to compete (Sun, et.al. 2019 and Di, et.al. 2019).

$$EIR=F/(N+R) \qquad (11)$$

where EIR is energy investment ratio; F is sum of energy from actions taken (F1) and energy from operating actions (F2); N is natural resources; R is natural resources.

The emergy sustainability index (SI) is the division between the emergy efficiency ratio and the Environmental loading rate and indicates whether the system contributes energy at the expense of the environmental balance or whether the impacts can be absorbed by the system (Zhang, et.al. 2017 and Li, et.al. 2021).

$$SI = EYR/ELR \qquad (12)$$

where SI is emergy sustainability; EYR is emergy yield ratio; ELR is environmental charge rate.

The emergy exchange ratio (EER) is the ratio of emergy received to emergy supplied in an exchange. Products from labor of nature are likely to have a higher EER value than products from human labor (Zhang, et.al.2017).

$$EER = Y / [\text{unit production} \times \text{price} \times (\text{emergy/dollar})] \quad (13)$$

where EER is emergy exchange ratio.

Equations 14 and 15 were adapted from the work of Pan, et.al. (2020), according to the application of the emergetic theory to enable the evaluation of ecosystem services incorporated into urban revitalization processes.

The ecosystem services evaluated in the depollution of the Charles de Gaulle stream, used in this work, include calculations for regulating ecosystem services (Equation 14) and supporting ecosystem services (Equation 15). These equations are derived from the study by Chen et al. (2009), which utilized them for the emergy assessment of water resources in China. However, they have not been previously applied in urban river depollution processes.

$$Res = S * BODc * Tr \quad (14)$$

where Res is regulation ecosystem services; BODc is Biochemical oxygen demand in clean stream; Tr is transformity.

$$Ses = P * \rho * G * Tr \quad (15)$$

where Ses is supporting ecosystem services; P is precipitation of rain; ρ is density of water; G is Gibbs free energy; Tr is transformity.

Application of the emergy assessment procedure for the depollution of the Charles de Gaule stream in Brazil - Case Study

This case study outlines research results based on official data from relevant authorities regarding the revitalization of the Charles de Gaulle stream. It demonstrates the connection between the collected data and the emergy assessment approach, highlighting its contributions to urban river sustainability and decision-making.

The data collection and field analysis enhance the application of emergy equations from Odum (1996), supporting the replicability of evaluations in similar depollution scenarios for rivers or urban streams with BOD data. This systematic approach provides a framework for assessing and improving the sustainability of urban waterways in various contexts.

Data collection procedure

Data collection was conducted using official websites of the São Paulo sanitation company, the municipal government, and the Brazilian meteorological institute. These publicly accessible resources allow for monitoring the funds allocated for the depollution process by relevant authorities.

The Charles de Gaulle stream, located in western São Paulo (see Figure 3), originates in Parque São Domingos and flows through fully urbanized areas, presenting unique challenges and opportunities for revitalization efforts.

The depollution initiative benefits approximately 8,500 residents and a transient population visiting for leisure and nature engagement. It addresses environmental, social, and economic needs by improving water quality, revitalizing stream banks, mitigating flood risks, and enhancing property values. These multifaceted benefits underscore the project’s importance in fostering a healthier, more sustainable urban environment.

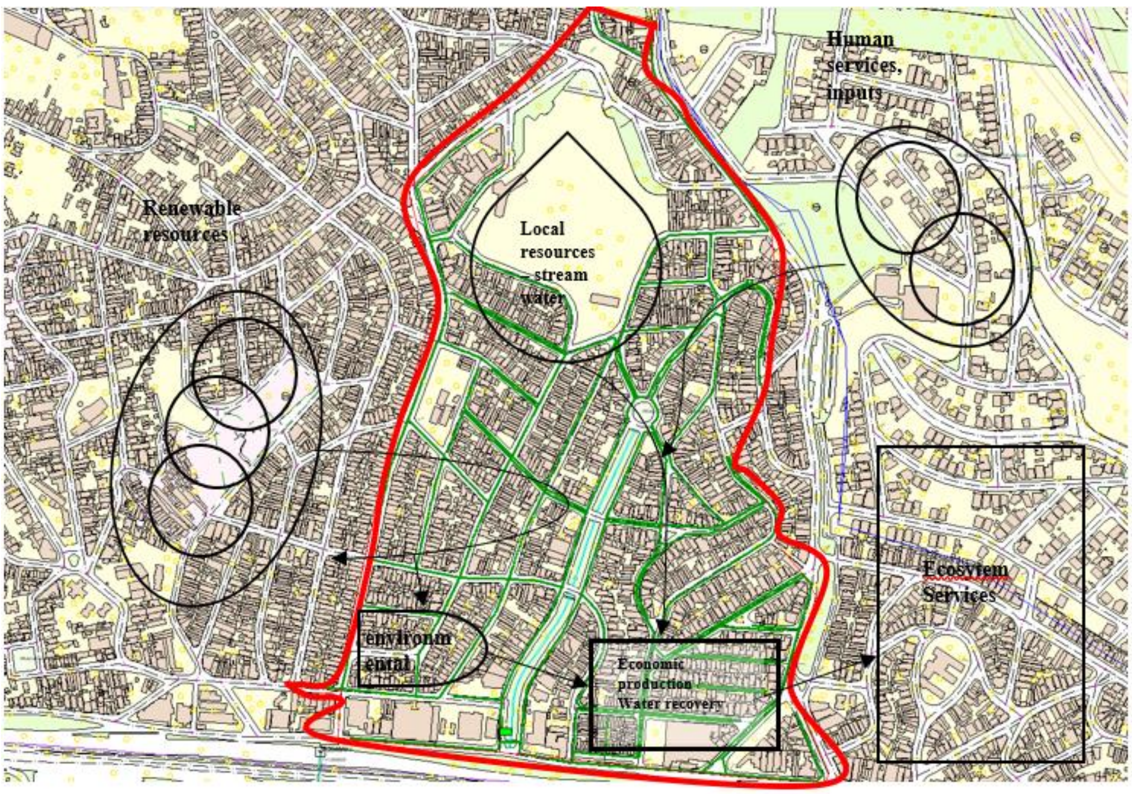
The biochemical oxygen demand (BOD) data, which indicate improvements in water quality, were collected from analyses conducted by the sanitation company of São Paulo, Brazil. Streams are classified as unpolluted when the BOD value is equal to or less than 30 mg/L (Ratnayaka et al., 2009). This threshold is critical for assessing the effectiveness of the depollution efforts and ensuring that the stream meets the necessary environmental quality standards).

Rainfall data used in the emergy equations were sourced from the Brazilian National Institute of Meteorology (INMET), which provides monthly rainfall information nationwide (INMET, 2022). Solar energy data for Brazil were obtained from the National Institute for Space Research (INPE), responsible for measuring and disseminating solar energy results (Pereira et al., 2017). This comprehensive data collection is vital for accurately applying emergy assessment in evaluating the sustainability of the revitalization process.

Economic values associated with the stream's revitalization were gathered from the São Paulo sanitation company (SABESP), which manages sewage removal in the area (SABESP, 2011). Additionally, costs related to maintaining and clearing garbage from the stream banks were obtained from the municipal government of São Paulo (SABESP, 2011).

Figure 3

Emergy diagram of the Charles de Gaulle Stream basin



Data analysis procedure

The research strategy was based on theoretical propositions, leading to a case study that involved data selection, organization, and description. Identifying the data used in the assessment enhances understanding for all stakeholders (Yin, 2010). The exploratory research outlined in section 2.2.1 aligns with the procedure proposed by Flausino et al. (2023), highlighting the importance of the chosen parameters in analyzing the Charles de Gaulle stream. This correlation emphasizes the comprehensive nature of the emergy assessment and its relevance to theoretical and practical applications in urban river revitalization.

Results

Based on the emergy diagram of the stream presented in Figure 1 and the procedural framework illustrated in Figure 2, the quantities of equivalent emergy values are compiled in Table 3. This table categorizes the input and output flows of the socioeconomic and natural systems for the year 2020 into three distinct groups: renewable resources, non-renewable resources, and purchased resources (including construction and maintenance costs). These classifications are in good agreement with the transformities defined by Odum (1996), ensuring consistency and rigor in the calculations.

The results presented in Table 1 indicate that the volume of rainfall significantly impacts the emergy calculations within the urban stream system, with a recorded value of 1.17E+14, highlighting renewable resources (R) as a critical factor in the calculation of transformities and emergy analysis (Chen et al., 2009).

Furthermore, the assessment of emergies calculated for non-renewable resources (N) reveals the influence of biochemical oxygen demand (BOD) on this indicator. Specifically, the BOD levels measured prior to depollution were 167 mg/L, while post-depollution measurements dropped to 30 mg/L (SABESP, 2011). This substantial reduction in BOD underscores the effectiveness of the depollution process.

The emergy analysis demonstrates an improvement in the process, as indicated by the emergy values calculated for the water quality. The emergy associated with depolluted water is significantly higher (2.55E+05 J) compared to that of polluted water (4.10E+04 J), reflecting the enhanced energy incorporation achieved through the depollution efforts. This finding emphasizes the positive outcomes of the revitalization process on water quality and ecosystem health.

The economic flow (F) utilized in the emergy assessment of this study reveals that expenditures associated with the construction of sewage networks (1.13E+10 J) and the maintenance of stream banks (3.49E+11 J) significantly contribute to the overall resource flows allocated for the revitalization of the studied stream. These economic factors have a direct impact on the formulation of the proposed emergy indicators, which are essential for analyzing sustainability in the depollution process of the urban stream.

Charles de Gaulle Stream emergy calculations

This study considers solar energy (Es), rainfall energy (Ec), and the energy associated with polluted water (Eap) as parameters for renewable and non-renewable natural resources. Solar energy (Es) and rainfall energy (Ec) are classified as renewable resources due to their continuous availability and role in the natural hydrological cycle. In contrast, the energy of polluted water (Eap) is regarded as a non-renewable resource, as its degraded quality indicates a loss of potential ecological benefits, necessitating remediation efforts to restore its integrity.

Emergy indicators

The transformities needed to develop the emergy calculations are presented in Table 1. The renewable resources (I) used in the analysis were sunlight (Sun energy = 1.45E+04 J/year) and rain (Rain energy = 6.41E+09 J/year), the renewable emergy was considered as 1.14E+14 sej/year. For the calculations performed, the non-renewable resource (N) adopted in this work is the water from the polluted stream, with the water volume and quality measured in BOD (Biochemical oxygen demand) in the polluted stream = 1.58E+16 J/year. After the depollution process, the value of (N) becomes 4.84E+16 J/year. The financial resources (F) adopted for the emergy assessment derive from the costs with sewage system implantation 1.13E+10 J/year and the costs related to the maintenance of the stream banks and in emergy represent 3.49E+11.

The transformities necessary for developing the emergy calculations are summarized in Table 1. The renewable resources utilized in the analysis include sunlight, with an energy value of and rainfall, valued at 6.41 E+9 J/year. The total renewable emergy was calculated as 1.14 E+14 sej/year. For the non-renewable resource (N) in this study, the energy associated with the polluted stream water was determined, with a measured BOD indicating a value of 1.58 E+16 J/year. After the depollution process, the emergy value for the non-renewable resource increases to 4.84 E+16 J/year. Financial resources (F) considered for the emergy assessment include the costs associated with the implementation of the sewage system, calculated at 1.13 E+10 J/year, and the maintenance costs for the stream banks, represented as 3.49 E+11 J/year. These values provide a comprehensive understanding of the emergy dynamics in the urban stream revitalization process, highlighting both the ecological and economic dimensions.

The emergy indicators proposed for assessing the urban stream depollution process were calculated as detailed in Section 4.1. The resulting indicators demonstrate a significant improvement in the depollution of the urban stream, along with a reduction in the operational costs associated with the process. Furthermore, these indicators highlight the enhancement of ecosystem services in the region surrounding the studied stream.

The application of the emergy assessment procedure significantly contributed to the enhancement of urban river depollution, as illustrated in Table 1. The analysis of indicators before and after the depollution process reveals positive outcomes. Notably, the transformity (TR) value calculated prior to the depollution of the stream is higher (3.86E+11 sej) than that observed after revitalization (1.73E+11 sej). This result indicates an improvement in process efficiency, evidenced by the reduction in emergy utilized within the system (Pan et al., 2020

Table 1

Charles de Gaulle stream emergy parameters

Code	Item	Value (unit/year)	Unit	UEV (sej/unit)	Emergy (sej/year)
Natural resources (I)					
R1	Sun	1.45E+04	J	1.00E+00	1.45E+04
R2	Rain	6.41E+09	J	1.82E+04	1.17E+14
Nonrenewable resources (N)					
N	Stream water with sewage	3.86E+11	J	4.10E+04	1.58E+16
N	Stream water without sewage	1.90E+11	J	2.55E+05	4.84E+16
Feedback from the economy (F)					
S1	Costs with sewage networks	2.82E+03	U$	4.00E+06	1.13E+10
S2	Margin maintenance costs	8.72E+04	U$	4.00E+06	3.49E+11
Total emergy (Y)					
Y	Dirty stream total emergy				1.59E+16
Y	Cleaner stream total emergy				4.85E+16
Product energy (Ep) and transformity (Tr)					
Ep	Depolluted water	1.73E+11	J	2.80E+05 sej/J	
Result withot DBO change					
Ep	Polluted water	3.86E+11	J	4.13E+04 sej/J	

The calculated renewability index (R) demonstrates a significant increase over the studied period, rising from 4.16E+08 before depollution to 2.82E+09 after depollution. These results indicate that revitalization enhances the sustainability of the system, as evidenced by the increase in renewability over time (Odum, 1996). Furthermore, the emergy yield index (EYR) assessment yields a value of 4.43E+04 sej prior to depollution, which increases to 1.35E+05 sej following the process. This increase signifies that society derives greater benefits from the revitalization, thereby rendering the effective use of resources economically feasible (Sun et al., 2019), as detailed in Table 2. The analysis of stress associated with the use of renewable resources, specifically stream water, is quantified using the environmental load rate (ELR). The results obtained from the assessment of the stream depollution process indicate a significant reduction in environmental stress, with values of 7.39E-03 sej before depollution and 2.42E-03 sej following the revitalization. This reduction underscores the positive impact of the depollution efforts on the health of the water body (Su et al., 2013).

The emergy investment index (EIR) assessed during the depollution of the studied stream reveals a notable decrease in the intensity of emergy associated with the process. Specifically, the EIR decreased from 2.28E-05 sej prior to revitalization to 7.44E-06 sej following the revitalization efforts. These results indicate that the depollution process is making a positive contribution to environmental sustainability.

Table 2

Emergy indicators of the Charles de Gaulle stream

Indicator	Equation	Unit	Polluted result	Unpolluted result
Transformity (*Tr*)	Equation 7	sej/J	3.86E+11	1.73E+11
Renovability (%R)	Equation 8	%	0.74%	32.86%
Emergy Yield ratio (*EYR*)	Equation 9	-	4.43E+04	1.35E+05
Environmental load ratio (*ELR*)	Equation 10	-	7.39E-03	2.42E-03
Emergy investment ratio (*EIR*)	Equation 11	-	2.28E-05	7.44E-06
Emergy sustainability index (*SI*)	Equation 12	-	5.99E+06	5.57E+07
Emergy exchange ratio (*EER*)	Equation 13	sej/$	4.97E+15	4.62E+16

The results of the emergy assessment conducted in the Charles de Gaulle stream basin indicate that the investments made have significantly contributed to the site's sustainability. Prior to the depollution process, the environmental sustainability index (ESI) was measured at 5.99E+06 sej. Following the investments, the ESI increased to 5.57E+07 sej, demonstrating a substantial enhancement in local sustainability. This positive impact underscores the effectiveness of the investments in facilitating the depollution process.

The calculations conducted to determine the exchange ratio in emergy (EER) demonstrate the efficient utilization of resources allocated for the stream's depollution process. Initially, the EER was recorded at 4.97E+15 sej/$. After the improvements, this value increased to 2.73E+06 sej/$, indicating a more effective utilization of resources without exacerbating stress on the aquatic ecosystem. This analysis underscores the positive impact of the revitalization efforts on resource efficiency and environmental sustainability (Wu et al., 2019).

Emergy assessment and ecosystem services

The analysis of regulatory services using emergy indicators enhances the sustainability evaluation of the urban river depollution process by clarifying the direct environmental impacts in the Charles de Gaulle stream basin. The focus on improving water quality while mitigating pollution and sediment accumulation helps reduce the risk of flooding (Pan et al., 2020). Additionally, improvements in water quality and emergy values related to regulatory ecosystem services positively affect air quality, oxygen production, and soil conservation, thereby preventing erosion.

Supporting ecosystem services derived from the emergy assessment indicate that enhanced water quality and emergy increase due to revitalization significantly regulate pest populations, protect against solar UV radiation, and preserve biodiversity and genetic heritage (Millennium Ecosystem Assessment, 2005). These enhancements are crucial for maintaining ecological balance and ecosystem resilience.

Results in Table 3, calculated using Equations 14 and 15, illustrate a significant improvement in ecosystem service provision due to the depollution of the Charles de Gaulle stream. These findings highlight the positive impact of revitalization efforts on the stream's ecological health and the benefits to the surrounding community.

Table 3

Ecosystem Services

Stream condition	Equation	ES support (sej)	ES regulation (sej)
Clean Stream	Equation 14	2.62E+10	5.74E+12
Polluted Stream	Equation 15	4.21E+09	4.00E+12

Sensitivity Analysis of Emergetic Indicators

The sensitivity analysis significantly improved the evaluation of the stream depollution process's sustainability by identifying critical points for achieving sustainability. This approach shows that emergy theory enables a comprehensive analysis of each action taken and assists decision-makers in optimizing resource allocation for revitalization efforts (Oliveira Neto et al., 2017). In this study, sensitivity analysis involved gradually varying emergy parameters, directly influencing the emergy indicators used to assess sustainability (Oliveira Neto et al., 2017).

The data in Figures 4, 5, 6, and 7 were normalized based on their attributes (see Tables 2 and 3) using a database equation, allowing values to range from 0 to 1 (Equation 5).

$$X_{\text{norm}} = \frac{(x_i - x_{min})}{x_{max} - x_{min}}$$

Figure 4 illustrates the evolution of renewability and emergy output ratio indicators, while also depicting a decline in transformability alongside an increase in total emergy. This trend indicates an improvement in sustainability, as evidenced by the reduced consumption of useful energy within the system. This highlights that the environment requires fewer resources to sustain its quality.

Figure 4

Sensitivity analysis of emergy, transformability, emergy yield ratio and renewability.

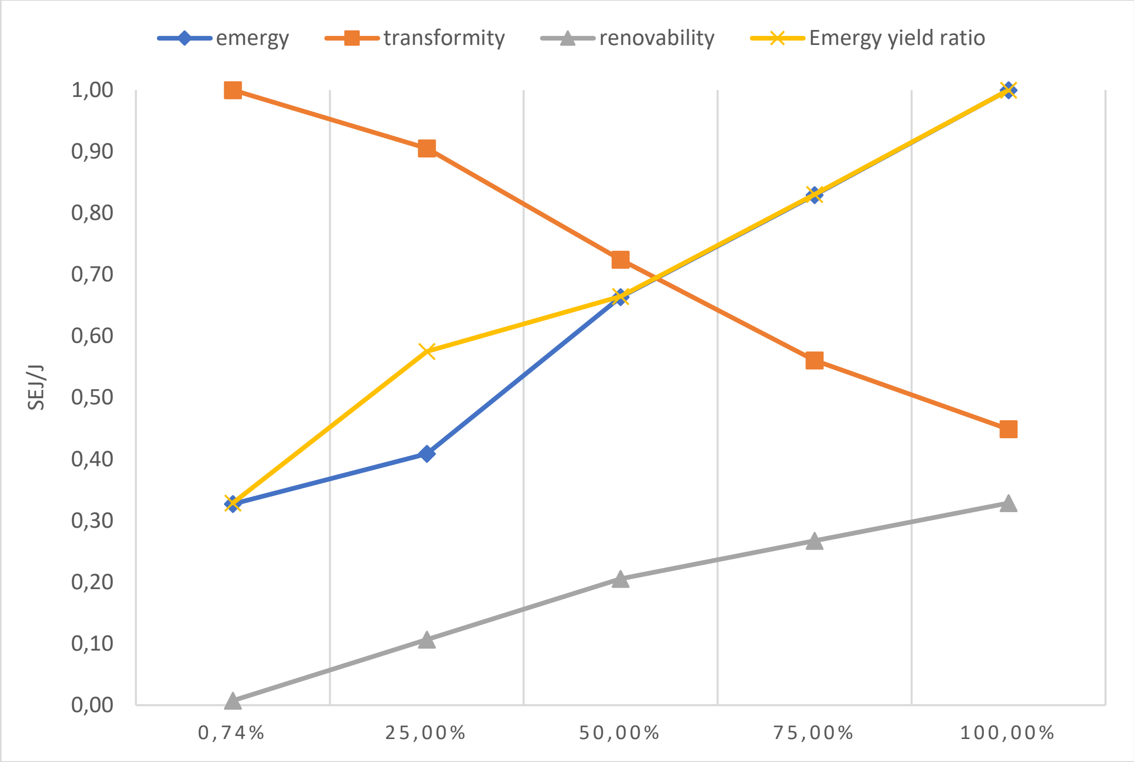


Figure 5

Sensitivity analysis of emergy, Environmental Charge Rate, Emery Investment Ratio, Environmental Sustainability Index and Emery Exchange Ratio

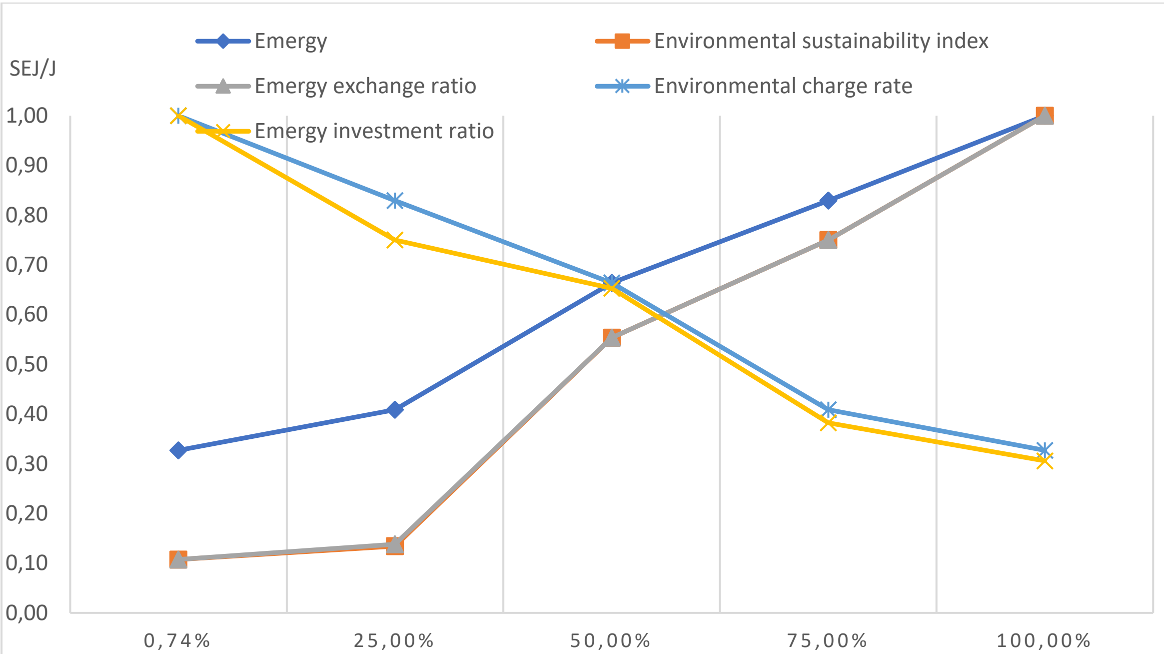


Figure 5 illustrates the relationships between emergy indicators that exhibit a decline—specifically, the Environmental Exchange Rate and the Emergy Investment Ratio—and those that demonstrate an increase, such as the Environmental Sustainability Index and the Emergy Exchange Ratio. The analysis of this graph indicates an overall increase in emergy within the system as a result of the actions taken for the depollution of the stream. Notably, this trend reflects a reduction in environmental stress, characterized by decreased useful energy consumption and diminished biochemical oxygen demand (BOD) required for site restoration. This improvement is further supported by enhanced local sustainability and a more favorable emergy exchange index associated with the resources expended.

The ecosystem services quantified through the emergy assessment conducted in this study are depicted in Figure 6, which illustrates the progression in the provision of regulatory and supporting ecosystem services. The graph highlights a decline in the transformational aspects of the studied system, indicating that with the enhancement of water quality in the stream, there is a corresponding increase in sustainability. As a result, the emergy indicators demonstrate growth, while the energy consumption within the system is notably reduced. This reflects a positive trajectory towards improved ecological health and resource efficiency, underscoring the beneficial impact of the revitalization efforts

Figure 6

Sensitivity analysis of Ecosystem Services and Transformity

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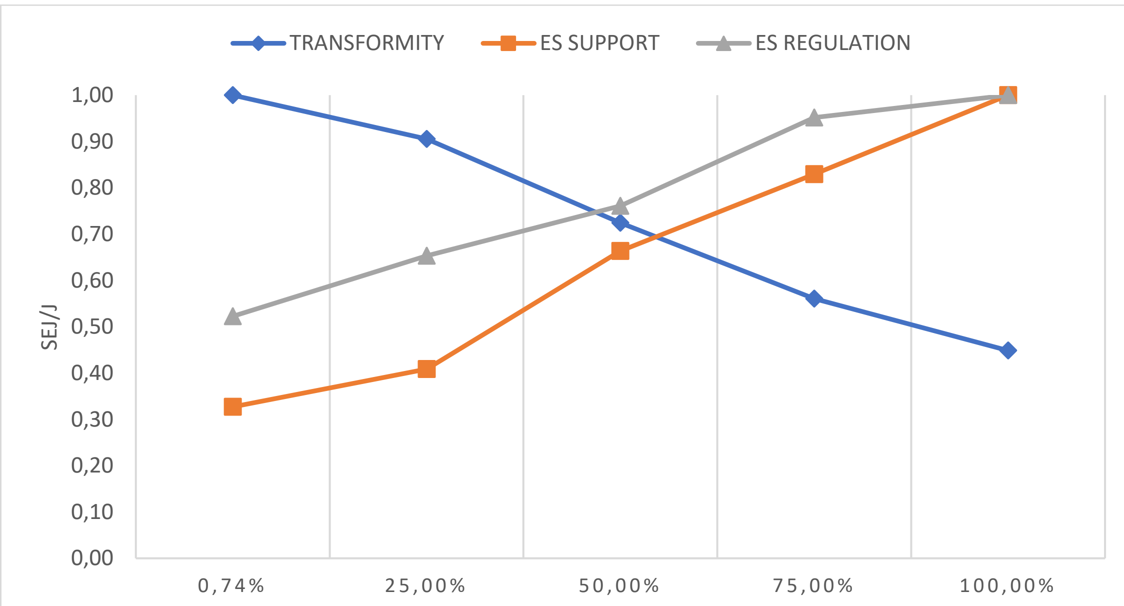

Discussion

The findings presented here illustrate the emergy results aimed at enhancing the depollution process of the Charles de Gaulle stream. It is important to acknowledge that various approaches exist within the scientific literature regarding the application of emergy in water-related issues. For instance, Chen et al. (2009) focus on the valuation of rivers for water supply, while Wu et al. (2009, 2019) explore environmental aspects within river basins. However, this study offers a significant contribution by applying emergy theory in a novel context, specifically targeting the depollution of urban streams. This innovative approach not only expands the applicability of emergy assessments but also enhances our understanding of sustainable water management practices in urban environments.

By addressing the research question this study aims to answer, namely, identifying the feasibility of applying emergy indicators in urban river decontamination processes. This innovative approach not only expands the applicability of emergy assessments but also enhances our understanding of sustainable water management practices in urban environments."

Emergy assessment serves as a valuable tool for developing practical indicators that can be monitored over time. These emergy indicators effectively illustrate the impact of investments made in the revitalization of urban streams. Furthermore, they highlight the relationship between the local population and the improved environment, emphasizing the significance of ecosystem services that are perceptible to the community. This includes both regulatory services, which manage environmental quality, and supporting services that maintain the ecological balance. By demonstrating these connections, emergy assessment not only aids in evaluating the effectiveness of revitalization efforts but also fosters community engagement and awareness regarding the benefits of a healthier ecosystem.

The development of new tools for improving urban river revitalization processes is connected to societal demands regarding the enhancement of the population's quality of life, as well as the integration of treated water bodies into the community. This is illustrated by Flausino and Gallardo (2021), who presented changes in the perceptions of residents in the Charles de Gaulle stream area regarding the revitalized location.

The emergy assessment contributes to the process of depollution of streams, as found in the application of the Charles de Gaulle stream, Brazil presenting the improvement of efficiency of the revitalization process according to the adopted emergy indicators: Transformity (TR) before the process (3.86E+11 J) and after the revitalization (1.73E+11 J). The renewability index (R) before depollution (4.16E+08 sej) and after depollution (2.82E+09 sej), emergyield index (EYR) before depollution (4.43E+04 sej) and after the process (1.35E+05). Research on the topic indicates that Su, et.al. (2013) used emergy to verify the impact of urban cleaning and population control actions, as well as Zhang, et.al. (2017) proposed the use of emergy for health assessment in water bodies and Pulselli, et.al. (2011) presented the need for emergy assessment in water loss issues, as well as the analysis of the environment in urban regions performed by Lv, et.al. (2020).

However, the cited studies did not present the aforementioned indicators in the specific context of urban river decontamination. The objective of this article is to demonstrate the effectiveness of these indicators in the application of emergy in revitalization processes.

The emergy assessment plays a crucial role in enhancing the depollution processes of streams, as demonstrated in the case of the Charles de Gaulle stream in Brazil. This assessment reveals a significant improvement in the efficiency of the revitalization process, reflected in several emergy indicators. Specifically, the Transformity (TR) decreased from 3.86E+11 J before the revitalization process to 1.73E+11 J afterward. Additionally, the Renewability Index (R) showed substantial growth, increasing from 4.16E+08 sej prior to depollution to 2.82E+09 sej post-depollution. Similarly, the Emergy Yield Ratio (EYR) improved from 4.43E+04 sej before the intervention to 1.35E+05 after the revitalization process.

Further research in this area underscores the utility of emergy assessments. For instance, Su et al. (2013) employed emergy to evaluate the effects of urban cleaning and population control initiatives. Similarly, Zhang et al. (2017) advocated for the application of emergy in health assessments of water bodies, while Pulselli et al. (2011) highlighted the critical need for emergy assessments to address issues related to water loss. Additionally, Lv et al. (2020) conducted analyses of environmental conditions in urban areas using emergy frameworks. Collectively, these studies illustrate the significant potential of emergy assessment in promoting sustainable management practices for urban water systems.

The enhancement in the evaluation of investments related to the depollution process of the Charles de Gaulle stream in Brazil was effectively demonstrated through the emergy assessment conducted in this study. The results indicate a substantial improvement in the Environmental Sustainability Index (ESI), which increased from 5.99E+06 sej before the depollution process to 5.57E+07 sej afterward, reflecting a notable enhancement in local sustainability. Furthermore, the analysis of the Emergy Exchange Ratio (EER) highlights the efficiency of the resources allocated for the revitalization process. Initially measured at 4.97E+15 sej/$, the EER improved significantly to 2.73E+06 sej/$ following the revitalization. This decline in the EER indicates a more efficient use of emergy resources, demonstrating the effectiveness of the investments made in the stream's depollution efforts.

The application of sensitivity analysis in this study underscores the effectiveness of emergy indicators proposed by Odum (1996) in enhancing sustainability during the depollution process of the stream. Additionally, the integrated analysis of these indicators reveals the detrimental effects of inadequate urbanization on the environment, as noted by Zhong et al. (2018).

The graphical representation of emergy indicators, alongside their relationship with supporting and regulating ecosystem services, provides a systematic framework for decision-makers to evaluate the revitalization process. This approach highlights the positive impact that efficient emergy utilization has on restoring urban rivers, aligning with the findings of Pan et al. (2020).

Consequently, stakeholders responsible for implementing revitalization initiatives can extend their monitoring beyond mere water quality assessments. They can utilize comprehensive indicators that facilitate a thorough evaluation of the entire system and the investments made, thereby ensuring a more holistic approach to environmental management.

The results of the sensitivity analysis facilitate the identification of broader aspects embedded within the depollution process, particularly the tangible outcomes of investments correlated with environmental improvement. From a theoretical standpoint, the concurrent application of sensitivity analysis and emergy indicator calculations offers a novel perspective on utilizing emergy as an evaluative method for urban river depollution processes, as outlined in the procedure proposed by Flausino et al. (2023). This innovative approach not only enhances the understanding of the interrelationships between investments and environmental outcomes but also establishes a robust framework for assessing the sustainability of revitalization efforts in urban waterways.

Conclusion

Based on the emergy assessment applied to the depollution of the Charles de Gaulle stream, several key insights were identified regarding the optimization of the revitalization process, the capacity for cost reduction, and the assessment of sustainability at the site. The main conclusions are as follows:

(1) Integration of Ecological and Economic Systems:

The emergy assessment highlights the interconnectedness of ecological and economic systems. By evaluating both renewable and non-renewable resources, the study enhances human resource allocation while facilitating depollution. This approach offers a framework for future research in urban water management, optimizing revitalization processes.

(2) Through the examination of water quality enhancement in the studied stream, the positive effects and influences on the economic, social, and ecological environments can be articulated comprehensively. The findings indicate that the advantages of this integrated analysis encompass:

(a) Enhancements in the management of resources utilized for stream depollution, whereby the emergy assessment establishes conditions for the economic viability of the process and facilitates the ongoing monitoring of revitalization efforts through the developed indicators.
(b) The emergetic indicators derived from Biochemical Oxygen Demand (BOD) indices (water quality) enable a comprehensive evaluation of the depollution process, encompassing all aspects associated with the stream. This contributes to the development of indicators aimed at minimizing stress on the water body within a fully urbanized environment.
(c) Improvements in the relationship between the local population and the revitalized area. The restored environment fosters interaction between

humans and nature, and this dynamic can be effectively monitored through the ecosystem service indicators established in the study.

(3) The emergy assessment model, enhanced by the sensitivity analysis in this study, enables a thorough examination of the factors affecting urban river depollution. By converting various units—such as monetary values ($), volume ($m^3$), and Biochemical Oxygen Demand (BOD) (mg/L)—into emergy (sej), the model calculates indicators that monitor the depollution process's progression. This unified approach provides a comprehensive evaluation of the interconnected elements of urban river revitalization, facilitating the analysis of ecological, economic, and social dimensions concurrently.

(4) The case study of the Charles de Gaulle stream shows that continuous improvements and the incorporation of new control parameters can sustainably manage the costs of depollution and water quality maintenance. Additionally, using emergy indicators for monitoring effectively captures the dynamics of ecosystem services, offering valuable insights into the ecological and economic viability of revitalization efforts.

(5) The application of emergy assessment in analyzing the depollution process of an urban stream, complemented by graphical presentations derived from sensitivity analysis, illustrates the significant impact of the calculated emergies on the sustainability of revitalization efforts. In essence, the utilization of emergy indicators facilitates effective process control, showcases the outcomes of depollution through the lens of sustainability, and contributes to the advancement of emergy theory within a relatively unexplored area of scientific inquiry.

The main limitation of this study lies in its nature as a single exploratory investigation, which inherently lacks generalization. However, as the inaugural study on this topic, it offers a significant contribution to the field. In this sense, future research is encouraged to apply the emergy calculations alongside the identified indicators to other case studies, thereby facilitating comparative analyses that can enhance the understanding and applicability of emergy assessments in various contexts.

References

Anin, D. O., & Banahene, P. (2021). Urbanization and stream ecosystems: The role of flow hydraulics towards an improved understanding in addressing urban stream degradation. *Environmental Reviews, 29*(3), 401–414. https://doi.org/10.1139/er-2020-0063

Brown, M. T., & Ulgiati, S. (2002). Emergy evaluations and environmental loading of electricity production systems. *Journal of Cleaner Production, 10*(4), 321-334. https://doi.org/10.1016/S0959-6526(01)00043-9

Chen, D., Chen, J., Luo, Z., & Lv, Z. (2009). Emergy evaluation of the natural value of water resources in Chinese rivers. *Environmental Management.* DOI:10.1007/s00267-009-9320-x

Di, D., Wu, Z., Guo, X., Lv, C., & Wang, H. (2019). . alue stream analysis and emergy evaluation of the water resource eco-economic system in the Yellow River Basin. *Water, 11*(4), 710. *Water* **2019**, *11*(4), 710; **https://doi.org/10.3390/w11040710**

Flausino, F. R., & Gallardo, A. L. C. F. (2021). Oferta de serviços ecossistêmicos culturais na despoluição de rios urbanos em São Paulo. *Revista Brasileira de Gestão Urbana, 13*, e20200155. https://doi.org/10.1590/2175-3369.013.e20200155

Flausino, F. R., Oliveira Neto, G. C., & Librantz, A. F. H. (2023). Procedure for emergetic assessment in urban river de-pollution. *Water Science and Technology, 88*(8), 2068. https://doi.org/10.2166/wst.2023.318

INMET - Instituto Nacional de Meteorologia. Banco de Dados Meteorológicos para Ensino e Pesquisa - BDMEP. Brasília, DF, Brasil. Disponível em:

http://www.inmet.gov.br https://portal.inmet.gov.br/dadoshistoricos. Acesso em 29 de julho de 2022.

Li, H., Lv, C., Ling, M., Gu, C., Li, Y., Wu, Z., & Yan, D. (2021). Emergy analysis and ecological spillover as tools to quantify ecological compensation in Xuchang City, Qingyi River Basin, China. *Water, 13*(4), 414. DOI:10.3390/w13040414

Liu, W., Zhan, J., Zhao, F., Yan, H., Zhang, F., & Wei, X. (2019). Impacts of urbanization-induced land-use changes on ecosystem services: A case study of the Pearl River Delta Metropolitan Region, China. *Ecological Indicators, 98*, 228-238. DOI 10.1016/j.ecolind.2018.10.054

Lv, C., Ling, M., Guo, X., Di, D., & Zhou, H. (2018). Evaluation method of water resource contribution rate in terms of emergy. In *Proceedings of the International Workshop on Environmental Management, Science and Engineering (IWEMSE 2018)* (pp. 34-41). https://www.scitepress.org/Papers/2018/75568/75568.pdf

Lv, H., Guan, X., & Meng, Y. (2020). Study on economic value of urban land resources based on emergy and econometric theories. *Environment, Development and Sustainability, 23*, 1019–1042. DOI: 10.1007/s10668-019-00573-4

Millennium Ecosystem Assessment (MEA). (2005). *Ecosystems and human well-being: Synthesis*. Washington, DC. ISBN 1-59726-040-1

Nahiduzzaman, K. M., & Sadiq, R. (2023). Planejamento e gestão de água e infraestrutura hídrica sob estresse climático. *Environmental Reviews, 31*(1), 1-3. https://doi.org/10.1139/er-2022-0127

Odum,H.T.(1996).*Environmental accounting, EMERGY, and decision making*. John Wiley & Sons. ISBN: 978-0-471-11442-0

Odum,H.T.,&Odum,E.C.(2001).*Prosperous way down: Principles and policies* (1st ed.). Brasil: Editora Vozes. ISBN: 978-0-87081-908-7

Oliveira Neto, G. C., Oliveira, J. C., & Librantz, A. F. H. Selection of logistic service providers for the transportation of refrigerated goods. *Production Planning & Control: The Management of Operations.* https://doi.org/10.1080/09537287.2017.1319986

Pan, Y., Zhang, B., Wu, Y., & Tian, Y. (2020). Sustainability assessment of urban ecological-economic systems based on emergy analysis: A case study in Simao, China. *Ecological Indicators, 121,* 107157. https://doi.org/[inserir DOI]

Pereira, E. B., Martins, F. R., Gonçalves, A. R., Costa, R. S., Lima, F. L., Ruther, R., Abreu, S. L., Tiempolo, G. M., Pereira, S. V., & Souza, J. G. (2017). *Atlas brasileiro de energia solar* (2nd ed.). São José dos Campos: INPE. http://doi.org/10.34024/978851700089

Pulselli, F. M., Patrizi, N., & Focardi, S. (2011). Calculation of the unit emergy value of water in an Italian watershed. *Ecological Modelling, 222*(16), 2929-2938. DOI: 10.1016/j.ecolmodel.2011.04.021

Ratnayaka, D. D., Brandt, M. J., & Johnson, K. M. (2009). Chemistry, microbiology, and biology of water. In *Water supply* (pp. 195–266). https://doi.org/10.1016/b978-0-7506-6843-9.00014-7

SABESP (2011).*Programa Córrego Limpo - 100 Córregos 2007 – 2010*. Companhia de Saneamento Básico do Estado de São Paulo. São Paulo, SP, Brasil. pp. 01–151.

Song, F., Su, F., Zhu, D., Li, L., Li, H., & Sun, D. (2019). Evaluation and driving factors of sustainable development of the wetland ecosystem in Northeast China: An emergy approach. *Journal of Cleaner Production, 248*, 119236. DOI:10.1016/j.jclepro.2019.119236

Song, F., Su, F., Mi, C., & Sun, D. (2021). Analysis of driving forces on wetland ecosystem services value change: A case in Northeast China. *Science of The Total Environment, 751,* 141778. https://doi.org/10.1016/j.scitotenv.2020.141778

Su, M., Fath, B. D., Yang, Z., Chen, B., & Liu, G. (2013). Ecosystem health pattern analysis of urban clusters based on emergy synthesis: Results and implication for management. *Energy Policy, 59,* 600–613. https://doi.org/10.1016/j.scitotenv.2020.141778

Sun, J., Yuan, X., Liu, G., & Tian, K. (2019). Emergy and eco-exergy evaluation of wetland restoration based on the construction of a wetland landscape in the northwest Yunnan Plateau, China. *Journal of Environmental Management, 252,* 109499. DOI: 10.1016/j.jenvman.2019.109499

Sun, J., Yuan, X., Liu, H., & Liu, G. (2021). Emergy and eco-exergy evaluation of wetland reconstruction based on ecological engineering approaches in the Three Gorges Reservoir, China. *Ecological Indicators, 122,* 107278. https://doi.org/10.1016/j.ecolind.2020.107278

Wang, C., Li, X., Yu, H., & Wang, Y. (2019). Tracing the spatial variation and value change of ecosystem services in the Yellow River Delta, China. *Ecological Indicators, 96,* 270–277. https://doi.org/10.1016/j.ecolind.2018.09.015

Wu, Z, Di, D, Wang, H*, Wu, M, He, C. Analysis and emergy assessment of the eco-environmental benefits of rivers. Ecological Indicators, 2019, 106: 105472. https://doi.org/10.1016/j.ecolind.2019.105472

Yin, R Y. (2010). *Estudo de caso – planejamento e métodos* (4th ed.). Porto Alegre: Bookman. ISBN-10, 8577806553

Zeng, R., Zhao, Y., & Yang, Z. (2010). Emergy-based health assessment of Baiyangdian watershed ecosystem in temporal and spatial scales. *Procedia Environmental Sciences, 2,* 359–371. DOI:10.1016/j.proenv.2010.10.041

Zhan, J., Zhang, F., Chu, X., Liu, W., & Zhang, Y. (2018). Ecosystem services assessment based on emergy accounting in Chongming Island, Eastern China. *Ecological Indicators, 105,* 464-473. DOI:10.1016/j.ecolind.2018.04.015

Zhang, J., Fu, Y. C., Shi, W. L., & Guo, W. X. (2017). A method for estimating watershed restoration feasibility under different treatment levels. *Water Science and Technology: Water Supply, 17*(5), 1232–1240. DOI:10.2166/ws.2017.017

Zhong, S., Geng, Y., Kong, H., Liu, B., Tian, X., Chen, W., & Ulgiati, S. (2018). Emergy-based sustainability evaluation of Erhai Lake Basin in China. *Journal of Cleaner Production, 178,* 142–153. DOI:10.1016/j.jclepro.2018.01.019

Appendix A

Systematic review on emergy assessment and water resources

Author	Year	Country	Method	Economic	Society	Environmental	Emergy aplication
Li, et.al. 2021	2021	China	Case Study			changes of big impact on ecological compensation	ES Valuation
Song, et.al. 2021	2021	China	Case Study	Regional economic development and the urbanization rate		Positive effect on improving wetland ESVs	ES Valuation
Wang, et.al. 2019	2019	China	Case Study	Values of soil conservation and maintenance			ES Valuation
Liu, et.al. 2019	2019	China	Experimental model	Importance to the economy and the development.	Facility communication between stakeholders and policy makers		ES Valuation
Zeng, et.al. 2010	2010	China	Experimental model	Continuing increase in economic development requirements			ES Valuation
Sun, et.al. 2021	2021	China	Experimental model			Emergy have been shown to be adequate to assess the effects of the wetland restoration project.	Sustainability and revitalization of wetlands
Song, et.al. 2019	2019	China	Case Study	Externally acquired resources have become the most important part of total emergy used in the study area.		Renewable resources have shown a positive contribution for development of wetlands.	Sustainability and revitalization of wetlands
Sun, et.al. 2019	2019	China	Case Study	The wetland ecosystem after restoration depends mainly on renewable resources from the local environment.		Ecological integrity of wetland ecosystems should be restored as much as possible	Sustainability and revitalization of wetlands
Zhan, et.al. 2018	2018	China	Experimental model	Increased cost of urban land		Changes in land use and land cover and loss of SE	Sustainability and revitalization of wetlands

Author	Year	Country	Method	Economic	Society	Environmental	Emergy aplication
						function and environmental degradation	
Di, et.al. 2019	2019	China	Experimental model		Application of water resources in social life and in the ecological environment maintain the ecological environment	It is necessary to avoid the deterioration of the environment caused by industrial water intrusion.	Valuation of water resources
Lv, et.al. 2018	2018	China	Experimental model			The contribution rate of water resources calculated by the emergy method proved to be useful to assess the real benefits and contributions of water resources	Valuation of water resources
Chen, et.al. 2009	2009	China	Experimental model	Therefore, this method provides new insights into the entire Chinese economy and the value of river water.			Valuation of water resources
Pan, et.al. 2020	2020	China	Case Study		It is imperative to take measures more sustainables through the balance between ecological protection and economic growth.	Enormous contributions from Simão's natural ecosystem to human benefit	Sustainability in urban areas
Su, et.al. 2013	2013	China	Experimental model		Establish appropriate management schemes according to the specific conditions of the urban ecosystem	Reducing dependence on external inputs from energy and materials.	Sustainability in urban areas
Zhang, et.al. 2017	2017	China	Experimental model			Mitigate the ecological damage and providing positive protection actions for assessing the health of the river.	Sustainability and revitalization in watersheds

Author	Year	Country	Method	Economic	Society	Environmental	Emergy aplication
Pulselli, et.al. 2011	2011	Italy	Case Study	The investment analysis showed the water losses that influence the emergy indicators.			Sustainability and revitalization in watersheds
Lv, et.al. 2020	2020	China	Case Study	The result showed that urban land for construction has the highest economic value.		The model can improve the accounting system for the value of urban land resources.	General land use plan
Wu, et.al. 2019	2019	China	Experimental model		Promote the construction of a society that saves water and performs the coordination of sustainable development in economic society	Eco-environmental benefits effectively with the contribution and benefits of river water resources in the ecosystem.	Eco-environmental assessment in rivers
Zhong, et.al. 2018	2018	China	Case Study		Sustainable watershed management considering local realities.		Sustainability in watershed