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A County-Scale Spillover Ecological Value Compensation Standard of Ecological Barrier Area in China: Based on an Extended Emergy Analysis

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Abstract: Ecological compensation (EC) is an important way to solve the imbalance of cross-regional economic development and realize regional coordinated development. How to quantify the standard of EC has become a hot research topic. Firstly, this paper selected the Three Gorges Reservoir Region (TGRR) as the study area, and constructed a cross-regional spillover ecological value measurement model based on the extended emergy analysis. From the perspective of the "ecology–economy–society" complex ecosystem, this paper used emergy to reflect the social, economic, and ecological function and service value of the TGRR, and estimated the ecosystem emergy supply and consumption in the TGRR. Then, comparing the watershed ecosystem emergy supply and consumption, we can judge the status of the ecological surplus and deficit of the TGRR, and transfer the spillover ecological emergy to spillover ecological value (SEV) by using the emergy currency ratio (ECR). Finally, combined with different actual payment level coefficient, we can obtain a relatively objective and robust compensation standard. The results show that the SEV of the TGRR in 2016 is 2.70×10^{11} USD, which indicates that the TGRR is in the state of ecological surplus. The TGRR should get EC about 2.85×10^{11} USD according to the ECR. Based on the research results, it is suggested to expand the transfer payment to the TGRR. At the same time, it is suggested to formulate different ecological compensation standard (ECS) according to regional differences, which has important practical significance to establish the allocation standard of EC, and provides a typical case basis for other large reservoir areas or typical reservoir areas.

Keywords: Three Gorges Reservoir Region; emergy analysis; spillover ecological value; coordinated development; ecological compensation standard

1. Introduction

As the basis for the sustainable development of human society, natural ecosystems provide vitally important resources and energy for human survival and development. With the rapid expansion of the global economy and population, human activities put increasing pressure on ecosystems over time [1]. Correspondingly, the consumption of resources, products, and energy provided by ecosystems also increased [2]. The over-pressure and over-exploitation of natural resources threaten the ecosystem security, accompanied by a series of problems that seriously threaten the future survival and development of human beings and restrict social and economic development, such as global resource depletion, energy crisis, and ecological environment deterioration [3,4]. To mediate the imbalance and inadequacy between ecological protection and socioeconomic development, various techniques and institutions have been proposed to assure the sustainable use of natural resources and the ecosystem's health [5–7].

As an efficacious economic incentive means to encourage positive externalities, EC has been widespread around the world since the 1950s [8]. The concept of EC is ordinarily used in China, which corresponds to the popular term of payment for ecosystem services (PES) among the international society [9]. It is one of the effective methods to coordinate the contradictory relationship between economic development and environmental protection [10]. To be specific, EC can transform ecological products and ecosystem services with non-marketability and externality into an economic stimulus to increase the environmental protectors' commitment, enhance ecosystem services and compensate for the losses of stakeholders [11]. In contrast to the punitive environmental protection policy and measures such as environmental protection tax and sewage tax, the EC aims to repair and eliminate the negative impact of human economic and social development on the ecosystem, give consideration to fairness and efficiency, alleviate the ecological interest conflict between different regions, and achieve the balance and coordination between regional economic development and ecological protection [12–14].

Currently, many countries worldwide have implemented EC schemes. Developed countries mainly implement the "market-based payment instrument". CostaRica is recognized as a pioneer in formal PES mechanism, setting up a national program in 1997 called Pago Por Servicios Ambientales (PSA), aiming at reversing the severe deforestation [15]. The wetland mitigation bank (WMB) of the United States is the most mature market EC mechanism [16]. The main goal of WMB is to compensate for the impact on nearby wetlands by restoring large scale wetland areas [17]. Under the control of regulators, balance the gains from wetland restoration against the losses from wetland damage through a market of "mitigation credits". Finally, the net loss of wetlands within the service area can be reduced or disappeared [18]. In China, the practice of EC began with forest conservation in the 1980s. In the 21st century, the practice of EC has accelerated development, and the positive progress and preliminary results have been achieved in the fields of forests, grasslands, wetlands, watersheds and water resources, mineral resource development, oceans, and key ecological function zones. The total amount of EC funds arranged by the central government had increased from RMB 2.3 billion in 2001 (USD 1.00 = RMB 8.28 in 2001) to about RMB 78 billion in 2012, a total of about RMB 250 billion (USD 1.00 = RMB 6.30 in 2012). Since 1998, China has successively initiated and implemented major ecological construction projects such as returning farmland to forest, returning grazing land to grassland, and natural forest protection, with a total investment of about RMB 800 billion (USD 1.00 = RMB 6.30 in 2012). The establishment and improvement of EC mechanism, together with ecological construction and comprehensive environmental management, has become an indispensable part of China's ecological protection work. As of 2013, the effective protection area of China's public welfare forests reached 2.36 billion ha, the project of returning farmland to forests had afforested a total of 440 million ha, and the accumulated soil erosion area has been constrained to 55 million ha. Generally, the ecological deterioration has been initially curbed.

Although China's EC has achieved phased results, there are still many problems that cannot be ignored in practice. On the one hand, the scope of EC is not clear. At present, China adopts a government-led EC mechanism, in which the most common method of government support in river basin EC is to establish an EC fund jointly funded by stakeholders [19]. This method can solve the problem of cross-regional EC to some extent, but due to the limitation of administrative region, compensation often occurred at the provincial level or municipal level, which resulted in the lack of more detailed scientific research on the specific scope of EC [20]. Milder et al. pointed out that the existing instances of PES benefiting the poor have been limited mainly to specific localities, small-scale projects, and a handful of broader government programs [21]. On the other hand, the single ECS is mainly based on water quality, carbon storage, or ecosystem service values (ESV) [22–26]. The compensation standard is either too low for the various costs of the conservationist; or too high to increase the government's financial pressure, and stagnate the ecological and environmental protection projects. To date, there is considerable debate regarding the effectiveness of EC programs for alleviating the poverty of protectors and enhancing conservation [27–29]. Analyzing and comparing the existing EC schemes, it can be found that the uncertainty of the scope and standard of EC is the biggest reason for the continuous intensification of conflicts among stakeholders and the difficulty in reaching consensus on compensation cost negotiation [30]. This is also why the central government is still the main payer of EC, although it has been implemented in China for a long time [20]. Therefore, it is urgent to specify the protection costs and economic benefits of ecological protection areas from a more micro administrative regional scale, scientifically determine the cross-regional differentiated ECS. Only after solving these key issues will the ECS become a more scientific and fairer project.

ECS accounting is a core part of the establishment of cross-regional EC mechanism, and also a key link in the implementation of EC mechanism. According to the current research, the ECS was generally calculated according to the ESV, the investment and opportunity costs of conservationist, the profit of ecological beneficiaries, the recovery cost of ecological damage, the public willingness to pay, and willingness to accept [31]. Several methods, such as the contingent valuation method (CVM) [32,33], ecological footprint method [34,35], ESV evaluation method [36–38], carbon stock balance method [22], have been widely used to evaluate ECS. However, these methods lack verification and need to be discussed further. On the one hand, some methods only consider the ecological factors and ignored the economic and social factors. As the formulation of ECS requires comprehensive consideration of factors such as regional economic and social development, environmental resource abundance and distribution, the lack of these relevant factors in the EC mechanism will limit the sustainable development of the ecological environment and hinder the high-quality economic development [39]. Therefore, the ECS should fully consider the ecological, social and economic factors in the formulation, reflecting the differences [40,41]. On the other hand, the ESV evaluation method is vulnerable to market price distortions caused by incomplete market and government intervention, and it is also prone to the problem of repeated estimation. The CVM is easy to produce errors in the process from the implementation of the investigation to the processing of the results.

Emergy analysis is able to improve or make up for the deficiency of the value judgment standard of the above measurement methods. This method was founded by Odum [42], who proposed to convert different masses, different kinds, and incomparable energy in ecosystem into the same standard emergy for comparative analysis by using the law of energy conservation. Since emergy analysis adopts the same emergy standard, the material flow, currency flow, and energy flow in ecosystem are additive and comparable. This analysis method has been widely used in water resources protection and management, comprehensive analysis of ecosystem services, evaluation of urban ecological carrying capacity and sustainable development of regional ecological economy [43–46]. However, few scholars used emergy analysis to study cross-regional differentiated ECS in an ecological barrier area from the perspective of supply and consumption of ecological values. Fu and Miao suggested that based on the perspective of supply and consumption, if the supplying subject of ecological environment can provide the remaining ecological value to other regions after eliminating its own consumption, that is, there is a surplus in a certain area [47]. In other words, the area has a positive spillover ecological value (SEV), which should be compensated, and the SEV is the compensation standard. It is worth noting that the ESV calculated by the existing research using the emergy analysis method is different from the SEV. It measured the total ESV in a region without considering the ecological value of local consumption [48–50].

Thus, this paper proposed a SEV evaluation method at the county level to develop a more reasonable and fairer ECS. Firstly, the SEV model based on extended emergy analysis was built to reflect the regional supply and consumption values. Secondly, from the perspective of "ecology–economy–society" watershed complex ecosystem (Figure 1), the ecological emergy surplus and deficit were determined by comparing regional emergy supply and consumption, and further transferred the spillover ecological emergy to SEV by using the ECR, thus obtaining a relatively objective and robust compensation standard. The results of this study can provide decision support for policy makers on cross-regional EC.

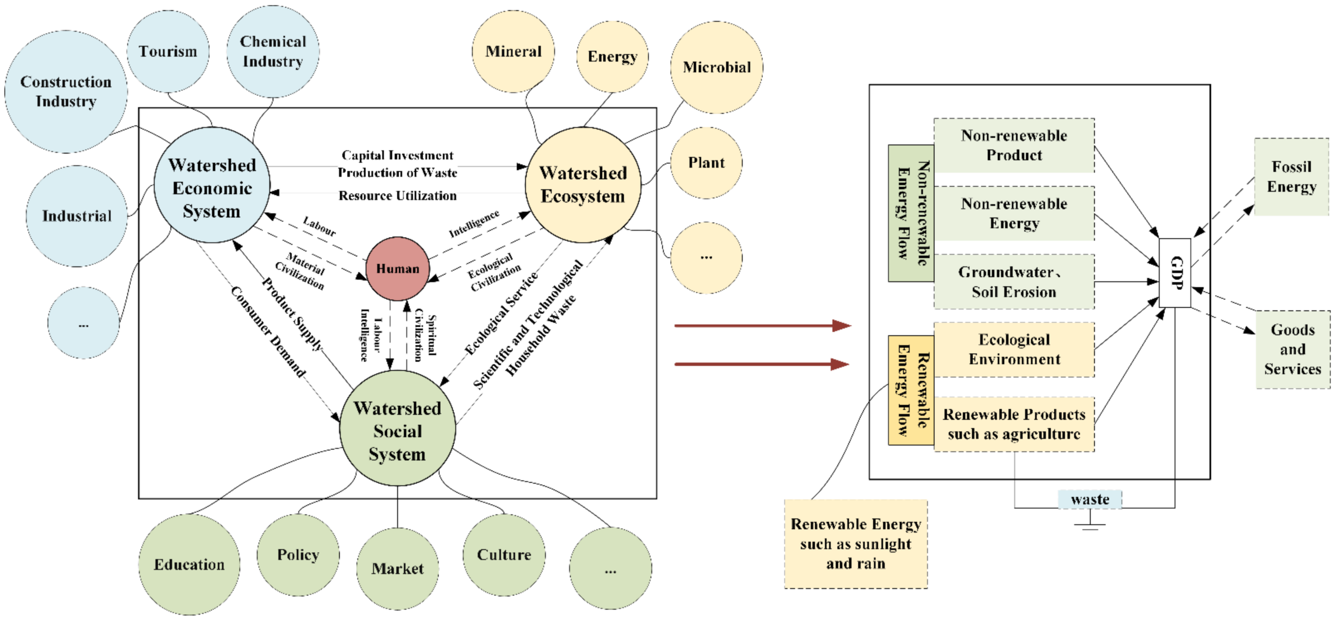

Figure 1. "Ecology–Economy–Society" watershed complex ecosystem and system energy flow diagram.

2. Methodology and Data

2.1. Study Area

The Three Gorges Reservoir Region (TGRR), as affected by the inundation of the Three Gorges Project, which is the biggest project of irrigation works hinge in the world. It is located at the heart of the Yangtze River Basin (East longitude 105°44′–111°39′, North latitude 28°32′–31°44′) with an area of approximately 58,000 km^2 [51]. It has a subtropical humid monsoon climate, and the average annual precipitation is about 1250 mm/year with most precipitation occurring between May and September, the average annual temperature is 15–19 °C [52]. The TGRR has various types of land, with large hills and mountains, small flat area, complex land structure, and obvious vertical differences [53]. Therefore, different regions in the reservoir are marked by distinct economic and social levels, as well as diverse resource and environmental endowments. Based on the particularity of regional development, the TGRR is divided into three regions: the head, the belly, and the tail of the reservoir (Figure 2). The head of the reservoir is the Hubei section of the TGRR, including four districts (counties): Badong County, Xingshan County, Zigui County, and Yiling District; the belly and the tail of the reservoir together form the Chongqing section of the TGRR. Among them, the belly covers 11 districts (counties) including Wushan County, Wuxi County, Fengjie County, Wanzhou District, Kaizhou District, Yunyang County, Zhongxian County, Shizhu County, Fengdu County, Fuling District, and Wulong County. The tail covers 11 districts (counties) including Yuzhong District, Dadukou District, Jiangbei District, Shapingba District, Jiulongpo District, Nan'an District, Beibei District, Yubei District, Banan District, Jiangjin District, and Changshou District.

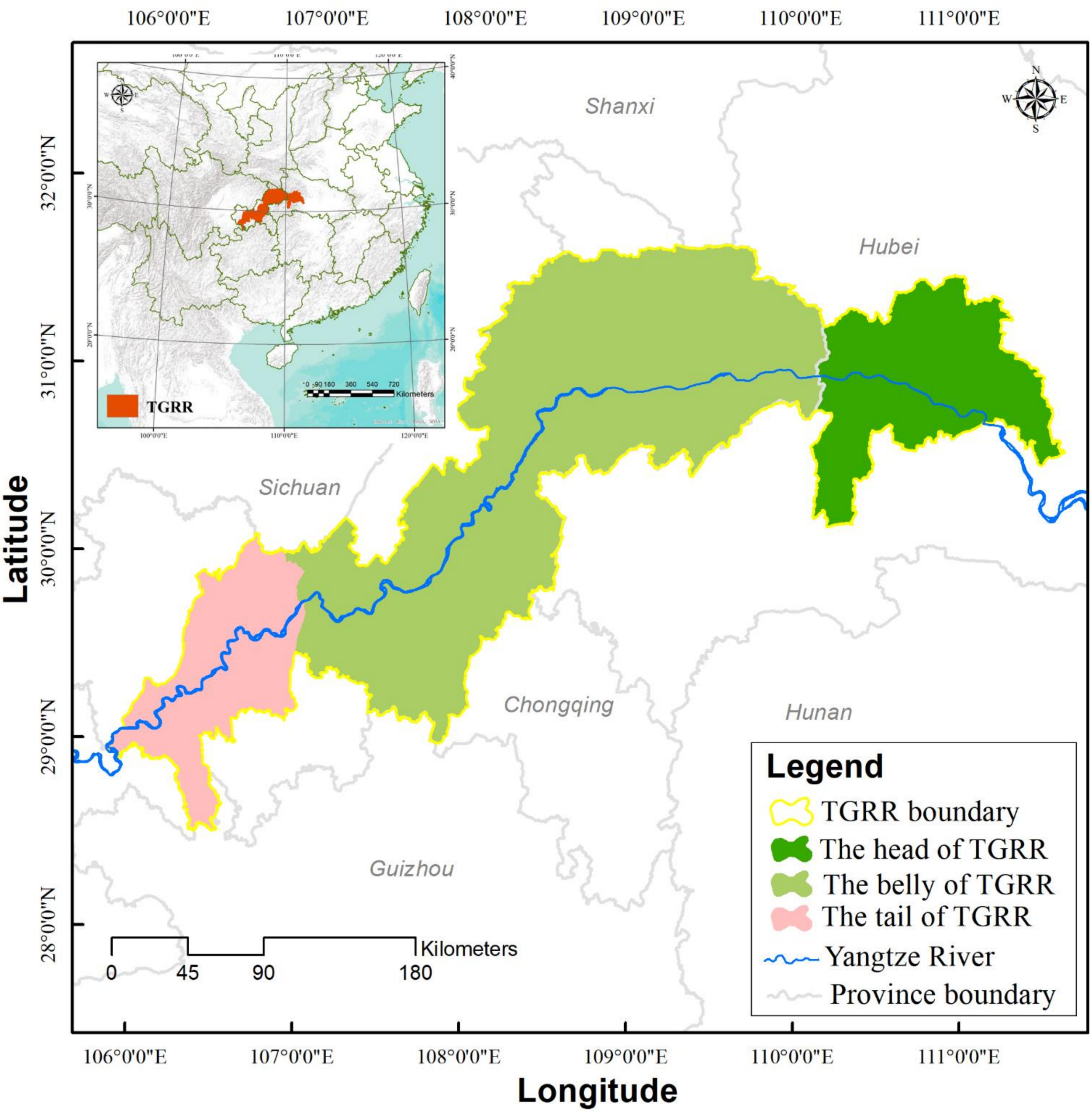

Figure 2. Location of the Three Gorges Reservoir Region (TGRR).

The TGRR is the largest freshwater resource reservoir in China. It controls a drainage area of 1 million km^2, accounting for 56% of the total drainage area. It is a significant ecological barrier in the Yangtze River Basin and one of the China's most important ecological function areas. With the expansion of urbanization and the rapid development of economy and society, the ecological environmental protection work in the Yangtze River Basin has been restricted and hindered by different aspects, and the contradiction between regional economy, society and ecological environment has become increasingly prominent. Whether sustainable development can be smoothly promoted is one of the severe challenges faced by mankind [54]. In order to achieve better environmental rehabilitation and protection, the national government issued a series of regulations, such as Outline of the Development Plan for the Yangtze Economic Belt (2016), Action Plan for the Yangtze River Protection and Restoration Battle (2018), and Guidance on Establishing and Perfecting Long-term Mechanism of Ecological Compensation and Protection in the Yangtze Economic Belt (2018). These regulations cover EC mechanisms, which aim to protect the ecological environment, and take the road of ecological priority and green development [55]. Nevertheless, the EC of the TGRR is still in its infancy, and it needs to be improved. Based on the input–output analysis, this paper examined the logic of the inter-regional emergy in the TGRR. It used an extended emergy model to investigate the ECS, and to explore the inter-regional EC measures in the TGRR.

2.2. Research Framework

EC can be divided into two types: one is punitive EC. It is to charge fees for environmental pollution and resource utilization, which increases the cost of pollution behavior, thereby achieving the purpose of restraining damage to the ecological environment. This method must be supplemented by relevant laws and regulations to achieve effective control, such as environmental protection taxes and pollution discharge fees. The second is to provide incentive compensation for ecological environment protection. Incentive EC is the value compensation for the behavior of protecting the ecological environment, increasing the marginal benefits of the behavior, thereby encouraging people to protect the ecological environment more actively. The ultimate goal is to maintain and improve the carrying capacity of the ecological environment, so that it can provide ecological services for social production and life in the long term. We mainly studied the transfer payment compensation in the ecological barrier area of a river basin, which belongs to the category of incentive compensation.

In order to protect the ecological environment and ensure water quality in the upper reaches of the river basin, it is necessary to pay high ecological environmental protection costs, while the downstream of the river basin freely enjoy the good ecological environment provided by the upper reaches. The downstream of the river basin also continuously developing social economy, which will inevitably lead to conflicts between the upper and lower reaches of the basin. In order to ensure the fairness and efficiency of the overall development of the river basin, appropriate economic compensation for the upstream area by the downstream area has become an important means to solve the problem of unbalanced economic development of the river basin in China and realize the high-quality development of the basin. From the perspective of the supply and consumption subjects of the ecological environment, the ecological resources provided by the ecological barrier area are the typical ecological resources with clear supply subject, but with unclear consumption subject. The supply subjects of the ecological environment were mainly compensated by the government. In terms of the connotation of compensation, if the supply subjects can provide the surplus ecological value after excluding their own consumption, then there will be SEV. The purpose of SEV compensation is to make up for the loss of development opportunity cost caused by the supply subjects in the process of protecting the ecological environment (China prohibits and restricts the development of ecological barrier areas), so that the supplier can better protect the ecological environment. In addition, in the calculation of ECS, the fiscal transfer payment capacity is also considered to be one of the key factors affecting the success of EC [20].

Therefore, from the perspective of the "ecology–economy–society" complex ecosystem, this paper took the typical ecological barrier area of the river basin the TGRR as the study area, and constructed an extended emergy model to measure the SEV. The combination of emergy analysis method and the input–output analysis can effectively avoid the problems of simply calculating the ESV and ignoring the limitations of the ecological value of the region's own consumption. According to the spillover emergy, we can judge the ecological profit and loss state of each county (district) of TGRR, and further use the ECR to transform the spillover emergy into SEV, so as to combine the fiscal payment capacity of each region to obtain fair and objective compensation standard (Figure 3).

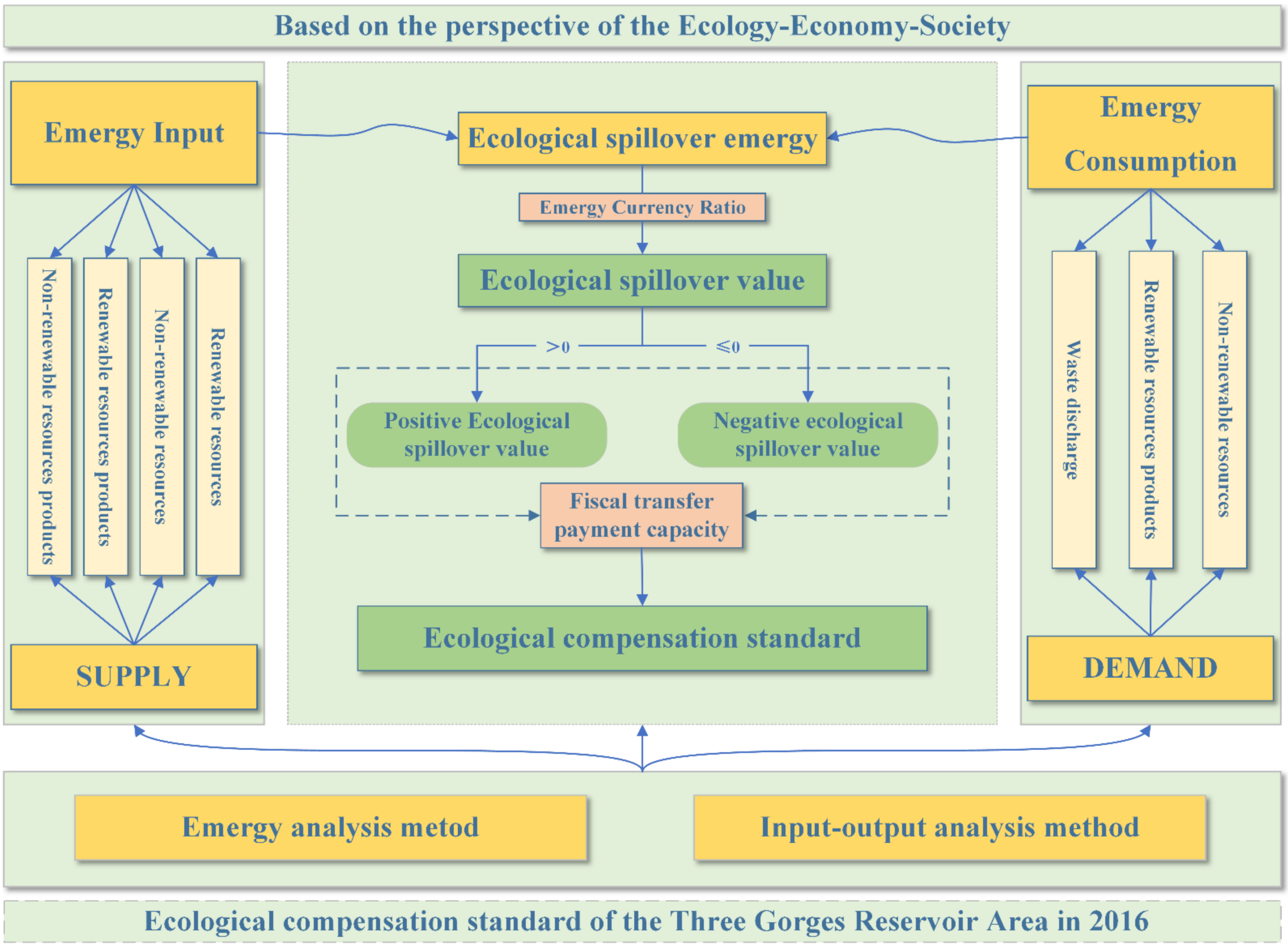

Figure 3. The research framework.

2.3. Method

2.3.1. Spillover Ecological Value: An Extended Emergy Model

In the process of calculating the SEV, the principles of reasonable basis, scientific method, and objective comparability should be fully reflected in the following three aspects: (1) Based on the existing relevant studies, it is considered that the SEV is obtained by subtracting the ecosystem's own consumption emergy from the emergy value provided by the entire study area, then the SEV is obtained by using the ECR. (2) The scientific method is the core of measuring SEV, the emergy model and input–output analysis selected in this study can scientifically measure the cross-regional SEV. (3) The SEV of each region must be objective and comparable. Emergy can reflect the objectively existing social, economic, and ecological value of the study area, and avoid the problem of incomparability caused by ignoring or omitting the ecosystem functions.

Based on the above principles, an extended emergy model (EEM) was constructed to measure the SEV as a basis for EC in the ecological barrier area. The formula of evaluating SEV is as follows:

$$V_i = \lambda_i \times OE_i \quad (1)$$

$$OE_i = FE_i - CE_i + EFD_i \quad (2)$$

where i represents the ith region in TGRR; V_i represents the SEV of the ith region; λ_i represents the ECR of the ith region, which is the annual emergy utilization of a region divided by its annual gross domestic product (GDP). OE_i represents the spillover emergy of the ith region; FE_i represents the total emergy generated by the ith region, CE_i represents the consumed emergy of the ith region, and EFD_i is the emergy of the currency flow difference of the ith region. When $OE_i > 0$, it means that the ith region provides emergy for other regions after deducting its own consumed emergy, and it is the ecological surplus, which should obtain theoretical EC fees V_i. On the contrary, when $OE_i \leq 0$, it indicates that the emergy provided by the ith region is not enough or just enough to offset the emergy consumption of its own ecosystem, so the region is in ecological deficit or ecological balance.

In this study, the TGRR involves two municipal administrative regions, comprising of 26 county (district) administrative regions. Each county (district) provides a certain amount of emergy for itself and other regions, but also consumes the emergy of itself and other regions. In the "many-to-many" EC relationship, each county (district) administrative region needs to calculate the emergy supply to other areas and its own emergy demand respectively. At the same time, the EC payment capacity of each region should be considered. This study mainly considered returning to the essence of EC, that is, compensation for the real nature losses, so as to avoid falling into the vicious circle that the more developed areas receive more compensation the worse the ecological environment. In the calculation of ECS, natural attributes are put first in EC, economic development level and artificial input are considered at the same time. It is also because each region is the main body of EC, and the compensation standard needs to refer to each region's economic affordability and fiscal stimulus. Reasonable compensation standard will promote the continuous progress of compensation projects. Therefore, this study modified the existing EC framework by taking natural contribution, artificial input, and existence value as important reference factors of emergy supply and consumption, and using the actual payment level coefficient of EC to characterize fiscal payment capacity. The calculation method of the actual payment level coefficient of EC is as follows:

$$l_i = \frac{V_i}{V_{total}} \tag{3}$$

where l_i is the actual payment level of EC of the ith region; V_{total} represents the total SEV of the study area.

Because emergy of each region may have ecological deficit or ecological surplus, and the actual payment capacity of each region should also be considered, the modified ECS of the ith region (ESC_i) is as follows:

$$ECS_i = \sum_{i=1}^{n} |V_i| \times l_i \tag{4}$$

where n is the number of county (district).

2.3.2. Emergy Analysis Method

Emergy theory was proposed by American ecologist Odum in 1980. Emergy is defined as the total effective energy directly or indirectly applied to the process of service or product formation, generally measured by solar energy [43,56]. According to this theory, all kinds of material, energy, information and economic value can be transformed into solar energy by using different solar transformities, so as to realize the connection and unification of energy flow, logistics and value stream. This is called emergy analysis method. Based on the principle of energetic and system ecology, different types or incomparable forms of energy generated by ecosystems can be converted into a single standard energy unit by this method to evaluate the functional and structural characteristics and economic benefits of different ecosystems [34,57]. What needs to be emphasized is that solar transformity is one of the key factors for us to use the emergy analysis method, which represents the emergy content per unit energy, as expressed in solar emergy joules per joule (sej/J) [42]. Further, a resource or a product's solar transformity (t) is equivalent to its solar emergy divided by its available energy, and a resource or a product's emergy can be express as [57]:

$$M = \mathrm{t} \times E \tag{5}$$

where M denotes emergy of a resource or a product (*sej*), and E is the available energy of a resource or a product (J).

2.3.3. The Total Emergy

In order to calculate thoroughly and comprehensively the cross-regional emergy of TGRR by emergy analysis, the supply and consumption emergy of the environment and resources of the regional ecosystem and the difference of cash flow must be taken into account. The input emergy of the ecosystem include renewable natural resources, non-renewable natural resources, renewable resource products, and non-renewable resource products. Among them, renewable natural resources include solar energy, wind energy, rain water chemical energy, rain water potential energy, and earth rotation energy. To avoid repeated accounting and measurement, the maximum value of renewable energy is selected as the total amount of renewable energy in a region [57]. Non-renewable natural resources include topsoil loss and soil erosion. The renewable resource products mainly consider the labor force and hydroelectric power. Because the TGRR is the largest water conservancy and hydropower project in the world, and its hydroelectric power is the main output of ecosystem products. In addition, Ghisellini et al. pointed out that labor should be regarded as a renewable resource product [58]. Moreover, Non-point source water pollution generated by agricultural production is considered a major environmental issue in the TGRR, which is related to the ecological security of the whole Yangtze River Basin and even China [59]. Due to the availability of county data, the non-renewable resource products in this study mainly include the use of agricultural chemical fertilizers and pesticides. Ecosystem emergy consumption include biological, energy, and waste emissions. The output emergy of the biological resources includes the consumption of cereal, oil plants, tobacco, vegetables, tea, fruits, meat, milk, aquatic products and forest products, and the consumption of energy resources item include the total energy consumption in each districts (counties). Waste discharge mainly include industrial waste gas and industrial waste water discharge. The currency flow includes import goods, export commodities, and foreign capital utilized. The currency flow difference refers to the sum of import goods and foreign capital utilized minus export goods (Table 1).

2.3.4. Emergy Currency Ratio

Selecting solar energy as the measurement index and benchmark facilitates the evaluation of natural resources and environmental resources, solar energy is converted into the price of natural and environmental resources through the ECR. This not only solves the problem that natural and environmental resources are difficult to measure because of the inconsistent units of measurement, but also provides a way to bridge the gap between the value of ecological resources and economic value. By introducing the ratio of total emergy to GDP (R, *sej/USD*), different natural and environmental resource's ECR_i can be calculated by the following equation:

$$ECR_i = \frac{e_i}{R} \tag{6}$$

where e_i is ith input and output resource's emergy amount (*sej*).

2.4. Data

According to the above indicators for measuring the SEV, this study takes the typical ecological barrier area of the river basin, that is, the TGRR, as an example to calculate the ECS of 26 districts (counties) in 2016. It includes the calculation of the total emergy input, ecosystem emergy consumption, currency flow input–output, and SEV. All the data are sourced from the statistical yearbook of 26 districts (counties) in 2017 and characteristic database—The Economic and Social Characteristics Development Database of the Three Gorges Reservoir Region (https://sanxia.ctbu.edu.cn/index.htm, accessed on 21 July 2021). The emergy transformities of the products involved in this paper are calculated according to previous studies [42].

Table 1. Emergy analysis in Three Gorges Reservoir Region.

Category	Item	Transformitya (*sej/J*)
Input of renewable natural resources	Solar radiation energy	1
	Rain chemical energy	15,444
	Rain geo-potential energy	8888
	Wind kinetic energy	623
	Earth cycle energy	29,000
Input of non-renewable natural resources	Topsoil loss	74,000
	Soil erosion	1.70×10^{9}
Input of renewable resource products	Hydropower	80,000
	Labor	7,560,000
Input of non-renewable resource products	Agricultural fertilizers	2.90×10^{15}
	Pesticides	1.60×10^{15}
Output of biological resources	Cereal	148,000
	Oil plants	690,000
	Tobacco	84,900
	Vegetables	83,000
	Tea	200,000
	Fruits	530,000
	Meat	4,000,000
	Milk	2,000,000
	Aquatic products	2,000,000
	Forest products	44,000
Output of energy resources	Energy consumption	25,200
Output of industrial waste	Industrial waste gas	860,000
	Industrial waste water	48,000
Currency flow	Warenimport	1.66×10^{12}
	Foreign capital actually utilized	1.66×10^{12}
Commodity export	Export commodities	1.73×10^{12}

Note: Transformities are taken from Odum et al. [42].

3. Results

3.1. The Input Emergy

By using solar transformity and ECR, the input emergy values of 26 districts (counties) in the TGRR in 2016 can be obtained, including renewable natural resources, non-renewable natural resources, renewable resource products, and non-renewable resource products (Table 2). Among them, renewable resource products (manpower and hydropower) produced the most emergy dollar values (97.91%), while the emergy dollar values of the non-renewable natural resources (topsoil loss and soil loss) supplied by the ecosystem were the least (0.08%). In terms of renewable resource products, Wanzhou District, Fuling District, and Yuzhong District had higher emergy dollar values. Among them, the emergy dollar value of renewable resource products in Wanzhou District reached the highest level (5.43×10^{10} USD), 181 times higher than in Jiulongpo District (0.033×10^{10} USD). In terms of non-renewable natural resources, Fuling District had the highest topsoil loss and soil erosion emergy value, which was 4.83×10^{7} USD, 242 times of Yuzhong District (0.02×10^{7} USD), the core urban area of Chongqing. In terms of renewable natural resources, Fuling District, Wanzhou District, and Jiangjin District produced more emergy values, which is mainly related to the rain chemical emergy value in this region. The area and annual rainfall of these three regions were relatively high. In terms of non-renewable resource products, among the 26 districts (counties), Fuling District had the highest emergy value of agricultural fertilizer and pesticide (3.22×10^{8} USD). On the contrary, because there was no agricultural land in Yuzhong District, the emergy value of non-renewable resource products was 0.

Table 2. Input emergy dollar value of ecosystem in the Three Gorges Reservoir Region in 2016.

Area	Emdollar Value of Renewable Natural Resource (Dollar)	Emdollar Value of Non-Renewable Natural Resources (Dollar)	Emdollar Value of Renewable Resource Products (Dollar)	Emdollar Value of Non-Renewable Resource Products (Dollar)
Yuzhong District	0.07×10^8	0.02×10^7	4.44×10^{10}	0.00
Jiangbei District	0.19×10^8	0.07×10^7	0.82×10^{10}	0.01×10^8
Nan'an District	0.40×10^8	0.18×10^7	1.52×10^{10}	0.07×10^8
Dadukou District	0.17×10^8	0.10×10^7	0.89×10^{10}	0.06×10^8
Shapingba District	0.09×10^8	0.05×10^7	0.34×10^{10}	0.02×10^8
Jiulongpo District	0.61×10^8	0.41×10^7	0.03×10^{10}	0.14×10^8
Beibei District	1.37×10^8	0.65×10^7	1.75×10^{10}	0.54×10^8
Yubei District	0.70×10^8	0.37×10^7	0.62×10^{10}	0.23×10^8
Changshou District	1.34×10^8	0.98×10^7	1.64×10^{10}	0.84×10^8
Banan District	2.77×10^8	1.44×10^7	2.09×10^{10}	0.73×10^8
Wanzhou District	7.34×10^8	4.07×10^7	5.43×10^{10}	2.96×10^8
Jiangjin District	5.07×10^8	3.11×10^7	3.09×10^{10}	2.35×10^8
Fuling District	6.72×10^8	4.83×10^7	5.04×10^{10}	3.22×10^8
Zhong County	1.60×10^8	1.33×10^7	1.16×10^{10}	0.91×10^8
Kaizhou District	0.92×10^8	0.53×10^7	0.42×10^{10}	0.41×10^8
Fengdu County	2.19×10^8	1.34×10^7	0.79×10^{10}	0.66×10^8
Yunyang County	2.75×10^8	1.42×10^7	1.14×10^{10}	0.67×10^8
Fengjie County	3.14×10^8	1.55×10^7	1.13×10^{10}	0.72×10^8
Wushan County	1.71×10^8	0.88×10^7	0.57×10^{10}	0.37×10^8
Shizhu County	2.95×10^8	1.40×10^7	0.53×10^{10}	0.73×10^8
Wulong District	2.41×10^8	1.24×10^7	0.51×10^{10}	0.44×10^8
Wuxi County	2.12×10^8	0.82×10^7	0.28×10^{10}	0.39×10^8
Yiling District	4.58×10^8	1.78×10^7	1.18×10^{10}	2.33×10^8
Zigui County	1.33×10^8	0.46×10^7	0.29×10^{10}	0.53×10^8
Badong County	1.01×10^8	0.45×10^7	0.27×10^{10}	0.39×10^8
Xingshan County	0.93×10^8	0.45×10^7	0.21×10^{10}	0.12×10^8
Total	5.45×10^9	2.99×10^8	3.62×10^{11}	1.99×10^9

From the perspective of spatial differences, the region with the most emergy value is the belly of the TGRR, with a total of 11 districts (counties) in Chongqing, accounting for 47.28% of the input total emergy value. Followed by the tail of the TGRR, a total of 11 districts (counties) in Chongqing, accounted for 47.13% of the total emergy value of the input. As the head of the TGRR has only four districts and counties in Hubei Province, it accounted for the least value of the total emergy value of the input (5.59%). In the belly of the TGRR, Wanzhou District and Fuling District of Chongqing had a higher total emergy value. In the tail of the TGRR, Yuzhong District and Jiangjin District of Chongqing had a higher total emergy value. The total emergy value invested in Jiulongpo District was the least among the 26 districts (counties) in the study area. In head of the reservoir, Yiling District had the highest total emergy value among the four districts (counties) of Hubei Province (Figures 4 and 5).

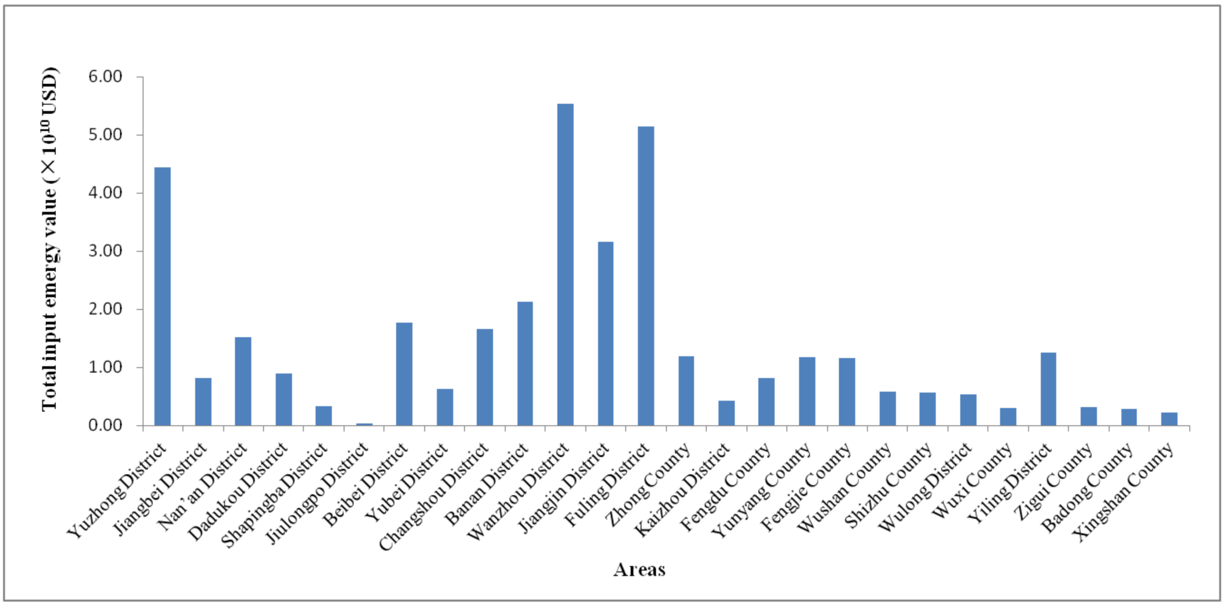

Figure 4. Total input emergy value in the Three Gorges Reservoir Region in 2016.

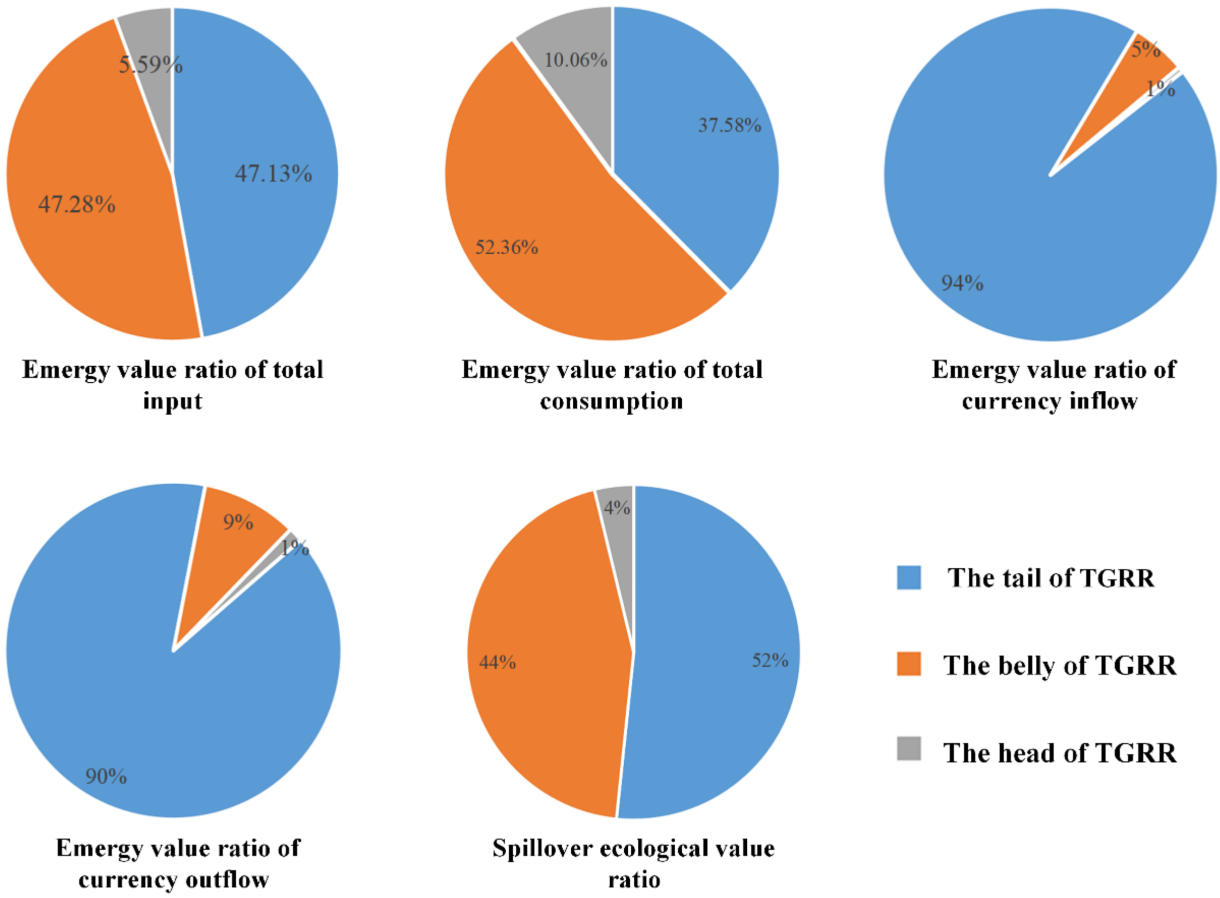

Figure 5. Emergy value ratio in the Three Gorges Reservoir Region in 2016.

3.2. The Emergy Consumed by Ecosystem

The emergy value consumption of the ecosystem in the TGRR is mainly evaluated from three aspects: waste discharge, biological resources, and energy consumption. The total consumption of the 26 districts (counties) shows that the emergy consumption value of biological resources was the highest, reaching 68.06 × 10^9 USD, followed by the emergy consumption value of 29.90 × 10^9 USD. The waste discharge had the lowest emergy value at 24.24 × 10^8 USD (Table 3), indicating that the TGRR, as an important ecological barrier area in the Yangtze River Basin, controlled the discharge of industrial waste relatively well. In terms of waste discharge, among the 26 districts (counties), Jiulongpo District, Yiling District, and Yuzhong District had higher waste discharge emergy value. Among them, Jiulongpo District was the highest, 590 times of Badong County and Wushan County. In terms of biological resources, Wanzhou District and Fuling District had higher emergy consumption value of biological resources. Wanzhou District had the highest emergy consumption value of 9.57 × 10^9 USD, while Jiangbei District had the lowest emergy consumption value of biological resources, only 0.03 × 10^9 USD. In terms of energy consumption, Fuling District and Changshou District had higher emergy value, among which Fuling District had the highest emergy value, while Wushan County, Wuxi County, and Badong County had lower emergy value, only 1/712 of Fuling District.

Table 3. Consumed emergy dollar value of ecosystem in the Three Gorges Reservoir Region in 2016.

Area	Emdollar Value of Waste Discharge (Dollar)	Emdollar Value of Consumption of Biological Resources (Dollar)	Emdollar Value of Energy Consumption (Dollar)
Yuzhong District	2.91 × 10^8	0.31 × 10^9	0.05 × 10^9
Jiangbei District	0.22 × 10^8	0.03 × 10^9	0.15 × 10^9
Nan'an District	0.32 × 10^8	1.79 × 10^9	0.63 × 10^9
Dadukou District	0.27 × 10^8	0.96 × 10^9	0.52 × 10^9
Shapingba District	0.08 × 10^8	0.06 × 10^9	0.08 × 10^9
Jiulongpo District	5.90 × 10^8	3.26 × 10^9	1.34 × 10^9
Beibei District	0.21 × 10^8	0.91 × 10^9	1.26 × 10^9
Yubei District	0.17 × 10^8	0.86 × 10^9	0.21 × 10^9
Changshou District	2.34 × 10^8	3.71 × 10^9	6.45 × 10^9
Banan District	0.81 × 10^8	2.98 × 10^9	0.48 × 10^9
Wanzhou District	1.25 × 10^8	9.57 × 10^9	4.04 × 10^9
Jiangjin District	2.26 × 10^8	6.28 × 10^9	3.84 × 10^9
Fuling District	2.04 × 10^8	8.23 × 10^9	7.12 × 10^9
Zhong County	0.04 × 10^8	3.30 × 10^9	0.43 × 10^9
Kaizhou District	0.36 × 10^8	5.23 × 10^9	0.13 × 10^9
Fengdu County	0.18 × 10^8	2.10 × 10^9	0.65 × 10^9
Yunyang County	0.46 × 10^8	2.70 × 10^9	0.06 × 10^9
Fengjie County	0.11 × 10^8	2.78 × 10^9	0.05 × 10^9
Wushan County	0.01 × 10^8	1.29 × 10^9	0.01 × 10^9
Shizhu County	0.53 × 10^8	1.61 × 10^9	0.37 × 10^9
Wulong District	0.03 × 10^8	1.46 × 10^9	0.05 × 10^9
Wuxi County	0.03 × 10^8	0.87 × 10^9	0.01 × 10^9
Yiling District	3.37 × 10^8	5.41 × 10^9	1.18 × 10^9
Zigui County	0.04 × 10^8	1.03 × 10^9	0.37 × 10^9
Badong County	0.01 × 10^8	0.77 × 10^9	0.01 × 10^9
Xingshan County	0.32 × 10^8	0.54 × 10^9	0.41 × 10^9
Total	24.24 × 10^8	68.06 × 10^9	29.90 × 10^9

It can be seen from the total emergy consumption value that among the 26 districts (counties) in the TGRR (Figure 6), the emergy consumption values of Fuling District and Wanzhou District were higher. Among them, the emergy consumption value of Fuling District was the highest, reaching 1.55 × 10^{10} USD, and Shapingba District had the lowest emergy consumption value, only 0.01 × 10^{10} USD. Among the four districts (counties) in Hubei Province, Yiling District had the highest emergy consumption value (0.69×10^{10} USD), which was 8.63 times that of Badong District (0.08×10^{10} USD) with the lowest emergy consumption value. The emergy value ratio of total consumption of the three regions in the TGRR (Figure 5) shows that the four districts (counties) in the head of the reservoir only consumed 10.06%, which was also due to the small number of districts (counties) in the head of the reservoir. The 11 districts (counties) in the belly of the reservoir consumed the most emergy value, accounting for 52.36% of the total emergy value, and the 11 districts (counties) in the tail of the reservoir accounted for 37.58% of the total emergy value.

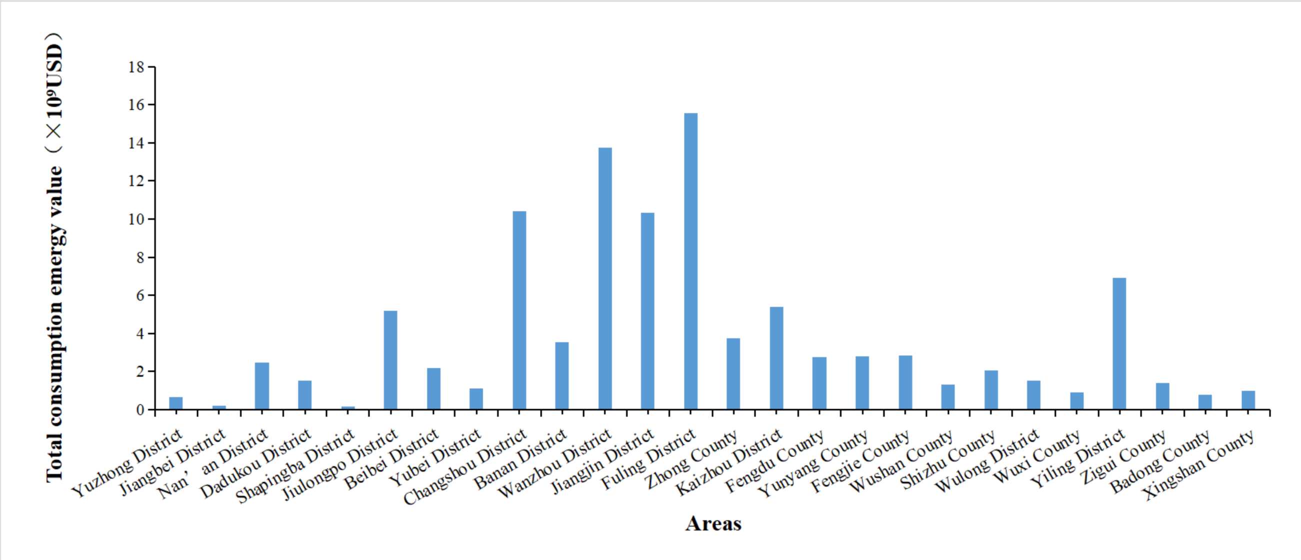

Figure 6. Total consumption emergy value in the Three Gorges Reservoir Region in 2016.

3.3. The Emergy Currency Flow

The emergy currency flow includes emergy currency inflow and emergy currency outflow. In the TGRR, emergy currency inflow is mainly evaluated from two aspects: importation of goods and utilization of foreign capital, and emergy currency outflow is mainly accounted for by commodity export. Through the inflow and outflow of emergy currency, we can get the difference of emergy currency among the 26 districts (counties) of the TGRR. The total emergy currency flow of the 26 districts (counties) shows that the total value of emergy currency inflow was the highest, reaching 4.65×10^{10} USD, followed by total value of consumption of commodity export about 4.56×10^{10} USD, and consequently the total value of currency difference of the TGRR was obtained, approximately 9.74×10^{8} USD (Table 4).

In regard to emergy currency inflow, among the 26 districts (counties), Yuzhong District, Yubei District, Jiangbei District had higher value of emergy currency inflow. Among them, Yuzhong District was the highest, about 29,000 times of Fengjie County. In regard to emergy currency outflow, Shapingba District had the highest value of emergy currency outflow (8.32×10^{9} USD). In addition, Wuxi County had the lowest value of emergy currency outflow, only 9.23×10^{5} USD. In terms of emergy currency difference (Figure 7), Yuzhong District (4.87×10^{9} USD), Jiangbei District (1.90×10^{9} USD) and Banan District (1.84×10^{9} USD) had higher value of emergy currency difference. These areas were dominated by currency inflow. On the other hand, Shapingba District (-4.92×10^{9} USD), Wanzhou District (-2.20×10^{9} USD) and Yubei District (-1.76×10^{9} USD) had lower value of emergy currency difference. These areas were dominated by currency outflow.

Table 4. The emergy currency flow in the Three Gorges Reservoir Region in 2016.

Area	Emdollar Value of Emergy Currency Inflow (Dollar)	Emdollar Value of Consumption of Commodity Export (Dollar)	Emdollar Value of Emergy Currency Difference (Dollar)
Yuzhong District	9.80×10^9	4.92×10^9	4.87×10^9
Jiangbei District	6.70×10^9	4.80×10^9	1.90×10^9
Nan'an District	4.37×10^9	4.72×10^9	-3.58×10^8
Dadukou District	8.10×10^8	5.66×10^8	2.45×10^8
Shapingba District	3.40×10^9	8.32×10^9	-4.92×10^9
Jiulongpo District	3.58×10^7	8.36×10^7	-4.78×10^7
Beibei District	3.82×10^9	2.18×10^9	1.64×10^9
Yubei District	8.37×10^9	1.01×10^{10}	-1.76×10^9
Changshou District	7.27×10^8	1.86×10^9	-1.14×10^9
Banan District	3.98×10^9	2.15×10^9	1.84×10^9
Wanzhou District	1.60×10^8	2.36×10^9	-2.20×10^9
Jiangjin District	1.82×10^9	1.02×10^9	8.02×10^8
Fuling District	2.28×10^9	1.64×10^9	6.39×10^8
Zhong County	3.70×10^6	2.29×10^7	-1.92×10^7
Kaizhou District	5.06×10^6	1.33×10^7	-8.20×10^6
Fengdu County	8.01×10^6	7.34×10^7	-6.54×10^7
Yunyang County	4.90×10^6	4.23×10^6	6.67×10^5
Fengjie County	3.38×10^5	7.15×10^6	-6.82×10^6
Wushan County	1.28×10^6	3.20×10^6	-1.92×10^6
Shizhu County	1.21×10^6	4.51×10^7	-4.39×10^7
Wulong District	6.63×10^5	1.90×10^7	-1.83×10^7
Wuxi County	1.02×10^6	9.23×10^5	1.01×10^5
Yiling District	2.00×10^8	3.14×10^8	-1.14×10^8
Zigui County	1.95×10^7	3.74×10^7	-1.80×10^7
Badong County	8.97×10^6	4.12×10^7	-3.22×10^7
Xingshan County	2.15×10^7	2.29×10^8	-2.08×10^8
Total	4.65×10^{10}	4.56×10^{10}	9.74×10^8

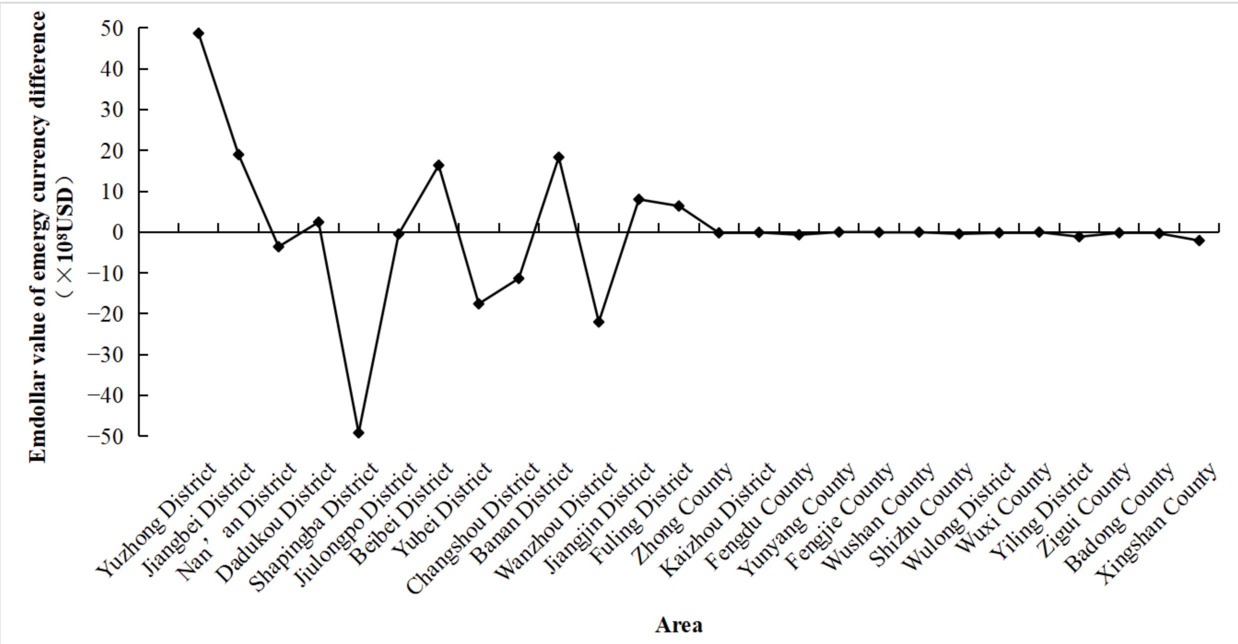

Figure 7. Emdollar value of emergy currency difference in the Three Gorges Reservoir Region in 2016.

Emergy currency flow ratio of the three regions in the TGRR (Figure 5) shows that the emergy currency inflow and outflow of the head of the TGRR, only four districts and counties in Hubei Province, accounted for only about 1%. Nevertheless, the emergy currency inflow and outflow of the tail of the TGRR accounted for the largest, about 94% and 90%. This is mainly due to the fact that the main economic activities of the TGRR are concentrated in this area. Additionally, The main function of the belly of the TGRR is to protect the ecological environment, so economic activities are not so frequent. The emergy currency inflow and outflow in the belly of the TGRR accounted for about 5% and 9%, respectively.

3.4. Spillover Ecological Value

According to the calculation results of emergy input, emergy consumption, and emergy currency difference of the ecosystem in the TGRR, the SEV in the TGRR can be obtained by putting them into the calculation formula (1). Among them, emergy input of the ecosystem in the TGRR is composed of renewable natural resources, non-renewable natural resources, renewable resource products, and non-renewable resource products. Emergy consumption of the ecosystem in the TGRR is consist of three aspects: waste discharge, biological resources, and energy consumption. Emergy currency difference of the ecosystem is obtained by emergy currency inflow minus emergy currency outflow.

In regard to emergy input (Table 5 and Figure 8), it can be seen that the emergy input of Wanzhou District was the highest, reaching 5.54×10^{10} USD, followed by the emergy input of Fuling District, about 5.14×10^{10} USD. However, Jiulongpo District had the lowest emergy input, about 4.18×10^{8} USD, that was 1/132 of Fuling District. On the other hand, emergy consumption and emergy currency difference of the ecosystem in the TGRR have been analyzed in Sections 3.2 and 3.3, and will not be repeated here. In regard to SEV, Yuzhong District, Wanzhou District, and Fuling District had higher SEV. Among them, Yuzhong District was the highest, reaching 4.86×10^{10} USD, about 50 times of Xingshan County. On the contrary, Jiulongpo District, Shapingba District, and Kaizhou District had lower SEV with negative values, which were -4.82×10^{9} USD, -1.66×10^{9} USD, and -1.10×10^{9} USD, respectively. The SEV ratio of in the TGRR (Figure 5) shows that the belly and tail of TGRR contributed the most to the SEV, with the combined contribution rate reached 96%. The SEV of the head of TGRR only accounted for 4%. In accordance with the above results, we concluded that the total SEV of the TGRR was 2.70×10^{11} USD. It can be seen that the TGRR is in the state of ecological surplus and should be compensated accordingly.

3.5. Ecological Compensation Standard

It is well known that the compensation paid or received should be included in the total EC amount. To calculate the actual compensation amounts of different regions in the TGRR, we take the absolute value of the ESV of the TGRR (i.e., the total EC amount). Based on the above analysis results of Section 3.4, Shapingba District, Jiulongpo District, and Kaizhou District are consumers of ecosystem services, and other areas are providers of ecosystem services. Combined with the EC principle of "who benefits, who pays", different regions of TGRR should assume more different degrees of mission and obligation for the ecological environment protection and management of the reservoir area, obtaining or paying corresponding compensation funds. According to the actual payment level coefficient and the total SEV of TGRR, the ECS can be calculated by Formulas (3) and (4), as shown in Table 6.

Table 5. Spillover ecological value in the Three Gorges Reservoir Region in 2016.

Area	Emdollar Value of Input (Dollar)	Emdollar Value of Consumption (Dollar)	Emdollar Value of Emergy Currency Difference (Dollar)	Spillover Ecological Value (Dollar)
Yuzhong District	4.44×10^{10}	6.52×10^{8}	4.87×10^{9}	4.86×10^{10}
Jiangbei District	8.25×10^{9}	2.01×10^{8}	1.90×10^{9}	9.95×10^{9}
Nan'an District	1.53×10^{10}	2.45×10^{9}	-3.58×10^{8}	1.25×10^{10}
Dadukou District	8.95×10^{9}	1.51×10^{9}	2.45×10^{8}	7.68×10^{9}
Shapingba District	3.41×10^{9}	1.47×10^{8}	-4.92×10^{9}	-1.66×10^{9}
Jiulongpo District	4.18×10^{8}	5.19×10^{9}	-4.78×10^{7}	-4.82×10^{9}
Beibei District	1.77×10^{10}	2.19×10^{9}	1.64×10^{9}	1.71×10^{10}
Yubei District	6.26×10^{9}	1.09×10^{9}	-1.76×10^{9}	3.41×10^{9}
Changshou District	1.66×10^{10}	1.04×10^{10}	-1.14×10^{9}	5.06×10^{9}
Banan District	2.13×10^{10}	3.54×10^{9}	1.84×10^{9}	1.96×10^{10}
Wanzhou District	5.54×10^{10}	1.37×10^{10}	-2.20×10^{9}	3.95×10^{10}
Jiangjin District	3.17×10^{10}	1.03×10^{10}	8.02×10^{8}	2.21×10^{10}
Fuling District	5.14×10^{10}	1.55×10^{10}	6.39×10^{8}	3.65×10^{10}
Zhong County	1.19×10^{10}	3.73×10^{9}	-1.92×10^{7}	8.13×10^{9}
Kaizhou District	4.30×10^{9}	5.39×10^{9}	-8.20×10^{6}	-1.10×10^{9}
Fengdu County	8.17×10^{9}	2.77×10^{9}	-6.54×10^{7}	5.33×10^{9}
Yunyang County	1.18×10^{10}	2.80×10^{9}	6.67×10^{5}	9.00×10^{9}
Fengjie County	1.17×10^{10}	2.83×10^{9}	-6.82×10^{6}	8.82×10^{9}
Wushan County	5.87×10^{9}	1.31×10^{9}	-1.92×10^{6}	4.57×10^{9}
Shizhu County	5.67×10^{9}	2.04×10^{9}	-4.39×10^{7}	3.58×10^{9}
Wulong District	5.43×10^{9}	1.52×10^{9}	-1.83×10^{7}	3.89×10^{9}
Wuxi County	3.08×10^{9}	8.83×10^{8}	1.01×10^{5}	2.20×10^{9}
Yiling District	1.25×10^{10}	6.93×10^{9}	-1.14×10^{8}	5.47×10^{9}
Zigui County	3.14×10^{9}	1.41×10^{9}	-1.80×10^{7}	1.71×10^{9}
Badong County	2.84×10^{9}	7.82×10^{8}	-3.22×10^{7}	2.03×10^{9}
Xingshan County	2.17×10^{9}	9.83×10^{8}	-2.08×10^{8}	9.84×10^{8}
Total	3.70×10^{11}	1.00×10^{11}	9.74×10^{8}	2.70×10^{11}

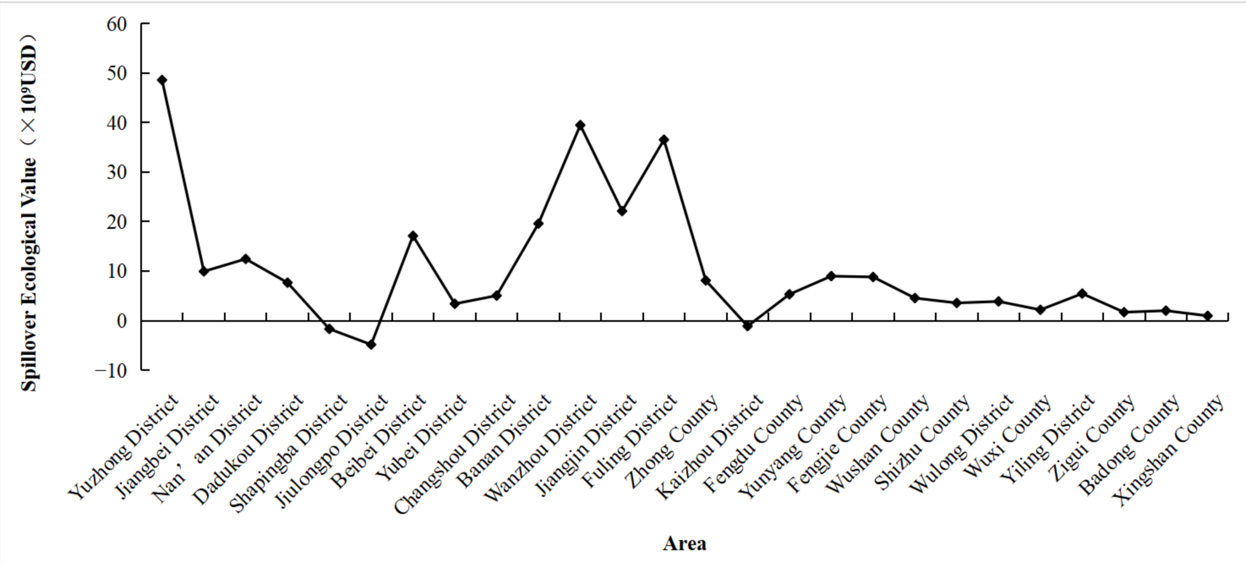

Figure 8. Spillover ecological value in the Three Gorges Reservoir Region in 2016.

Table 6. Actual compensation amount in the Three Gorges Reservoir Region in 2016.

Area	Spillover Ecological Value (Dollar)	Actual Payment Level Coefficient (Dollar)	Actual Compensation Amount (Dollar)
Yuzhong District	4.86×10^{10}	0.1798	5.13×10^{10}
Jiangbei District	9.95×10^{9}	0.0368	1.05×10^{10}
Nan'an District	1.25×10^{10}	0.0461	1.32×10^{10}
Dadukou District	7.68×10^{9}	0.0284	8.11×10^{9}
Shapingba District	1.66×10^{9}	−0.0061	-1.75×10^{9}
Jiulongpo District	4.82×10^{9}	−0.0178	-5.09×10^{9}
Beibei District	1.71×10^{10}	0.0634	1.81×10^{10}
Yubei District	3.41×10^{9}	0.0126	3.60×10^{9}
Changshou District	5.06×10^{9}	0.0187	5.35×10^{9}
Banan District	1.96×10^{10}	0.0726	2.07×10^{10}
Wanzhou District	3.95×10^{10}	0.1461	4.17×10^{10}
Jiangjin District	2.21×10^{10}	0.0819	2.34×10^{10}
Fuling District	3.65×10^{10}	0.1352	3.86×10^{10}
Zhong County	8.13×10^{9}	0.0301	8.58×10^{9}
Kaizhou District	1.10×10^{9}	−0.0041	-1.16×10^{9}
Fengdu County	5.33×10^{9}	0.0197	5.63×10^{9}
Yunyang County	9.00×10^{9}	0.0333	9.50×10^{9}
Fengjie County	8.82×10^{9}	0.0327	9.32×10^{9}
Wushan County	4.57×10^{9}	0.0169	4.82×10^{9}
Shizhu County	3.58×10^{9}	0.0133	3.78×10^{9}
Wulong District	3.89×10^{9}	0.0144	4.11×10^{9}
Wuxi County	2.20×10^{9}	0.0081	2.32×10^{9}
Yiling District	5.47×10^{9}	0.0203	5.78×10^{9}
Zigui County	1.71×10^{9}	0.0063	1.81×10^{9}
Badong County	2.03×10^{9}	0.0075	2.14×10^{9}
Xingshan County	9.84×10^{8}	0.0036	1.04×10^{9}
Total	2.85×10^{11}	1	2.85×10^{11}

Known from Table 6, through the different actual payment level coefficient, the EC amount can be redistributed in different regions that can increase the reliability, operability and rationality of EC. According to the results, listed in descending order of the EC amount in each district: Yuzhong District > Wanzhou District > Fuling District > Jiangjin District > Banan District > Beibei District > Nan'an District > Jiangbei District > Yunyang County > Fengjie County > Zhong County > Dadukou District > Yiling District > Fengdu County > Changshou District > Wushan County > Wulong District > Shizhu County > Yubei District > Wuxi County > Badong County > Zigui County > Xingshan County > Kaizhou District > Shapingba District > Jiulongpo District. On the one hand, Shapingba District, Jiulongpo District, and Kaizhou District were negative compensation areas. These regions enjoy the ecosystem services provided by other regions and need to pay corresponding EC amounts to other regions, about 1.75×10^9 USD, 5.09×10^9 USD, and 1.16×10^9 USD, respectively. On the other hand, except for the above three areas, the other areas were all positive compensation areas which provided different degrees of positive SEV and need to be compensated. In terms of actual compensation amount, Yuzhong District (5.13×10^{10} USD), Wanzhou District (4.17×10^{10} USD) and Fuling District (3.86×10^{10} USD) had higher compensation amount (Figures 9 and 10).

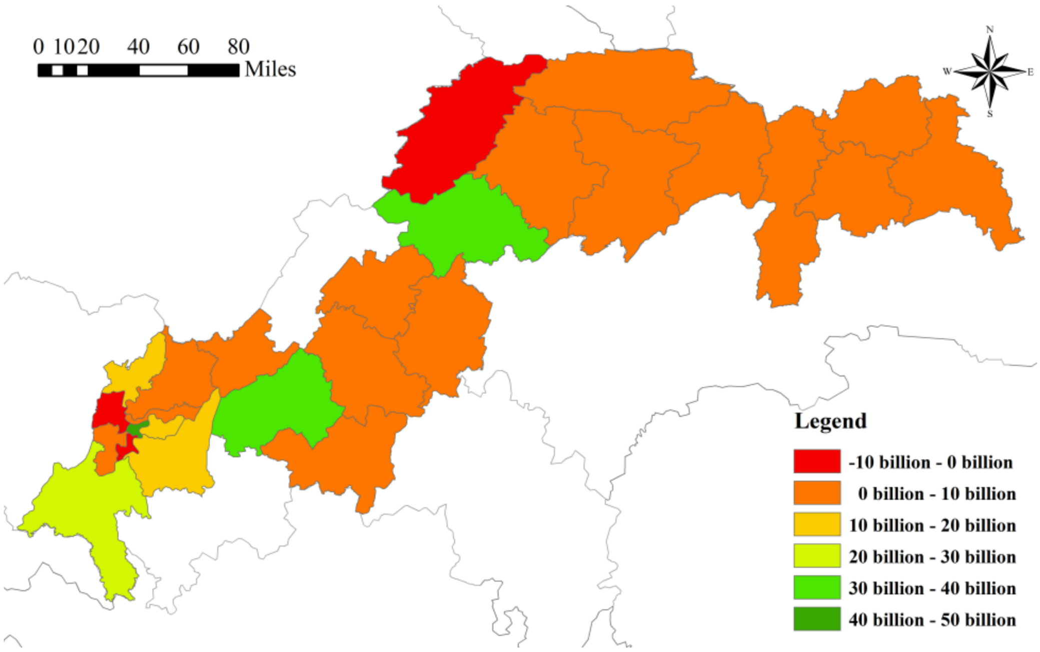

Figure 9. Ecological compensation standard map of the Three Gorges Reservoir Region in 2016.

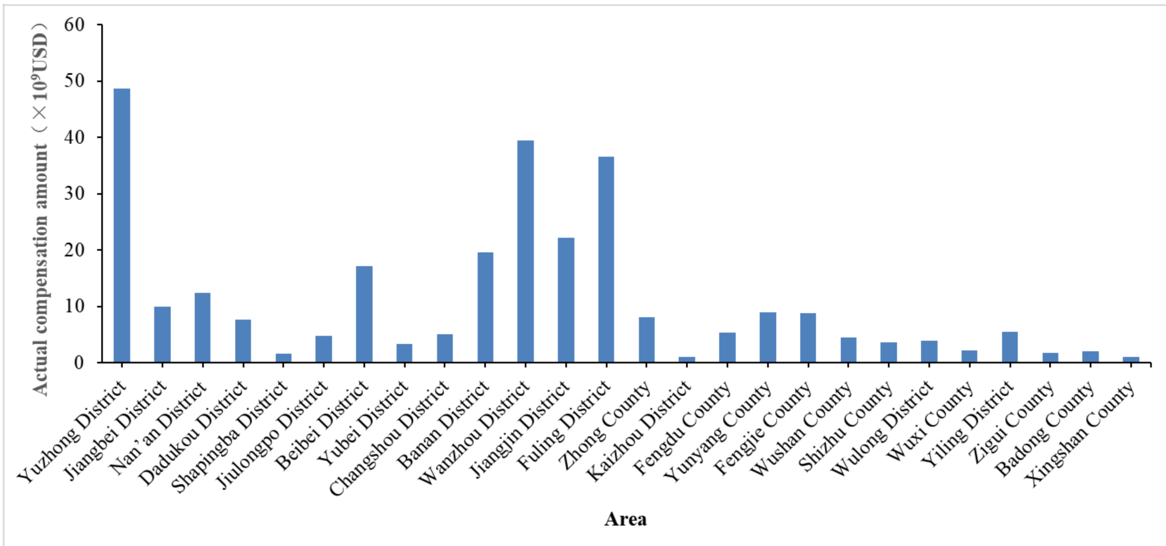

Figure 10. Actual compensation amount in the Three Gorges Reservoir Region in 2016.

4. Discussion

4.1. The Rationality and Reliability of Emergy Analysis

Based on the research results of ECS, it can be seen that the methods for determining ECS mainly include a contingent valuation method (CVM) [32,33], ecological footprint method [34,35], ESV evaluation method [36–38], etc., but it is difficult to reach a uniform standard. Emergy analysis uses emergy as a unified standard for measuring ecological service functions, which overcomes the disadvantages of previous environmental economics methods that are subjective [60–62], and solves the difficulty in connecting material flow, energy flow and economic flow [63]. The calculated results are clear and accurate, and can reflect the dynamic changes of the compensation standard, which is convenient for further analysis of the internal and objective characteristic of EC related issues. Therefore, the emergy analysis method is very suitable for complex system. It can comprehensively analyze the sustainability of the system from different aspects such as ecological environment, society and economy. It has been applied in many different fields, such as industrial system [64], urban eco-economic system [65], forestry ecosystem [66], Land resource management [67] and so on. Emergy analysis method improves people's understanding of complex system and promoted the advancement of research [68]. Drawing lessons from the advantages of emergy in dealing with the relationship between unmeasurable factors, this paper presents the research system of watershed ECS based on emergy analysis, and specifically calculates the watershed ECS in the TGRR, which verifies the feasibility and advancement of applying emergy analysis to EC research.

4.2. Relevant Analysis of Results

Ecosystem can continuously provide energy for human life, promote ecological environmental protection and reconstruction, and contribute to the sustainable development of regional economy. For example, in 2017, the total ecosystem production value of Aba Autonomous Prefecture in Sichuan Province was 1.54×10^{11} USD, which is about 35 times the local GDP (4.37×10^{9} USD) (China Environment News, 2017). Similarly, in 2019, the ecological value of Inner Mongolia (6.49×10^{11} USD) was about 2.6 times of its GDP (2.50×10^{11} USD) in the same period (China Youth Network, 2019). In this study, by considering actual payment capacity, the theoretical total value of EC amount of TGRR was 2.85×10^{11} USD, about 1.51 times of GDP of the TGRR in 2016 (1.88×10^{11} USD), which is proved reasonable and reliable.

Further, our results showed significant differences in emergy among regions. Specially, the total emergy values of Wanzhou District, Fuling District and Yuzhong District are higher in both the input and output regions. In terms of Wanzhou District, located in the core belly of the TGRR, it is the district and county with the largest population, the largest urban volume and the most management units in Chongqing. It has frequent economic activities, rich water energy resources, large resource consumption and high employment. At the same time, Chongqing Three Gorges Water Conservancy and Electric Power Group is located in Wanzhou District. It has its own power plant and power supply network, which can provide a lot of power for the Wanzhou District. This is also one of the reasons why Wanzhou District ranks first in emergy input and output areas. On the other hand, most areas in Western China are ecologically fragile, and Wanzhou District is no exception. Due to the continuous expansion of human activities, problems such as topsoil loss and soil erosion have gradually emerged, and the ecological environment and biodiversity of Wanzhou District are also facing challenges. In order to protect the ecology, in recent years, the Yangtze River Shelterbelt Project, Natural Forest Protection Project, Returning Farmland to Forest Project, Reservoir Week Greening Project and other system projects have been implemented on Wanzhou District, which has facilitated the regeneration and renewal of the internal resources of the ecosystem. This also shows that policy support and promotion have a significant impact on ecological compensation and ecological protection, and can effectively promote the coordinated development of the economy and the ecological environment [69]. Because of the particularity of the ecological environment, most areas of the TGRR is not suitable for the development of industry, but for the development of agriculture. This is the case in Fuling District. Fuling District has the largest cultivated land area in the study area. The terrain rises from northwest to southeast with the climatic characteristics of progressive temperature, increasing precipitation, daily sufficient and abundant rain. Therefore, the local leading industry is agriculture, and agricultural employees account for more than half of the region's population, which also strongly promotes the development of local employment. On the other hand, the utilization rate of non-renewable resource products such as chemical fertilizers and pesticides in Fuling District is relatively prominent in the TGRR, which is inseparable from the development of agriculture. But this is also one of the main reasons for non-point source water pollution in the TGRR. Therefore, Fuling District is also in the vanguard of emergy input and output areas. In terms of Yuzhong District, one of the nine main districts of Chongqing, is an area with an economy based on the tertiary industry, and there is basically no agriculture. This area is the main circulation hub of trade industry, financial industry and tourism, as well as the main gathering place of various talents. It has brought a large part of the economic flow to the TGRR, which is also one of the main reasons why Yuzhong District ranks the top three in terms of emergy input and emergy currency flow.

Remarkably, in addition to the typical areas mentioned above, Shapingba District had the highest value of emergy currency outflow. This is mainly because it as an important fulcrum connecting "One Belt and One Road" and the starting point of the new western land-sea corridor. Shapingba District is one of the open platforms of the transportation hub, railway port, and bonded center of the Chongqing. It has advantages in location and transportation, which is convenient for goods transportation relying on the channel and port resources. However, the construction of infrastructure in this area will have a negative impact on the ecosystem due to spatial compression. Likewise, Jiulongpo District is a typical industrial district, with the number of industrial parks ranking second in Chongqing. Automobile and motorcycle industry is one of the traditional advantageous industries in this area, and a large number of aluminum processing enterprises are highly concentrated here. Therefore, the emergy value of industrial waste discharge in Jiulongpo District is relatively high compared with other regions (Table 3). Similarly, as the traditional industrial base and the main battlefield of new industrialization in Chongqing, the leading industries of Changshou District are chemical industry and steel industry, so the energy consumption of this area is far higher than that of other areas. These reasons have brought great impact and hindrance to the healthy development of the ecosystem in the TGRR. Finally, according to the results of Figure 9, besides Shapingba District and Jiulongpo District, Kaizhou District is also a negative compensation area. Kaizhou District has the largest area of hydro-fluctuation belt in the TGRR. The hydro-fluctuation belt is the area where the submerged land periodically emerges from the water surface when the water level changes seasonally, and it is a sensitive area with very fragile ecological environment. During the dry season, land plants and near-shore aquatic plants on bare ground grow rapidly, and a large number of plants rot after being flooded with water. If not handled in time, serious internal pollution is easily formed. Moreover, agricultural non-point source pollution in Kaizhou District in 2016 was also very serious without timely control. Under the superposition of the dual reasons, the local ecosystem has been seriously damaged, which has caused a great impact on the economy, society and ecology of the TGRR. Therefore, it is normal for Kaizhou District to be a negative compensation area.

4.3. Policy Implications

The National People's Congress of the People's Republic of China has taken the establishment of the EC mechanism as a key recommendation for three consecutive years, indicating the importance and urgency of establishing the EC mechanism. The TGRR is an important part of the Yangtze River Economic Belt, its ecological environment construction and protection is one of the three key tasks of the follow-up work of the Three Gorges Project, which is also related to the sustainable development of the upper, middle and lower reaches of the Yangtze River Basin. Therefore, it is of great significance to calculate and explore the ECS in the TGRR. According to the calculation results of this study, there are obvious differences in the amount of EC among different areas of the TGRR. Some areas are positive compensation areas, and some areas are negative compensation areas. The government should not adopt a "one-size-fits-all" approach when formulating policies, but adopt diversified and differentiated policy measures in response to different situations [70]. Based on this, the following policy implications are given:

Firstly, The government of TGRR should establish corresponding regional EC mechanisms according to the status quo of different regions and realize differentiated EC standards [71], such as establishing county-level EC funds or ecological industry compensation funds. Meanwhile, the government should actively optimize the allocation structure of financial resources, improve the standard of EC, expand the transfer payment of ecologically protected areas, and expand the scope of vertical EC [72], such as compensation for the cost of protecting or destroying the ecosystem in the TGRR, compensation for the development opportunity cost of environmental sacrifice of protecting the ecosystem in the TGRR, and compensation for the region or object with significant ecological value in the TGRR.

Secondly, The government of TGRR should actively raise compensation funds through multiple channels and establish a market-oriented and diversified EC mechanism [73]. China's river basin EC funds are mainly provided by the central government or government departments of different provinces and cities. The government faces relatively heavy financial pressures, and it is difficult to guarantee the orderly implementation of EC [74]. Therefore, it is very meaningful to establish a cooperative mechanism between the government, the market and the society, which can broaden the channels for marketization and socialization of EC [75], and ensure the smooth advancement of differentiated EC in different regions.

Thirdly, the leading industries in some areas of the TGRR are polluting industries, posing a potential threat to the ecosystem. There is a dynamic impact between the EC policy and the upgrading of the industrial structure [72]. Therefore, the government and enterprises should actively promote the upgrading and transformation of the industrial structure in various regions, promote the development of low-carbon industries, reduce pollution and damage to the ecological environment, and promote the improvement of EC mechanism. Simultaneously, the upgrading and renewal of the industrial structure can effectively promote the development of green ecology [76], the government and enterprises could adjust the industrial structure by the ecological advantages and resources of the TGRR, promote the development of ecological green economy, and then deepen the harmonious development of society, economy and ecology.

Finally, combined with Chinese characteristics, the relevant departments in the TGRR should give full play to the leading role of the government, actively promote regional exchanges and cooperation, establish friendly consultation system, build cross-regional EC coordination mechanism, and jointly build early warning consultation and emergency response linkage working mechanism for cross-regional environmental pollution events and regional environmental pollution problems. Moreover, it is necessary to actively promote the establishment of multi-safeguard systems such as inter-regional ecological environmental information notification, water pollution prevention and control, and coordination of special funds for ecological restoration. On the basis of comprehensive consideration of ecological, economic, social and other factors, explore reasonable ways of harmonious coexistence [73] and realize the situation of "cost sharing, benefit sharing, and cooperation and co-governance".

5. Conclusions

The essence of EC is the purchase of ecological services. Determining the allocation standard of EC amount in the TGRR is equivalent to determining the ecological value that each region can provide. In this paper, the allocation standard of EC is defined as spillover ecological value. At present, few scholars have used spillover ecological value to calculate the ECS. The measurement methods of ECS mainly include equivalent method, market value method, and shadow engineering method, etc., and their applicable conditions are all different. Based on an extended emergy analysis in this paper, it converted all kinds of energy in the ecosystem that cannot be directly compared into solar energy value that can be measured uniformly, which took into account not only the ESV of all regions in the TGRR, but also the scarcity value of the ecosystem in the TGRR and its own consumption of resources in the the TGRR.

The results showed that in 2016, the total EC of TGRR reached 2.85×10^{11} USD, and the TGRR was in the state of ecological surplus. Comparison of SEV of the TGRR shows that the level of SEV is mainly affected by ecology, economy and society, and is fluctuated with the change of the scarcity of ecosystem resources and the consumption of resources themselves. Therefore, different ECS can be formulated according to regional differences.

At the same time, many factors can determine the allocation standard of cross-regional EC. Since the complexity of ecological, economic and social factors of TGRR is fully considered in the emergy calculation process, taking SEV as the intermediate conversion variable can more comprehensively reflect the losses caused by different factors, and make the quantitative results of EC more accurate and specific. The study of the mechanism of watershed EC is beneficial, for it can provide some references for relevant departments to improve the cross-regional EC system. It is worth noting that the allocation standard of cross-regional EC constructed in this paper is only applicable to the incentive cross-regional EC. In addition, the method discussed in this paper can also be applied to more macro or micro fields.

This study also has limitations. It only calculates the SEV of the TGRR in 2016, and lacks the time dynamic comparison of the same type data. Research on the time dynamic comparison needs further research in the future. Meanwhile, some data cannot be obtained when calculating the emergy value. The next step will be to make up for the lack of data by conducting a more micro approach to household surveys.

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